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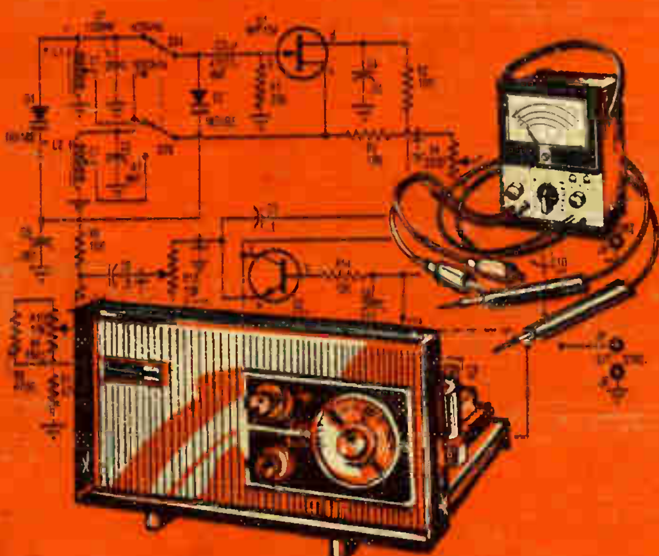
RADIOMANS GUIDE



RADIOMANS GUIDE

by Edwin P. Anderson

Revised and Updated
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Foreword

When radio was first developed, it was hailed as the miracle of the age, yet even the early experimenters responsible for its inception could never have realized the true significance of their efforts. Early radio (wireless) equipment provided communication by such means as the Morse, Continental, and Navy codes. This was a major achievement at that time, making possible the rescue of many victims of ship disasters and greatly facilitating commercial transactions. From the beginning, wireless communication captured the imagination of the amateur fraternity, with the result that radio "hams" were instrumental in the development of short-wave technology. In turn, round-the-world radio communication became possible at any time of the day or night, using low-power transmitters.

Today, the uses of radio are practically unlimited in the fields of industry, broadcasting, two-way communication, navigation, space exploration, surveillance, and medicine—just to name a few. To become active in the ever-expanding field of radio requires that a person first have a considerable knowledge of electronic theory and principles. There is no better way to acquire this knowledge than by reading and benefiting from the experience of others.

It is therefore the purpose of this book to provide a sound understanding of the principles of radio and to stimulate your interest to the point where further study and research are desired. The primary objective has been to present the subject as briefly and clearly as possible by arranging the discussions in a progressive and logical order. Mathematics has been kept to a minimum, but where problems were necessary, examples have been worked out to aid the reader.

It is our sincere hope that you find this book both interesting and informative, and that you will utilize the information contained herein to your advantage.

ROBERT G. MIDDLETON

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CHAPTER 1

Elements of Radio

The theory of radio is based on the radiation and reception of energy transmitted through space. To understand radio one must first become familiar with the basic principles of this energy and the circuits associated with it.

RADIO WAVES

It is a well-known fact that a stone thrown into a pond produces ripples or waves on the surface of the water. These waves travel outward from the point of disturbance in concentric circles of ever increasing diameters until they reach the shore (Fig. 1). The number of waves breaking on the shore in one second is called the frequency of the wave motion, while the distance between the waves (measured from crest to crest), is termed the wavelength (Fig. 2). Notice that the waves are the strongest at the point of disturbance and gradually become weaker as they travel away from this point. If the distance is sufficiently great the waves will become so weak they can no longer be detected.

It is recognized that *frequency* and *wavelength* are closely related; in other words, a low frequency corresponds to a long wavelength, while a high frequency corresponds to a short wavelength. As a wave becomes weaker, it is said that its *amplitude* becomes less. Fig. 3 shows the distinction between amplitude and frequency (or wavelength).

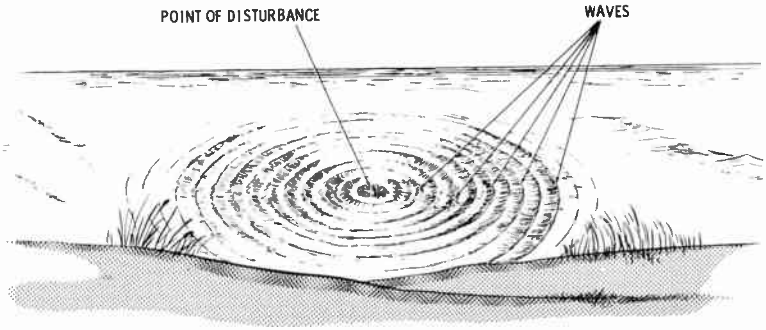


Fig. 1. Effect of throwing a stone in still water.

Radiocommunication is made possible by a form of wave motion which acts similar to waves of water. In radio, however, these waves of energy (known as radio waves) travel from one point to another through air or vacuum rather than water. Radio waves are a form of electromagnetic energy; another common form is light. Unlike the wave motion in the water which occurs at a very slow rate, electromagnetic energy travels away from its source at a speed of approximately 186,000 miles or 300,000,000 meters per second. This is the speed of light. (A meter is equal to 39.37 inches, or somewhat more than a yard.)

It should also be pointed out that radio waves do not travel at the same rate of speed in all mediums. The figures given here indi-

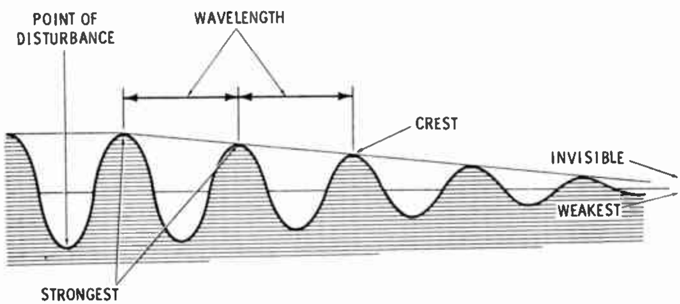
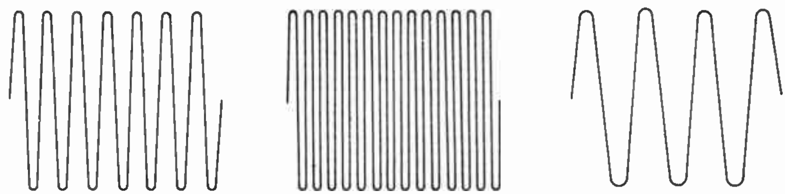
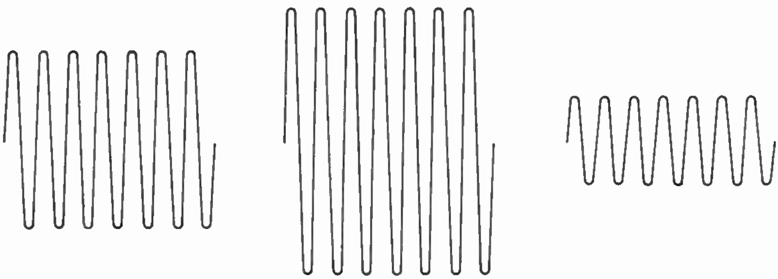


Fig. 2. Cross-sectional view of waves produced by throwing a stone in still water.



(A) Sine waveforms with same amplitude.



(B) Sine waveforms with same frequency (or wavelength).

Fig. 3. Distinction between amplitude and frequency (or wavelength).

cate their speed in air or vacuum. The speed factor in the propagation, or travel, of radio waves is dependent on the dielectric constant of the medium through which the waves must pass. Air, which is considered to be a standard reference, has a dielectric constant of one. Thus radio waves will travel at slightly reduced speeds through mediums having a dielectric constant higher than one.

It has been proven that sounds are produced when a disturbance of the air produces air waves similar to the ripples in the pond. Radio waves, however, do not depend on the air for their movement from one point to another. In fact, these waves travel equally well through a vacuum (complete absence of air). At one time it was theorized that when all air is removed, a medium known as ether remains. Furthermore, it was thought that this medium permitted the propagation of radio waves. Even today you will often hear reference made to ether waves.

The late Dr. Albert Einstein denounced the theory of radio's ethereal medium as fiction. He called it a makeshift fabrication to explain something for which scientists have not had the correct explanation. Einstein believed that radio was made possible by an *electromagnetic phenomenon;* so did Charles Proteus Steinmetz.

Steinmetz was a close friend of the wireless pioneers, such as Marconi, de Forest, and Edison. Unlike his contemporaries, Steinmetz was a mathematical genius who succeeded in describing sine-wave circuit action by means of exact equations. Thenceforth, progress was rapid. His first book, "Alternating Current Phenomena," was published in 1897 by the W. J. Johnston Co. This remarkable book is still available in historical libraries.

Shortly before his death, Steinmetz said that he believed radio and light waves are merely properties of an alternating electromagnetic field of force that extends through space. "Scientists," he contended, "need not consider the idea of ether. They can think better in terms of electromagnetic waves." Steinmetz, like Einstein, pointed out that the conception of the ether theory is one of those hypotheses made in an attempt to explain some scientific difficulty. He contended that the more study is applied to the ether theory, the more unreasonable and untenable it becomes. Steinmetz called attention to the fact that belief in an ether is in contradiction to the relativity theory of Einstein; thus, if science agreed that the theory of relativity is correct the ether theory must be abandoned.

Dr. Lee de Forest stated that radio is simply a cause and effect. The cause is the radio transmitter and the effect is the radio waves resulting from the electromagnetic "splash" produced by this device. Dr. de Forest started his investigations with a form of incandescent lamp invented by Edison. This lamp contained a carbon filament and a metal plate called a "wing." It was used to demonstrate the "Edison Effect," or the flow of electricity through a vacuum. Although the Edison Effect was first used in wireless communication by Fleming and Marconi, de Forest improved the Fleming Valve by adding a spiral of wire which he called a *grid.* Subsequently, the wing was called a *plate.* Details of de Forest's work are explained in a later chapter.

The Modern Concept

The currently accepted electromagnetic theory states that radio waves are composed of moving fields of electric and magnetic energy. These waves cannot be seen or felt, but instead are recognized only by their effects. These fields are composed of lines of force which appear at right angles to each other as shown in Fig. 4. When the lines of force in the electric field are perpendicular to the earth, the lines of force in the magnetic field will be horizontal, and vice versa. An electromagnetic field can be produced by either an electric or a magnetic field alone. That is, when either an electric or magnetic field is caused to move through space or to vary in intensity, it produces the opposite type of field. Furthermore, as electromagnetic waves travel through space, the lines of force in the respective fields are constantly changing direction at a predetermined rate, or frequency.

Wave Characteristics

Radio waves have a number of characteristics, which include such things as frequency, amplitude, and polarization. These characteristics are important because they determine the behavior and usefulness of the waves for communications.

Two basic devices are necessary to achieve radiocommunications. First is the transmitter which generates the radio waves and second is the receiver which selects these signals and converts them into sound waves that can be heard and understood. In order to produce radio waves, it is necessary to have two separated surfaces and to create between them an electric pressure which changes its direction (first toward one surface then toward the other) many times per second. It is common practice to use the ground for one surface and to provide another surface by erecting a radiating structure consisting of one or more metal elements insulated from the earth and suspended a specific distance above it. The latter structure is known as an antenna. It, together with the radio transmitter, determines many of the characteristics of the radio waves. Between these surfaces (the ground and the antenna), an electrical pressure is produced by means of suitable transmitting equipment, thus causing electromagnetic energy to be radiated in all directions.

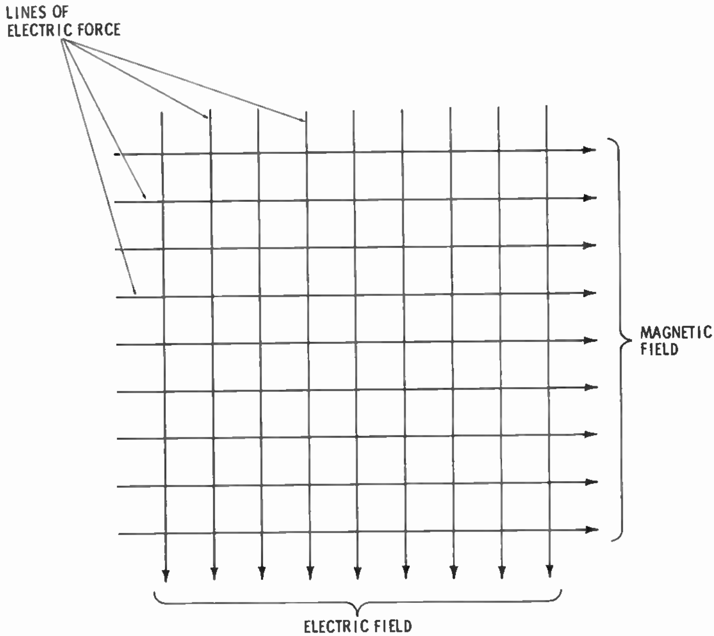


Fig. 4. Electric and magnetic lines of force in a radio wave.

Early forms of aerials, or antennas, are shown in Fig. 5. It was known at that time that electricity flowed in conductors such as copper wires. Edison had demonstrated that electricity also flows in a vacuum, as in the space between the filament and wing in his Edison Effect lamp. He proved that this flow of electricity in a vacuum was an ordinary direct current (DC), which was similar in all basic respects to the flow of electricity in a wire connected to a battery. Heinrich Hertz had demonstrated that high-frequency alternating current (AC) was radiated from an antenna wire into surrounding space. Hertz' discovery of electromagnetic waves was of the greatest possible significance, as can be well understood. Today, Heinrich Hertz is honored by having one cycle per second called one hertz.

It was the genius of Hertz that led to a clear distinction between *free* electrical energy and *bound* electrical energy. That is, he demonstrated that low-frequency AC is largely bound to a conducting wire from which it cannot readily escape into surrounding space. He also demonstrated, by remarkable experiments, that high-frequency AC is only partially bound to a conducting wire, and that an antenna radiates a considerable portion of its AC energy into space as free electromagnetic waves. After AC energy escapes from a wire into surrounding space, the resulting electromagnetic waves are completely *independent* of conditions in the wire. However, when these waves "cut" a distant antenna wire, they *induce* an AC voltage in the wire.

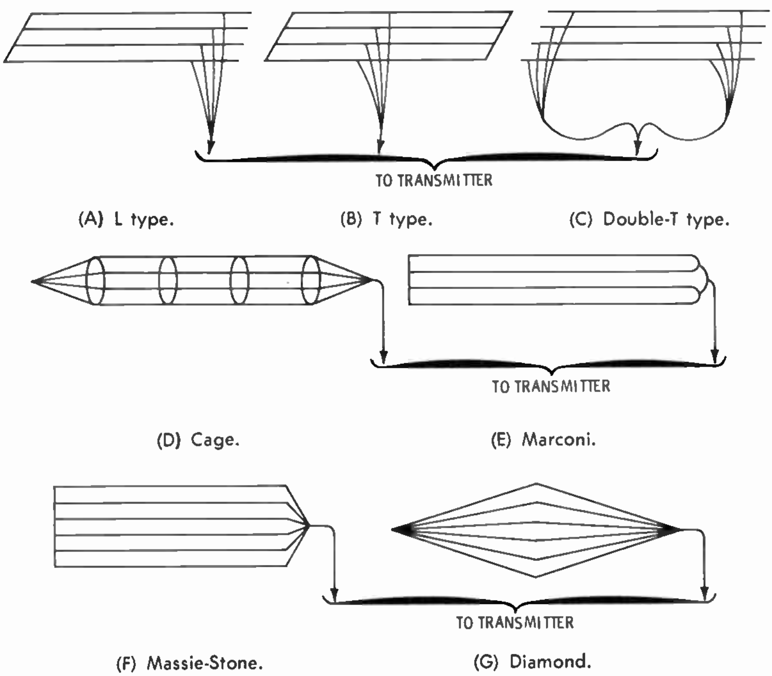


Fig. 5. Early forms of aerials or antennas.

If we compare these waves to the action of hurling a rock into a pool of water, the amount of electrical pressure producing the radio waves corresponds to the size of the rock producing the ripples in the pond. In other words, the larger the rock the bigger the ripples of water, and the larger the electrical pressure between the ground and the antenna, the stronger will be the radio waves.

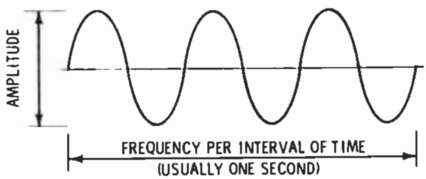


Fig. 6. Characteristics of a radio wave.

The strength of a radio wave is indicated by its amplitude (Fig. 6). The greater the amplitude, the stronger the wave. Just as a larger ripple in a pond of water will travel farther than a smaller one, so will a radio wave of higher amplitude travel farther before being dissipated.

Radio waves are capable of traveling thousands and even millions of miles before they dissipate. The farther radio waves travel the less their field strength (energy) becomes. Under purely free-space conditions (no material objects nearby), the field intensity of radio waves would be inversely proportional to the distance from the transmitting antenna. However, the inverse-distance rule does not hold true in actual practice because unequal amounts of energy are absorbed from the waves over the path of travel. The amount of energy absorbed is dependent on such factors as the frequency and transmission of these waves. Some of the energy is absorbed by the earth and atmosphere as well as obstructions such as trees, buildings, etc.

The polarization of a radio wave is determined by the position of the lines of force in the electric field with respect to the earth. If a radio wave is transmitted in such a way that the electric lines of force are at right angles to the earth the wave is said to be vertically polarized. If, however, the lines of force in the electric field are parallel to the earth, the radio wave is horizontally polarized. Radio waves at the lower frequencies retain their polarization fairly well as they travel along the earth's surface, while those at the higher frequencies tend to be broken up more readily into waveforms of varying polarization. Polarization will be discussed more fully in later chapters.

PROPAGATION

The propagation or movement of radio waves through a medium is not as simple as one might imagine. In fact, an entire volume could be devoted to propagation theory alone. For this reason, only the basic principles will be discussed here.

Basically there are two types of radio waves—ground waves and sky waves. Ground waves travel along the earth's surface and even follow its curvature to some degree. Sky waves, as their name implies, travel upward toward space. There are many factors which affect the behavior of these waves and hence their usefulness for communications purposes. After leaving the transmitting antenna, radio waves may be refracted (bent), reflected, broken up, reradiated, or influenced in some other way as they travel through space.

Ground Waves

Radio waves that are directed along the surface of the earth are limited as to the distance they will travel before being attenuated (reduced) to a point where they are no longer useful. Energy is absorbed from these waves from a number of sources but primarily intervening objects such as trees, buildings, and terrain. Either high- or low-frequency radio waves can be utilized for ground-wave communications; however, where greater distances must be covered, sky-wave propagation is generally employed. Table 1 lists the various frequency bands.

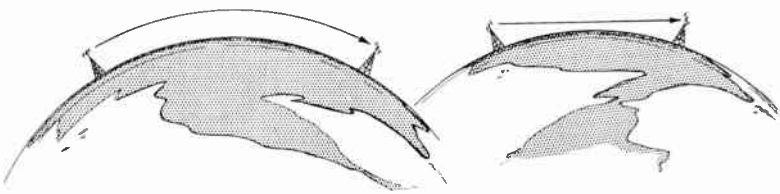
Another factor in ground-wave propagation is the absorption effect of the earth itself. A certain amount of wave energy is lost in the ground. The amount of loss is not always the same, but instead is dependent to a great extent on the frequency of the radio waves. At times conditions are such that even ground waves of the same frequency will travel considerably farther than usual, providing what is known as extended ground-wave propagation.

As the frequency of radio waves is increased, they assume much different propagation characteristics. Instead of following the curva-

Table 1. Bands of Frequencies

Abbreviation	Frequency band	Frequency range
VLF	Very low frequency	below 30 kHz
LF	Low frequency	30-300 kHz
MF	Medium frequency	300-3000 kHz
HF	High frequency	3000-30,000 kHz
VHF	Very high frequency	30-300 mHz
UHF	Ultra high frequency	300-3000 mHz
SHF	Super high frequency	3000-30,000 mHz
EHF	Extremely high frequency	30,000-300,000 mHz

ture of the earth as in Fig. 7A, the radio waves tend to follow a straight line as in Fig. 7B. This characteristic is known as line-of-sight. Obviously, at the high frequencies where this occurs, the range of communication is extremely limited. Under these conditions reliable communication can generally be obtained only when a line-of-sight path exists between the transmitting and receiving antennas. At these line-of-sight frequencies, radio waves bend and reflect very little compared with the lower frequency waves and their energy is dissipated much more rapidly.



(A) Extended. (B) Line-of-sight.

Fig. 7. Two types of ground-wave propagation.

Sky Waves

Sky waves experience much less attenuation than ground waves because they do not have to give up energy to intervening objects. They do, however, lose some of their energy due to absorption by the atmosphere.

The frequency of sky waves has a considerable effect on their behavior, just as it does with radio waves traveling along ground-wave paths. At low frequencies (usually below 30 mHz), radio waves traveling upward into space are bent back to earth at some point many miles away. This action may occur once or several times depending upon atmospheric conditions. It is this phenomenon that makes worldwide radiocommunications possible.

The Kennelly-Heaviside Layer

The refraction and reflection of radio waves as they travel through space is due primarily to ionized masses which form a belt around the upper atmosphere of the earth. This highly ionized region which is supposed to extend from 50 to 400 miles above the earth was discovered by an American electrical engineer named A. E. Kennelly and Oliver Heaviside, an English physicist. This region is actually broken up into several layers designated as D, E, F_1, and F_2. The latter region (F) is actually one layer, but it divides periodically into two separate layers and hence carries the subdesignations. The ionization properties of these layers change from time to time, and their positions in the atmosphere likewise vary. These changes occur not only with the season of the year, but also between night and day. While most of these variations follow established patterns, some are not predictable.

Fig. 8 shows how the ionization properties of these layers affect the propagation of sky waves. As mentioned previously, radio waves do not travel at the same speed through all mediums but instead are affected by the dielectric constant of the medium. When radio waves travel upward through the ionized layers they are refracted and eventually may or may not be reflected back to earth at some remote point hundreds of miles away. The bending action is the result of an abrupt change in the propagation velocity (speed) of the radio waves as they pass from one medium into another (the ionized layers) having a greater dielectric constant.

The degree to which the radio waves will bend is determined primarily by the frequency of the waves and the ionization properties of the layer at that instant. For example, at frequencies below 30 mHz, conditions are generally such that a radio wave might follow

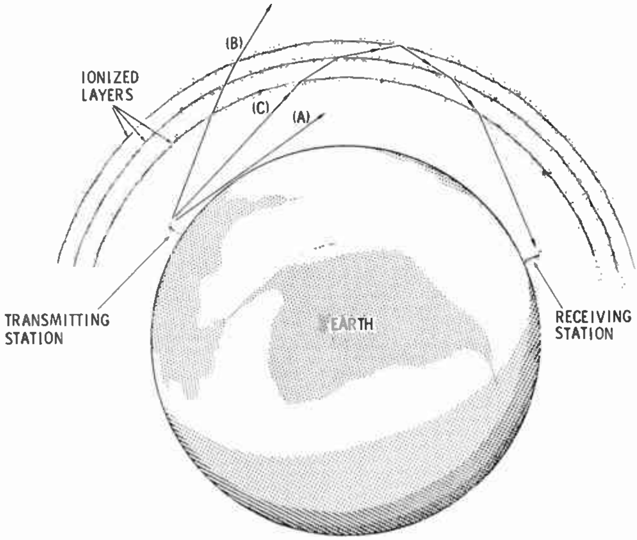


Fig. 8. The effect of frequency on sky-wave propagation.

a path similar to C in Fig. 8. As you can see, the wave is refracted gradually as it passes through the ionized layers until it finally reaches a point where it is reflected back to earth. This is referred to as a *skip* or *skip communications*. Depending on conditions, the skip may occur only once or it may occur several times. The degree of refraction is considerably less as the frequency of the waves is increased. Under the same ionospheric conditions as above, another radio wave of a much higher frequency will tend to travel straight through the layers or at best be refracted only slightly as shown by B in Fig. 8. Obviously, radio waves at this frequency and under these atmospheric conditions will be dissipated in space and serve no useful purpose. Therefore, at frequencies above 30 mHz, it is common practice to use antennas that direct the radio waves along ground-wave paths in order to utilize energy that would normally be lost as sky waves. Path A in Fig. 8 illustrates the line-of-sight characteristics of ground waves as compared with sky waves B and C.

Although the frequency of radio waves has a considerable effect on their behavior as they pass through the ionized layers of the atmosphere, there can be no set limits as to what frequencies will or will not be bent back to earth. The ionization properties of these layers are also a contributing factor and one that varies considerably. At times these layers exhibit unusual characteristics which cause radio waves at the very high frequencies to be reflected back to earth. It has been theorized that one of the contributing factors to the increase in ionization properties is sun spots, which are believed to have some connection with magnetic disturbances on earth, hence radiocommunications.

SUMMARY

The principle of radio is based on the radiation and reception of energy transmitted through space. The movement of this energy through space is similar to the action of water waves produced when a stone is thrown into still water. Radio waves travel very much faster than water waves, however—approximately 186,000 miles or 300,000,000 meters per second, the same as the speed of light.

The present theory of radio energy movement through space states that radio waves are composed of moving fields of electric and magnetic energy. The characteristics of these radio waves include their frequency, wavelength, amplitude, and polarization.

Basically, two devices are needed to achieve radiocommunications—a transmitter to generate the radio waves, and a receiver to select the signals and convert them into sound waves. After leaving the transmitter, the radio waves travel in two basic ways. Some of the energy travels along the ground, and is called a *ground wave*. Other portions of the radio energy travel upward toward space, and is called a *sky wave*. Radio waves may be refracted (bent), reflected, broken up (scattered), reradiated, or influenced in other ways as they travel through space.

An ionized layer of gas forms a belt around the earth in the upper atmosphere. This belt is called the Kennelly-Heaviside layer and has a great influence on radio transmission and reception. Radio energy encountering this belt may be refracted, reflected, scattered, or relatively unaffected, depending on the frequency of the radio waves and the strength and position of the layer. This phenomenon makes possible long-distance radiocommunication at certain frequencies.

REVIEW QUESTIONS

1. How far can a radio wave travel in one minute?
2. What is the relation between frequency and wavelength?
3. How does the strength of a radio wave vary with distance?
4. Does the reception of local radio programs depend mainly on ground waves or sky waves?
5. Give an example of communication that depends entirely on sky waves.
6. What is the Kennelly-Heaviside layer?
7. What importance, if any, does the Kennelly-Heaviside layer play in modern radio?
8. Are all radio waves reflected by the Kennelly-Heaviside layer?
9. Is the effect of the Kennelly-Heaviside layer on radio waves always constant and predictable?
10. What is skip distance?

CHAPTER 2

The Physics of Sound

When air is caused to vibrate by any means, sound is produced, provided the frequency of vibration is such that it is audible. If a violin string is plucked (Fig. 1), it springs back into position, but due to its weight and speed, it goes beyond its normal resting position, oscillates back and forth through its normal position, and gradually comes to rest. As the string moves forward, it pushes and compresses air before it; also air rushes in to fill the space left behind the moving string. In this way the air is set into vibration. Since air is an elastic medium, the disturbed portion transmits its motion to the surrounding air so that the disturbance is propagated in all directions from the source of disturbance. These vibrations produce sound.

If the violin string were to be connected in some way to a diaphragm such as a stretched drum head, the motion is transmitted to the drum. The drum, having a large area exposed to the air, sets a greater volume of air in motion and a much louder sound produce sound. Fig. 2 illustrates sound waves in a speaking tube.

If a light piston several inches in diameter and surrounded by a suitable baffle board several feet across were caused to oscillate rapidly by some external means (Fig. 3), sound would be produced. When we watch and listen to a carpenter at a distance, we observe that his hammer strikes before we hear the resulting sound.

Fig. 1. Sound produced by vibration of a violin string.

Therefore, we conclude that sound waves travel slower than light waves. The speed of sound in air at 0° C is 1,087 feet per second. In water, the speed is about 4,600 feet per second, and in iron, 16,700 feet per second. The speed of sound in air increases with temperature. Sound waves can be focused like light waves (or

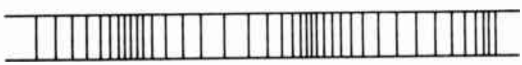


Fig. 2. Sound waves in a speaking tube.

radio waves). For example, if an ordinary clock is suspended in front of a large concave reflector, as at W in Fig. 4, a place will be found at some distance in front, as at E, where the clock can be heard with great distinctness. But if the large reflector is removed, the ticking is inaudible. This is the principle of a "whispering gallery," as exemplified by some auditoriums.

CHARACTERISTICS OF SOUND

If the atmospheric pressure could be measured at many points along a line in which the sound is moving, it would be found that the pressure along the line at any given instant varied in a manner similar to that shown by the wavy line in Fig. 3.

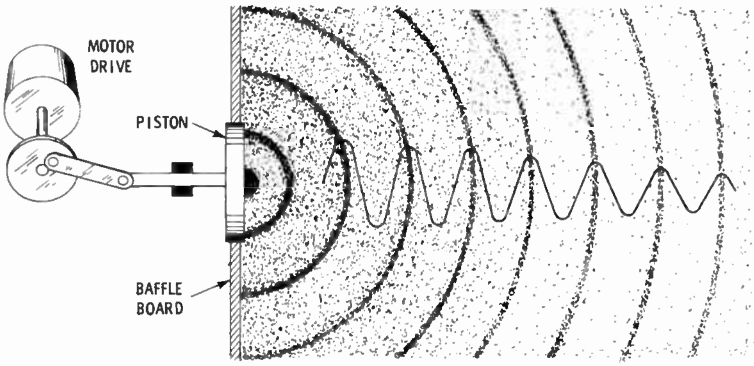


Fig. 3. Generation of sound waves by the oscillation of a piston.

To illustrate, if extremely sensitive pressure gauges could be set up at several points in the direction in which the sound is moving, we would find that the pressure varied as indicated in Fig. 5. If a pressure gauge could be set up at one point and the eye could follow the rapid vibrations of the pointer, we would find that the pressure varied at regular intervals and in equal amounts above and below the average atmospheric pressure. The eye, of course, cannot see such rapid vibrations; it can see wave motion in water, however, which is very similar to sound waves with the ex-

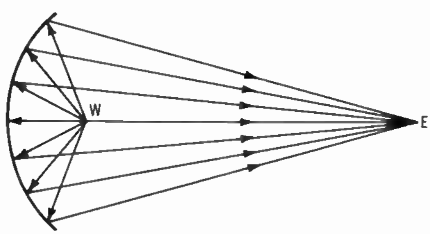


Fig. 4. Focusing of sound waves by a large reflector.

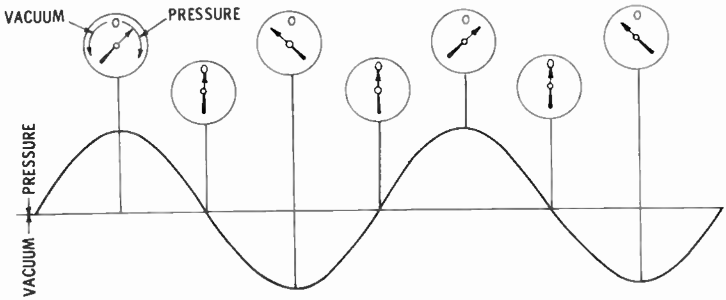


Fig. 5. Diagram illustrating pressure variations due to sound waves.

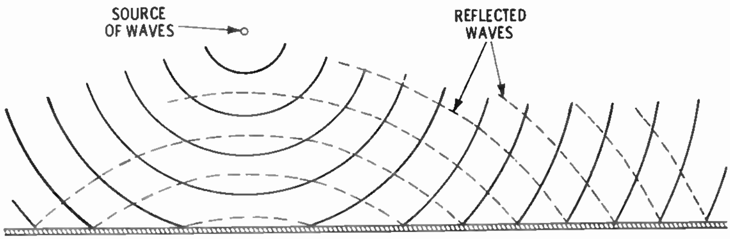


Fig. 6. Reflection of waves from a plane surface.

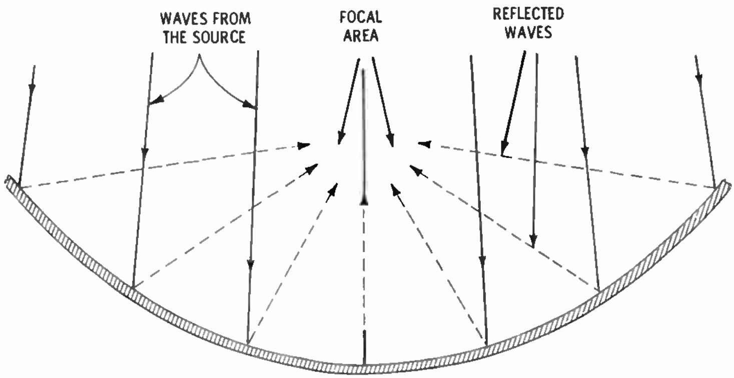


Fig. 7. Reflection of waves from a curved surface. The solid lines show the direction of the original waves, and the dotted lines show the direction and focusing of the reflected waves.

ception that water waves travel on a plane surface, whereas sound waves travel in all directions.

If a pebble is dropped into a still pool, waves will travel outward in concentric circles, becoming lower and lower as they progress farther from the starting point, until they are so small they cannot be seen, or until they strike some obstructing object.

If the pond is small, the waves which strike the shore will be reflected from it. If the waves strike a shore that is parallel with the waves, they will be reflected back in expanding circles, as in Fig. 6. If the waves strike a hollow or concave shore line, as in Fig. 7, the reflected waves will tend to converge (focus) to a point.

Comparing water and air as media for wave propagation, we see that water waves travel in expanding circles and air waves in expanding spheres. Sound waves are reflected in a manner similar to water waves, causing echo and reverberation. If the sound waves focus to a point, loud and dead spots are produced.

Wave motion has certain definite characteristics and these characteristics determine:

1. Loudness.
2. Pitch.
3. Tone.
4. Wavelength.
5. Resonance.

Loudness—By definition, loudness is the relative intensity of the sound. Loudness (or amplitude) is determined by the amount of difference in pressure between the maximum compression and the maximum rarefaction. This corresponds in water waves to the vertical height of the crest above the trough of the wave. Loudness is illustrated in Fig. 8.

Pitch or Frequency—Any one of a series of vibrations, starting at one condition and returning once to the same condition, is called a *cycle*. Observe some point on the surface of water in which waves exist and it will be noticed that at this point the water will rise and fall at regular intervals. At the time at which the wave is at its maximum height the water begins to drop, and continues until a trough is formed, after which it rises again to its maximum height.

Accordingly, all the variations of height which one point on the surface of the water goes through in the formation of a wave constitute a cycle of wave motion.

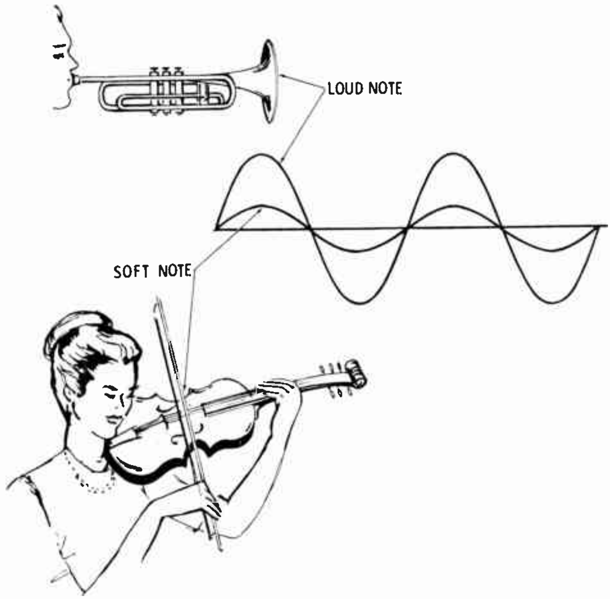


Fig. 8. Properties of wave motion illustrating the causes of loudness of tone.

The number of cycles a wave goes through in a definite interval of time is called the *frequency*. Therefore the number of times the water rises or falls at any point in one minute would be called the frequency of the waves per minute, expressed as the number of cycles per minute. In sound, the number of waves per minute is large, and it is more convenient to speak of the frequency of sound waves as the number of waves per second, or, more commonly, as the number of cycles per second. Thus, a sound which is produced by 256 waves a second is called a sound of a frequency of 256 cycles. When speaking of sound, cycles always mean cycles per second.

Considered from the standpoint of traveling waves, frequency is determined by the number of complete waves passing a given point in one second, and this, of course, is equal to the number of vibrations per second generated at the source. Fig. 9 is a chart showing pitch frequencies corresponding to the various keys of the piano and the ranges of the human voice and various instruments. This chart represents the relation between the musical scale and the piano keyboard, giving the frequency of each note in terms of complete vibrations, or cycles, according to the standard used in scientific work, such as the scientific scale based on middle C at a frequency of 256 cycles. The piano keyboard covers nearly the

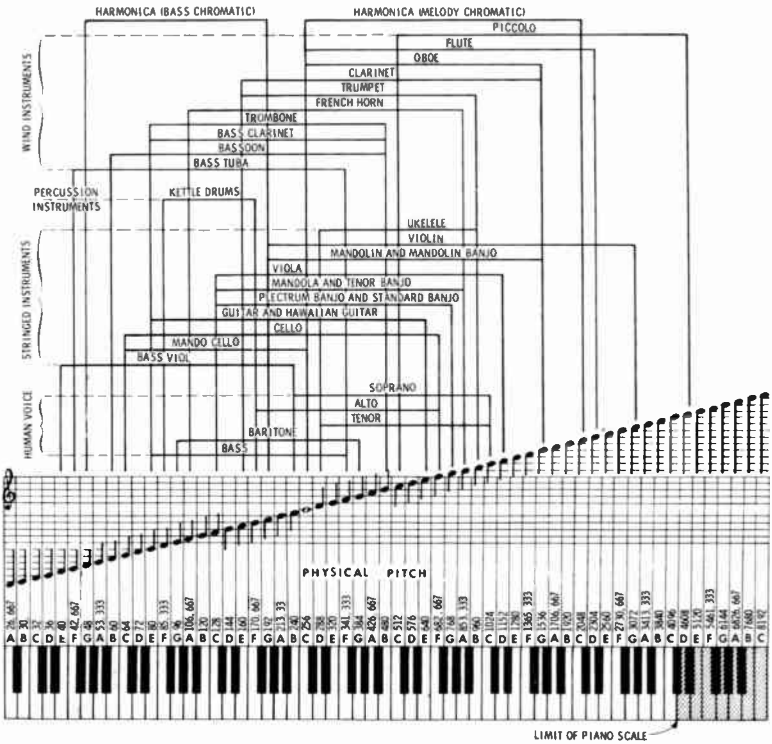


Fig. 9. Musical pitch chart for piano, voice, and various instruments.

entire range of musical notes and extends from 26.667 cycles to 4,096 cycles. The piccolo reaches two notes beyond the highest note of the piano. The extreme organ range, not shown on the chart, is from 16 cycles to 16,384 cycles, scientific or physical pitch, as it is usually called. Music seldom utilizes the full keyboard of the piano, the extremely high notes and extremely low notes being seldom used. Therefore a reproducing device which reproduces all frequencies from 50 to 4,000 cycles would be satisfactory in reproducing musical notes. The properties of wave motion versus pitch are illustrated in Fig. 10.

Tone—By definition, tone is sound in relation to volume, quality, duration and pitch. By common usage in music, tone generally means the timbre or quality of sound. A pure note of a given pitch always sounds the same, and the frequency of this note is termed

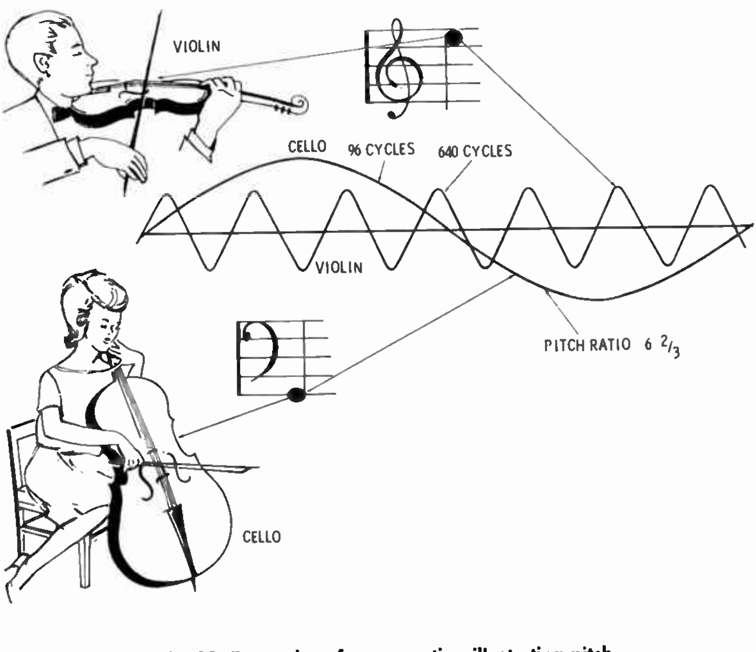


Fig. 10. Properties of wave motion illustrating pitch.

its fundamental frequency. However, notes of the same pitch from two different kinds of instruments do not give the same sound impression. This difference is due to the presence of *overtones*, sometimes called *harmonics*.

Consider again the case of a taut string which is plucked to set it in vibration. If the string is plucked at its exact center, it will vibrate as a whole and will produce, essentially, a pure note; but if the string is plucked at some other point, say one-third of the length from one end, it will vibrate as three parts as well as a whole, and a change of tone will be noticed. If the string is plucked indiscriminately, various tones will be heard, all of the same fundamental pitch.

Hollow cavities built into the bodies of the various musical instruments give them their characteristic tones, because the air chambers, called resonance chambers, strengthen overtones of certain frequencies and give a very pronounced tone to the instruments. Other instruments have built into them means of suppressing certain overtones, which help to give them their characteristic sounds. The frequency of an overtone is always some multiple of the fundamental frequency; that is, the second overtone has twice the frequency of the fundamental note, and the third overtone, three times the frequency, etc. Overtones of twenty times the frequency of the fundamental note are present in the sounds of some musical instruments, but overtones of this order are important only when the fundamental note is low, because the frequency of the twentieth overtone of even a moderately high note would be beyond the ability of the human ear to detect.

Overtones give character and brilliance to music, and their presence in reproduced sound is necessary if naturalness is to be attained. The combined result of all overtones is the quality or timbre of the tone; that is, the characteristic sound of a voice or instrument. A great variety of tone is found in the orchestra as exemplified by the strings, woodwinds, brass and reed choirs.

In singing, the range of notes covered is approximately from 64 to 1,200 cycles, extreme limits, but this range cannot be covered by one person's voice. The frequency of 1,200 cycles does not represent the highest frequency produced in singing, because overtones of several times the frequency of the fundamental note are always present in the human voice. It is the presence of these overtones that gives the pleasing quality to singing. This quality of the singing voice is called timbre, and it is this characteristic that enables you to distinguish one singer from another just by sound. The timbre of the voice transmits the emotions of joy, sadness, etc., from the performer to the audience, and therefore is very important in the enjoyment of vocal music.

Fig. 11 shows the waveform of the sound "or" produced by a typical voice. This is called a *complex wave,* and it can be shown that complex waves are built up from sine waves of various frequencies and amplitudes. If you speak the word "or," and I speak the word "or," these relative frequencies and amplitudes are slightly different. Therefore, the human ear can distinguish between the "same" sound produced by different people. However, the meaning conveyed by the slightly different sounds is the same, and is called the *invariant* of the two complex waves.

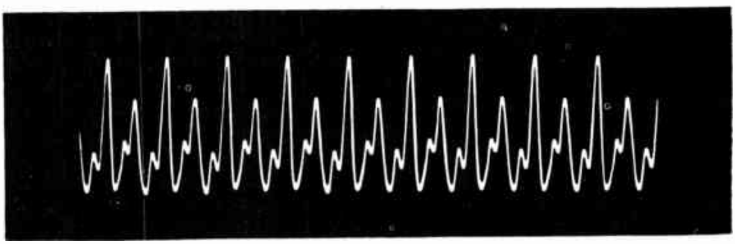


Fig. 11. Waveform of the sound "or."

Wavelength—By definition, the wavelength (of a water wave, for instance) is the distance between the crest of one wave and the crest of the next wave. This distance remains the same as long as the wave continues, even though the wave becomes so small as to be barely perceptible.

Frequency in wave motion is related to wavelength. All waves produced do not have the same wavelength. A small pebble dropped into a pond will produce a wave of short length, and a large stone will produce a wave of correspondingly longer length.

In sound the wavelength is dependent upon the frequency of the source. Similarly, the length of a sound wave is the distance between the point of maximum compression of one wave to the point of maximum compression of the next wave. Sounds of all frequencies, or pitches, travel at the same speed. The speed at which sound travels divided by the frequency gives the wavelength of the sound.

Resonance—When the note C is struck on the piano (Fig. 12), the sound waves vibrate 256 times per second and either a C tuning fork or another wire tuned to C and in the immediate vicinity will vibrate 256 times per second also. Thus, the two wires are said to be in resonance.

The waves radiated by a radio transmitter always have a definite number of vibrations per second and, in order to hear a station, the receiving equipment must be put in resonance with the waves radiated by the transmitter. This operation is known as tuning.

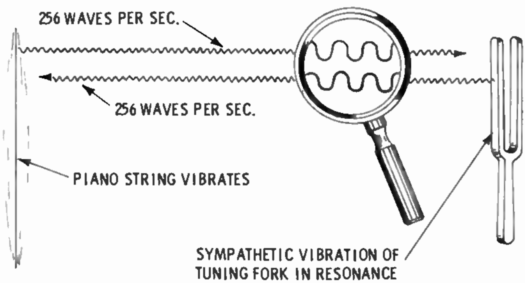


Fig. 12. Sympathetic vibration of tuning fork with vibrating piano string when tuned to the same pitch.

THE HUMAN EAR

The actual mechanism of hearing is not very well understood, but certain facts regarding the ability of the ear to register sounds of various frequencies have been determined very accurately. The range of frequencies which the average person can hear is from about 20 to 17,000 cycles, but a comparatively large amount of sound energy is required before the ear can detect sound of extremely low or extremely high frequencies.

The ear is most sensitive to frequencies between 500 cycles and 7,000 cycles, and is most sensitive to changes of pitch and changes of intensity of sound in this same band of frequencies.

SUMMARY

Vibration of the air, or certain other materials, produces sound, providing that the frequency of vibration is within the audible range. Sound is a wave motion similar to radio waves or water waves except that the medium in which the wave motion takes place is different and the frequency and speed is different.

The amplitude of sound determines its loudness. The frequency determines its pitch. Tone is sound in relation to volume, quality, duration, and pitch.

The average human can hear sounds having frequencies between about 20 cycles per second up to about 17,000 cycles per second. At the higher and lower frequencies, more sound energy is required before the ear can detect the sound. Therefore, the ear is most sensitive to sounds between 500 and 7,000 cycles per second.

REVIEW QUESTIONS

1. How are radio, water, and sound waves alike?
2. How are radio, water, and sound waves different?
3. Discuss the reflection of sound waves and give examples of practical applications.
4. To what characteristic of a sound wave does pitch correspond?
5. Define tone.
6. What causes two different musical instruments, both playing the same note, to sound differently?
7. What are harmonics?
8. What is resonance?
9. Give a practical application of resonance in a musical instrument.
10. What is the range of sound frequencies audible to an average human?

CHAPTER 3

Magnetism

Since the "dawn of history," the word "magnet" has been used to describe certain hard black stones which possess the property of attracting small pieces of iron, and as discovered later, to have the still more remarkable property of pointing north and south when freely suspended on a piece of string. At this time the magnet received the name of lodestone or "leading stone."

KINDS OF MAGNETISM

Magnets have two opposite kinds of magnetism called magnetic poles. The characteristics of these poles are such that when opposite poles of two magnets are brought close to each other, they attract; similar poles, however, exhibit a repelling force.

In our early school days, we learned that the earth is a huge, permanent magnet with its north geographic pole somewhere in the Hudson Bay region and that the compass needle marked "North" points toward that magnetic pole. Thus, the north geographic pole is actually a south pole, magnetically speaking (Fig. 1). The present locations of the North and South magnetic poles are shown in Fig. 2. It has been found that the earth's magnetic poles tend to drift slowly with the passage of time. In fact, geologists have

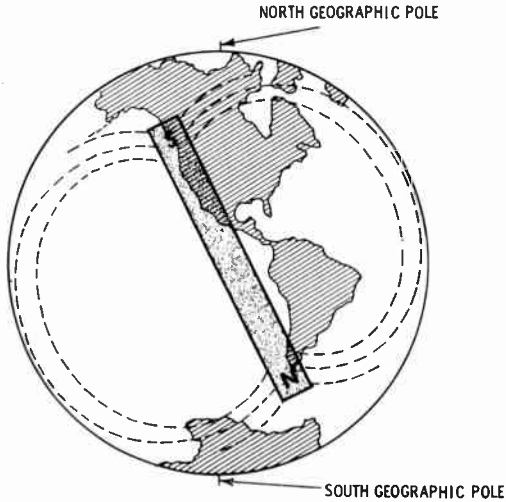


Fig. 1. The magnetic properties of the earth.

discovered that the earth's magnetic poles have reversed in past ages. It is also known that the strength of the earth's magnetic poles is slowly decreasing at present.

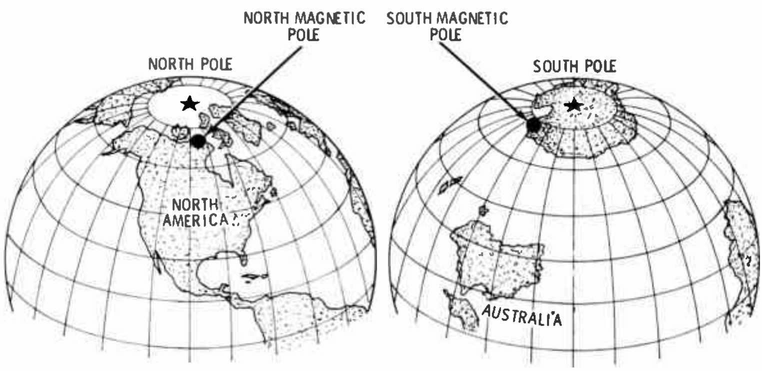


Fig. 2. Present locations of the earth's magnetic poles.

One of the two ends of a compass needle points north and the other south; they are called poles. One is called the north-seeking pole (N) and the other the south-seeking pole (S). A typical compass is shown in Fig. 3.

The compass itself consists essentially of a magnetic needle resting on a pivot and protected by a brass case covered with glass. A graduated circle marked with the letters N, E, S and W, to indicate the cardinal points, is called the compass card.

It is seen in Fig. 1 that the earth's magnetic lines of force tend to "dip" into the earth at points away from the magnetic equator. Magnetic dip, or *inclination,* is measured with a dipping needle, as shown in Fig. 4. A dipping needle is a vertically mounted compass needle. The angle of dip at a given point on the earth's surface tends to slowly change from year to year.

Experiments with Magnets

If the south-seeking or S pole of a magnet is brought near the S pole of a suspended magnet, as shown in Fig. 5, we find that the poles repel each other. If we bring two N poles together, they also repel each other, but if we bring an N pole toward the S pole of

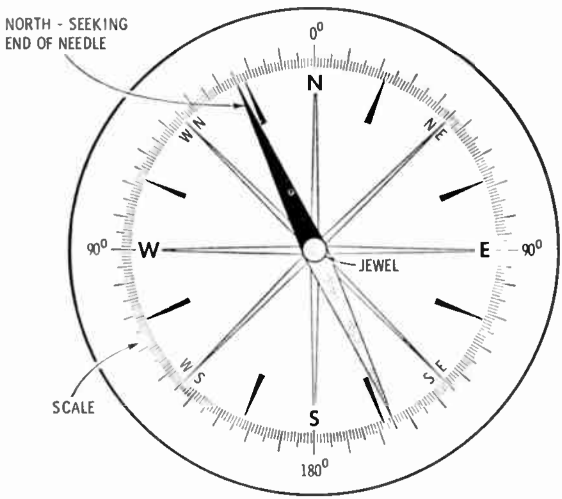


Fig. 3. A typical compass card.

It can also be shown by further experiments that these attractive or repulsive forces between magnetic poles vary inversely as the the moving magnet, or an S pole toward the N pole, they attract each other; that is, like poles repel each other and unlike poles attract each other.

Fig. 4. A dipping needle.

square of the distance between the poles. Also, if a magnetic substance like iron filings is placed in a glass tube (Fig. 6A), and the tube is stroked from end to end with a permanent magnet, the filings themselves become a magnet (Fig. 6B). The acquired magnetism of the filings, however, will disappear as soon as the filings are shaken up.

If a magnetized needle is heated sufficiently, it will be found to have lost its magnetism completely. Again, if such a needle is jarred, hammered or twisted, the strength of its poles, as measured by the ability to pick up tacks or iron filings, will be found to be greatly reduced. Furthermore, if a magnetized needle is broken, each part will be found to be a complete magnet, that is, two new poles will appear at the breakage point, a new N pole on the part which has the original S pole, and a new S pole on the part which has the original N pole. This subdivision of the needle may be continued indefinitely, but always with the same results as indicated in Fig. 7. Thus it will be noted that no single magnetic pole can exist by itself, but will always appear with a pole of the opposite type, irrespective of the size involved.

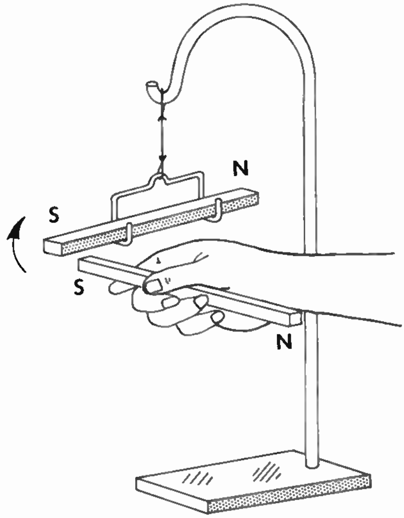
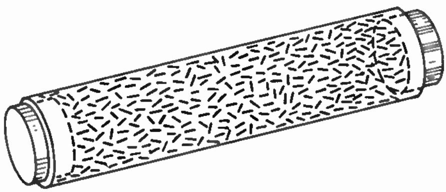
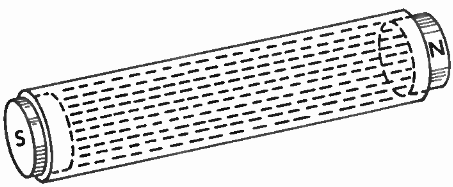


Fig. 5. Repulsion between like magnetic poles.

The foregoing facts also point to the conclusion that in any unmagnetized piece of iron, the atoms which comprise it are not lined up in any particular order; that is, the electrons circling the nuclei of the iron atoms produce magnetic effects, but these effects cancel



(A) Before magnetization.



(B) After magnetization.

Fig. 6. Behavior of iron filings in a glass tube.

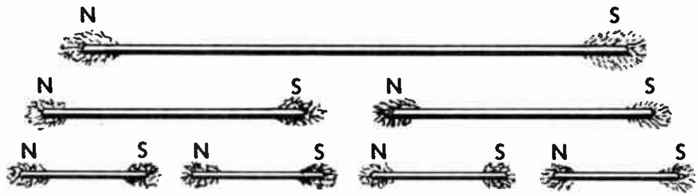
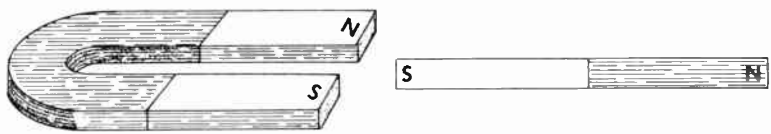


Fig. 7. Effects of breaking a magnet into several pieces.

each other. When the iron is magnetized, however, the iron atoms are forced into a more definite alignment. Also the more strongly a piece of iron is magnetized, the more the atoms are brought into alignment. There is a definite limit to the number of atoms that can be made to stay in alignment. When a piece of iron cannot be magnetized beyond a certain limit regardless of the magnetizing force, the iron is said to be fully magnetized or saturated.

Magnetic Materials

Iron and steel are the only natural substances which exhibit magnetic properties to any marked degree. Nickel and cobalt are also attracted appreciably by strong magnets. Bismuth, antimony, and a number of other substances are actually repelled instead of



(A) Horseshoe. (B) Bar.

Fig. 8. Two types of permanent magnets.

attracted, but the effect is very small. For practical purposes, iron and steel may be considered the only magnetic materials. Fig. 8 shows two types of permanent magnets.

The Magnetic Field

It can be shown easily that when a straight bar magnet is held under a piece of cardboard upon which iron filings are sprinkled, the filings will arrange themselves in curved lines radiating from the poles. If a horseshoe magnet is held at right angles to the plane of the cardboard, the filings will arrange themselves in curved lines between the poles as shown in Fig. 9. These lines are called *magnetic lines of force* or simply *lines of force*; they show that the medium surrounding a magnet is in a state of stress. The space so affected is called the *magnetic field*, and the lines of force are collectively referred to as *magnetic flux*.

The strength of a magnetic field is measured in *gauss* with an instrument called a *gaussmeter*. Note that the strength of the earth's magnetic field is approximately ½ gauss. On the other hand, the strongest magnet that has been constructed at present has a strength of about 500,000 gausses. One gauss is represented by one line of force per square centimeter. Thus, the strength of the earth's magnetic field is about 3 lines of force per square inch. In terms of force exerted, a unit magnetic pole will exert a force of 1 dyne on another unit pole at a distance of 1 centimeter. There are 444,800 dynes in 1 pound, or, a dyne is equal to 1/444,800 pound.

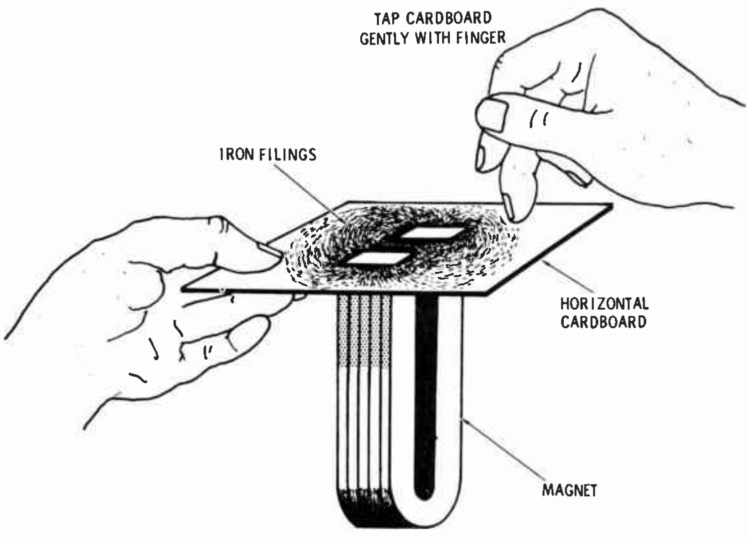


Fig. 9. Results obtained by placing iron filings on cardboard above a horseshoe magnet.

A modern permanent magnet that weighs 1½ pounds may have a strength of 900 gauss and will lift about 50 pounds of iron. Another horseshoe magnet that weighs 5 pounds may have a strength of 2,000 gauss and will lift about 100 pounds of iron. A 16-pound magnet may have a strength of 4,800 gauss and will lift approximately 250 pounds of iron. Although steel is the basic substance for constructing permanent magnets, much stronger fields can be developed by alloying iron with cobalt, nickel, aluminum, and copper. *Alnico* is a trade name for a widely used magnetic alloy.

Characteristics of the Magnetic Field

The foregoing discussion of magnets and iron filings indicates certain characteristics common to all magnets, in that they produce lines of force and that these lines arrange themselves in certain

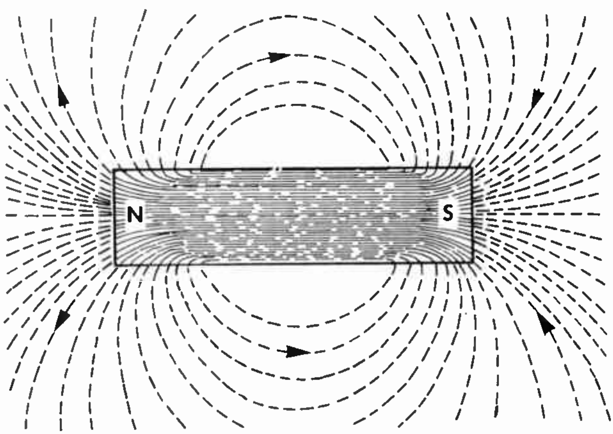


Fig. 10. Theoretical concept of lines of force surrounding the poles of a bar magnet.

geometrical patterns stretching from one pole of the magnet to the other. Fig. 10 shows the theoretical pattern formed by the lines of force around a permanent bar magnet; Fig. 11 is an actual pattern formed by iron filings.

It would be incorrect, however, to think of these magnetic lines of force as actual lines extending through the space surrounding the magnet. The lines are only imaginary, and the idea of referring to magnetism in terms of lines of force has been adopted merely as an aid in understanding the theory of magnetism.

Permanent and Temporary Magnets

Certain substances like steel retain their magnetism after the magnetic field used to magnetize them has been removed, and are therefore referred to as *permanent magnets.* Other substances, like soft iron, remain magnetized only as long as the magnetizing force is present. These are called *temporary* magnets.

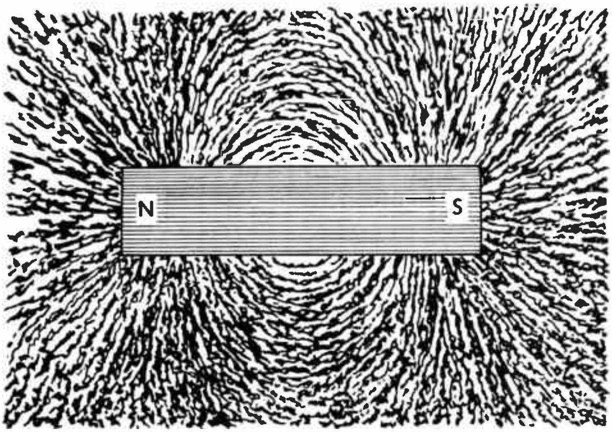


Fig. 11. The magnetic lines of force as exerted by a bar magnet on iron filings.

SUMMARY

Magnets are certain objects that have the property of attracting or repelling other like objects or of attracting certain materials. Magnets are always composed of two poles—a North and a South. One of the rules of magnetism is that like poles repel and unlike poles attract one another.

A compass needle is a magnet freely suspended so that it is able to line up with the magnetic lines of force of the earth. Since the magnetic poles of the earth are near the geographic poles, the compass needle lines up approximately north and south.

The attractive or repulsive forces between magnets vary inversely as the square of the distance separating them. Only iron and steel are considered as magnetic materials. However, certain alloys of other metals exhibit magnetic properties.

Magnetic attraction or repulsion is caused by lines of force and is called flux. These lines are imaginary and cannot be seen or felt directly. Their effect can be noted, however.

REVIEW QUESTIONS

1. Why does a compass needle point North?
2. Will two like magnetic poles repel or attract each other?
3. By how much will the attractive or repulsive force between magnetic poles be diminished if the distance separating them is doubled?
4. Will heat make a magnetic material more or less susceptible to being magnetized?
5. What are some metals that can be alloyed with others to produce a magnet?
6. What are lines of force called?
7. Do lines of force actually exist?
8. If a bar magnet is broken into a number of pieces, what happens to each individual piece from a magnetic standpoint?
9. Would the needle of a compass be classified as a temporary or permanent magnet?
10. If a soft-iron nail were magnetized, would it become a permanent magnet?

CHAPTER 4

Fundamentals of Electricity

WHAT IS ELECTRICITY?

The term "electric" was derived from the Greek word "elektron," meaning amber. An early Greek experimenter named Thales found that electricity could be produced by briskly rubbing an amber rod. Some time later Benjamin Franklin, an American, proved lightning to be electricity. It was not until the 1890's, however, that the present electron theory came into being. It is this theory that defines electricity as the movement or accumulation of electrons.

Electricity is now defined as a *fundamental entity* of nature. This means that electricity is one of the basic building blocks of ordinary matter. Two kinds of electricity are observed, which are called *positive* and *negative* electric polarities. Negative electricity consists of electrons, whereas positive electricity consists of protons, or possibly positrons. The two basic kinds of electricity are known by their effects, such as in the attraction or repulsion of substances that have been electrified by friction. Other common effects of electricity are exemplified by lightning and the *Aurora Borealis* and *Aurora Australis.* The most basic characteristics of electricity may be listed as follows:

1. Electricity is charge.
2. There are two basic kinds of charge.
3. Electricity is not mass, although electricity may be associated with mass, as in electrons or in protons.
4. Electricity is not energy, although electricity may be associated with energy, as in a lightning stroke or in the *Borealis*.
5. Electricity is a subatomic entity, which means that an electron or a proton is the smallest possible subdivision of an electric charge.

From this it becomes apparent that you will have to have some knowledge of electrons in order to better understand just what electricity is.

THE STRUCTURE OF MATTER

It is now a well-known fact that all matter is comprised of submicroscopic particles. These particles, which are the smallest into which matter can be subdivided and still retain the properties of the original substance, are called *molecules*.

Molecules of different substances vary greatly in complexity, ranging from extreme simplicity in some substances to extreme complexity in others. All molecules, however, may be broken up into simpler constituents called *atoms*, of which there are more than one hundred distinct kinds known, each representing one of the chemical elements from which all matter is constructed.

Only a few elements, however, appear in the molecules of any one of even the most complex substances. An element, then, is a fundamental substance composed of only one kind of atom. In some elements, the molecules are composed of single atoms; in other elements, two or more similar atoms are associated to form the molecule. Some of the more common elements are hydrogen, oxygen, nitrogen, carbon, iron, copper, etc.

If we carry the analysis still further, atoms are noted for their complex structures. The most widely accepted modern physical analogy of the atom corresponds roughly to a miniature of our solar system. Corresponding to the sun in the solar system is the nucleus of the atom, which, in general, is a very small, compact structure composed of a combination of extremely minute particles called *protons* and *neutrons*. (See Fig. 1.)

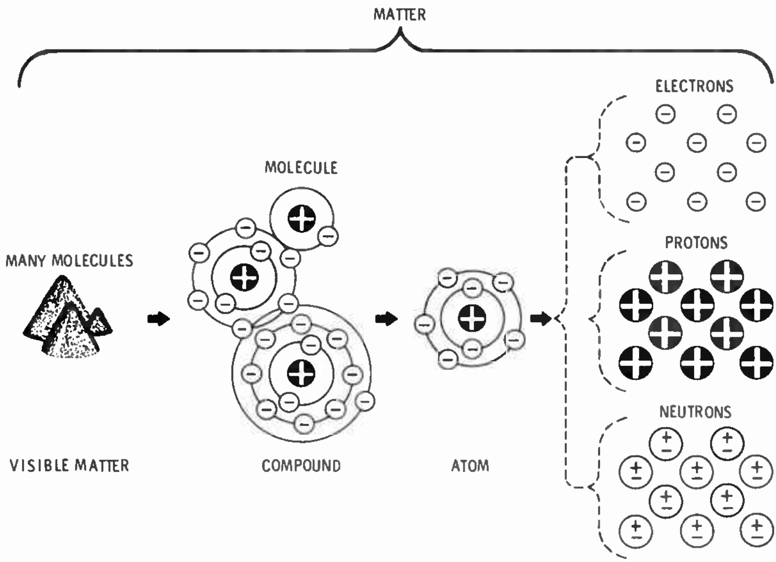


Fig. 1. Breakdown of visible matter to electrical particles.

The proton, whose mass may be taken as the unit of atomic weight, has a positive charge equal in magnitude, but opposite in sign, to that of the electron. Its mass is very large compared with that of the electron.

The neutron has very nearly the same mass as the proton, but is uncharged (neutral). Practically all the mass of the atom is associated with the small, dense nucleus. Revolving about the nucleus, in orbits at relatively large distances from it, are one or more electrons.

The simplest of all atoms is that of hydrogen, whose nucleus consists of a single proton with a single electron revolving about it (Fig. 2). In other words, atoms have a *subatomic structure*. When we speak of subatomic structure, we denote the action of

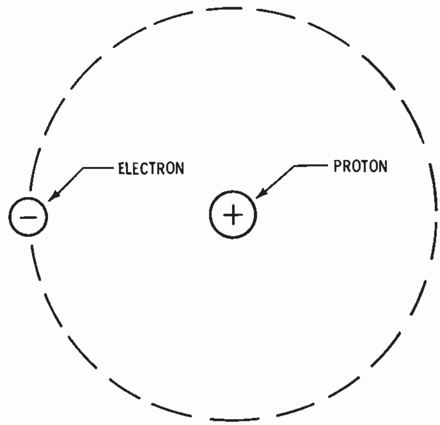


Fig. 2. Structure and electron orbit of a hydrogen atom.

particles *inside* atoms. That is, we are describing the relations of particles that are smaller than atoms. An *electron* is a *subatomic particle;* it is known that an electron is a charge of negative electricity and that it consists of 1.6×10^{-19} coulomb. (Remember that a current of 1 ampere consists of a flow of 1 coulomb past a point per second.) An electron has a mass or weight of 9.1×10^{-28} gram. One gram is equal to 3.5×10^{-2} ounce.

A *proton* is also a subatomic particle; it is known that a proton is a charge of positive electricity, and that it also consists of 1.6×10^{-19} coulomb. In other words, the charge of a proton is equal and opposite to that of an electron. A proton has a mass or weight of 1.67×10^{-24} gram, which makes it 1,836 times heavier than an electron. A *neutron* is another subatomic particle; it has no external charge and therefore consists of mass only. The mass or weight of a neutron is approximately the same as that of a proton.

A *positron* is yet another subatomic particle, and is sometimes called a *positive electron.* A positron has the same mass as an electron, with an equal but opposite charge. At the present time, positrons are not as well understood as protons. However, subatomic physicists have produced experimental evidence that the most fundamental unit of positive electricity is the positron. We may note that the *photon* is the most fundamental unit of energy —that is, energy does occur in subatomic units. Subatomic physicists have shown that a photon can change into an electron and a positron. This transformation of subatomic particles is called *pair production.*

Another simple atom is that of helium, whose nucleus consists of two protons and two neutrons bound together in a compact central core of great electrical stability. Revolving about this compact nucleus are two electrons (Fig. 3).

Atoms of other elements become increasingly more complex by the successive addition of one electron to those revolving about the nuclei, and with the progressive addition of protons and neutrons to the nuclei. In every instance the normal atom has an exactly equal number of positive and negative elementary charges, so that the atom as a whole is neutral; that is, it has no electrical charge.

Note in passing that a very simplified form of atomic and subatomic structure has been discussed. In other words, many refinements must be added to explain the characteristics of atoms and molecules precisely. As a matter of fact, the simplified structure that has been considered can account satisfactorily only for the

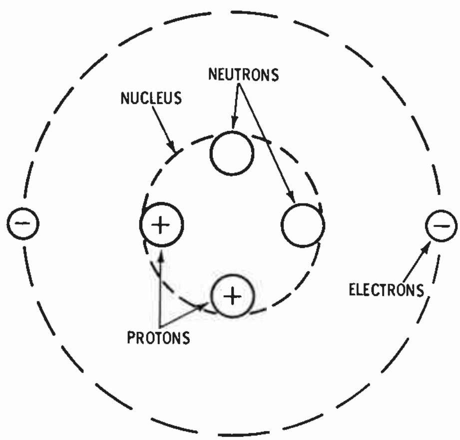


Fig. 3. Structure and electron orbit of a neutral helium atom.

characteristics of the hydrogen atom. To describe the characteristics of copper atoms precisely, for example, many refinements must be taken into account. However, the elementary principles that have been discussed serve as an adequate basis for the understanding of ordinary electric circuit action as well as the action of vacuum-tube and semiconductor circuits.

Positively and Negatively Charged Substances

With reference to the picture of the neutral atom, it will be easy to understand what takes place when a substance is electrically charged.

Assume that by some means one of the external electrons of the neutral helium atom is removed as shown in Fig. 4. The result will be an unsatisfied atom insofar as the balance between the positive and the negative charges is concerned. The excess of one proton in the nucleus gives the atom a positive charge, and if the previously removed electron is permitted to return to the atom, it will again become neutral.

A positively charged body is, therefore, one which has been deprived of some of its electrons, whereas a negatively charged body is one which has a surplus (more than its normal number)

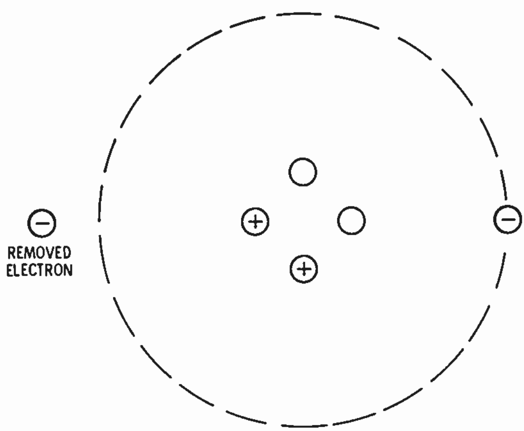


Fig. 4. Structure and electron orbit of a positively charged helium atom.

of electrons. In its unbalanced positive state, the atom will tend to attract any free electrons that may be in the vicinity. This is exactly what takes place when a stick of sealing wax or amber is rubbed with a piece of flannel. The wax becomes negatively charged and the flannel positively charged (Fig. 5A).

During the rubbing process, the friction rubs off some of the electrons from the atoms composing the flannel and leaves them on the surface of the wax. If the wax and the flannel are left together after being rubbed, there will be a readjustment of electrons, the excess on the wax returning to the deficient atoms of the flannel, as shown in Fig. 5B.

Most of the electrons in the universe exist as component parts of atoms as described, but it is possible for an electron to exist in the free state apart from the atom, temporarily at least. Free electrons exist to some extent in gases, in liquids and in solids, but are much more plentiful in some substances than in others.

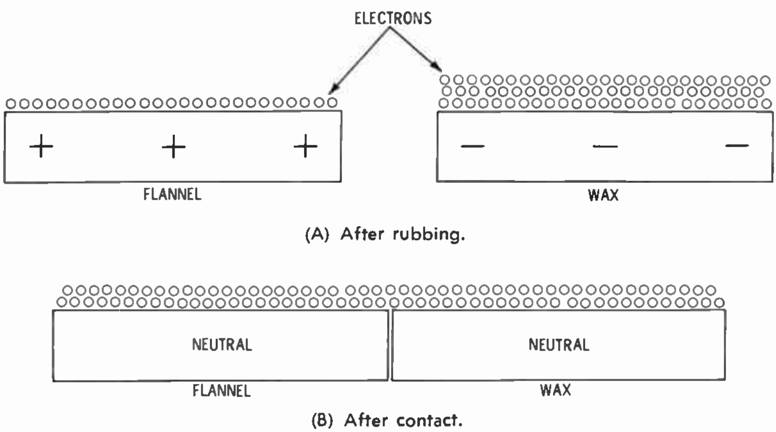


Fig. 5. Distribution of electrons in flannel and wax.

Conductors and Insulators

In metals, enormous quantities of free electrons exist, while such substances as glass and rubber contain only small amounts. It is the presence of free electrons in some substances that enables us to account for the conduction of electricity. The more free electrons a substance contains, the better conductor of electricity it is. Because of their great numbers of free electrons, metals are very good electrical conductors. Again, substances such as glass, rubber, mica, etc., with their comparatively few free electrons, are poor conductors of electricity but instead are good insulators or non-conductors.

Actually, there is no sharp dividing line between conductors and insulators because free electrons exist to some extent in all matter. We simply use the best conductors as wires to carry current, and use the poorest conductors as insulators to prevent the escape of electricity into undesired conducting paths. Listed below are some of the best conductors and some of the best insulators, arranged in their order of respective abilities to conduct or to resist the flow of electrons.

Conductors	**Insulators**
Silver	Dry air
Copper	Glass
Aluminum	Mica
Zinc	Rubber
Brass	Asbestos
Iron	Bakelite

TYPES OF ELECTRICITY

Basically there are two types of electricity, namely static and dynamic. Static electricity is the storage of positive or negative charges on a body. For example, rubbing a rubber rod with a piece of fur will cause electrons from the fur to be deposited on the rod, giving it a negative charge which can be transferred to another object by touch. This charge was produced by friction.

Most of us have, at some time or another, received an electric shock as we slid across the plastic seat covers in an automobile to reach the door handle, or walked across a wool rug to a drinking fountain. These are examples of static electricity. Here a static charge which has built up on us or our clothing is of sufficient magnitude to discharge to the metal object we are about to touch.

This discharge is evident from the electrical shock and the spark produced by the discharge.

Another form of static electricity is lightning, although it cannot be attributed entirely to friction. Lightning and the thunder which accompanies it are caused when static charges which have built up on clouds discharge between clouds or between the clouds and earth. Thunder is produced by this discharge but we hear it some time after the lightning flash due to the fact that light waves travel faster than sound waves.

Dynamic electricity is a type produced by a continuous source such as a battery or a generator. This type of electricity can be controlled and is, therefore, the most useful for practical purposes where energy must be exerted.

ELECTRIC CURRENT

As mentioned previously, some substances such as copper, silver, etc., have an abundance of free electrons. These free electrons are in a state of continual rapid motion, or thermal agitation. The situation is analogous to that in a gas where it is known that the molecules, according to the kinetic theory, are in a state of rapid motion with a random distribution of velocity. If it were possible at a given instant to examine the individual molecules or electrons, it would be found that their velocities vary enormously, and the average velocity is a function of the temperature. The higher the temperature of a substance the higher the velocity of the atoms and electrons.

Now if by some means the random motion of the molecules or electrons in a conductor can be controlled and made to flow in a specific manner, there results what is called a flow of electric current. This current may be one of two types—direct or alternating—depending on the device used to produce it. An alternating current (AC) is one in which the electron flow changes direction and amplitude at a specified rate, or frequency. With direct current (DC), however, electrons flow in one direction only. The rate of current flow may be steady or it may vary at a specific or random rate, but as long as it moves only in one direction, it is classified as direct current. Such a means of controlling or directing the electron motion is provided by such devices as an electric battery or a DC generator (a mechanical device that converts mechanical energy into direct-current electrical energy). The battery, of course, is simply a "storehouse" of energy that permits electrons to flow whenever a conductive path is provided between its terminals (Fig. 6). Alternating current is produced by either mechanical or electronic means.

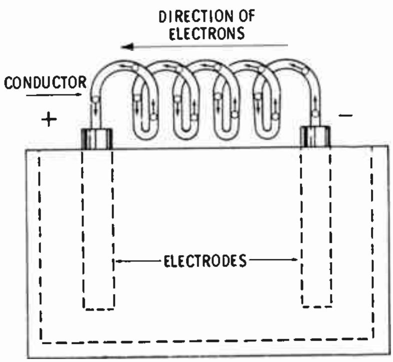


Fig. 6. The movement of electrons from the positive to the negative terminal of a battery.

In practical work, we are usually concerned with mixtures of AC and DC. That is, we are concerned with voltage relations such as shown in Fig. 7. When an AC voltage is mixed with a DC voltage, the combination is described as having an AC and a DC component. If the combination has a DC component sufficiently great that the AC component does not cross the zero axis, the waveform is described as *pulsating DC*. This means that the waveform has one polarity only. On the other hand, if the DC component is comparatively small so that the AC component does cross the zero axis, the waveform is described as *AC with a DC component*. This means that the waveform has two polarities. These basic facts will be explained in greater detail when electric circuit action is discussed.

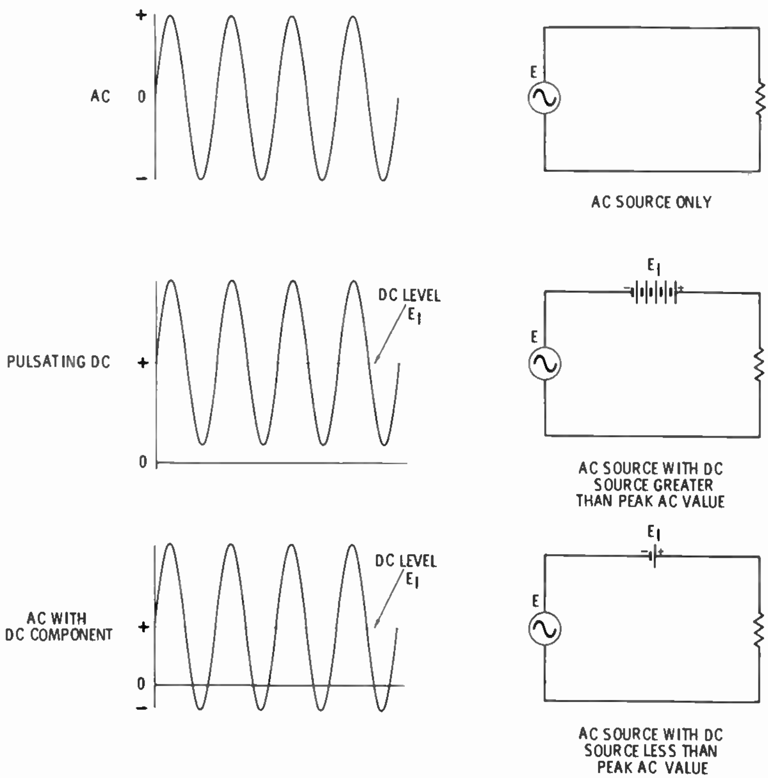


Fig. 7. Three basic combinations of AC and DC values.

Resistance to the Movement of Electrons

The progressive motion of electrons in a conductor is retarded by collisions with the atoms of the substance, and it is this hindrance to their movement that constitutes the electrical resistance in a conductor.

This resistance varies in different conductors, and also with the temperature of the conductor. When the temperature increases, the velocity (speed) of the atoms and electrons increases, which in turn causes more frequent collisions and, as a result, a greater hindrance to their progress. The frequency of collisions between the atoms and electrons is also increased when a greater number of electrons are present. Because of this the heating in a current-carrying conductor increases with the amount of current that is flowing.

ELECTRICAL PRESSURE (VOLTAGE)

As previously mentioned, the directed motion of free electrons in a conductor constitutes an electric current. To understand how a flow of current may be established, it is well to consider the analogy of a water pump in a hydraulic system (Fig. 8).

In this case, by virtue of the pump impeller the water enters the pump at the intake end at low pressure and leaves the discharge end at high pressure. The difference in pressure at the two ends of the pump causes water to flow through the pipe as indicated by the arrows.

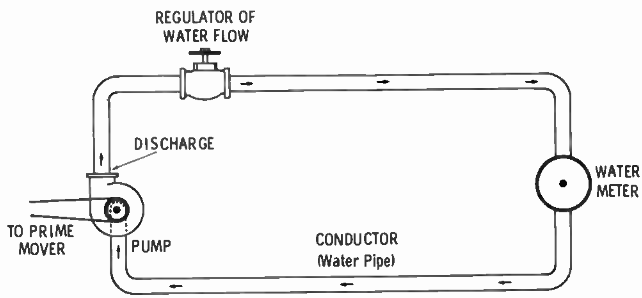


Fig. 8. Water system analogy to an electrical circuit.

The action of the electrical system is similar. In any electrical circuit, a generator or battery may be used to supply an *electromotive force*, or *voltage*, in a manner similar to the pump in the hydraulic system. Here the positive and the negative terminals of the generator correspond to the intake and the discharge of the pump, respectively (Fig. 9).

Similarly, in the case of the generator, it is said that the pressure is higher at the negative end and lower at the positive end, corre-

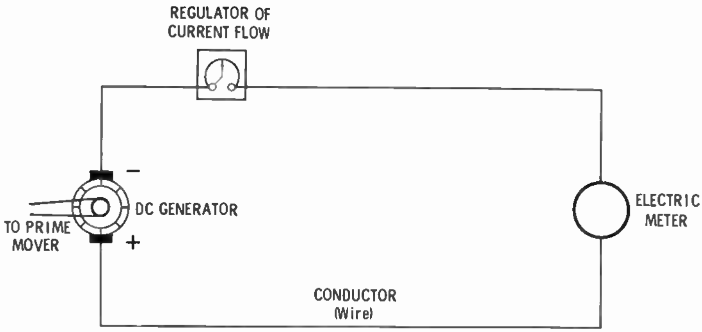


Fig. 9. Equivalent electrical circuit of the water system in Fig. 8.

sponding to difference in pressure at the discharge and intake ends of the pump in the hydraulic system. It is this difference in pressure between the generator terminals which causes an electric current to flow in the circuit, in much the same way as the water is forced through a pipe in the hydraulic system.

Electrical pressure, also referred to as *potential difference* and electromotive force, is measured in terms of a unit known as the *volt*.

THE COULOMB AND AMPERE

Again using the water system as an analogy, the rate at which water is flowing through the pipe may be measured in gallons per second. Similarly, the amount of current in the electric circuit is measured in a unit called the *coulomb*.

When the current in a circuit flows at the rate of one coulomb per second the term *ampere* is used. This term facilitates the expression of current flow in that it makes it unnecessary to say "per second" each time, as second is already a part of the ampere unit. Thus, one coulomb per second is one ampere.

The relationship between coulombs and amperes may be expressed as follows:

$$I = \frac{Q}{t} \qquad \text{or} \qquad Q = I \times t$$

where,

I is the current in amperes,
Q is the quantity of electricity in coulombs,
t is the time of flow in seconds.

Thus, if a battery sends a current of 5 amperes through a circuit for one hour, the number of coulombs of electricity that will flow through the circuit will be $5 \times 60 \times 60 = 18{,}000$ coulombs.

ELECTRICAL RESISTANCE IN DC CIRCUITS

All conductors of electricity oppose the flow of current through them, i.e., they have electrical resistance. The unit of resistance is called the *ohm*. A conductor may be said to have one ohm of resistance if the ratio of the electrical pressure (in volts) to the current flowing through it is unity. For example, if 10 amperes of current is flowing through a circuit, with an electrical pressure of 10 volts producing this flow, the resistance of the circuit will be

$$\frac{10}{10} = 1 \text{ ohm.}$$

ALTERNATING CURRENT

An alternating current may be defined as a current which continually changes in magnitude and periodically reverses in direction. The action of an alternating current can be plotted as a sine wave as shown in Fig. 10. The upper half of the curve represents the forward, or positive, movement of the current and the lower half represents the reverse, or negative, movement. The completion of one forward and reverse movement of the current constitutes a complete cycle. The number of cycles that occur in one second of time is given as the frequency of the current.

At this point the reader may wonder why the sine wave was chosen to discuss AC circuit action. For example, the square wave shown in Fig. 11 *seems* to be simpler than a sine wave. However, it will be found that it is very difficult to discuss AC circuit action if the square wave is chosen as a fundamental AC waveform. On

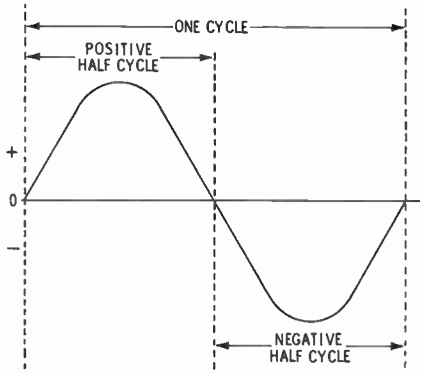


Fig. 10. A sine wave.

the other hand, it is comparatively easy to discuss AC circuit action if the sine wave is chosen. This fact is based on mathematical relations which can be ignored at this time. Merely note that Ohm's law is comparatively simple when applied to sine-wave voltages and currents, but becomes extremely complicated when applied to square-wave voltages and currents.

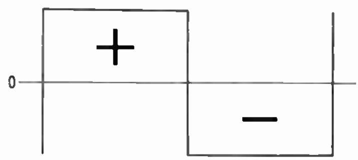


Fig. 11. A square wave.

Average Values of Voltage and Current

In the sine curve, or sine wave, it will be noted that the voltage and current in an alternating-current circuit are always changing during a complete cycle from a positive peak or maximum value to a negative peak of the exact opposite value. Therefore, when considering a complete cycle, the true average value is zero. When we consider the average values of current and voltage in AC circuits, we do not refer to the averages of the full cycle, but instead, to the average of each half cycle only.

To obtain the average value of each half cycle, it is, therefore, necessary to add the instantaneous values of one half cycle as plotted on a curve and divide by the number of such values used.

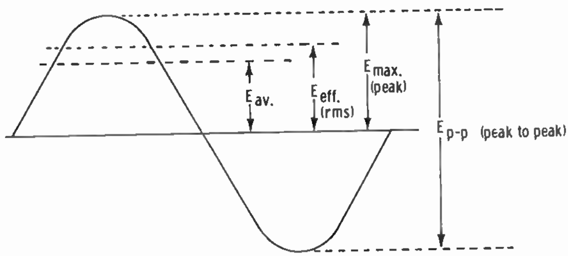


Fig. 12. Relationship between average, effective (rms), maximum (peak), and peak-to-peak voltages and current.

If this is done, the results show that the average value of voltage or current is 0.636 times the maximum or peak value (Fig. 12). This is usually written:

$$\text{average voltage} = 0.636 \times \text{maximum voltage}$$

$$\text{and average current} = 0.636 \times \text{maximum current}$$

$$\text{or } E_{av} = 0.636\ E_{max}$$

$$\text{and } I_{av} = 0.636\ I_{max}$$

In practical work, we are often concerned with sine waveforms in which both half cycles have the same polarity, as shown in Fig. 13. It will be found that the average and effective values of these waveforms are the same. Note that only the peak-to-peak values

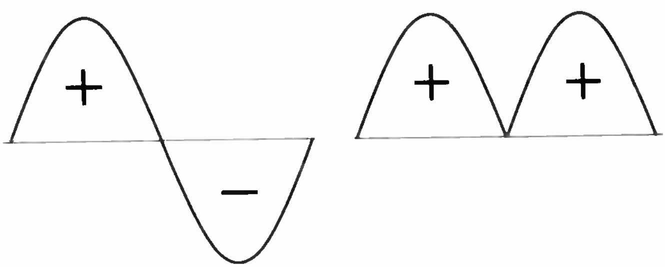


Fig. 13. The average and effective values of these waveforms are the same.

are different. That is, the waveform with positive and negative half cycles has twice the peak-to-peak voltage compared to the waveform that has positive half cycles only.

Effective Values of Voltage and Current

In practical calculations, however, the instantaneous or average values of voltage and current are seldom used, but the effective values are. Because voltages and currents in an AC system are actually of different instantaneous values throughout the time periods of an alternating cycle, and since the cycles follow one another in rapid sequence per second of time, the actual effective voltage or current can only be determined by comparing the heating effect of an alternating current with that of a direct current. This is known as the *effective* or *root-mean-square* (abbreviated as rms) value of an alternating current or voltage (Fig. 12). If the instantaneous values of current during a cycle are taken, the results squared, an average value obtained, and the square root of this value derived, the heating effect will be the same as in a direct-current circuit; that is, the heating effect is proportional to the square of the current.

It follows then that the amplitude or peak factor of an alternating voltage must be the ratio of its maximum value to its effective or rms value, or $\sqrt{2}$, but since this value is approximately 1.414 and its reciprocal value is 0.707, we may write:

$$E_{eff} = E_{rms} = E_{max} \times 0.707 = \frac{E_{max}}{1.414}$$

Similarly,

$$E_{max} = E_{eff} \times 1.414 = \frac{E_{eff}}{0.707}$$

When an alternating current is considered, we may similarly write:

$$I_{eff} = I_{rms} = I_{max} \times 0.707 = \frac{I_{max}}{1.414}$$

$$\text{or } I_{max} = I_{eff} \times 1.414 = \frac{I_{eff}}{0.707}$$

It should be noted that whenever an alternating current or voltage is mentioned without specific reference as to instantaneous, maximum or average values, the effective value is always assumed, because it is this current or voltage that is measured by the respective instruments. If a maximum or peak value of the current or voltage is desired, it may readily be obtained by multiplying the instrument or meter reading by 1.414.

The Sine Curve

Since the generation of an alternating current or potential is always represented by means of a sine curve, certain factors concerning its construction will be considered; and although the sine of an angle is a trigonometric figure, it may be represented by the aid of one or more right-angle triangles as shown in Fig. 14.

By definition, the sine of an angle, such as (A) in Fig. 14, is equal to the opposite side of the triangle divided by the hypotenuse. This may be written:

$$\text{sine A} = \frac{\text{opposite side}}{\text{hypotenuse}}$$

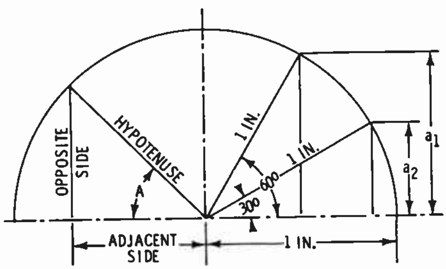


Fig. 14. Diagram illustrating the sine of an angle.

It may easily be proved with the aid of simple mathematical relations that the sine values for angles such as 30°, 45° and 60° are ½, $\frac{1}{2}\sqrt{2}$, and $\frac{1}{2}\sqrt{3}$, respectively. Approximate sine values for various angles may easily be obtained from triangles inscribed in a circle of unity length radius as illustrated in Fig. 14. Thus, if

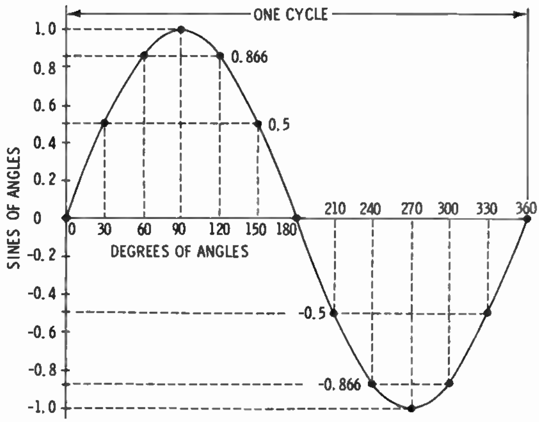


Fig. 15. Relationship between angles in 30° steps and the respective sines. The complete curve, covering angles from 0° to 360°, represents one complete cycle of an alternating current.

the radius of the circle is one inch, for example, the hypotenuse will also be one inch in length. Similarly, we have the sine for an angle of 30° = $a_2/1$ or a_2, which may be found by direct measurement to be 0.5. The sine for a 60-degree angle will likewise be found to be approximately 0.87, or 0.8660, from a table of sine values.

A further study of our sine function will show that the sines for angles of 120° and 150° are equal to the sines for 60° and 30°, respectively. By using the foregoing values on a coordinate-axis system as illustrated in Fig. 15, with the sines plotted on the vertical axis (ordinate) and the number of degrees from 0° to 360° on the horizontal axis (abscissa), it will be found that the projecting intersections when properly joined together represent a true sine curve.

Vector Representation of Voltage and Current

The periodic change which occurs in the value of an alternating voltage or current during a cycle need not be represented by a curve plotted as illustrated in Fig. 15, but may be more easily represented by vectors, as shown in Fig. 17B.

In order to show how vectors may be applied to the study of an alternating current, refer to Fig. 16. Here, two sine curves, R and S, are drawn on the same base, with a time difference of $\phi°$. The curves indicate the various instantaneous values throughout the complete cycle. At θ degrees from the starting point, for example, the value of R is O′A′, while that of S is O′B′. In Fig. 16, two circles are drawn, their radii being equal to the maximum value of the two sine curves. The lines OR and OS are assumed to rotate about O as a center and in a counterclockwise direction. At an angle $\theta°$ from the start, OR and OS have reached the position shown. The vertical projections of these two lines are OA and OB respectively, and these lines represent the instantaneous values under consideration.

Now since both OR and OS are assumed to rotate at the same speed, corresponding to the same frequency, it follows that the angle ROS $= \phi$ remains constant throughout the cycle. The projections OA and OB on the vertical axis vary according to a sine law since the points A and B perform a simple rotating motion about the point O.

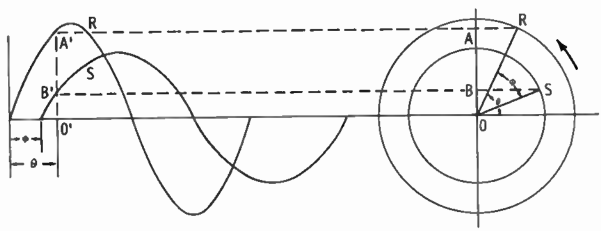
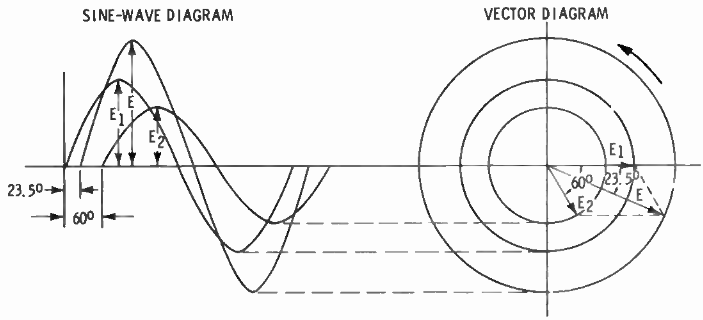


Fig. 16. Vectorial representation of two alternating-current sine waves.

Diagrams of this type are often made to represent alternating current or voltage values since they lend themselves more readily to exact mathematical treatment.

Addition of Alternating-Current Voltages

In the study of alternating currents, vector representation is always used since this method greatly facilitates representation of all the factors involved. Assume, for example, that it is desired to add two voltages E_1 and E_2 as illustrated in Fig. 17A, with effective values of 75 and 50 volts, respectively. Assume further that E_2 is lagging behind E_1 by an angle of 60°. These voltages will have maximum values of $75\sqrt{2} = 106$ and $50\sqrt{2} = 70.7$ volts, respectively.



(A) By plotting. (B) By vectorial representation.

Fig. 17. Addition of two sine waves.

The addition may be performed by plotting the two sine curves as shown, and adding, at equally spaced distances, their instantaneous values to give a new sine curve, E. This new sine curve will be found to have a maximum value of 154 volts, an effective value of 109 volts, and will lag E_1 by 23.5°. Thus, the sum of the two voltages with effective voltages of 75 and 50 volts and differing in phase by an angle of 60° is 109 volts.

A considerable saving of time will be obtained if the three sine curves are added vectorially as previously considered instead of being plotted. You will notice in the vector diagram of Fig. 17B that two vectors (E_1 and E_2) are geometrically added by completing the parallelogram and drawing the diagonal. This diagonal represents the resultant vector E. It should be pointed out, however, that since effective values are 0.707 times the maximum values, if maximum values are used in laying out the vectors, the resultant vector should be divided by 1.414 to obtain the effective value.

The geometric addition of vectors E_1 and E_2 may be performed mathematically as follows:

$$E = \sqrt{(75 + 50 \times \cos 60°)^2 + (0 + 50 \times \sin 60°)^2}$$
$$= \sqrt{100^2 + 43.3^2} = 109 \text{ volts}$$

and $E_{max} = 109\sqrt{2} = 154$ volts

The angle can readily be verified, since

$$\tan \phi = \frac{43.3}{100} = 0.433 \text{ and } \phi = 23.5°$$

OHM'S LAW

When considering the flow of electrons in a conductor, it is evident that the greater the electromotive force (emf), or voltage, the more electrons will flow in the circuit; and also the greater the resistance of a conductor, the less the number of electrons that will flow through.

It has been found that there is a definite mathematical relationship between the emf (voltage) applied to a circuit having a definite resistance and the flow of current in the circuit. This relationship is expressed in a formula known as *Ohm's law*. Here voltage, current, and resistance are represented by the letters E, I, and R, respectively. The value of any one of these electrical units can be computed if the other two are known. Ohm's law states that the current flowing through a resistance under a given emf is inversely proportional to the resistance and directly proportional to the voltage. Thus, $I = \frac{E}{R}$, in which I is the current in amperes; E is the emf in volts and R is the resistance in ohms.

This formula can be manipulated mathematically into two other forms that are often used.

$$I = \frac{E}{R}, \qquad R = \frac{E}{I} \qquad \text{and} \qquad E = I \times R$$

A convenient memory aid for Ohm's law is shown in Fig. 18. This diagram shows graphically that if you cover I with a finger,

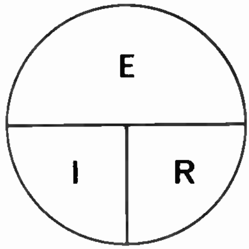


Fig. 18. Memory aid for Ohm's law.

the result is E/R. If you cover R, the result is E/I. If you cover E, the result is I $\times$ R.

Series Circuits

If several resistances are placed in series, as in Fig. 19:

$$I = \frac{E}{R_1+R_2+R_3} \text{ or } E = I\ (R_1+R_2+R_3)$$

$$\text{or } E = I \times R_1 + I \times R_2 + I \times R_3$$

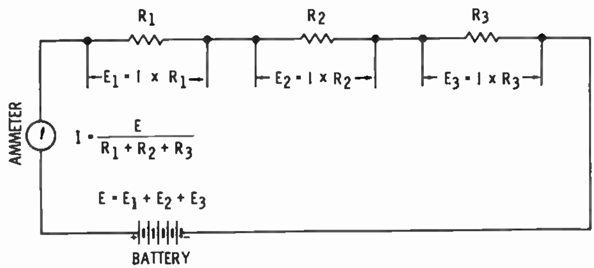


Fig. 19. Simple circuit with three resistances connected in series.

The sum of the differences of potential across the various parts of the circuit is equal to the total voltage impressed on the circuit. Thus, $E = E_1 + E_2 + E_3$. In the circuit of Fig. 19, the current I is the same in each part of the circuit, but the voltage across each resistance depends directly upon the value of that resistance being considered.

Example: What voltage must be furnished by the battery in Fig. 19, in order to force 0.25 ampere through the circuit, if R_1, R_2 and R_3 are 5, 15 and 20 ohms, respectively?

The total resistance R = 5+15+20 = 40 ohms. The total voltage is 40×0.25 = 10 volts.

The voltage required for each part may be conveniently used as a check. Thus:

$$E_1 = 0.25 \times 5 = 1.25 \text{ volts}$$
$$E_2 = 0.25 \times 15 = 3.75 \text{ volts}$$
$$E_3 = 0.25 \times 20 = 5 \text{ volts.}$$

Hence, 1.25 + 3.75 + 5 = 10 volts, as before.

In practical work, a constant-voltage source may be used, as has been exemplified in the foregoing discussion. It will be found, for example, that many vacuum tubes and transistors are basically constant-current sources. Ohm's law applies to both constant-voltage and constant-current sources. Fig. 20 shows the relation between current and voltage when the *resistance* is held constant. Many practical circuits are constant-resistance circuits. Note that there is a linear relation between voltage and current in Fig. 20. Next, Fig. 21 shows the relation between current and resistance when

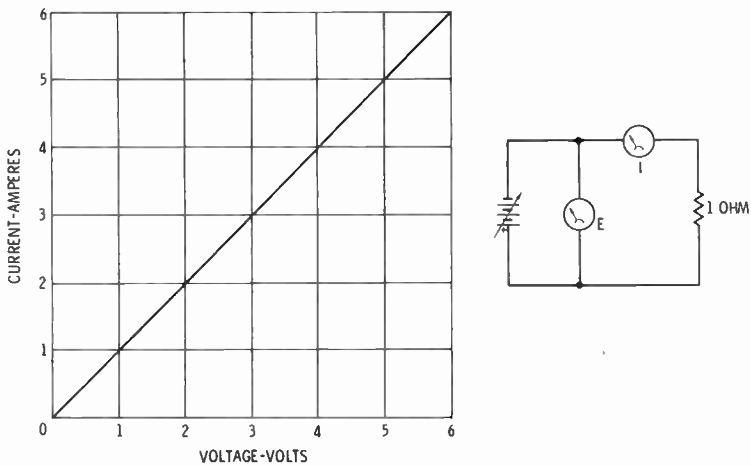


Fig. 20. Current vs voltage, with resistance constant.

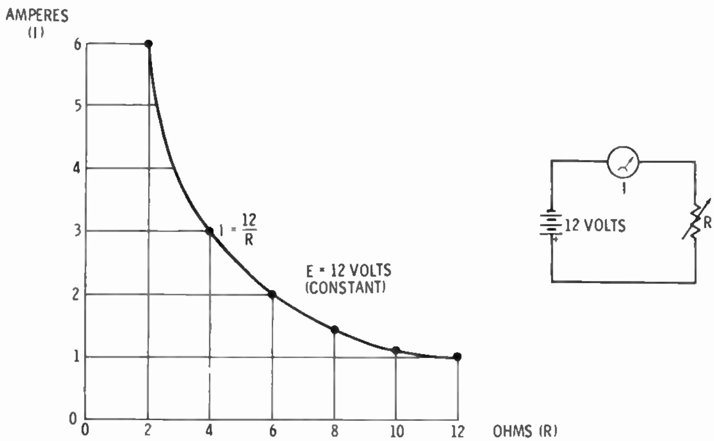


Fig. 21. Relation between current and resistance, with voltage constant.

the applied *voltage* is held constant. As the resistance is increased, the current decreases rapidly at first, and then decreases more slowly for larger increases in resistance.

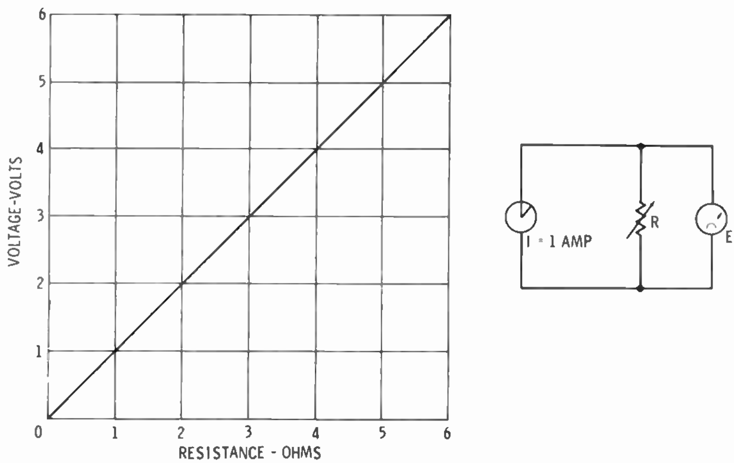


Fig. 22. Relation between voltage and resistance, with current constant.

Note in Fig. 21 that each time 1 ohm of resistance is added to the circuit, its effect becomes less, because its effect on the total resistance value is less. In other words, if there is originally 1 ohm of circuit resistance, and then 1 ohm is added, the total circuit resistance is *doubled*. But if there is originally 10 ohms of circuit resistance, and then 1 ohm is added, the total circuit resistance is increased by only *one-tenth*. Therefore, a *nonlinear* relation exists between the resistance and current in Fig. 21.

Next, consider the constant-current source I shown in Fig. 22. The symbol for a constant-current source is a circle with an inscribed angle. In this example, the constant-current source supplies 1 ampere, regardless of the value of the load resistance. It follows from Ohm's law that voltage plotted against resistance is linear (Fig. 22) when current is held constant. If Fig. 20 is compared with Fig. 22, it can be seen that the graphical forms are similar when voltage is substituted for current and resistance substituted for voltage. The relations shown in Figs. 20, 21, and 22 are basic examples of *variational analysis* in electrical work. As we proceed with the study of circuit action, we will find many other useful examples of variational analysis.

Parallel Circuits

In a parallel circuit (Fig. 23), the voltage across the various resistances is the same and the current flowing through each resist-

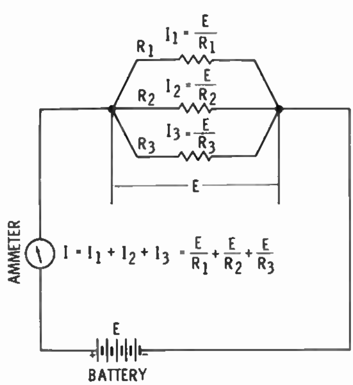


Fig. 23. Simple circuit with three resistances connected in parallel.

ance varies inversely with the value of the resistance. The sum of all the currents, however, is equal to the main current leaving the battery. Thus:

$$E = I_1 \times R_1 = I_2 \times R_2 = I_3 \times R_3$$

and,

$$I = I_1 + I_2 + I_3$$

When Ohm's law is applied to the individual resistances, the following is obtained:

$$I_1 = \frac{E}{R_1}, \qquad I_2 = \frac{E}{R_2} \quad \text{and} \quad I_3 = \frac{E}{R_3}$$

Hence:

$$I = \frac{E}{R_1} + \frac{E}{R_2} + \frac{E}{R_3} \quad \text{or} \quad I = E\left(\frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3}\right)$$

and since $\frac{E}{I} = R$, the equivalent resistance of the several resistances connected in parallel is $\frac{1}{R} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3}$.

A simple and convenient method of finding the equivalent resistance of two resistances in parallel is to use the formula:

$$R = \frac{R_1 \times R_2}{R_1 + R_2}$$

If more than two resistances must be considered, this formula can be applied to the first two, then the value of the answer and the value of the second resistor can be used, etc.

Example: If the resistances in the circuit of Fig. 19 were connected in parallel, as in Fig. 23, what will be the total current and the current flowing through each resistance if the voltage remains unchanged or 10 volts?

The total resistance (R) for the combination will be found as follows:

$$\frac{1}{R} = \frac{1}{5} + \frac{1}{15} + \frac{1}{20} = \frac{19}{60}$$

Then:

$$R = \frac{60}{19} = 3.16 \text{ ohm.}$$

The total current $= \dfrac{10}{3.16} = 3.16$ amperes.

The current in the 5-ohm resistance is $\dfrac{10}{5} = 2$ amperes.

The current in the 15-ohm resistance is $\dfrac{10}{15} = 0.66$ amperes.

The current in the 20-ohm resistance is $\dfrac{10}{20} = 0.5$ amperes.

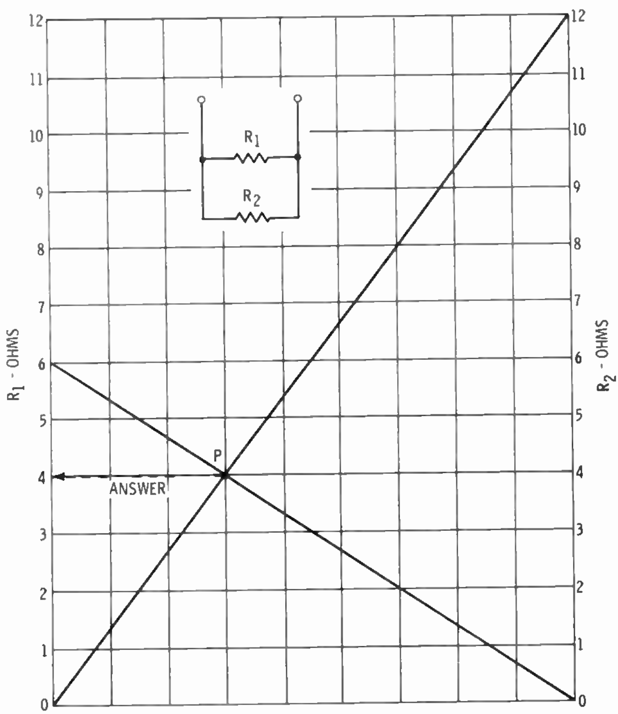


Fig. 24. Graphical solution for two resistors connected in parallel.

The currents through the resistances may conveniently be added as a check of the answer. Thus 2 + 0.66 + 0.5 = 3.16 amperes as before.

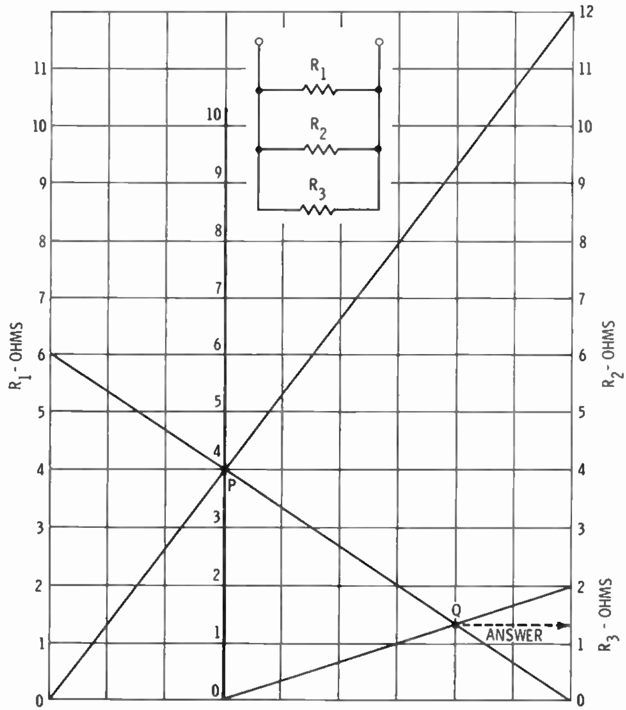


Fig. 25. Graphical solution for three resistors connected in parallel.

Fig. 24 shows how the resistance of two resistors connected in parallel may be found graphically. In this example, $R_1 = 6$ ohms, and $R_2 = 12$ ohms. The lines intersect at point P, from which we project over to the vertical axis to find the total resistance, which is 4 ohms. Note that the length of the horizontal interval between the vertical axes is arbitrary. If we are working with higher values of resistance, both of the values on the vertical axes may be multiplied by any power of 10. For example, suppose that 60 ohms are connected in parallel with 120 ohms; then the total resistance is 40 ohms. Again, if 60K (60,000) ohms are connected in parallel with 120K (120,000) ohms, the total resistance is 40K (40,000) ohms.

Suppose now that we have three resistors connected in parallel, as shown in Fig. 25, with $R_1 = 6$ ohms, $R_2 = 12$ ohms, and $R_3 = 2$ ohms. We first determine that the total resistance of the 6-ohm and 12-ohm resistors is 4 ohms, as seen at point P. A line is now drawn for the 2-ohm resistor, as shown, and the point of intersection Q is obtained. Thus, we find that the total resistance of the three resistors connected in parallel is 1.33 ohms. The same method may be extended to any desired number of resistors connected in parallel.

Power in Electrical Circuits

As previously stated, the electrons in their movement through a circuit do not have a clear path, but are in constant collision with atoms of the metal, causing the metal to heat. The heat so developed varies with the number of collisions and increases with the increase in current flow. It has been found that the developed heat or power loss varies directly as the resistance and as the square of the current. This relationship can be expressed by three formulas:

$$W = I^2 \times R = \frac{E^2}{R} = E \times I$$

where,

W is the power in watts,
E, I and R are the voltage, current, and resistance of the circuit.

Example: If a particular heating element requires 25 amperes at a potential of 110 volts, what is the power consumption?

The power is $W = 25 \times 110 = 2{,}750$ watts = 2¾ kw (kilowatts).

Since the watt is a small unit of electrical power, the kilowatt, which is a unit 1,000 times larger, is more convenient when it is desired to express large amounts of power.

Therefore to change watts to kilowatts divide by 1,000, and to change kilowatts to watts multiply by 1,000.

One horsepower (HP) = 746 watts.

$$\text{Thus, one kilowatt} = \frac{1{,}000}{746} \text{ or } 1.34 \text{ horsepower.}$$

To obtain the horsepower consumption in the above heating element:

$$HP = \frac{2{,}750}{746} = 3.7 \text{ horsepower}$$

We have learned that the basic unit of power is the watt. Power is a rate unit, just as current is a rate unit. Current denotes the rate of charge flow, while power denotes the rate of energy flow. In other words, power is the rate at which work is being accomplished. Energy is measured in *joules*. One joule is equal to one watt per second. Thus, 1,000 joules are equal to one kilowatt per second. Or, as another example, 3,600 joules are equal to one kilowatt-hour. Both power and energy (watts and joules) are commonly represented by the symbol W. To avoid confusion,

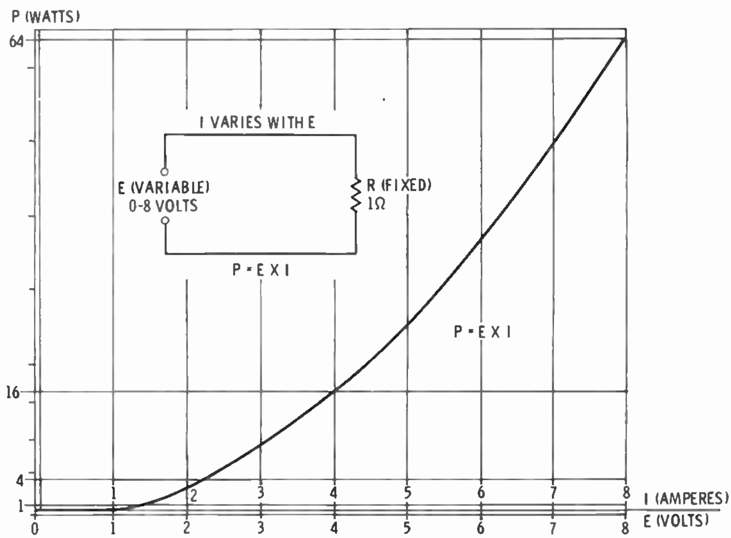


Fig. 26. Graph of power related to changing voltage and current.

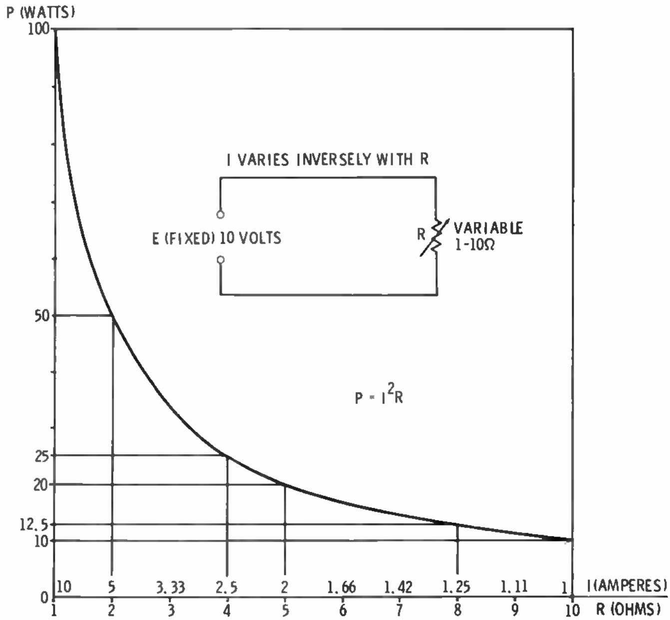


Fig. 27. Graph of power related to changing resistance and current.

however, it is preferable to write P for power and W for energy (or work). Thus:

$$P = EI \text{ watts}$$
$$W = EIt \text{ joules}$$

where,

E is in volts,
I is in amperes,
t is in seconds.

The horsepower is also a unit that denotes the rate of energy flow, or the rate of work being accomplished. Thus, HP can be equated to watts. However, horsepower-hours must be equated to joules, or to watt-hours. This is perhaps the most common source of error made by beginners—the confusion of power with energy (or work). Note that power is numerically equal to work. The amount of power in a circuit changes when either voltage or cur-

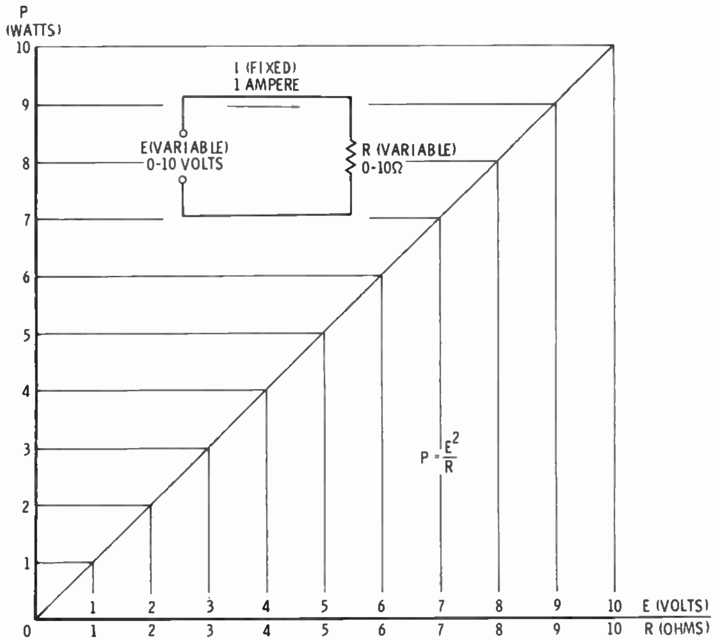
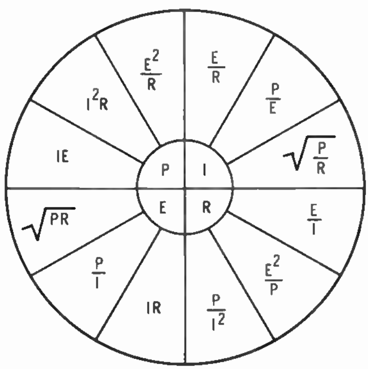


Fig. 28. Graph of power related to changing voltage and resistance.

rent, or both, are changed. This variational relation is shown in Fig. 26. Next, if the voltage is constant and the resistance is varied, the power varies with the resistance (or current) as shown in Fig.

Fig. 29. Summary of basic formulas.



27. Finally, if the current is constant, the relation of power to resistance (or voltage) is as shown in Fig. 28.

A graphical summary of voltage, current, resistance, and power relations is shown in Fig. 29. There are twelve basic formulas that you should know. The four quantities E, I, R, and P are at the center of the diagram. Adjacent to each quantity are three segments. In each segment, the basic quantity is expressed in terms of two other basic quantities. Note that no two segments are alike.

Series-Parallel Circuits

Finding the total resistance value of circuit (A) in Fig. 30 can be very simple if you keep in mind that any number of resistances connected in series may be replaced by a single resistor with a value equal to the arithmetical sum of the individual resistors, or that any number of resistors in parallel can be replaced by an equivalent whose value is equal to the reciprocal of the sum of the reciprocals of the individual units.

Circuit (A) in Fig. 30 consists of resistors R_a and R_b in series, and the two also in parallel with R_d. This group is connected in series with R_c and the whole combination is again connected in parallel with R_f. The simplest way to solve a resistance combination of this type is to go through the problem step by step, combining each series and each parallel group of resistances and replacing them with their equivalent resistance.

Hence, to solve this circuit, first replace R_a and R_b with their equivalent, R_g (Fig. 30B). The next step is to combine R_g and R_d, replacing them with their equivalent, R_h (Fig. 30C). By replacing R_c and R_h with their equivalent, R_j, the original circuit now assumes the form shown in Fig. 30D.

In a similar manner, R_j and R_f in parallel are replaced by resistance R_k, obtaining the result shown in Fig. 30E. Finally, as a result of these calculations, a resistance is obtained having the same current-limiting effect as all of the resistors shown in Fig. 30A.

Example: Assume the resistance values in Fig. 30A to be as follows, and compute the total resistance:

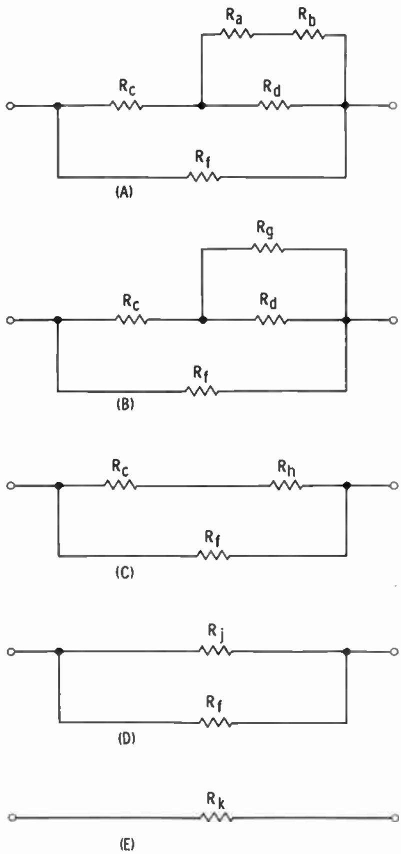


Fig. 30. A method by which a series-parallel combination of resistances may be reduced to an equivalent resistance.

$$R_a = 160 \text{ ohms}$$
$$R_b = 200 \text{ ohms}$$
$$R_c = 120 \text{ ohms}$$
$$R_d = 360 \text{ ohms}$$
$$R_f = 200 \text{ ohms}$$

First replace R_a and R_b with R_g.

$$R_g = R_a + R_b = 360$$

Replace R_g and R_d with R_h.

$$R_h = \frac{R_g \times R_d}{R_g + R_d} = \frac{360 \times 360}{360 + 360} = 180$$

Replace R_h and R_e with R_j.

$$R_j = R_h + R_e = 300$$

Replace R_j and R_f with R_k, the total resistance.

$$R_k = \frac{R_j \times R_f}{R_k + R_f} = \frac{300 \times 200}{300 + 200} = 120$$

A later discussion will explain how Ohm's law applies to AC circuits using resistors, capacitors, and inductors. Here a different type of opposition to current flow exists.

ANALOGY BETWEEN ELECTRIC AND MAGNETIC CIRCUITS

There is a great similarity between electric and magnetic circuits. For example, the total number of magnetic lines of force, or magnetic flux, produced in any circuit will depend upon the magnetomotive force (mmf) acting on the circuit and the opposition to magnetism in the circuit, just as the current depends upon the electromotive force and the resistance in the circuit. This similarity between the electric and the magnetic circuits becomes even more obvious when you consider Ohm's law in connection with both. Thus, according to Ohm's law:

$$\text{electric current} = \frac{\text{electromotive force}}{\text{resistance}}$$

$$\text{expressed in units, amperes} = \frac{\text{volts}}{\text{ohms}}$$

The resistance depends upon the materials of which the circuit is composed, and the geometrical shape and size of the circuit. Similarly, in the magnetic circuit, the total number of magnetic lines produced by a given magnetizing force depends upon the magnetomotive force, the material comprising the circuit, and its shape and size. That is,

$$\text{magnetic flux} = \frac{\text{magnetomotive force}}{\text{reluctance}}$$

$$\text{expressed in units, maxwells} = \frac{\text{gilberts}}{\text{reluctance}}$$

This is called Rowland's law. At the present time, there is no unit for the measurement of reluctance.

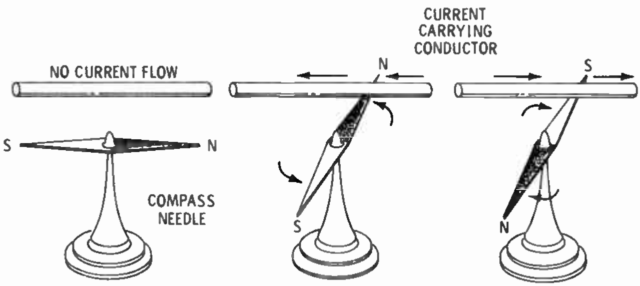


Fig. 31. Deflection of a compass needle when held near a current-carrying conductor.

It should be noted that in the electric circuit, resistance causes heat to be generated, resulting in wasted energy; but in the magnetic circuit, reluctance does not involve any similar waste of energy.

Electromagnetism

In the early part of the eighteenth century, a Danish physicist named Hans Christian Oersted discovered the effects of an electric current on the magnetic needle. While experimenting with the voltaic battery, Oersted found that joining the wires from a battery above a suspended magnetic needle caused the compass needle to turn on its axis and set itself at right angles to the wire. When the current was reversed, the compass needle turned in the opposite direction. This action is illustrated in Fig. 31.

The magnetic effect of an electric current was further demonstrated by sending electric current through a vertical wire which passes through a piece of cardboard covered with iron filings as shown in Fig. 32. A piece of copper wire is pierced through the center of a sheet of cardboard and carried vertically for two or three feet before being bent around to the terminals of a battery

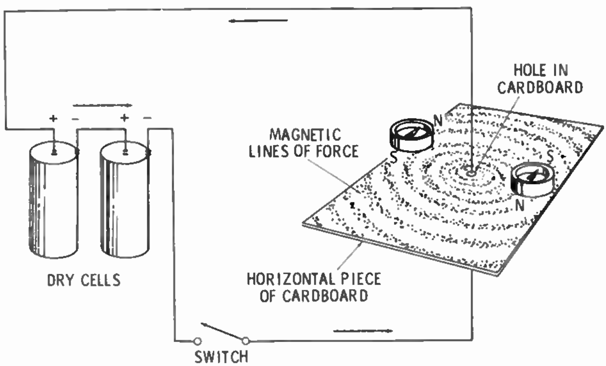


Fig. 32. Experiment showing direction of lines of force in the magnetic field of a conductor carrying an electrical current.

or other source of current. If iron filings are sprinkled over the card while the current is flowing, they will arrange themselves in circles around the wire, indicating the form of the magnetic field surrounding the conductor. It may be necessary to gently tap the cardboard to assist the iron filings in forming the pattern. An examination of the filings will show that each magnetic line forms a complete circle by itself. By placing small compasses at various positions on the cardboard, it will be observed that the needles always point in a direction parallel to the circular magnetic lines. When current flows through the wire in the direction indicated, the needles will point in a clockwise direction, and if the current is reversed, the needles will also reverse themselves—that is, they will swing around in a counterclockwise direction.

Fig. 33 shows a method of tracing the direction of the magnetic lines of force around a permanent magnet. If a small magnetic needle is suspended by a thread and held near the magnet it will point in some fixed direction, depending on the proximity of the poles of the magnet. The direction taken by the magnet is called the direction of force at that point, and if the suspended needle is moved forward in the direction of the pole, it will trace a curved line starting at one pole and ending at the other.

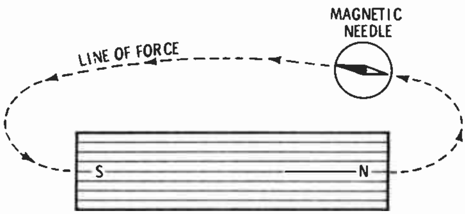


Fig. 33. Method of tracing the direction of magnetic lines of force by means of a magnetic needle.

Experiments such as these have proven conclusively that electric current possesses magnetic properties, in that it can move a magnet, and that a relationship exists between electricity and magnetism. It is perhaps true to say that these observations more than any other started a chain of events that has helped to shape our industrial civilization.

From the foregoing it is also clearly evident that a wire carrying an electric current behaves like a temporary magnet and that magnetic lines of force in the form of concentric circles surround the wire and lie in planes perpendicular to the wire. When several turns of wire are formed into a coil and current is passed through it, each turn adds its magnetic field to the others, resulting in an increased magnetic strength. It is this principle that makes the electromagnet possible. Electromagnets are essential elements in much of today's electrical and electronic equipment and in many machines.

Ampere Turns

In the construction of electromagnets, it is customary to wind the coil on a soft-iron core. When the coil is wound around the core several times, its magnetizing power is proportional both to the strength of the current and the number of turns in the coil.

The product of the current passing through the coil multiplied by the number of turns composing the coil is called the *ampere turns.*

It has been established that the magnetomotive force of such a coil is:

$$\text{mmf} = 0.4\pi \text{IN} = 1.257\ \text{IN}$$

where,

mmf is the magnetomotive force in gilberts,
I is the current in amperes,
N is the number of turns in the coil.

It follows, then, that the strength of an electromagnet depends upon the product (IN) or ampere turns. Thus, for example, an electromagnet of fifty turns with one ampere flowing through it has the same strength as an electromagnet of only ten turns with five amperes flowing through it. (See Fig. 34.)

The ampere-turn unit of magnetomotive force (MMF) is a very useful unit because it permits applying Rowland's law to a magnetic circuit. In practice, most magnetic circuits are simply continuous iron cores having a rectangular form. Note that one ampere-turn sets up one line of magnetic flux in a magnetic circuit having a reluctance of one rel. Thus:

$$\text{Number of flux lines} = \frac{\text{Ampere-turns}}{\text{Rels}}$$

For example, suppose that an iron core has an average length of 6 inches, a cross-sectional area of 1 square inch, and is energized by 120 ampere-turns. Since a typical iron core has 1/2000 the reluctance of air, the reluctance of the iron core is therefore about 0.00096 rel. Thus:

$$\text{Number of flux lines} = \frac{120}{0.00096} = 125{,}000 \text{ lines of force}$$

Note in this example that there are 125,000 lines of force per square inch. This is called the *flux density;* that is, flux density is defined as the number of flux lines per unit cross-sectional area. Also note that, since there are 125,000 lines of force in a core length of 6 inches, the *magnetizing force* is equal to 120/6, or 20 ampere-turns per inch of core. It is very important to avoid confusion between units of magnetomotive force and units of magnetizing force.

It is interesting to consider the magnetic force that is exerted by a magnetic circuit, as in the foregoing example. It can be shown that about 48 pounds of force will be required to separate and make an air gap in the core. As soon as an air gap is established, the attracting force between the ends of the core is greatly reduced, because air has a much greater reluctance than iron.

Determination of Polarity

There are several methods used to determine polarity of electromagnets. The simplest method, of course, is to employ a permanent magnet such as a compass needle or any other magnet of known polarity. Thus, if the north pole of a compass needle is brought

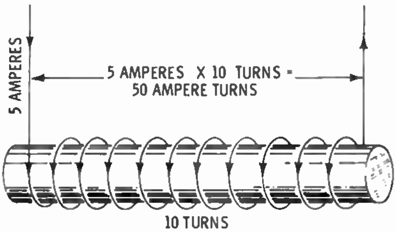


Fig. 34. Method of determining ampere-turns of a coil.

into close proximity to one of the poles of an electromagnet of unknown polarity, the action of the compass needle will immediately classify the pole as north or south depending upon whether the needle is repelled or attracted.

The Left-Hand Rule

Another method for determining the polarity of an electromagnet is by means of the so-called left-hand rule. This simple rule consists of grasping the coil in the left hand with the fingers pointing in the direction of the electron flow (from negative to positive); then the thumb points toward the North pole of the coil (Fig. 35). The grasping can be done mentally as well as physically.

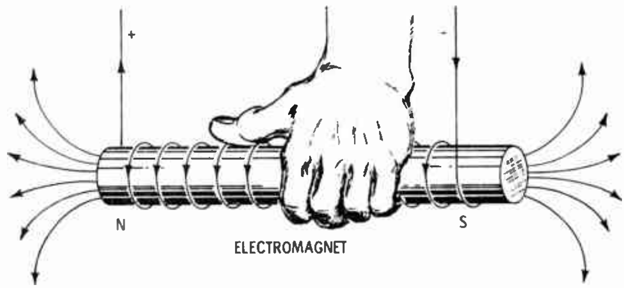


Fig. 35. Method of finding the polarity of a coil by means of the left-hand rule.

ELECTROMAGNETIC INDUCTION

Early experiments with electricity revealed that when a closed-circuit conductor such as a coil was moved in the vicinity of a magnet, a current would flow in the circuit. It was also found that a varying current in one conductor would cause similar current to flow in a second conductor, provided the second conductor was brought close enough to the first one. Such currents are said to be generated by induction and are termed induced currents. The combined action of induction and current flow is called *electromagnetic induction*.

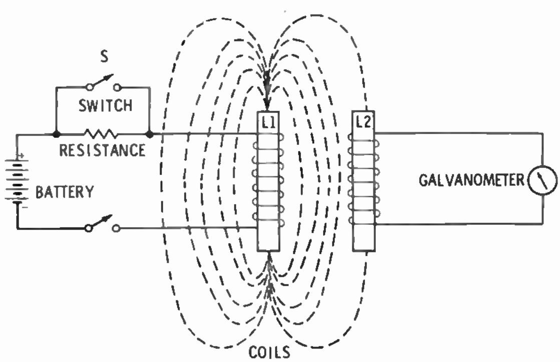


Fig. 36. Circuit showing how the effect of mutual induction may be measured by a galvanometer.

It is the ability of an electromagnet to produce a current in a conductor that makes possible the operation of motors and generators. Electromagnetic induction is also employed in transformers for the transfer of electrical energy from one circuit to another. Fig. 36 shows how electromagnetic induction couples two circuits and how the effect of this mutual induction can be measured by a galvanometer. If coils L1 and L2 are placed in axial relationship to one another as illustrated, and the current through coil L1 is varied by means of switch S, the induced current through coil L2 will also be varied as indicated by the deflection of the galvanometer.

Laws of Induction

Various experiments have been made resulting in several rules or laws for determining the value and direction of an induced current flow. These simple rules state:

1. When an emf is induced in a closed circuit by a conductor cutting a field, or vice versa, the amount of current flow is proportional to the rate of cutting and the number of lines of force being cut.
2. The induced emf sets up a current, the direction of which tends to oppose the cutting of the lines of force.
3. An induced current has a direction such that its magnetic action tends to resist the motion by which it is produced. This is known as Lenz's law.

It has been proved experimentally that if a conductor cuts 10^8 lines of force per second, a voltage of 1 volt is induced in the conductor. Thus, if a conductor cuts 10^6 lines of force in 1/100 second, a voltage of 1 volt is induced. Or, if 1,000 turns are wound in a coil, and is cut by 10^3 lines of force in 1/100 second, a voltage of 1 volt is induced in the coil.

Measurement of Magnetism

As previously noted, the magnetic lines of force are characterized by closed loops, in which the lines run from the North to the South pole outside the magnet and complete their circuit in the magnet itself. The space through which the lines of force act is called the magnetic field.

There are several terms used in connection with magnetism that must be clearly understood because of their importance and relationship to each other. These terms are *magnetic flux, flux density, magnetomotive force, reluctance, permeance,* and *permeability.*

Magnetic flux is equal to the total number of lines of force in a magnetic circuit and corresponds to the current in an electrical circuit. The unit of flux is one line of force and is called the *maxwell.*

Flux density is a measure of flux intensity. The unit of flux density is the *gauss* which is equal to one line of force per square centimeter.

Magnetomotive force (mmf) tends to drive the flux through the magnetic circuit and is similar to the electromotive force (emf) in an electrical circuit. The unit of magnetomotive force is the *gilbert.*

Reluctance is the resistance offered by a substance to the passage of magnetic flux and corresponds to resistance in an electrical circuit.

Permeance is the opposite of reluctance and may be defined as that property of a substance permitting the passage of magnetic flux. It is the reciprocal of reluctance and corresponds to conductance of an electrical circuit.

Permeability may be defined as the ratio of the flux existing in a certain substance to the flux which would exist if that material were replaced by air with the magnetomotive force acting upon this portion of the magnetic circuit remaining unchanged. The permeability of air is therefore taken as unity or 1 (one). The permeability of certain types of iron is often more than 5,000 times that of air, varying with the quality of the iron. It should also be noted that the permeability of any substance increases with the increase of its cross-section and decreases with an increase in its length.

Magnetization Curves

Curves are frequently used to determine the number of ampere turns required in an electromagnetic circuit when the magnetic material composing the circuit and other factors are known. Thus, to determine the ampere turns required per inch of a magnetic circuit it is only necessary to know the flux density and permeability. If a curve or curves are plotted, giving the direct relationship between flux density and ampere turns required per inch of various magnetic materials, they will appear as in Fig. 37.

Hysteresis

The term hysteresis has been given to the action of lag of magnetic effect behind the source. Hysteresis thus means to "lag be-

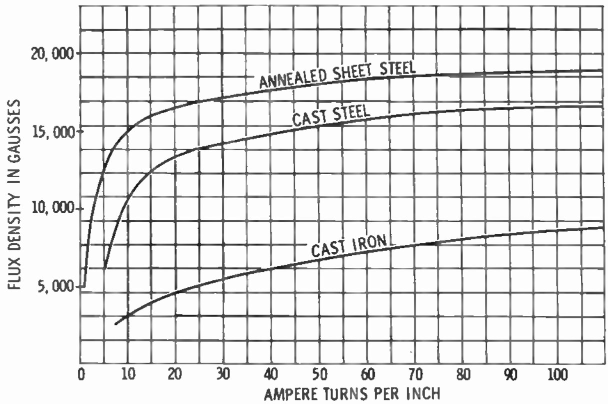


Fig. 37. Typical magnetization curves for cast iron, cast steel, and annealed sheet steel.

hind," hence its application to denote the lagging of magnetism in a magnetic material behind the magnetic flux which produces it. Hysteresis is caused by the friction between the molecules in a magnetic material, which require an expenditure of energy to be aligned in position. This change of position or alignment takes place in both the magnetization and demagnetization processes. The amount of energy expended and manifested by heat may be found by the use of a mathematical formula and is called the *hysteresis loss*.

This may best be understood by referring to the hysteresis loop or magnetic cycle shown in Fig. 38, which shows how B (flux density) changes when H (field intensity) is varied. In the figure, H equals the number of lines of force per sq. cm., and B equals the number of lines of induction per sq. cm. If H is gradually diminished to zero, it will be found that the value of B, for any given

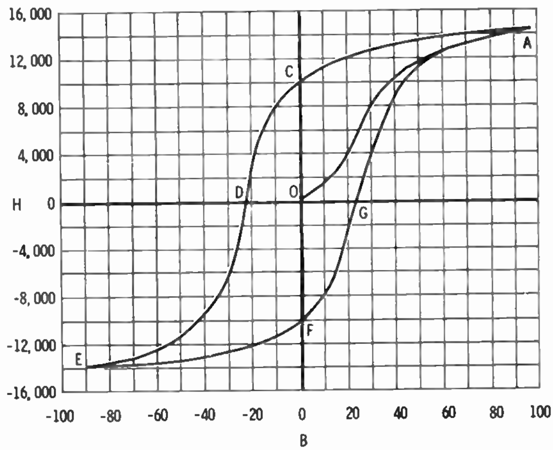


Fig. 38. A typical hysteresis loop.

value of H, is considerably greater when that value of H is reached by decreasing H from a higher value than when the same value is reached by increasing H from a lower value. In other words, curve AC when H is decreased is very different from curve OA or GA when it is increased.

Consider the value of B = 20. When this is reached by increasing B from 0 to 20, the corresponding value of H is 4,000, but when it is reached by decreasing B from 94 to 20, the value of H is 12,200. You will also notice that when B is reduced to zero, H still has a value OC of 10,300, which is nearly three-quarters the value it had when B was 94. This induction is known as *residual magnetism*.

In soft iron, the residual magnetism will nearly all disappear when the iron is tapped or hit, or it can be removed by reversing the current in the magnetizing coil, so as to demagnetize the iron. The curve in Fig. 38 shows that a demagnetizing force of B = 23 is required to make H zero at point D. This force is called the *coercive force* of the iron and is a measurement of the tenacity with which the iron holds the residual magnetism.

As the magnetizing force is further increased in the reverse direction, the curve passes from D to E, where the iron becomes saturated negatively. On gradually returning B to zero, the curve passes from E to F because of the residual magnetism. The magnetizing force has now completed the cycle from zero to a positive value and to a negative value; and if this cycle is repeated several times, the B-H curve becomes a loop, FGACDE, which is symmetrical about the center O.

SUMMARY

Electricity is defined as a fundamental entity of nature. There are two basic kinds of electricity—positive and negative—which are known by their effect on certain substances.

All matter is composed of submicroscopic particles. The particles are the smallest into which any substance can be subdivided and still retain its properties. These particles are called molecules. In turn, molecules can be broken up into parts called atoms, each representing one of the chemical elements from which all matter is constructed.

Atoms are composed of electrons rotating around a central mass, called a nucleus, made up of protons and neutrons. The electrons carry a negative charge while the nucleus carries a positive charge.

It is the movement of one or more electrons from one atom to another that constitutes a flow of electric current. In order for the electrons to move from one atom to another, they must be relatively free. Atoms of some substances hold all their electrons very tightly while the atoms of other substances hold them loosely. Thus, some substances permit electron flow more readily than others. This determines whether the substance is a good conductor or a good insulator.

There are two main types of electricity—static and dynamic. Lightning is a good example of static electricity, while electricity produced by a battery or generator is an example of the dynamic variety. Dynamic electricity is further divided into two types—direct and alternating. A battery produces direct current, which causes electrons to flow along a conductor in only one direction. An alternator (AC generator) produces alternating current which causes electrons to flow first in one direction through a conductor and then in the opposite direction.

The opposition offered to the flow of electrons by a substance is known as resistance. Different substances offer different amounts of resistance. Temperature of the substance also has a bearing on its resistance. In most substances, an increase in temperature causes an increase in resistance. The unit measurement of resistance is the ohm.

Voltage is an electrical pressure that is necessary to cause electrons to flow. This pressure can be produced by chemical means (battery), by heat (thermocouple), by mechanical action (generator), or by light (photocell). The two most common methods are chemical and mechanical. The unit of electrical pressure is called the volt.

The amount of electron flow is measured by a unit called a coulomb. A much more common unit is the measurement of quantity of flow in a given time, called the ampere.

An alternating current is an electron flow which continuously changes in magnitude and periodically reverses direction. The output of an AC generator can be plotted as a sine wave in which the forward, or positive, current movement is represented by the upper portion of the wave, and the reverse, or negative, movement is represented by the lower portion. One forward and one reverse movement constitutes a cycle. The number of cycles occuring in one second is called the frequency.

The effective or root-mean-square (rms) value of an alternating current produces the same amount of heat in a resistance as an equal value of direct current. The effective value of a sine wave can be found by multiplying the peak value of the wave by 0.707.

A definite relationship exists between the voltage, current, and resistance in a given circuit. This relation is called Ohm's law. If any two of the unit values are known, the third can be determined.

Resistances can be connected in series, parallel, or series-parallel.

The total value of resistances connected in series is merely the sum of the individual resistances. When paralleled, the total value is always less than the smallest resistance and can be found by adding the reciprocals of all the resistances. Series-parallel combinations can be solved for total resistance by reducing the various combinations in a series of steps.

Current flowing through a conductor produces a magnetic field around the conductor. This field can be strengthened by winding the conductor into a coil. The strength of the field produced by a coil is determined by the amount of current in amperes multiplied by the number of turns in the coil. This is known as ampere-turns. The magnetic polarity of a coil can be determined by using the left-hand rule.

Two coils placed adjacent to each other, or wound on the same core, constitute a transformer. Current flowing in one coil induces a current in the other coil (if part of a closed circuit) by means of electromagnetic induction.

REVIEW QUESTIONS

1. What is a molecule?
2. What is an atom?
3. What charge does an electron possess?
4. What makes a substance a good or poor conductor of electricity?
5. What is the difference between direct and alternating current?
6. What is the opposition to electron flow called and what is the unit of measurement?
7. What is the relation between voltage, current, and resistance in an electrical circuit?
8. What is the unit of measurement for the rate of current flow?
9. How is the total resistance of parallel resistances found?
10. How is the magnetic polarity of a coil determined?

CHAPTER 5

Resistors

A resistor is a device that opposes or impedes the flow of electrons. Resistance itself is a common property exhibited by every electrical component. Even a short length of wire has a certain amount of resistance. As mentioned previously, some materials conduct electrons better than others. A resistor is composed of a material designed to provide a specific amount of resistance to electron flow and to maintain this value constantly.

RATINGS

Resistors have two basic ratings—the electrical value expressed in ohms (the unit of electrical resistance) and the power rating which is given in watts. The electrical opposition a resistor offers reduces the amount of current flow in a circuit. Thus, a resistor can be made to limit current. It can also be used to reduce voltages at various points in a circuit because of its resistive effect; when current flows through a resistor a voltage drop is developed across it. In other words, the voltage measured at one end of a current carrying resistor will be less than the voltage at the opposite end. This voltage drop, which is computed by Ohm's law, is referred to as the IR drop and is the product of the current and resistance.

Thus,

$$E = I \times R$$

where,

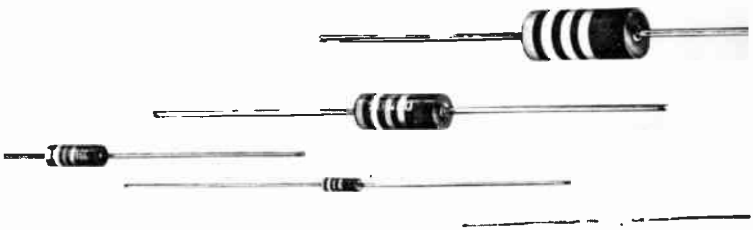
E is the voltage in volts,
I is the current in amperes,
R is the resistance in ohms.

The second resistor rating is in terms of wattage. This is a measure of the amount of power the resistor is capable of handling without being damaged by heat. The larger a resistor is physically, the greater is its heat-dissipating capability, hence wattage rating. It should also be pointed out that the wattage rating has no bearing on the resistance value. For example, a 1,000-ohm resistor with a 1-watt rating could be replaced with a 1,000-ohm, 2-watt unit. Although the 2-watt resistor is physically larger, it offers the same amount of opposition to current flow. Replacing a resistor with one of the same value but with a lower wattage rating, however, can result in the resistor changing value or even burning up.

Next, suppose that a 1,000-ohm resistor is replaced by a pair of 500-ohm resistors connected in series. If the 1,000-ohm resistor has a power rating of 1 watt, then each 500-ohm resistor need have a power rating of only ½ watt. As another example, suppose that the 1,000-ohm, 1-watt resistor is replaced by a pair of 2,000-ohm resistors connected in parallel. In this case, each 2,000-ohm resistor need have a rating of only ½ watt. In other words, when resistors of equal value are "doubled up" in either a series or parallel arrangement, each unit is called upon to dissipate only half of the total power.

PHYSICAL AND ELECTRICAL CHARACTERISTICS

There are many kinds of resistors and they appear in any number of shapes and sizes. However, all resistors fall into one of two categories—fixed or variable. Two of the most common types are carbon and wirewound. Fig. 1 shows several examples of fixed carbon resistors. As its name implies, the carbon resistor is made of a carbon composition designed to provide a specific opposition, or resistance, to the flow of electrons. Carbon in its natural form is a conductor of electricity. By varying the amount of carbon in the composition, the resistance of the unit can be controlled. There are other resistance compositions used in the manufacture of resistors, but carbon is the most common. Out of necessity, a carbon resistor must be quite large physically to handle fairly heavy power loads. Because of this, such resistors are generally used where the power requirements total five watts or less. Where greater power-handling capabilities are required, wirewound resistors are normally employed. Several examples are shown in Fig. 2.



Courtesy Ohmite Manufacturing Co.

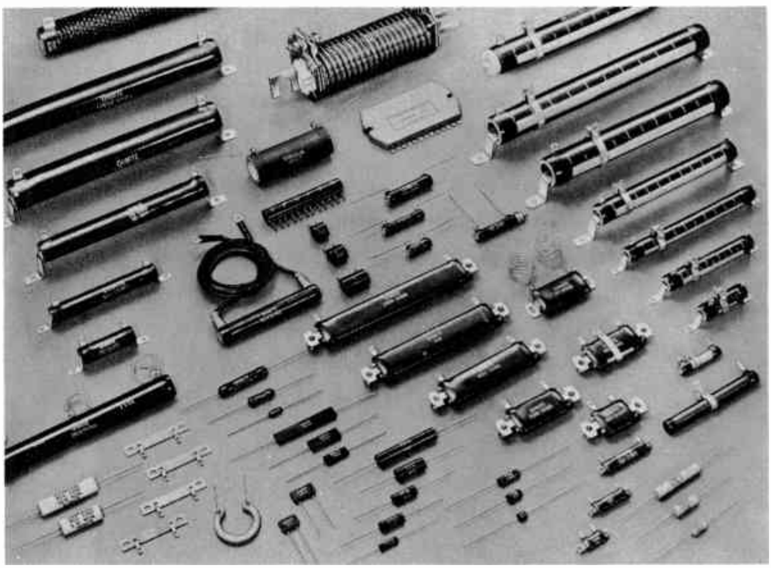
Fig. 1. Several examples of fixed carbon resistors.

Power ratings of resistors are usually based on installations that operate at normal room temperatures, and with reasonable ventilation in the space around the resistor. When a resistor is operated in spaces having higher than normal temperatures, or in a space with little or no ventilation, the power rating of the resistor must be *derated* accordingly. Manufacturers can provide derating information for their resistors if advised of the abnormal operating condition. It should also be noted that resistance values and power ratings of resistors are usually based on DC or low-frequency AC operation. For example, the peak power of a narrow pulse is far greater than its average power. For this reason, a resistor is "worked harder" in pulse circuit, and must be suitably derated.

In high-frequency AC applications, a wirewound resistor has appreciable inductance, with the result that its *impedance* may be much greater than its rated resistance value. On the other hand, a composition resistor has significant residual capacitance at high frequencies, causing it to have an impedance much less than its rated resistance value. These considerations will be explained in greater detail in a later chapter. The important point is that a graphical symbol is a form of technical shorthand that implies facts which must be understood if the component is to be operated properly in various types of circuits and under different environments.

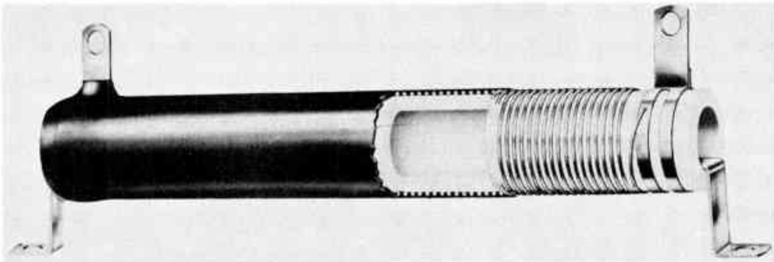
Most wirewound resistors consist of a fine high-resistance wire cut to a specific length (one that will provide the proper value of resistance). The wire is wound around an insulated form and covered with some type of vitreous or ceramic material (see Fig. 3). This type of resistor can be made to handle power in the hundreds of watts. Here again, as the wattage rating increases, so does the physical size of the resistor body.

Variable resistors are used in circuits where values must be changed from time to time. For example, the volume control on



Courtesy Ohmite Manufacturing Co.

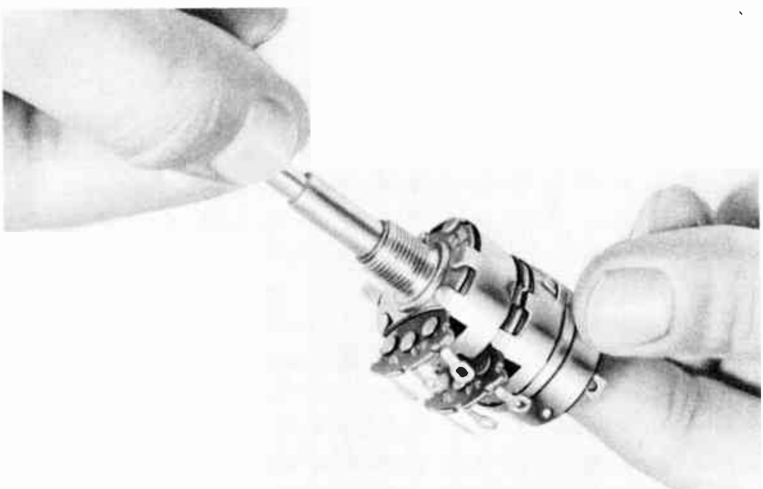
Fig. 2. Examples of fixed wirewound resistors.



Courtesy Ohmite Manufacturing Co.

Fig. 3. Construction details of a wirewound resistor.

your radio receiver is nothing more than a circular resistance element with a rotating contact that permits its effective resistance value to be varied. This in turn controls the loudness of the sound issuing from the speaker. This type of continuously variable control is known as a potentiometer and is illustrated in Fig. 4. The resistance element in this device will be either carbon or wire depending on the power requirements. Potentiometers rated above three watts are generally of wirewound construction.

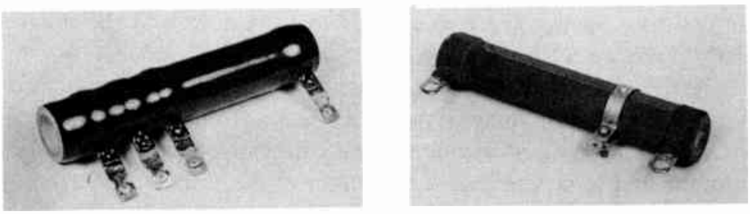


Courtesy Clarostat Manufacturing Co., Inc.

Fig. 4. A potentiometer.

Another type of variable resistance uses one or more taps along its resistance element as shown in Fig. 5A, while still another type has a single adjustable tap (Fig. 5B). The schematic symbols for the various types of resistors are illustrated in Fig. 6.

Unlike capacitors and inductors (to be discussed shortly), a resistor does not cause a phase shift between the current passing through it and the voltage developed across it.



(A) Fixed taps. (B) Adjustable tap.

Fig. 5. Two types of variable wirewound resistors.

The power rating of a potentiometer is often misunderstood. For example, consider a potentiometer which has a power rating of 1 watt. With reference to Fig. 7, the potentiometer dissipates 1 watt if the 1K load is disconnected. However, when the 1K load is connected, and the potentiometer operated at its midpoint, the battery supplies approximately 1.7 watts to the circuit. The current

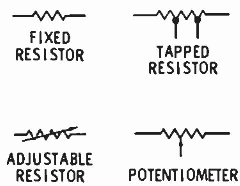


Fig. 6. Schematic symbols for various types of resistors.

flow is about 17 ma., which means that the top half of the potentiometer must dissipate about 4.5 watts. This will cause the unit to overheat badly and be damaged. This example shows that a potentiometer must be derated accordingly when it is required to supply current to a load.

RESISTOR IDENTIFICATION

There are several methods of identifying the value of resistors. If the body of the unit is large enough, the ohmic value may be printed on it, while wirewound resistors built in metal enclosures generally have the value stamped on the enclosure. The most widely used method of resistor identification, however, is a color code. The color code used almost exclusively with low-wattage carbon resistors consists of three or more colored bands near one end of the resistor. Each color corresponds to a number and the combination, when read from left to right, indicates the value.

Another method of identifying resistor values with the color code involves making the body of the unit one color and the left end another color, and the third identifying color appears in the form of a dot located somewhere near the center of the resistor. A variation

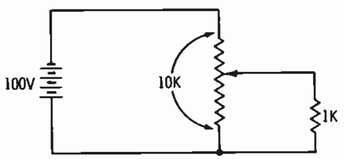
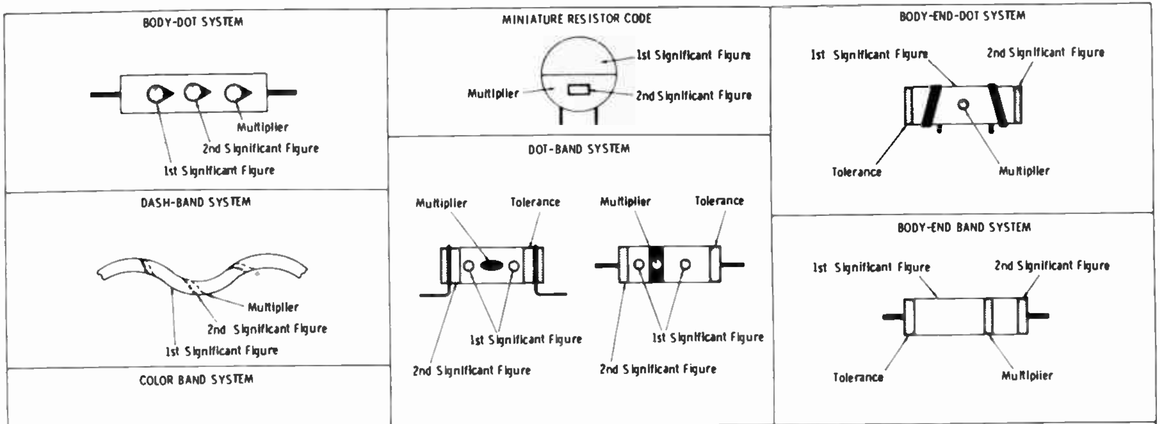
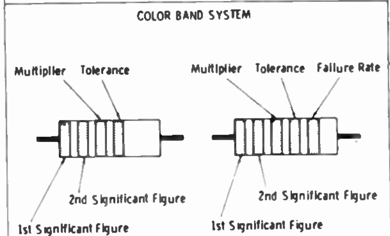


Fig. 7. Analysis of potentiometer power rating.

of this method uses a body color to indicate the first digit, a band at the right end to indicates the second number, and an adjacent color band to indicate the multiplier. The opposite end may or may not have a colored band to designate the tolerance. Fig. 8 illustrates the standard resistor color code, and various methods used to indicate values.

In cases where the ohmic value is marked on the resistor it may also appear in several different ways. A 1,000-ohm resistor, for example, may simply have the number 1,000 marked on it or may be marked 1,000Ω. The latter symbol (Ω) is the Greek letter omega used to indicate the word ohm. You will also find the letter K (short for kilo) used to designate 1,000 and the word meg (short for mega) meaning million. Thus, a 1,000-ohm resistor may be marked 1K or a 1,000,000-ohm unit may be marked 1 meg. Wattage ratings are generally indicated with a W, i.e., 1W, 5W, etc.





Resistors With Black Body Color Are Composition, Non Insulated.
Resistors With Colored Bodies Are Composition Insulated.
Wirewound Resistors Have The 1st Digit Color Band Double Width.

RESISTOR COLOR CODE

COLOR	1ST + 2ND SIGNIFICANT FIGURES	MULTIPLIER	TOLERANCE	FAILURE RATE*
Black	0	1	-	-
Brown	1	10	±1%	1.0
Red	2	100	±2%	0.1
Orange	3	1000	±3%	0.01
Yellow	4	10000	±4%	0.001
Green	5	100000	-	-
Blue	6	1000000	-	-
Violet	7	10000000	-	-
Gray	8	100000000	-	-
White	9	-	-	Solderable*
Gold	-	0.1	±5%	-
Silver	-	0.01	±10%	-
No Color	-	-	±20%	-

When used on composition resistors, indicates percent failure per 1,000 hours. On film resistors, a white fifth band indicates solderable terminal.

Fig. 8. Resistor color code.

Let us see how tolerances are affected by connecting resistors in series and in parallel. The general rule is that if the tolerances on individual resistors are the same, the tolerance on a series or parallel combination remains the same. For example, if we connect a pair of 1,000-ohm resistors in series, and the tolerance on each resistor is 20%, the tolerance on the series combination will remain 20%. This is easily shown by taking *worst-case values.* In other words, a 1,000-ohm resistor with a tolerance of 20% will have an actual value that falls in the range from 800 to 1,200 ohms. These are worst-case values. If we connect a pair of 800-ohm resistors in series, their total resistance will be 1,600 ohms, and this is a tolerance of 20% on their nominal total resistance of 2,000 ohms. Again, if we connect a pair of 1,200-ohm resistors in series, their total resistance will be 2,400 ohms, and this is a tolerance of 20% on their nominal total resistance of 2,000 ohms.

The same principle holds if the resistors are connected in parallel. That is, if we connect a pair of 800-ohm resistors in parallel, their total resistance will be 400 ohms, and this is a 20% tolerance on their nominal total resistance of 500 ohms. Or, if we connect a pair of 1,200-ohm resistors in parallel, their total resistance will be 600 ohms, and this is a 20% tolerance on their nominal total resistance of 500 ohms. Next, if we connect a 1,000-ohm, 20% resistor in series with a 1,000-ohm, 10% resistor, our worst-case values are 800 ohms, 1,200 ohms, 900 ohms, and 1,100 ohms. When an 800-ohm resistor is connected in series with a 900-ohm resistor, the total resistance becomes 1,700 ohms, and this is a 15% tolerance on the nominal total resistance of 2,000 ohms. Or, if we connect a 1,200-ohm resistor in series with an 1,100-ohm resistor, the total resistance will be 2,300 ohms, and this is a 15% tolerance on the nominal total resistance value of 2,000 ohms. In other words, the tolerance on the combination becomes the average of the tolerances of the individual resistors.

RESISTORS IN COMBINATION

A single resistor offers a certain amount of opposition to current flow, depending on its value. As mentioned previously, connecting two resistors of equal value in *series* doubles the effective resistance of the combination; whereas when two resistors of equal value are connected in parallel, the overall resistance becomes half the value of one of the resistors.

The results obtained by connecting resistors in various combinations of equal and unequal values were discussed previously in Chapter 4 under Ohm's law. Also included were some practical problems that help in understanding how resistors react in electrical circuits. Following the discussions on inductors and capacitors, you will see how resistors function in combination with these elements.

SUMMARY

A resistor is a device that opposes or impedes the flow of electrons through it. All resistors have two basic ratings—their electrical value, expressed in ohms, and their power rating, expressed in watts. Besides limiting the current flow in a circuit, a resistor also reduces the voltage. This reduction is called a voltage drop or IR drop, and can be computed by Ohm's law.

The wattage rating of a resistor is a measure of how much power it can handle without being damaged by heat. Wattage rating has no bearing on the resistance value.

All resistors are one or the other of two types—fixed or variable. Resistors are made in a wide variety of shapes and sizes, and from a number of different materials. Small-wattage resistors are commonly made of a carbon composition, while large-wattage units are usually of the wirewound type.

Variable resistors are often called rheostats or potentiometers, depending on how they are used in a circuit. Such units are widely used for applications like volume and tone controls, and many of the adjustable controls on radios, televisions, tape recorders, and other electronic equipment.

Resistor value identification is made possible by a number of methods. The value may be stamped or printed on the unit, but the most common method is designating the value by means of a color code.

Resistors are often used in combination. To increase the effective resistance, resistors are connected in series—to reduce the effective resistance, they are connected in parallel.

REVIEW QUESTIONS

1. Voltage is reduced by current flowing through a resistance. What is the reduction called?
2. How can this voltage reduction be calculated?
3. Does the physical size of a resistor have any effect on its resistance value? On its wattage rating?
4. Into what two main categories are resistors classified?
5. Is carbon a good or poor conductor of electricity?
6. Draw the schematic symbol for a tapped resistor.
7. Draw the schematic symbol for a potentiometer.
8. What is the most common method employed to designate resistor values and ratings?
9. What is the resistance value of a resistor having a red, red, orange color-band combination?
10. What resistance value is indicated where the body of a resistor is blue, one end is gray, and a dot in the center is red?

CHAPTER 6

Inductors

ELECTRICAL INDUCTANCE

The inductance of a circuit or component is the property that opposes any change in the existing current, and there must be a changing current before an inductance can exist. A straight piece of wire has a certain amount of inductance to an alternating or pulsating current. The amount of inductance can be increased by coiling the wire and increased still further by compressing the coils. Thus, a coil is commonly referred to as an inductor. Other factors which affect inductance are the number of turns in the coil, whether or not the coil is wound around a core, and the type of core. The electrical unit of inductance is the *henry*.

Whenever current is passed through a conductor, such as a wire, magnetic lines of force surround the conductor. The same is true when the conductor is in the form of a coil. When an alternating current flows in one direction through a coil it builds up a magnetic field around the coil. When the current changes direction, this field produces a self-induced electromotive force that opposes such change. The same action occurs each time the current changes.

One henry is defined as an inductance that permits a change of 1 ampere per second when 1 volt is applied, as shown in Fig. 1. That is, when switch SW is closed, 1 volt is impressed across the inductance. In turn, the current increases steadily by an amount of 1 ampere per second. Note that this example assumes that the circuit resistance is negligible; in other words, the circuit action is that of a pure inductance.

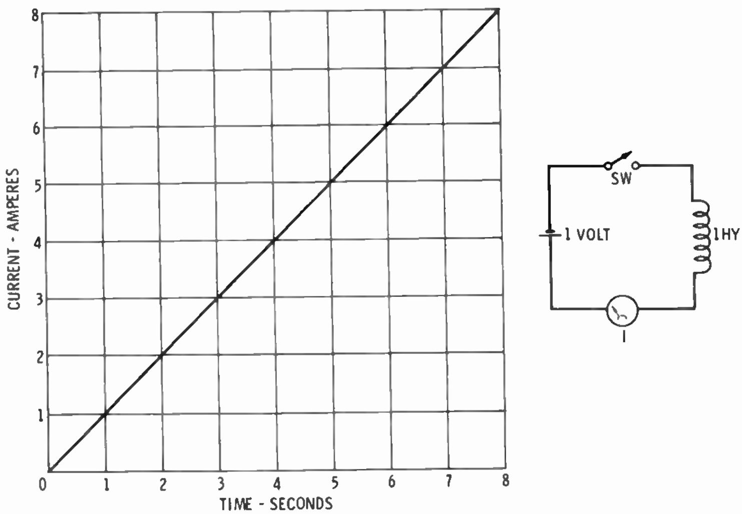


Fig. 1. Current increase in a pure inductance of 1 henry.

INDUCTIVE REACTANCE

The opposition that an inductance offers to the flow of an alternating or pulsating current is known as *inductive reactance*. It is similar to resistance except that the amount of opposition varies with the *frequency* of the current. A plain resistance offers the same opposition to current regardless of frequency. Inductive reactance, however, increases with frequency. Like resistance, inductive reactance is measured in ohms, and it is represented by the symbol

X_L. Mathematically it is equal to the inductance of a coil in henrys times 6.28 times the frequency in hertz. Or,

$$X_L = 2\pi fL$$

where,

X_L is the inductive reactance in ohms,
f is the frequency in hertz,
L is the inductance in henries.

Another major difference between resistance and inductive reactance is that a phase difference exists between the current through a coil and the voltage across it. In a coil the voltage leads the current by 90° whereas the voltage and current through a resistor are always in phase.

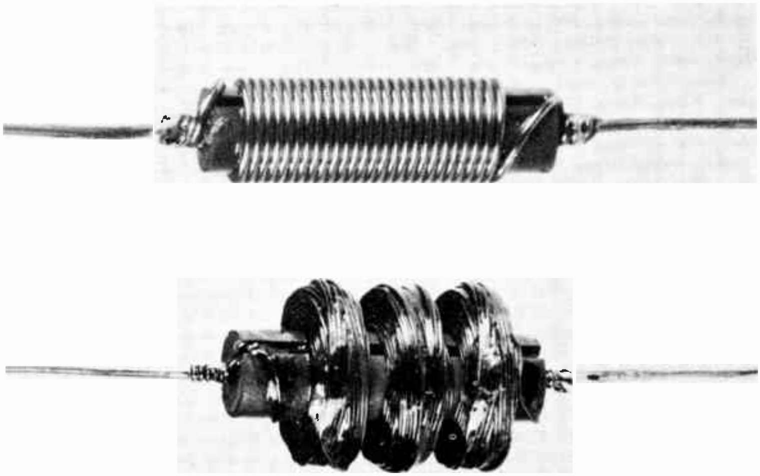
The electrical unit of inductance is the henry. Except for the larger iron-core choke coils, most inductors, or coils, are rated in smaller units such as the millihenry (mh) or microhenry (μh). One millihenry is equal to one one-thousandth of a henry whereas one mcirohenry is equal to one one-millionth of a henry or one one-thousandth of a millihenry.

TYPES OF COILS

Coils are generally classified according to either their usage or the type of construction. Some coils are wound around iron cores; others are made of rather heavy wire and are self-supporting, using air itself as the core. There are coils with fixed-inductance values and others that are variable. There are also coils with taps and those that have means for continuous adjustment of the inductance.

Coils used at radio frequencies (referred to as RF coils) generally require little inductance and are normally of the air-core type. Fig. 2 shows two types of air-core coils. Both of these have fixed values. We might also point out that a coil is considered to have an air-core even though it is wound on an insulated form.

In circuits operating at audio and power-line frequencies, the coils must have considerably more inductance than at radio frequencies. This increase in inductance is obtained by using more turns of wire and winding them around an iron core. This core provides a much better path for magnetic flux than does air, hence the



Courtesy Merit Coil and Transformer Corp.

Fig. 2. Two types of air-core coils.

inductance of the coil is increased. Fig. 3 shows an iron-core choke coil of the type used in some power supplies. Another type of iron-core coil is illustrated in Fig. 4. This one has a powdered-iron core,

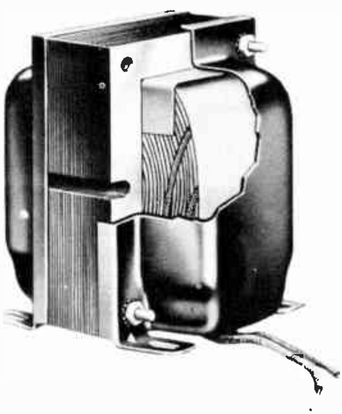


Fig. 3. Example of an iron-core coil.

Courtesy Merit Coil and Transformer Corp.

Fig. 4. Examples of coils using an adjustable powdered-iron core to vary inductance.

Courtesy Triad Distributor Division, Litton Industries.

the position of which is adjustable to vary the effective inductance. As mentioned previously there are also coils equipped with adjustable or fixed taps which provide a selection of values from a coil of fixed value. Fig. 5 shows some of the more common schematic symbols for the various coils.

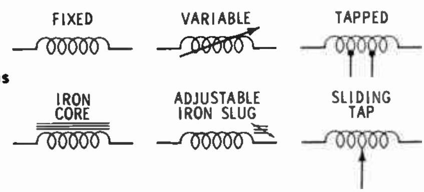


Fig. 5. Schematic symbols for various types of coils.

Although circuit analysis is based on the characteristics of pure (ideal) inductance, it should be noted that the resistance of practical coils is seldom negligible. Coils are usually used that have the equivalent circuit shown in Fig. 6. Thus, we are concerned with inductance in combination with resistance, or reactance in combination with resistance. This combination is called *impedance,* which is measured in ohms just as reactance and resistance is measured in ohms.

Fig. 6. Equivalent circuit for a practical inductor.

INDUCTANCE COMBINATIONS

When one or more coils are interconnected, their combined inductance value is different from that of either unit by itself. The effect on the combined value will depend on the manner in which they are connected.

The following formula can be used to calculate the total inductance when two coils are connected in series (with no mutual inductance) as shown in Fig. 7:

$$L_T = L_1 + L_2 + L_3 +$$

where,

L_T is the total inductance of the circuit,

L_1, L_2, and L_3 are the inductance values of the individual coils.

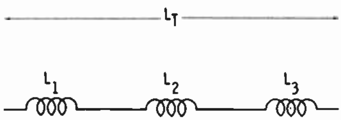


Fig. 7. Coils in series.

When two or more coils are connected in parallel, as in Fig. 8, their combined inductance can be found by using the following formula:

$$\frac{1}{L_T} = \frac{1}{L_1} + \frac{1}{L_2} + \frac{1}{L_3} + \ldots$$

A useful graphical solution for finding reciprocals is shown in Fig. 9. In this example, the reciprocal of 8 henrys is sought. A line is drawn from 0 to 8; this line intersects the unit level at P. Next, project down and find the value of the reciprocal, which is 0.125. Of course the graphical method "works backward" also. Thus, the reciprocal of 0.125 is 8. Note that all values on the vertical axis may be multiplied by 10 if all values on the horizontal axis are divided by 10. For example, the reciprocal of 80 henrys is 0.0125. Or, all values on the vertical axis can be divided by 10 if all values on the horizontal axis are multiplied by 10. As an example, the reciprocal of 0.8 henry is 1.25. Similarly, all values on the vertical

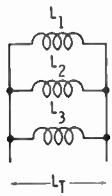


Fig. 8. Coils in parallel.

axis can be multiplied or divided by 100 if all values on the horizontal axis are divided or multiplied by 100.

Note that no name has been given to reciprocal inductance. In other words, reciprocal inductance is merely a means of calculation and does not denote a corresponding circuit component. After reciprocal inductances are added to find the total reciprocal inductance value, this value is then converted to total inductance.

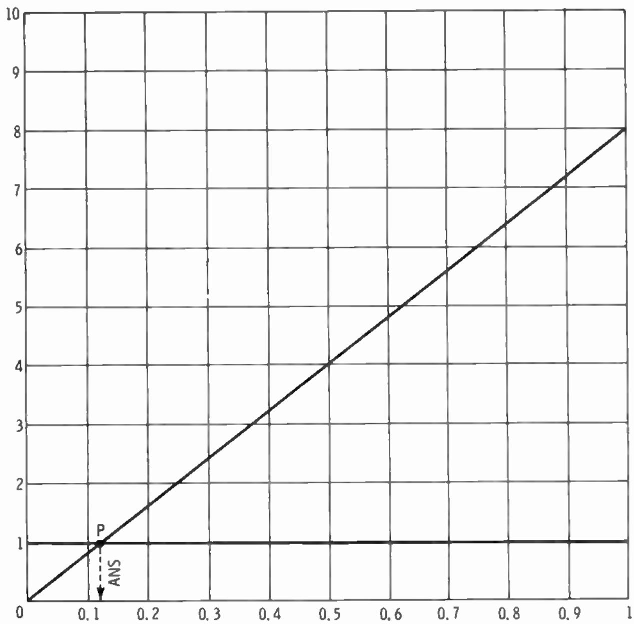


Fig. 9. Graphical method for finding a reciprocal.

The combined inductance of two coils connected in parallel is expressed as:

$$L_T = \frac{L_1 \times L_2}{L_1 + L_2}$$

Just as the total resistance of two resistors connected in parallel can be found by a graphical method, the total inductance of two inductors connected in parallel can be found by the graphical method shown in Fig. 10. In this example, $L_1 = 8$ henrys and $L_2 = 4$ henrys. The lines intersect at P, and the projection to the vertical axis shows that the total inductance value is 2⅔ henrys. The process may be repeated for three inductors connected in parallel, as was the case of three resistors connected in parallel. All values on both vertical axes may be multiplied by the same power of 10 or divided by the same power of 10.

It follows from Ohm's law for AC that the graphical method shown in Fig. 10 can also be used to find the total reactance of two

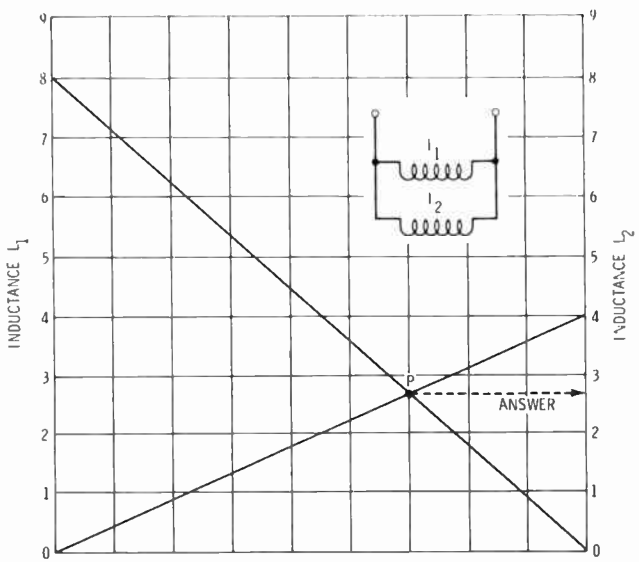


Fig. 10. Graphical method for finding total inductance of inductors in parallel.

inductive reactances in parallel. For example, if the inductive reactance of L_1 is 8 ohms and the inductive reactance of L_2 is 4 ohms, then the total reactance of the parallel combination is equal to 2⅔ ohms. In the foregoing examples, it is assumed that there is no magnetic coupling between L_1 and L_2. If magnetic coupling should be present, another method must be used to find the total inductance or the total inductive reactance. Details are reserved for later discussion.

SUMMARY

The inductance of a circuit or component is the property that opposes any change in the existing current. Any conductor through which current is flowing has a certain amount of inductance. This inductance can be increased by forming the conductor into a coil, further increased by compressing the coil into a smaller space, and still further increased by providing an iron or steel core for the coil. The electrical unit of inductance is the henry.

Inductive reactance is the opposition offered by an inductance to the flow of alternating or pulsating current. Inductive reactance is similar to resistance and is measured in ohms, but unlike resistance the opposition it offers varies with the frequency of the current.

Inductance in a circuit can be increased or decreased by connecting individual inductors in series or in parallel. The total inductance can be calculated in a manner similar to that used to calculate total resistance.

REVIEW QUESTIONS

1. How can the inductance of a coil be increased?
2. Is the inductive reactance of a coil constant?
3. State the formula for finding the inductive reactance of an inductor in a given circuit.
4. Does the current lead or lag the voltage across a coil?
5. What is the electrical unit of inductance?
6. What is the unit of measurement of inductive reactance?
7. Give a practical application for an air-core coil.

8. Give a practical application for a coil with a powdered-iron core.
9. Give the formula for calculating the total inductance of three inductors connected in series.
10. Give the formula for calculating the total inductance of three inductors connected in parallel.

CHAPTER 7

Capacitors

A capacitor is one of the major components used in electronic equipment. There are many different types of capacitors, and their uses are varied. A basic capacitor is nothing more than two conductors separated by a dielectric, or insulator (Fig. 1). There must be at least two conductors and often there are many more; regardless of the number of conductors or plates, the unit is terminated with two connections. The conductors can be practically any size and shape, and the dielectric may be any one of several materials including such things as paper, mica, chemicals, and even air.

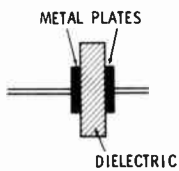


Fig. 1. Basic capacitor construction.

ELECTRICAL CHARACTERISTICS

If a battery were connected to two metal plates placed in close proximity as in Fig. 2, electrons woudl flow for an instant (when the switch is closed) from the negative terminal to the metal plate connected to it. Since the negative terminal of a battery has an excess of electrons and the positive terminal a deficiency, the plate marked minus, or negative, will acquire more than its normal amount of electrons. At the same time the proximity of the two metal plates and the potential applied across them produces an *electrostatic* force (a fixed electric field) which repels electrons

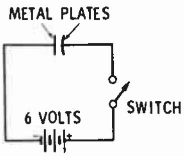


Fig. 2. Direct current applied across a capacitor.

from the other plate, causing them to move toward the positive terminal of the battery. After a brief instant electron motion ceases, and the end result is an electrical charge between the metal plates. The amount of charge is determined by the capacitance value of the unit (to be discussed shortly). If the switch in Fig. 2 is then opened, the metal plates will retain the charge. A capacitor will *not* conduct direct current.

DISPLACEMENT CURRENT

Displacement current is defined by the American Institute of Electrical Engineers as the current through a dielectric, such as the dielectric between the plates of a capacitor. The displacement current through a given surface of the dielectric increases as the *rate of change* of the electrostatic flux increases. If the rate of change is zero (as for DC), the displacement current is zero. On the other hand, if the rate of change is rapid (as for high-frequency AC), the displacement current is large. Note that if the dielectric is a vacuum, displacement current still flows between the plates of a vacuum capacitor energized by AC voltage. The only current that actually flows *"through"* a capacitor is *displacement current.*

To clearly understand displacement current, we must return to the basic idea of electric charge. A charge is basically a field (electrostatic), and electric current consists of charge (electrostatic field) in motion. Since there is an electrostatic field between the plates of a capacitor, an electric current (displacement current) is set up whenever this field is placed in motion by varying the value of the voltage applied to the capacitor. The term "displacement current" is somewhat of a misnomer. This misleading terminology was introduced by early electrical workers who supposed that capacitor action was due to reorientation (displacement) of molecules in the dielectric as the voltage changed. Later, it was recognized that displacement is merely an incidental action, and that the basic fact underlying displacement current is that any motion of an electrostatic field establishes an electric current.

Now let us consider what happens when an AC voltage is applied across a capacitor as in Fig. 3. As the voltage swings in a negative

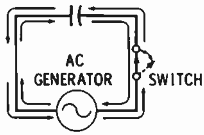


Fig. 3. Alternating current applied across a capacitor.

direction, current will flow from one side of the AC generator to one of the plates, causing it to assume more than its normal amount of electrons. At the same instant, the repelling action resulting from the electrostatic force drives electrons from the other plate toward the opposite terminal of the AC generator. At this particular instant, then, one plate is positive and the other is negative. On the positive half cycle, this action is reversed and the plates are charged in the opposite polarity, causing current to flow through the circuit in the opposite direction. Thus, a capacitor permits alternating current to flow through it while, at the same time, it blocks direct current. It should be pointed out here that the alternating current itself does not *pass through* the capacitor. Instead it is the electrostatic charge of alternating polarity which causes this movement to be transferred across the gap, thereby essentially completing the circuit.

Because of this action, capacitors can be used at points in electronic circuits where it is desirable to pass AC voltages and, at the same time, to block DC. As you will see shortly, capacitors can be used in combination with other components to filter, couple, bypass, provide frequency-selective tuned circuits, and change wave-shapes.

CAPACITIVE REACTANCE

Like the components discussed previously, capacitors also present an opposition to the flow of alternating current. You will recall that the opposition offered by a resistor is the same regardless of the frequency of the current and that a coil, or inductor, exhibits an inductive reactance which *increases* with frequency. The capacitor likewise tends to oppose the flow of alternating current, and this opposition is in the form of a capacitive reactance designated as X_C.

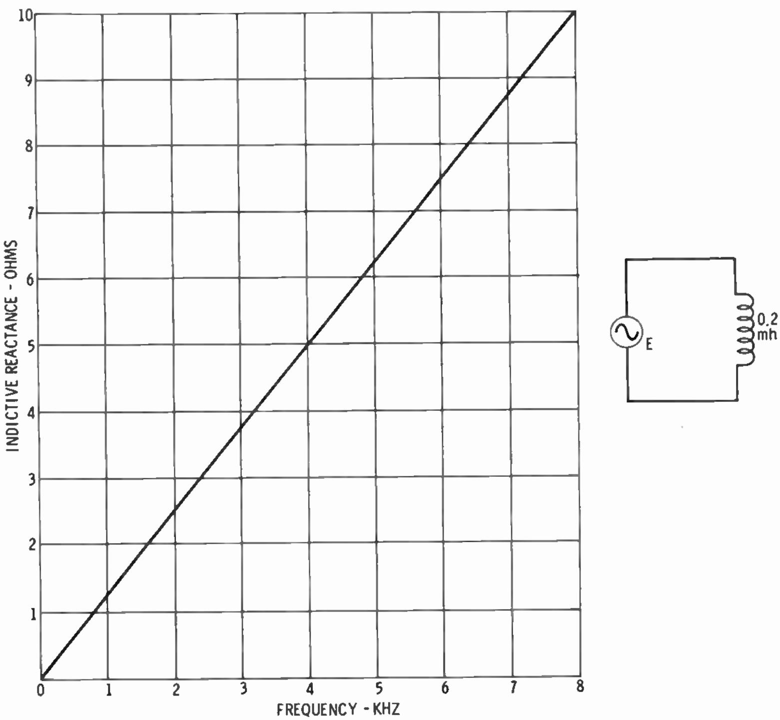


Fig. 4. Inductive reactance versus frequency.

The action of a capacitor in an AC circuit is opposite that of an inductor. The current flowing through any inductor *lags* the voltage by 90°, whereas the current in a capacitor *leads* the voltage by 90°. Furthermore, inductive reactance *increases* with frequency while capacitive reactance *decreases*.

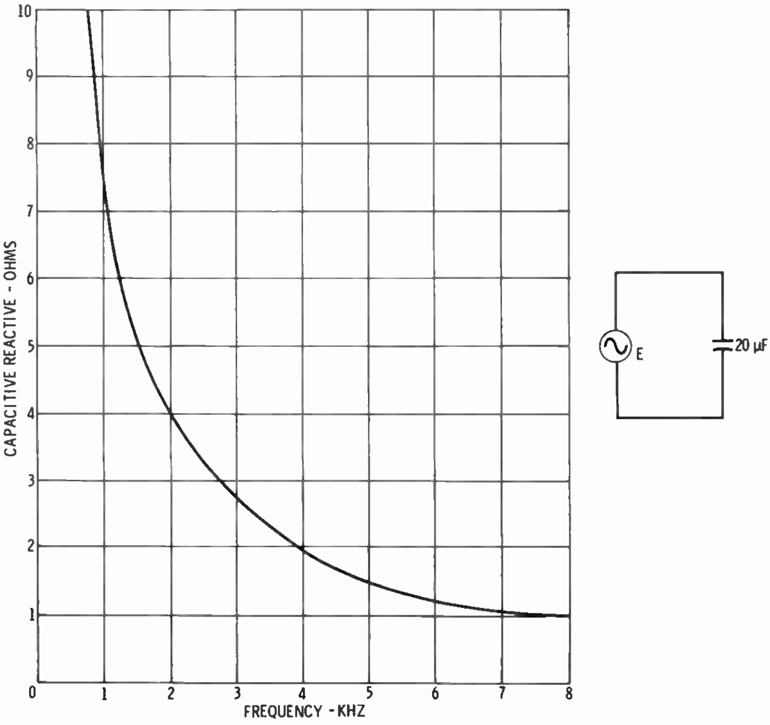


Fig. 5. Capacitive reactance versus frequency.

It is evident that inductive reactance increases linearly with an increase in frequency, as shown in Fig. 4. On the other hand, it will be found that capacitive reactance decreases nonlinearly with a frequency increase, as shown in Fig. 5. As we proceed to study AC circuit action, we will recognize that these characteristics, combined with the frequency-independent characteristic of resistance, are the foundation of AC circuit analysis.

CAPACITY VALUES

The ability of a capacitor to store electrons is a measure of its capacitive value. The electrical unit of capacity is the *farad.* A capacitor is said to have a value of 1 farad when a charge of 1 coulomb produces a change of 1 volt in the potential difference between its terminals. More common in radio work are the smaller values, microfarad (abbreviated mfd or μf), which is equal to one one-millionth of a farad, and micromicrofarad (abbreviated mmf or $\mu\mu$f), which is equal to one one-millionth of a microfarad.

Factors Which Determine Capacity Value

The value of a capacitor is determined by four factors, namely the *number* of plates used in its construction, the *area* of the plates, the *spacing* between the plates, and finally the type of *dielectric* employed. The larger the capacitive value, the greater the number of electrons the unit is capable of storing. Several of these factors are utilized in the construction of capacitors to make their values variable.

CONSTRUCTION

Capacitors fall into two major classes—fixed and variable. Within these classes there are many variations, differing not only in size and shape but also in the type of construction. There are a number of different materials used as dielectrics, the methods of arranging the elements vary, and the methods of varying the capacitive value vary. One of the most popular types is the paper capacitor. This is a fixed-value, tubular unit constructed of several layers of metal foil separated with paper (Fig. 6). Like so many other capacitors, its name is derived from the material used as the dielectric. The conductors consist of metal foil strips which are rolled into a spool of sufficient size to provide the desired capacitance. The value here is determined by both the spacing of the plates (thickness of the paper dielectric) and the area of the plates (number of rolls).

Another popular type of fixed capacitor uses mica as the dielectric and hence is termed a mica capacitor. Several examples are

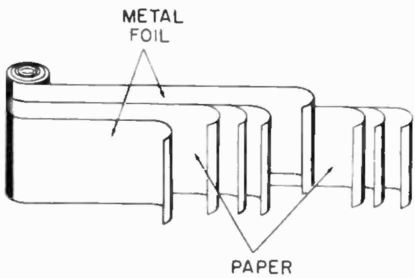


Fig. 6. Basic construction of a paper capacitor.

shown in Fig. 7. There are also ceramic capacitors which appear in both tubular and disc form, as shown in Fig. 8. When capacity values above 2 mfd are required, an electrolytic capacitor is generally employed. This capacitor generally consists of a set of electrodes embedded in an electrolytic mixture. Chemical action forms a very thin dielectric film on one of the plates, insulating it from the electrolyte. The electrolyte then acts as the other electrode of the capacitor and connection is made through the uninsulated elec-

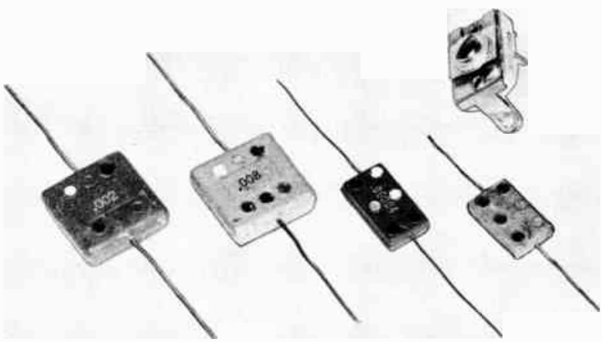
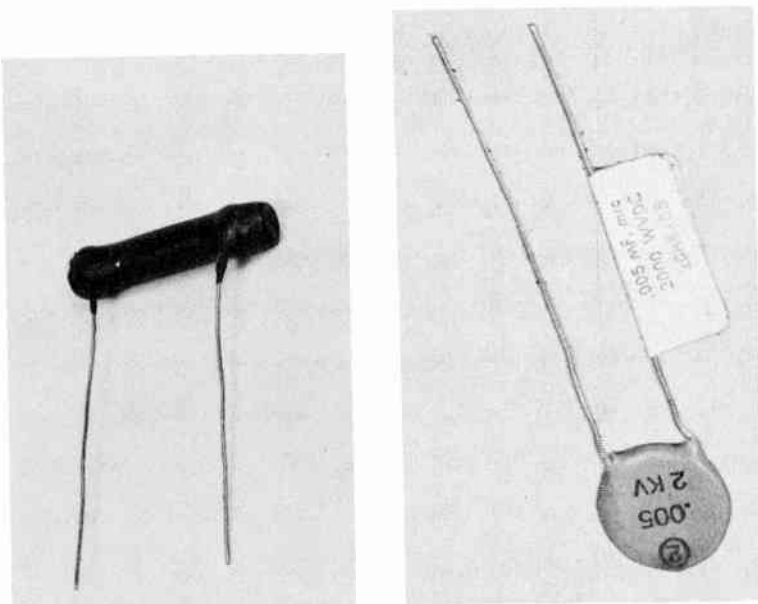


Fig. 7. Examples of fixed-value mica capacitors.

trode. Electrolytic capacitors are polarized, hence they are used only in circuits carrying DC or pulsating DC. Furthermore, they must be connected with respect to polarity; otherwise the dielectric film will break down and the unit will be ruined.

Two of the most common forms of variable capacitors are the trimmer and tuning capacitors. Actually, trimmers could be instrumental in tuning a circuit; however, the variable tuning capacitor is designed to permit large variations in capacity, whereas the trimmer generally provides only slight variations in value. Fig. 9 shows a typical example of a variable tuning capacitor of the type used in standard broadcast receivers. As you can see, the capacitance value is varied by changing the area of the plates. The dielectric in this instance is air.

This type of capacitor generally consists of two parallel sets of plates of which one is stationary and the other is movable. The movable (rotor) plates are made to intermesh (without touching)



Courtesy Sprague Electric Co.

(A) Tubular type.

(B) Disc type.

Fig. 8. Ceramic capacitors.

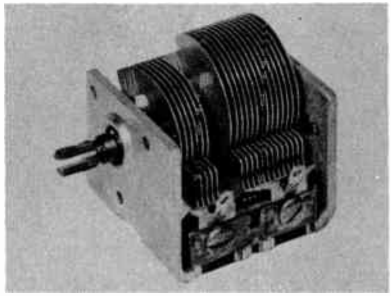


Fig. 9. A variable two-gang tuning capacitor.

with those of the stationary (stator) plates, and the maximum capacity is obtained when the full areas of the two sets of plates are exposed to each other. For various other positions, some intermediate value of capacitance exists (see Fig. 10). The shape of the movable plates determines the amount of capacitance variation with rotation.

Straight-Line-Capacity Tuning Capacitor—The plates of this type of capacitor are semicircular in shape (Fig. 11A), and the change in capacity is accomplished by rotation as previously discussed. However, due to the geometrical form of the plates, the capacity will vary in direct proportion to the angle of rotation; i.e., if a change in capacity of 0.0001 mfd is made by changing the rotor setting from 15 to 20 degrees, a similar change in capacity will be made by changing the setting from 35 to 40 degrees.

Straight-Line-Frequency Capacitors—For convenience in tuning, however, some capacitors employ logarithmic plates (Fig. 11B), i.e., the shape of the plates is such that a linear relationship

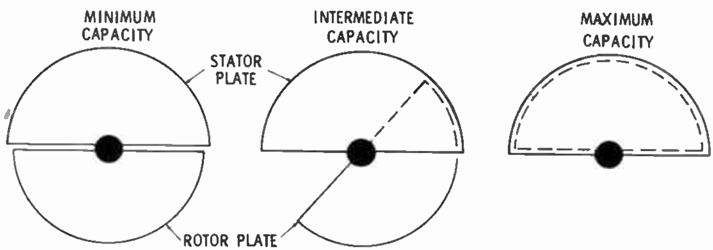
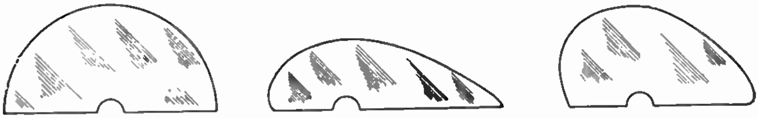


Fig. 10. Relationship between capacitor rotation and capacitor value.



(A) Straight-line capacity. (B) Straight-line frequency. (C) Straight-line wavelength.

Fig. 11. Shape of rotor plates in various types of air capacitors.

exists between the rotor setting in degrees and the frequency in the circuit. The advantage of this arrangement is obvious since the primary reason for using the ganged capacitor in circuits is for adjustment of frequencies.

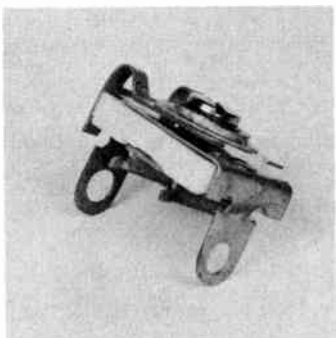


Fig. 12. Typical trimmer capacitor.

The frequency of such a circuit varies inversely as the square root of the capacity, and the wavelength varies directly as the square root of the capacity; hence in order to obtain a direct relationship between the rotor setting in degrees and the frequency in the circuit, the rotor plates must possess an exponential characteristic. Fig. 11C shows the shape of the capacitor plates in a straight-line-wavelength arrangement.

Another type of variable capacitor is the trimmer shown in Fig. 12. These are employed where only small variations in capacitive value are desired. The value of this unit is varied by changing the spacing between two plates.

Because of the wide variety of capacitor types it would be impractical to show them all. However, there is one other type that should be mentioned because of its construction, and that is the feed-through capacitor. As you can see from Fig. 13, this type of capacitor has a DC path through the center by means of the feed-through conductor. The capacity exists between this element and the outer conductor which forms a portion of the capacitor body. Feed-through capacitors are especially desirable at the higher frequencies because they do not exhibit the inductive properties present in capacitors using spiral-wound construction. Feed-through capacitors are generally employed to bring connections through a chassis. The metal portion of the capacitor body is usually soldered to the chassis or fastened with lock nuts to provide good contact.

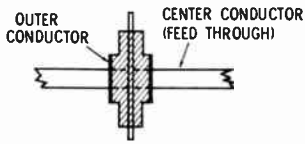


Fig. 13. Basic construction of a feed-through capacitor.

Courtesy Aerovox Corp.

Fig. 14. Examples of feed-through capacitors.

The capacity then is between the center conductor, or feed-through element, and the chassis itself. Several examples of feed-through capacitors are shown in Fig. 14, while Fig. 15 shows some of the more common schematic symbols for capacitors.

CAPACITOR RATINGS

Capacitors have other ratings besides capacitance value. One of the most important is the voltage rating. The dielectric in any capacitor can withstand only so much voltage. Practically all capacitors have this rating marked on them somewhere. This rating (known as the DC working voltage) should not be exceeded. In fact, if a capacitor is to be connected in a circuit with 400 volts applied, it should have a rating of approximately 600 volts. This provides a 200-volt safety factor. It should also be taken into consideration that a 400-volt capacitor used in such a circuit could be ruined by voltage surges.

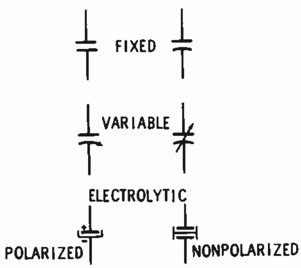


Fig. 15. Common schematic symbols for capacitors.

There is also the breakdown voltage rating although it is seldom indicated on the capacitor. This value is somewhat above the DC working voltage and is that value at which the dielectric material will actually break down and begin conducting. This will ruin some capacitors; others it will not. As an example, exceeding the breakdown voltage of a paper capacitor will cause the paper dielectric to carbonize and thus become conductive. Such a condition ruins the capacitor permanently. On the other hand, exceeding the breakdown voltage of a variable tuning capacitor will result in an arc between the plates (the air dielectric breaks down) but will cause no permanent damage. There are also some oil-type filter capacitors which will withstand overloads for short periods of time and then "heal" themselves.

Another capacitor rating is tolerance. This is not always indicated on a capacitor, especially the larger ones. Some of the smaller-value capacitors used in applications where values must be held within relatively close limits are marked with their value and a ± percentage.

There are also what are known as temperature-compensated capacitors. These are capacitors designed to offset the change in value normally encountered with temperature changes. Like resistors, capacitors often change value when heated. In some electronic circuits, capacitance values are critical and must remain stable despite variations in temperature. Some capacitors are manufactured in such a way that their value will not vary, or at least the change is negligible for all practical purposes. Others are designed to either increase or decrease in value by predetermined amounts as the temperature changes.

The temperature coefficient of a capacitor (or resistor) designates the amount of change in parts-per-million-per-degree centigrade. When a capacitor is marked with an N or minus sign it means that the capacity will decrease with an increase in tempera-

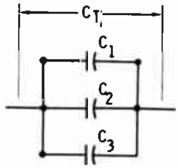


Fig. 16. Capacitors in parallel.

ture. Conversely, a capacitor marked with a P or a plus sign indicates that it will increase in value as the temperature increases.

Capacitive values will either be indicated directly or by means of the standard color code shown in Table I.

CAPACITORS IN COMBINATION

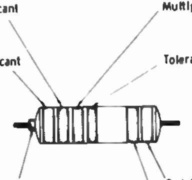
When capacitors are connected in series or parallel, the effect is opposite to that of connecting resistances and inductances in a simi-

Table 1. Capacitor Color Codes

MOLDED PAPER TUBULAR

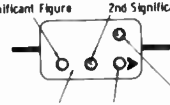
MOLDED PAPER CAPACITOR CODES (CAPACITANCE GIVEN IN PF)

COLOR	DIGIT	MULTI-PLIER	TOLER-ANCE
BLACK	0	1	20%
BROWN	1	10	
RED	2	100	
ORANGE	3	1000	
YELLOW	4	10000	
GREEN	5	100000	5%
BLUE	6	1000000	
VIOLET	7		
GRAY	8		
WHITE	9		10%
GOLD			5%
SILVER			10%
NO COLOR			20%

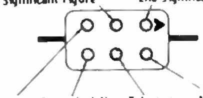


Add Two Zeros To Significant Voltage Figures.
One Band Indicates Voltage Ratings Under 1000 Volts.

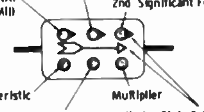
MOLDED FLAT PAPER CAPACITORS (COMMERCIAL CODE)



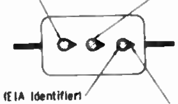
MOLDED FLAT PAPER CAPACITORS (MILITARY CODE)



CURRENT EIA AND MILITARY COLOR CODE FOR MOLDED MICA CAPACITORS



A (FRONT)



B (REAR)

NOTES:
1. The multiplier is the factor by which the two significant figures are multiplied to yield the nominal capacitance.
2. "A" illustrates standard six-dot system used for "N" temperature range capacitors manufactured according to EIA Standard RS-153-A.
3. Drawings "A" and "B" combined illustrate standard nine-dot system used for "O" temperature range capacitors manufactured according to EIA Standard RS-153-A, and for all units manufactured according to Military Specification MIL-C-5C.

MICA CAPACITOR COLOR CODE

COLOR	CHARAC-TERISTIC*	CAPACITANCE: 1ST AND 2ND SIGNIFICANT FIGURES	CAPACITANCE: MULTIPLIER	CAPACITANCE TOLERANCE	DC WORKING VOLTAGE	OPERATING TEMPERATURE RANGE	VIBRATION GRADE (MIL)
Black	A (EIA)	0	1	±20% (EIA)		- 55° to + 70°C (MIL)	10-55 Hz
Brown	B	1	10	±1%	100 (EIA)		
Red	C	2	100	±2%		- 55° to + 85°C	
Orange	D	3	1000		300		
Yellow	E	4	10000 (EIA)			- 55° to + 125°C	10-2000 Hz
Green	F	5		±5%	500		
Blue		6				- 55° to + 150°C (MIL)	
Purple (violet)		7					
Gray		8					
White		9					
Gold			0.1	±1/2% (EIA)	1000 (EIA)		
Silver			0.01 (EIA)	±10%			

* Denotes specifications of design involving Q factors, temperature coefficients, and production test requirements.
† Or ±0.5 pf, whichever is greater. All others are specified tolerance or ±1.0 pf, whichever is greater.

SILVERED MICA BUTTON CAPACITORS

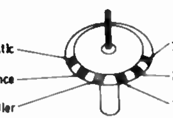
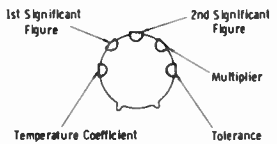
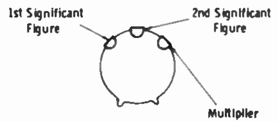


Table 1. Capacitor Color Codes—(Cont'd)

DISC CERAMICS (5-DOT SYSTEM)



DISC CERAMICS (3-DOT SYSTEM)

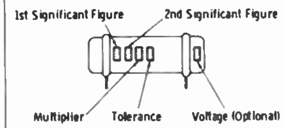


CERAMIC CAPACITOR CODES (CAPACITANCE GIVEN IN PF)

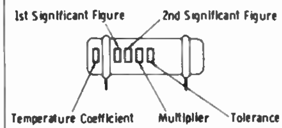
COLOR	DIGIT	MULTIPLIER	TOLERANCE: 10 PF OR LESS	TOLERANCE: OVER 10 PF	TEMPERATURE COEFFICIENT PPM °C	EXTENDED RANGE TEMP. COEFF.: SIGNIFICANT FIGURE	EXTENDED RANGE TEMP. COEFF.: MULTIPLIER
BLACK	0	1	± 2.0pf	± 20%*	0	0.0	-1
BROWN	1	10	± 0.1pf	± 1%	-33		-10
RED	2	100		± 2%	-75	1.0	-100
ORANGE	3	1000	± 0.25pf	± 2.5%*	-150	1.5	-1000
YELLOW	4	10000			-220	2.2	-10000
GREEN	5		± 0.5pf	± 5%	-330	3.3	+1
BLUE	6				-470	4.7	+10
VIOLET	7				-750	7.5	+100
GRAY	8	.01	± 0.25pf*		+30		+1000
WHITE	9	.1	± 1.0pf	± 10%	General Purpose		+10000
SILVER					Bypass & Coupling		
GOLD					+100 (MIL)		

*EIA only. Ceramic Capacitor capacitor voltage ratings are standard 500 volts, for some manufacturers, 1000 volts for other manufacturers, unless otherwise specified.

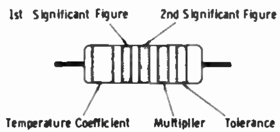
HIGH-CAPACITANCE TUBULAR CERAMICS INSULATED OR NONINSULATED



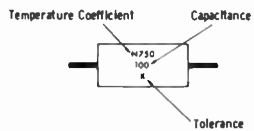
TEMPERATURE COMPENSATING TUBULAR CERAMICS



MOLDED-INSULATED AXIAL LEAD CERAMICS

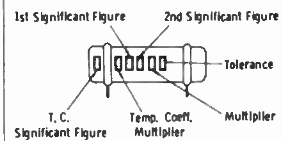


TYPOGRAPHICALLY MARKED CERAMICS

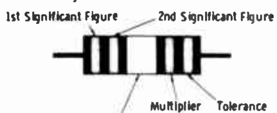


MIL LETTER	TOLERANCE: 10PF OR LESS	TOLERANCE: OVER 10PF
C	± 0.25pf	
D	± 0.5pf	
F	± 1.0pf	± 1%
G	± 2.0pf	± 2%
J		± 5%
K		±10%
M		±20%

EXTENDED RANGE T. C. TUBULAR CERAMICS

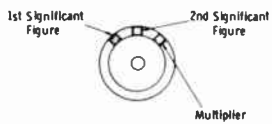


MOLDED CERAMICS Using Standard Resistor Color Code



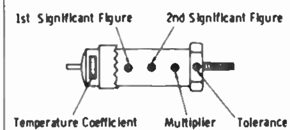
White Band Distinguishes Capacitor From Resistor

BUTTON CERAMICS

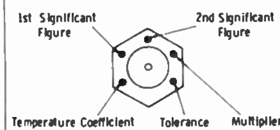


Viewed From Soldered Surface

STAND-OFF CERAMICS



FEED-THRU CERAMICS



lar arrangement. A simple method, therefore, and one which is easy to remember is as follows: Capacities connected in series should be added in a manner similar to that of resistances connected in parallel, and capacities connected in parallel should be added in a manner similar to that of resistances connected in series.

The formula for calculating the total capacitance when two or more capacitors are connected in parallel as in Fig. 16 is expressed as follows:

$$C_T = C_1 + C_2 + C_3 + \ldots$$

where C_T is the total capacitance, and C_1, C_2, and C_3 are the values of the individual capacitors.

For calculating capacitors in series (Fig. 17):

$$C_T = \cfrac{1}{\cfrac{1}{C_1} + \cfrac{1}{C_2} + \cfrac{1}{C_3} + \ldots}$$

Since the calculation of the total capacitance of two or more capacitors connected in series involves finding the reciprocals of numbers, the same graphical method explained previously for resistors or inductors in parallel can be used.

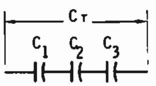


Fig. 17. Capacitors in series.

Example: A capacitor of 0.0002 mfd is connected in series with one of 0.002 mfd. What is the resultant value of capacitance, and what would the capacity be if they had been connected in parallel?

Solution: If C_T denotes the resultant capacity of the two capacities in series, then:

$$C_T = \cfrac{1}{\cfrac{1}{0.0002} + \cfrac{1}{0.002}}$$

or

$$\frac{1}{C_T} = \frac{1}{0.0002} + \frac{1}{0.002}$$

or

$$\frac{1}{C_T} = 5{,}000 + 500 = 5{,}500, \text{ from which it follows that}$$

$$C_T = \frac{1}{5{,}500} \text{ or } 0.00018 \text{ mfd (approximately)}$$

If connected in parallel, the total capacitance is simply the sum of the individual capacities or 0.002 + 0.0002 which totals 0.0022 mfd.

SUMMARY

Capacitors are major components in nearly all electronic equipment and are manufactured in a great variety of sizes, shapes, and capacitance values. Capacitors effectively block the flow of DC but appear to permit the flow of AC. Actually, electrons do not pass through a capacitor, but the effect is the same as if they did.

Capacitors offer an opposition to the flow of alternating current. This opposition is called capacitive reactance and is measured in ohms. Capacitive reactance decreases as frequency increases, which is exactly opposite to inductive reactance. Current leads the voltage in a capacitor.

The value of a capacitor depends on the area of the plates, and the thickness and type of dielectric. Another important rating of a capacitor is the amount of voltage it can stand without being damaged. A tolerance rating is also given many capacitors. These various ratings are either stamped or printed on the capacitor body, or represented by means of a system of color coding.

Capacitors can be connected in series or in parallel to change the amount of capacity in a circuit. Total capacity increases when capacitors are paralleled and decreases when they are connected in series.

REVIEW QUESTIONS

1. What is the material called that is placed between the plates of a capacitor?

2. Does capacity increase or decrease when the area of the capacitor plates is increased?
3. What is the opposition to the flow of AC in a capacitive circuit called?
4. Does this opposition increase, decrease, or remain the same as the AC frequency increases?
5. Does the voltage lead or lag the current in a capacitive circuit?
6. Give a practical application for a variable capacitor.
7. State the formula used to find the total capacity of three series-connected capacitors.
8. State the formula used to find the total capacity of three parallel-connected capacitors.
9. What is the formula for finding capacitive reactance?
10. Does the capacitive reactance of a circuit change if more resistance is added?

CHAPTER 8

Reactance in AC Circuits

In direct-current circuits, the current is exactly defined by the mathematical relationship between voltage and resistance, whereas in alternating-current circuits, this exact relationship no longer exists. For example, in the case of direct current, the current through a piece of wire will be the same regardless of whether the wire is coiled or straight. In the case of alternating current, the current will be less when the wire is coiled than when it is straight. This is due to the inductive reactance (X_L) of the wire ($X_L = 2\pi fL$).

If a direct-current source is connected across a capacitor, there will be a momentary current flow; but if the capacitor is connected across an alternating-current source of high frequency, the current will flow. This is due to the capacitive reactance (X_C) of the capacitor.

$$X_C = \frac{1}{2\pi fC}$$

The opposition offered to the flow of alternating current in a circuit containing inductance and/or capacitance will vary with the frequency of the current. This is due to inductive and capacitive reactance. The combined total opposition (resistance, inductive reactance, and capacitive reactance) is known as the *impedance* (Z).

RESISTANCE AND INDUCTANCE IN SERIES

When a circuit contains both resistance and inductance, as in the case of a coil, it is convenient to consider it as a resistance (R) connected in series with a pure inductive reactance (X_L). (See Fig. 1.)

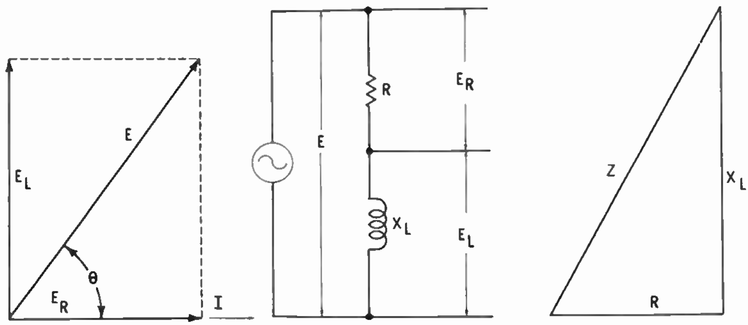


Fig. 1. Combination of resistance (R) and inductive reactance (X_L).

In this case it is necessary to know not only how to calculate inductive reactance but also how to combine R and X_L. (See the impedance triangle shown in Fig. 2.) To obtain the impedance: Resistance R (in ohms) is laid off horizontally; the inductive reactance X_L (also in ohms) is laid off to form the perpendicular. The hypotenuse is measured (in the same scale) to give the impedance of the circuit in ohms. This triangle is variously referred to as the impedance triangle, vector diagram or impedance calculator. The mathematical relationship between the impedance, the inductive reactance and the resistance is written:

$$Z^2 = X_L^2 + R^2 \quad \text{or} \quad Z = \sqrt{X_L^2 + R^2}$$

and since

$$X_L = 2\pi fL$$

the equation may also be written

$$Z = \sqrt{(2\pi fL)^2 + R^2}$$

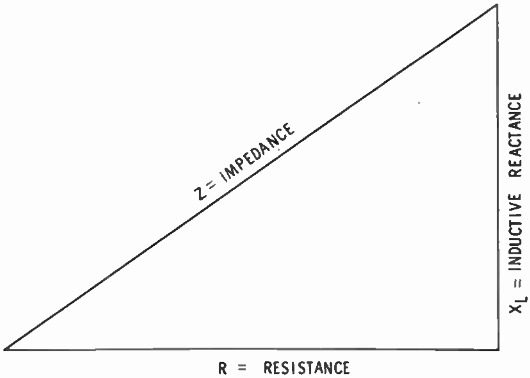


Fig. 2. Vector relationship between inductive reactance and resistance.

Example: A coil connected as shown in Fig. 1 contains a 5-ohm resistance and a 0.04-henry inductance. The voltage and frequency of the source are 100 and 60 respectively. To find (a) the impedance of the coil; (b) the current through the coil; (c) the voltage drop across the inductance; and (d) the voltage drop across the resistance:

(a) $X_L = 2\pi fL = 2 \times 3.14 \times 60 \times 0.04 = 15$ ohms

$Z = \sqrt{5^2 + 15^2} = \sqrt{250} = 15.8$ ohms

(b) $I = \frac{E}{Z} = \frac{100}{15.8} = 6.3$ amperes

(c) $E_L = I \times X_L = 6.3 \times 15 = 94.5$ volts

(d) $E_R = I \times R = 6.3 \times 5 = 31.5$ volts

A visualization of the frequency response of an RL series circuit is shown in Fig. 3. At any given frequency, the output voltage E_{out} is a certain fraction of the input voltage E_{in}. The vertical axis is calibrated in percent of the maximum possible output voltage. Of course the maximum possible output voltage is equal to E_{in}, and is approached at very low frequencies. The horizontal axis is calibrated basically in frequency; that is, it is

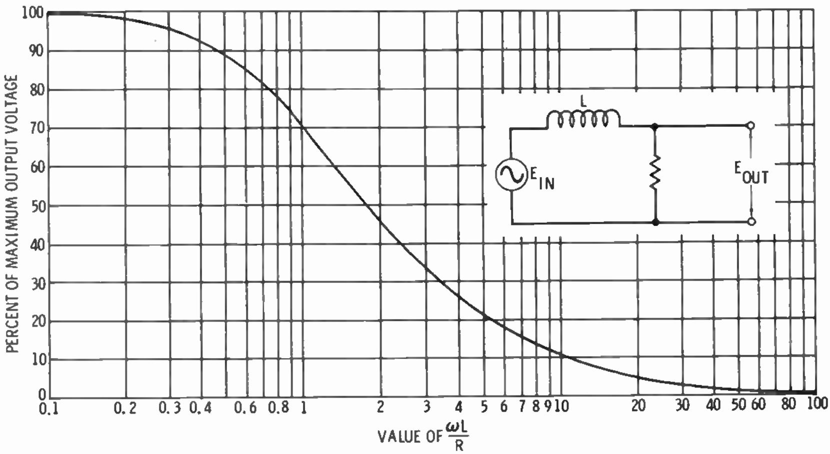


Fig. 3. Universal frequency-response curve for RL series circuits.

calibrated in $\omega L/R$ units, where $\omega L/R$ is equal to $2\pi fL/R$, L is in henrys, R is in ohms, and f is in hertz.

In a practical circuit situation, L and R are constant. Therefore, $2\pi L/R$ is also a constant. Thus, if we go from 1 to 10 along the horizontal axis, we see the effect of increasing the frequency 10 times. This corresponds to a decrease of output voltage from 70.7% to 10% of its maximum value (E_{in}). Note that when $\omega L/R$ is equal to 100, that E_{out} is very small. Universal frequency-response charts are helpful in practical work because they minimize the labor of calculation. They also provide a useful perspective of circuit action.

RESISTANCE AND CAPACITANCE IN SERIES

If a capacitance is connected in series with a resistance, as shown in Fig. 4, the impedance may be written $Z = \sqrt{R^2 + X_C^2}$, and since:

$$X_C = \frac{1}{2\pi fC}$$

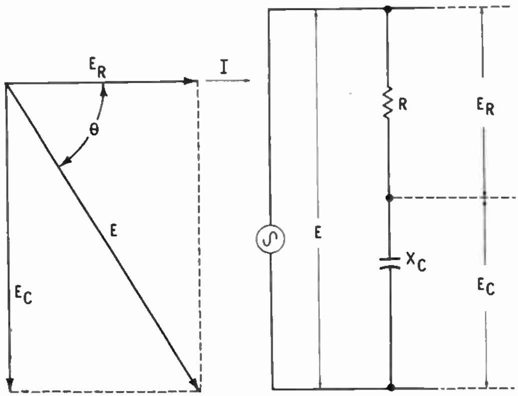


Fig. 4. Combination of resistance (R) and capacitive reactance (X_C).

it follows that:

$$Z = \sqrt{R^2 + \left(\frac{1}{2\pi fC}\right)^2}$$

Example: An alternating-current circuit, connected as shown in Fig. 4, contains a 10-ohm resistance in series with a capacitance of 40 microfarads. The voltage and frequency of the source are 120 and 60 respectively.

To find (a) the current in the circuit; (b) the voltage drop across the resistance; (c) the voltage drop across the capacitance:

$$X_C = \frac{1}{2\pi fC} = \frac{1}{2 \times 3.14 \times 60 \times 0.00004} = 66.3 \text{ ohms}$$

$$Z = \sqrt{10^2 + 66.3^2} = 67 \text{ ohms}$$

(a) $I = \frac{E}{Z} = \frac{120}{67} = 1.8$ amperes

(b) $E_R = I \times R = 1.8 \times 10 = 18$ volts

(c) $E_C = I \times X_C = 1.8 \times 66.3 = 119.3$ volts

A visualization of the frequency response of an RC series circuit is shown in Fig. 5. Note that this curve can be described as the "opposite" of the curve in Fig. 3, at least in the first analysis. The horizontal axis is calibrated in ωRC units, where ωRC is equal to $2\pi fRC$, C is in farads, R is in ohms, and f is in hertz.

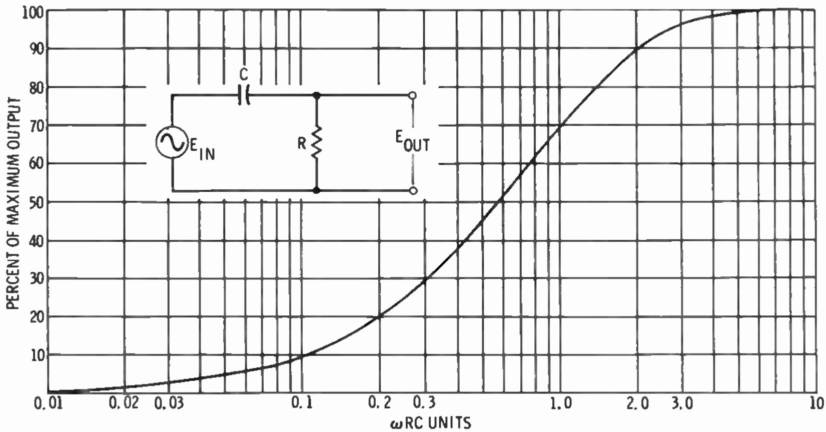


Fig. 5. Universal frequency-response curve for RC series circuits.

RESISTANCE, INDUCTANCE, AND CAPACITANCE IN SERIES

In a circuit which contains resistance (R), inductance (X_L), and capacitance (X_C), the reactance (X) is equal to the arithmetical difference between the inductive reactance (X_L) and the capacitive reactance (X_C), which may be written thus:

$$X = X_L - X_C$$

but as previously shown:

$$Z = \sqrt{R^2 + X^2} = \sqrt{R^2 + (X_L - X_C)^2}$$

and since:

$$X_L = 2\pi fL \quad \text{and} \quad X_C = \frac{1}{2\pi fC}$$

it follows that:

$$Z = \sqrt{R^2 + \left(2\pi fL - \frac{1}{2\pi fC}\right)^2} \text{ ohms}$$

Also, the current flowing in this circuit is:

$$I = \frac{E}{\sqrt{R^2 + \left(2\pi fL - \frac{1}{2\pi fC}\right)^2}}$$

The equations just derived are of the utmost importance in all alternating-current calculations and are generally referred to as Ohm's law for alternating current.

ALTERNATING-CURRENT PARALLEL CIRCUITS

In the previous analysis of direct-current parallel circuits, it was found that the voltage was equal across each branch of the parallel circuit, and that the current in each branch varied inversely as the resistance of that branch. The arithmetical sum of the currents in all branch circuits was also equal to the main current.

When considering a parallel circuit, such as that shown in Fig. 6, through which an alternating current flows, the voltage across each branch is equal, as in the case of the DC circuit.

The total current, however, cannot be obtained by arithmetical addition of the branch-circuit currents, but instead the branch-circuit currents must be added vectorially. This can best be shown by the following example.

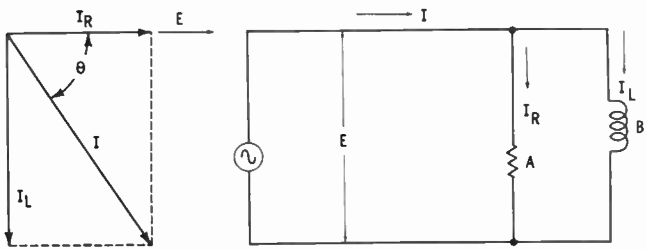


Fig. 6 Parallel connection of resistance (R) and inductive reactance (X_L).

A parallel connection consists of two branches A and B (Fig. 6). Branch A has a resistance of 40 ohms, and branch B has an inductive reactance of 30 ohms. If the impressed voltage is 120, you can determine: (a) the current through branch A, (b) the current through branch B, and (c) the line current.

(a) $I_R = \frac{120}{40} = 3$ amperes

(b) $I_L = \frac{120}{30} = 4$ amperes

(c) $I = \sqrt{3^2 + 4^2} = \sqrt{25} = 5$ amperes

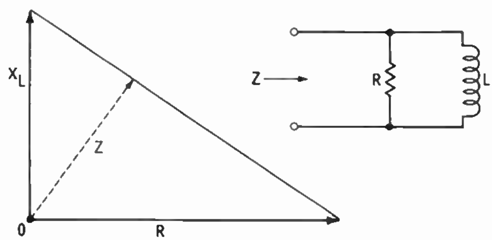


Fig. 7. Graphical solution of an RL parallel circuit.

The easiest way to solve a parallel circuit is to use the graphical method shown in Fig. 7. First, draw a line (X_L) proportional to the inductive reactance, and then a line (R) proportional to the resistance. Note that X_L and R are drawn at right angles to each other. Then, draw the hypotenuse of the right-angled triangle.

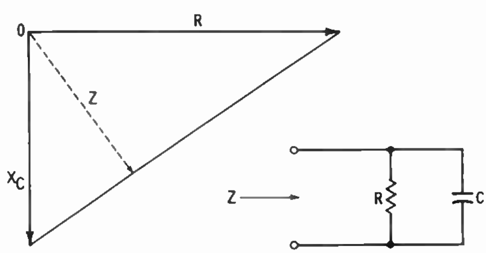


Fig. 8. Graphical solution of an RC parallel circuit.

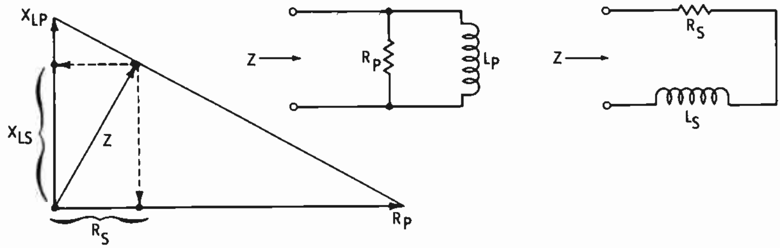


Fig. 9. Graphical solution for finding equivalent series and parallel circuits.

Finally, draw a line (Z) from O, perpendicular to the hypotenuse. The length of Z is then proportional to the impedance of the parallel RL circuit. This method not only saves time, but also shows the relative magnitudes of X_L, R, and Z at a glance.

It follows that the same type of graphical solution can be used to find the impedance of a parallel RC circuit, as shown in Fig. 8. First, draw a line (X_C) proportional to the capacitive reactance, and then a line (R) proportional to the resistance. Note that X_C and R are drawn at right angles to each other. Then, draw the hypotenuse of the right-angled triangle. Finally, draw a line (Z) from O, perpendicular to the hypotenuse. The length of Z is then proportional to the impedance of the parallel RC circuit.

At a given frequency of operation, any parallel RL or RC circuit has an equivalent series RL or RC circuit. The equivalent circuit is easily found by a slight extension of the graphical method, as shown in Fig. 9. An equivalent circuit has the same impedance as the original circuit. Therefore, Z has the same length for both the series and parallel circuit. Project from the tip of Z to the vertical and horizontal sides of the triangle to find the reactance of the series inductance and the resistance of the series resistor. Note that larger values of inductance and resistance must be paralleled to have the same impedance as smaller values of inductance and resistance connected in series.

RESONANCE

When the inductive reactance becomes equal to the capacitive reactance, the circuit is said to be in *resonance*. The only opposition to the current flow is resistance R (Fig. 10). A curve illustrating the current of a circuit approaching, at, and beyond the point of resonance is shown in Fig. 11.

This resonant condition may be written $X_L = X_C$, but since:

$$X_L = 2\pi fL$$

and:

$$X_C = \frac{1}{2\pi fC}$$

it follows that:

$$2\pi fL = \frac{1}{2\pi fC}$$

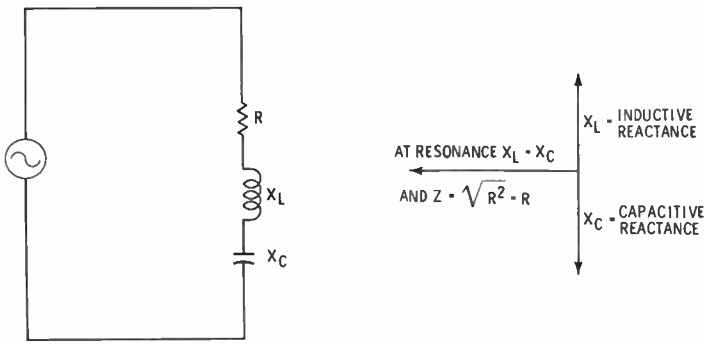


Fig. 10. A series-resonant circuit.

If it is desired to find the resonant frequency (f) for the circuit, the equation may be written:

$$f^2 = \frac{1}{4\pi^2 LC}$$

or

$$f = \frac{1}{2\pi\sqrt{LC}}$$

This equation is of importance in all kinds of radio calculations such as those for wavemeters, filters, circuit tuning, etc. If C is expressed in microfarads and L in microhenrys, the equation may be written:

$$f = \frac{159{,}000}{\sqrt{C\ (\text{microfarads}) \times L\ (\text{microhenrys})}}$$

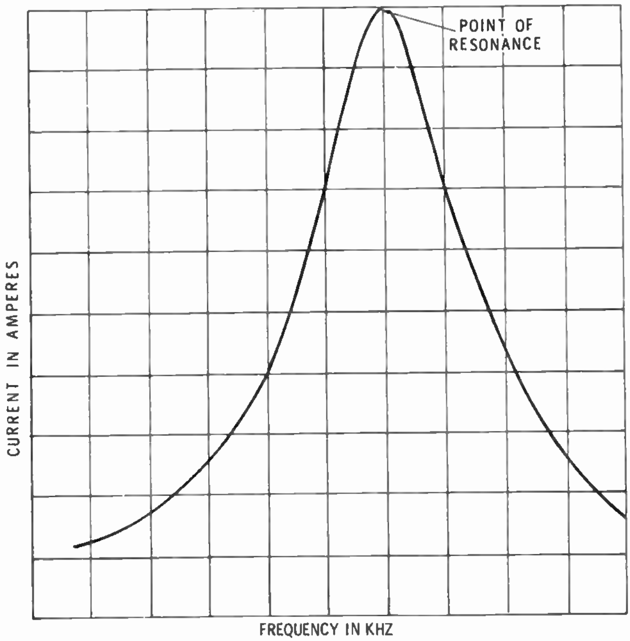


Fig. 11. Current versus frequency variations in a resonant circuit.

Fig. 12 provides a visualization of the filter action of individual series capacitors and inductors. The characteristic frequency discrimination of large and small capacitors, and of large and small inductors, is shown for four different types of input signals—audio-frequency, radio-frequency, AF and RF, and AF and RF with a DC component. Note how an inductance attenuates radio frequencies more than it attenuates audio frequencies. Also note that a capacitance attenuates audio frequencies more than it attenuates radio frequencies. A resistance provides no filter action in itself, because it has no frequency discrimination. An inductor passes, but a capacitor blocks, a DC component.

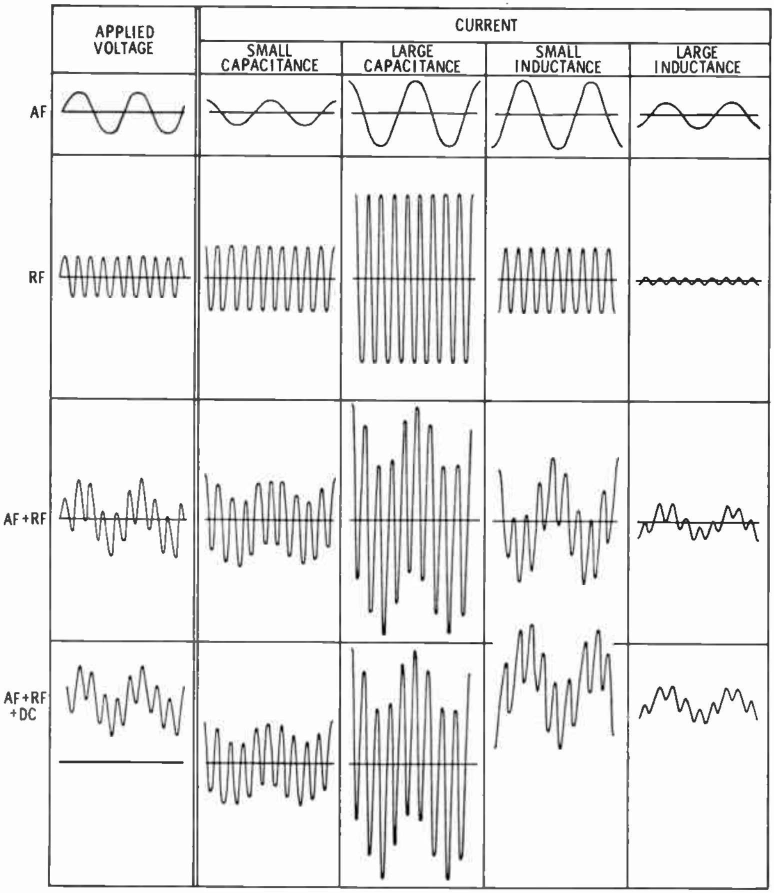


Fig. 12. Filter action of individual series capacitors and inductors.

In the closed loop, where the same current flows throughout, the component voltages produced by the current through the inductive and capacitive reactances are in opposition—when one is positive, the other is negative.

Thus, the voltage produced by the two reactances in series is the difference of the individual voltages. From this it follows that the inductive and capacitive reactances tend to neutralize each other's effects and the resultant reactance of the circuit is given by

$$2\pi fL = \frac{1}{2\pi fC} \text{ ohms}$$

It is evident from the above that the inductive reactance increases as the frequency is increased, whereas the capacitive reactance decreases. Therefore, there must be one particular frequency at which the two become equal and neutralize each other completely as far as their influence on the current is concerned. When this happens the circuit is tuned to resonance with the applied frequency (Fig. 13).

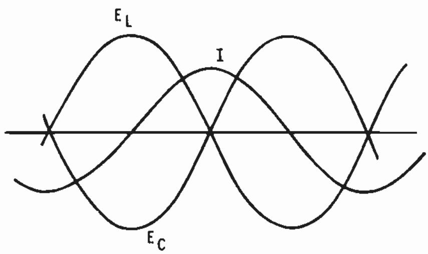


Fig. 13. Voltage and current in a series-resonant circuit.

At the resonant frequency, the resultant reactance of the circuit is zero, so that only the resistance remains to oppose the flow of current and, hence, Ohm's law may be applied.

At any frequency different from that of the resonant value, the inductive and capacitive reactances become unequal and their resultant is no longer zero. When this condition occurs, the current experiences an additional opposition which increases as the frequency departs in either direction from the resonant value. As a result, the current is reduced sharply on either side of the resonant frequency.

Obviously, then, the current is greatest at the resonant frequency, its value being $\frac{E}{R}$ amperes.

The formula for a current at any frequency is:

$$I = \frac{E}{\sqrt{R^2 + \left(2\pi fL - \frac{1}{2\pi fC}\right)^2}} \text{ amperes}$$

VOLTAGE AMPLIFICATION

The voltage across a capacitor is:

$$I \times \frac{1}{2\pi fC}$$

and, since at resonance:

$$\frac{1}{2\pi fC} = 2\pi fL\,,$$

it follows that the voltage developed across the tuned circuit is:

$$I\ (2\pi fL) \text{ volts}\,.$$

From Ohm's law, the applied voltage is IR and so the ratio of the developed voltage and the applied voltage is:

$$\frac{2\pi fL}{R}$$

This very important number is known as the voltage amplification of the tuned circuit.

At resonance:

$$2\pi f = \frac{1}{\sqrt{LC}}$$

and so the previous expression for voltage amplification may be rewritten in the form:

$$E_a = \frac{1}{R}\sqrt{\frac{L}{C}}$$

It now remains to be shown that the selectivity of the tuned circuit is directly proportional to the voltage amplification. This may best be accomplished with a graphic illustration.

Consider a circuit of fixed inductance and capacity and assume that a number of resonance curves are plotted, each for a different resistance value.

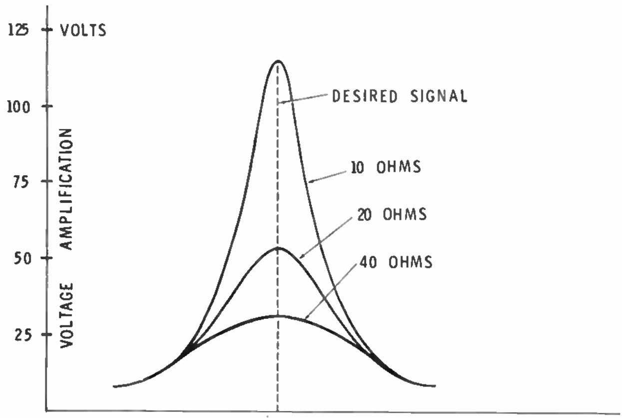
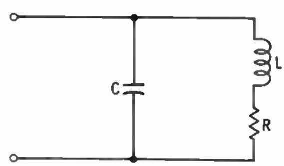


Fig. 14. Typical voltage characteristics indicating the effect of varying the effective resistance of a circuit at resonance.

With reference to Fig. 14, you will notice that the peak of each curve appears at the same frequency but their amplitudes are inversely proportional to their respective resistances.

It is important to note that all the resonance curves have approximately the same width near the base, so that by decreasing the resistance the strength of the desired signal can be increased at the resonant frequency without appreciably strengthening any signals whose frequencies differ moderately from the resonant value.

Fig. 15. Capacitance in parallel with a coil that has winding resistance.



CURRENT AMPLIFICATION

When a capacitor is connected across a coil (and its winding resistance), as shown in Fig. 15, a so-called parallel-resonant circuit is formed which resonates at a frequency given by the familiar resonant-frequency formula:

$$f=\frac{1}{2\pi\sqrt{LC}}$$

A series-resonant circuit has minimum impedance at resonance, but a parallel-resonant circuit has maximum impedance. Similarly, a series-resonant circuit exhibits voltage amplification, but a parallel-resonant circuit exhibits current amplification. The current amplification is given by the formula:

$$\frac{2\pi fL}{R}$$

Note carefully that the amplified current is a *circulating current* between the coil and capacitor. The impedance of the parallel circuit at resonance is given by the approximate formula:

$$Z=\frac{L}{RC}$$

Therefore, the line current that is drawn from the source is given by Ohm's law:

$$I_L=\frac{ERC}{L}$$

However, the connecting wires between the coil and capacitor must carry an amplified current given by the formula:

$$I_{CC}=2\pi EfC$$

Since the circulating current I_{CC} is much greater than the line current I_L in most practical situations, the conclusion is that heavy wire must be used to connect the capacitor to the coil in order to minimize the I^2R loss and obtain efficient operation.

SUMMARY

The current in an AC circuit is affected by factors other than applied voltage and resistance in the circuit. Inductive and/or capacitive reactance must be considered when calculating the amount of current that will flow. Therefore, the combined opposition to current flow is made up of resistance, inductive reactance, and/or capacitive reactance, and is known as impedance (Z).

Resistance causes no phase shift to take place between voltage and current. However, an inductance causes the current to lag the voltage by 90° while a capacitance causes the current to lead the voltage by 90°. Thus, inductance and capacitance each cause an exact opposite effect. This fact permits calculating impedance by means of a relatively simple graphical method or by means of an established formula, both methods based on the relationship of the angles, sides, and hypotenuse of a right-angle triangle.

A circuit containing both inductance and capacitance will have an impedance at some particular frequency that is equal only to the resistance in the circuit. This condition is known as resonance, which makes it possible for the circuit to select one frequency to the exclusion of all others. In practical circuits, excluding all but one particular frequency is not feasible. Instead, some frequencies on each side of the resonant frequency are also selected, but at a reduced amplitude.

REVIEW QUESTIONS

1. What determines the amount of current flow in a DC circuit?
2. What determines the amount of current flow in an AC circuit?
3. What is impedance?
4. State the mathematical relationship between impedance, inductive reactance, and resistance.
5. State the mathematical relationship between impedance, capacitive reactance, and resistance.

6. State the mathematical relationship between impedance, inductive reactance, capacitive reactance, and resistance.
7. Define resonance in terms of inductive and capacitive reactance.
8. Define resonance in terms of impedance and resistance.
9. State the formula for determining the resonant frequency of a circuit.
10. What is voltage amplification in a tuned circuit?

CHAPTER 9

Transformers

Basically, a transformer consists of two or more coils which couple energy from one circuit to another by means of electromagnetic induction. This transfer of energy occurs at the same frequency but usually at different voltage and current values. Some transformers, such as those used for interstage coupling, are designed primarily to provide the proper impedance match between the output of one circuit and the input of another.

MUTUAL INDUCTANCE AND SELF-INDUCTION

Without a knowledge of the fundamental principles of mutual induction, it is difficult to comprehend the theory of coil coupling. By definition, *mutual induction* is the electromagnetic property of two circuits or two parts of a single circuit, by virtue of which a changing current in one causes an electromotive force to be induced in the other.

Similarly it can be said that mutual induction is an electromagnetic property of two circuits so situated with respect to each other that a current in one sets up a magnetic field which is linked with the other—that is to say, a property of two circuits which are magnetically coupled together (see Fig. 1).

It is a fundamental principle that when a magnetic flux linked with a conductor is changing, an electromotive force is induced in

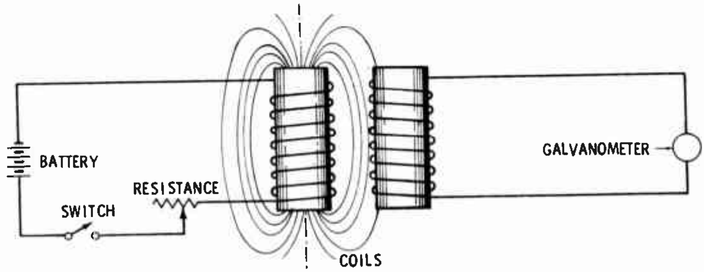


Fig. 1. Diagram showing the action of mutual induction between two coils. One circuit includes a source of electrical energy and a switch; the other includes an instrument to measure current but has no energy source. During an increase or decrease in current, as when the switch is closed, current is induced in the secondary. This current in the secondary flows in a direction opposite to that of the current in the primary.

the conductor with a magnitude proportional to the rate of change of flux. When the magnetic flux linked with a conductor is produced by a current in the conductor itself, then the flux will vary as the current is varied, and an emf proportional to the change in current is induced in the circuit.

Let us consider the equivalent circuit for a basic transformer, as shown in Fig. 2. The basic transformer has the same number of turns in both coils. Insofar as AC relations are concerned, the equivalent circuit depicted in Fig. 2 acts the same as the basic transformer with magnetically coupled coils. This equivalent circuit is very useful, because it provides a clear understanding of transformer action. For example, observe that there must be a voltage drop across the leakage inductance, and that there must be at least a small flow of reactive current through the mutual inductance.

This property in a single circuit is called self-induction. If, however, there are two circuits magnetically coupled as explained above, a variation of the current in the one will cause a variation of the magnetic flux through the other. Then, an emf or a current

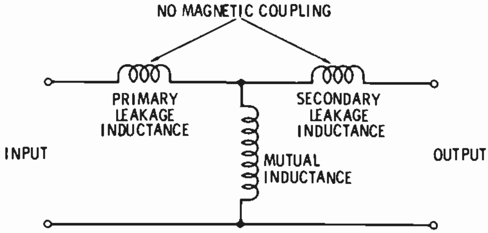


Fig. 2. Equivalent circuit for a basic transformer.

in the first circuit will cause an emf to be generated in the other circuit. This property is referred to as *mutual induction.*

The first circuit, in which the current is varied, is called the *primary*, and the second, in which the induced emf is considered, is called the *secondary* circuit. The practical unit in which mutual induction and self-induction are expressed numerically is the henry. The mutual inductance or coefficient of mutual inductance between two circuits is said to be one henry if one volt is induced in the secondary circuit when the current in the primary is changing at the rate of one ampere per second.

The mutual inductance in henrys is usually denoted by the symbol M, and the induced emf in volts in one circuit is equal to the product of M and the rate of change of current in amperes per second in the other. The mutual inductance (M) is the same whichever of the two circuits is taken as the primary. This is just another way of saying that the mutual inductance is *common* to the primary and the secondary. This fact is shown to good advantage by the equivalent circuit depicted in Fig. 3. In this diagram, L_p denotes the inductance of the primary coil when it is removed from the vicinity of the secondary coil. Similarly, L_s denotes the inductance of the secondary coil when it is removed from the vicinity of the primary coil. In the basic transformer that we are considering, $L_p = L_s$. Next, when the primary and secondary coils are brought near each other, and thereby magnetically coupled, a mutual inductance M is set up which is common to the primary and the secondary coils.

If the magnetic coupling were complete, there would be no leakage inductance left over. In turn, both $L_p - M$ and $L_s - M$

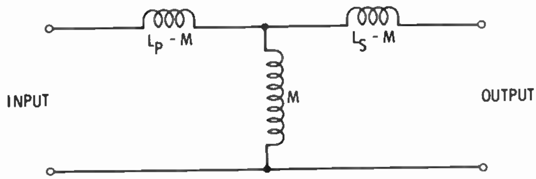


Fig. 3. Relation of primary and secondary inductances to the mutual inductance.

would equal zero. All of the transformer inductance would be mutual inductance in this case, and the equivalent circuit would be drawn as depicted in Fig. 4. On the other hand, if the magnetic coupling were zero, there would be no mutual inductance, and all

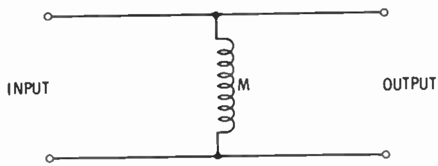


Fig. 4. Equivalent circuit for a basic transformer when magnetic coupling is complete.

of the transformer inductance would appear as a pair of leakage inductances (see Fig. 5). In practice, the leakage inductance might be very small, but it is impossible to obtain complete magnetic coupling. Therefore, the equivalent circuit of Fig. 3 represents the practical situation.

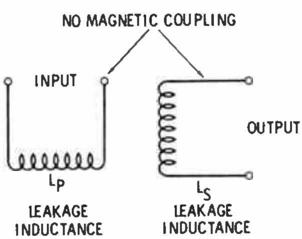


Fig. 5. Representation of a basic transformer with zero magnetic coupling.

Degree of Coupling

As an example, consider two coils (L_1 and L_2) placed in close proximity as shown in Fig. 6. When a current is passed through L_1, a magnetic field is established and some of the magnetic loops are linked with the second coil L_2. Let M represent the mutual inductance in henrys between the coils. Now if the current in L_1 is varied by changing the rheostat setting, the flux linked with L_2 will be varied in proportion and an emf will be induced in L_2. The degree of magnetic coupling obviously depends upon the proximity and relative positions of the two coils and is expressed numerically as the ratio of the mutual inductance to the square root of the product of the individual self-inductances. This is called the coefficient of coupling and is given by

$$K = \frac{M}{\sqrt{L_1 \times L_2}}$$

This number cannot exceed unity, and, in practice, never reaches unity.

Coils are said to be tightly coupled when they are brought close enough together to give a relatively high value of M and K and vice versa. The tightest coupling is obtained when two coils are wound on the same form (as for example in a transformer) or with the wires wound side by side, but even in this case the coefficient is less than unity.

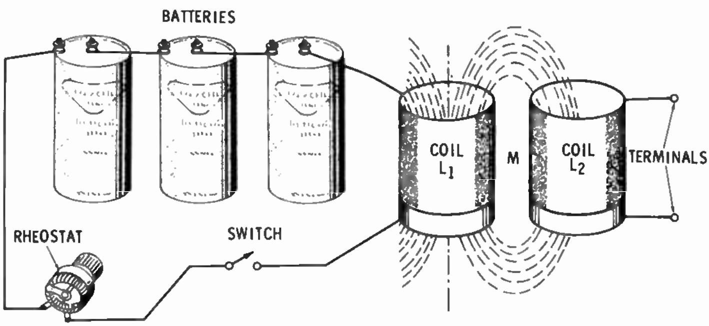


Fig. 6. Illustrating the degree of coupling between two coils.

Example: The mutual inductance of two coils is 160 microhenrys. If their self-inductances are 150 and 275 microhenrys, what is the coefficient of coupling?

$$K = \frac{160}{\sqrt{150 \times 275}} = \frac{160}{203} \text{ or approximately } 79\%$$

It should be observed that in problems of this kind only a ratio between the mutual inductance and self-inductance is required, and the values may be expressed in henrys, millihenrys or microhenrys.

BASIC TRANSFORMER

The alternating-current transformer represents an example of the practical ultilization of mutual inductance. A transformer is a form of stationary induction apparatus in which the primary and secondary coils, or windings, are ordinarily insulated from one another, their relative position being fixed. In the case of low-frequency and power transformers, the primary and secondary wind-

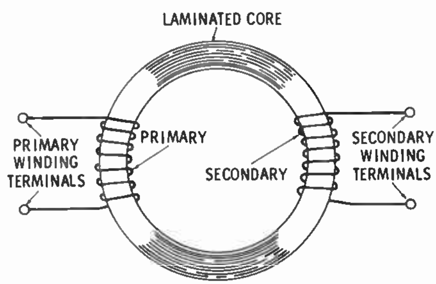


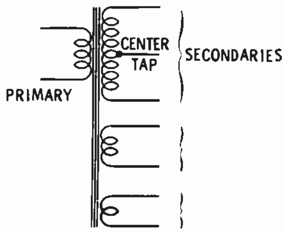
Fig. 7. A transformer, in its simplest form, consists of two separate and distinct coils of insulated wire wound around a common, laminated iron core.

ings are wound on a common iron core as shown in Fig. 3. In this case, the coefficient of coupling approaches 100%, but for radio-frequency transformers, the coils are generally wound around a nonmagnetic coil form (tubular) and have an air core.

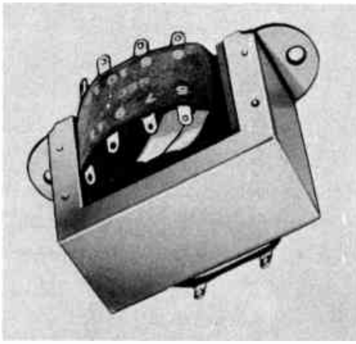
Transformer Function

A transformer does not generate power; its purpose is merely to change the power from one value to another or from one circuit to another. When used in connection with transformation of large amounts of power from one voltage to another, a transformer utilized to raise the received voltage is called a *step-up* transformer, and when used to lower the voltage, a *step-down* transformer.

In radio service, a power transformer (Fig. 8) is used to supply a high voltage to the rectifier tube for rectification of the alternating current and also to supply the filaments or heaters with the required



(A) Schematic symbol.



Courtesy Stancor Electronics, Inc.

(B) Transformer.

Fig. 8. A typical power transformer used in radio equipment.

voltage and current. For this purpose, the transformer is usually equipped with one primary and several secondary windings.

TRANSFORMER THEORY

A transformer is said to be loaded when a current is flowing in the secondary coil. When the secondary circuit is open and an alternating current from the power line flows through the primary coil, an alternating magnetic flux flows in the core. This magnetic flux, rapidly rising, falling and changing direction with the impressed frequency, cuts both primary and secondary coils and induces a voltage in each.

The voltage produced in the primary coil is opposite in direction and nearly equal to the voltage of the power line. The voltage appearing across the secondary coil is proportional (assuming there are no power losses in the transformer) to the number of turns of wire in the primary and secondary coils.

The choking effect produced within the highly inductive primary coil allows only a small current to flow through it. The small current, proportional to the difference between the power-line voltage and the counter electromotive force of the primary coil, keeps the core magnetized and maintains the voltages in the coils.

When the secondary circuit is closed, a current flows through it. This secondary current is 180° out of phase with the primary current, and its magnetizing action in the core opposes and neutralizes, to a certain extent, the primary flux. In doing so it reduces the choking effect or counter electromotive force. When this happens more current from the power line rushes into the primary coil and balances the demagnetizing action of the secondary circuit.

In this way the transformer automatically maintains its core flux practically constant regardless of the load on the secondary. Variations in the load on the secondary are reflected as similar variations in the primary circuit.

Relationship Between Primary and Secondary Voltage

The induced electromotive force in a transformer coil is due to three factors: flux, frequency and the number of turns.

Assuming a sine-wave current, the fundamental equation used in transformer design is as follows:

$$E = \frac{4.44 f \Phi N}{10^8} \qquad (1)$$

where,

f is the frequency in hertz,
Φ is the maximum flux of the sine wave,
N is the number of turns in the coils being considered.

The voltages in the secondary and primary coils are proportional to their respective turns, since both have the same frequency and are cut by the same flux. It has also been found that:

$$\Phi = B \times A \tag{2}$$

where,

B is the maximum flux density in lines per square inch,
A is the cross-sectional area in square inches.

If B × A is substituted for Φ in equation (1), then:

$$E = \frac{4.44BNfA}{10^8} \text{ volts} \tag{3}$$

Another formula for small power transformers is obtained by solving equation (3) with respect to turns per volt.

$$\frac{N}{E} = \frac{10^8}{4.44BfA} \tag{4}$$

A useful transformer design chart based on this equation is shown in Fig. 9. The left column represents the flux density (B), the center column is the core area (A), and the right column is the turns per volt.

Since the core flux of any transformer tends to remain constant regardless of load, the primary and secondary induced voltages remain practically constant; hence:

$$\frac{E_1}{E_2} = \frac{N_1}{N_2} \tag{5}$$

where,

E_1 is the voltage of primary coil,
E_2 is the voltage of secondary coil,
N_1 is the number of turns in primary coil,
N_2 is the number of turns in secondary coil.

It follows from the above that if N_1 and N_2 are the number of turns in the primary and secondary coils respectively, and if a voltage E_1 is impressed on the primary coil, the secondary voltage is given by the following relationship.

$$E_2 = \frac{E_1 \times N_2}{N_1} \tag{6}$$

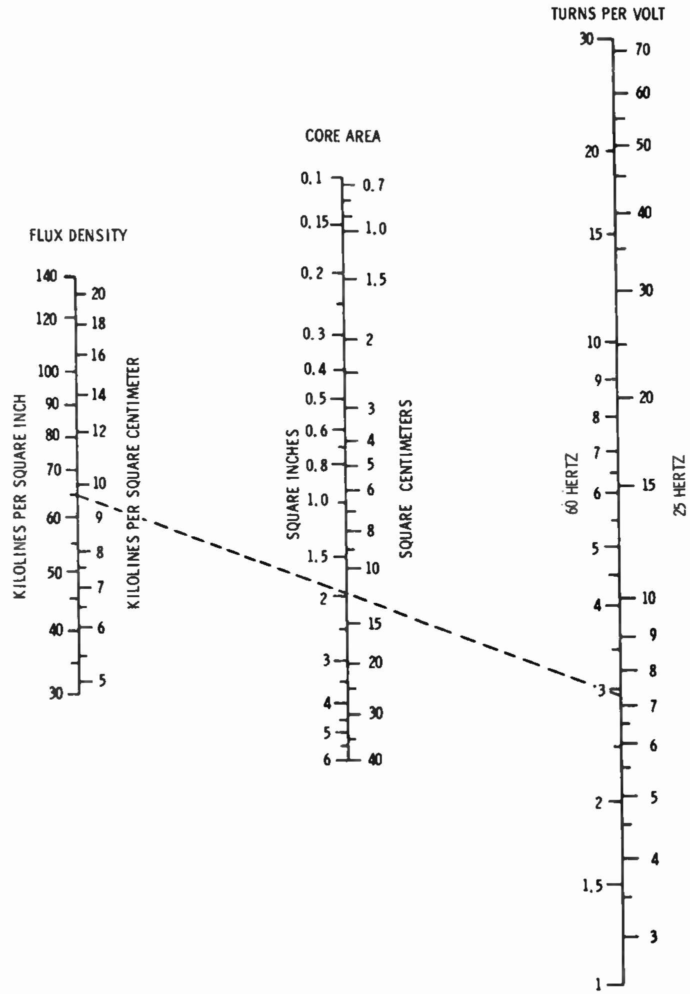
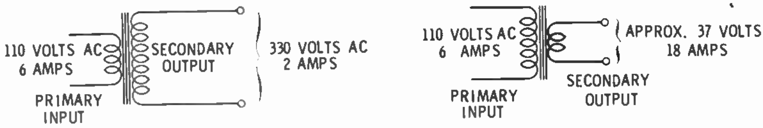


Fig. 9. Turns-per-volt chart.

Example: What will be the ratio of the primary and secondary turns in a power transformer having 110 volts impressed on the primary coil when an output of 660 volts is required from the secondary?



(A) A 1:3 voltage step-up ratio. (B) A 3:1 voltage step-down ratio.

Fig. 10. Diagram illustrating turns, voltage, and current ratios.

Solution:

$$\frac{E_1}{E_2} = \frac{N_1}{N_2} \quad \text{or} \quad \frac{110}{660} = \frac{N_1}{N_2} = \frac{1}{6}$$

From this it is determined that the secondary coil should have six times as many turns as the primary coil. By examining Fig. 10, it can be seen that a direct relationship also exists between the number of turns in the primary and secondary coils and the current flowing in the secondary. For example, Fig. 10A shows a step-up transformer with a 1:3 turns ratio. This means that, for all practical purposes, the voltage across the secondary coil will be three times as high as the voltage across the primary since there are three times as many turns in the secondary. However, the current flowing in the secondary is inversely proportional to the turns ratio. In other words, there are 6 amperes flowing in the primary coil, but only one-third as much (2 amperes) in the secondary.

Conversely, in the step-down transformer of 10B, there are 6 amperes of current flowing in the primary and 18 amperes in the secondary.

Of course no practical transformer is perfect. Because of this, when substantial current is drawn from the secondary, the secondary voltage decreases. This is shown in the equivalent circuit for the basic transformer in Fig. 11. Load resistor R places a current demand I_s on the secondary. In turn, a current demand I_p is placed on the primary. Because of the leakage inductances $L_p - M$ and $L_s - M$, there is an IX_L drop across each of the leakage reactances. These IX_L drops obviously subtract from the secondary voltage that would be obtained under no-load conditions.

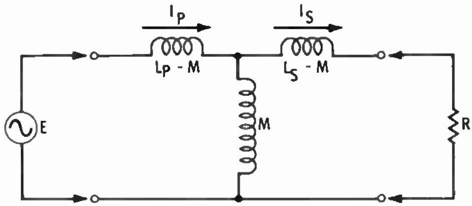


Fig. 11. Illustrating voltage decrease under load.

Leakage inductance, and its associated leakage reactance, results from primary flux lines that fail to cut the secondary turns. To minimize the amount of leakage reactance, the secondary may be wound over the primary in some transformers. In another design, the primary and secondary wires are wound side by side. Still other winding arrangements are used in high-efficiency transformers in order to minimize the leakage reactance.

Ampere Turns

When a load impedance (Z) of some form is connected across the secondary coil of a transformer as shown in Fig. 12, a current flows in the secondary winding and this in turn reacts on the pri-

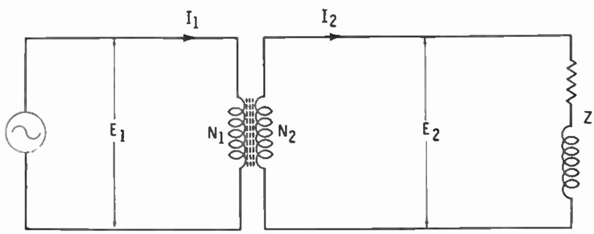


Fig. 12. Simple schematic of a typical transformer.

mary winding through the medium of the mutual induction. Therefore, the current taken by the primary winding will depend not only on the impedance of the primary winding itself, but also on the amount of current flowing in the secondary, although there is no direct electrical connection between the windings.

The extra current taken by the primary winding of a transformer is exactly proportional to the secondary current. Furthermore, these two currents have equal and opposite magnetic effects on the core. Thus, the extra primary ampere turns oppose the secondary ampere turns so that apart from the initial magnetizing current

$$I_1 \times N_1 = I_2 \times N_2 \tag{7}$$

Example: If in a certain step-up transformer, the number of turns in the primary and secondary windings are 40 and 400 respectively, what will the current ratio be?

Solution: Inserting the values in equation (7), the following is obtained:

$$\frac{40}{400} = \frac{I_2}{I_1}, \text{ or the current ratio} = \frac{1}{10}$$

Therefore, the current in the primary winding is ten times larger than the current in the secondary winding, or $I_1 = 10I_2$.

This is just the reverse compared with the relationship for the electromotive force. Therefore, a transformer which steps the voltage up will step the current down in the same ratio and vice versa.

Consequently the product of primary volts and amperes is approximately equal to the product of the secondary volts and amperes for iron-core transformers, but these conditions do not hold true for RF transformers where the coupling coefficient is considerably less than unity.

TRANSFORMER TYPES

The two types of power transformers usually found in radio receivers are:

1. Core type.
2. Shell type.

The core types may have either a closed or open magnetic circuit, and are thus referred to as the closed-core and the open-core type.

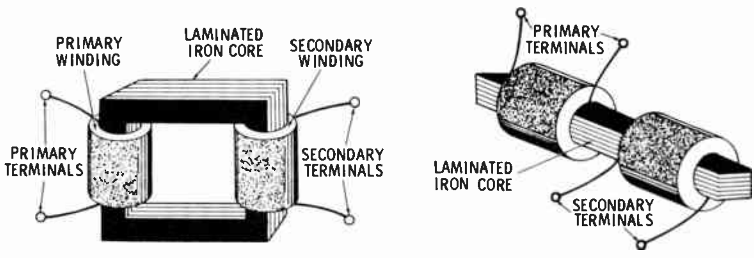
The open-core type consists primarily of two windings, wound on a straight piece of laminated iron. This type of construction is very economical, but because of very large leakage losses (the magnetic path is completed mainly through the surrounding air) it is used very sparingly in the radio field.

In the closed-core type, the windings are generally placed opposite each other as shown in Fig. 13A. The sides supporting the windings are referred to as the "core legs."

The coils generally consist of closely wound insulated copper wire of sufficient diameter so as not to cause excessive heating, i.e., the wire should be of sufficient size to carry the load of the transformer without overheating.

In transformers of higher voltage, each layer of the winding is usually separated from the next by a thin insulating paper to prevent the effective voltage between layers from short circuiting.

The best possible economy is secured when the winding encloses a maximum of core area with a minimum of wire and when the magnetic path is the shortest possible. A method widely adopted in small transformer design involves the use of a single winding form with all secondaries and the primary being placed on one leg of the core.

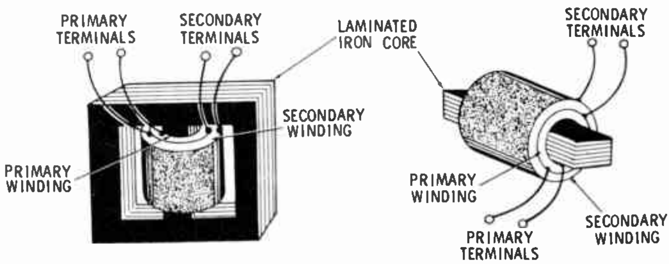


(A) Closed-core. (B) Open-core.

Fig. 13. Two core-type transformers.

The shell-type transformer in Fig. 14A has a completely closed core with a center and two outside legs forming two outside parallel paths for the magnetic lines of force.

Because of the above-mentioned feature, this type of transformer has very low magnetic leakage, and is most commonly used for power and audio applications in the radio field. As you can see from



(A) Shell-core type. (B) Open-core type.

Fig. 14. Two types of transformers having the primary and secondary windings placed directly on top of each other.

the figure, the windings are placed directly over each other on the center leg, thereby providing an economical and compact design. The transformer in Fig. 14B has coils wound in a similar manner except on an open core.

TRANSFORMER LOSSES

Not all of the energy drawn from the power line by a transformer serves a useful purpose. There are various losses incurred in the transformation process, some of which are known as *hysteresis loss, eddy-current loss, copper loss, magnetic-leakage loss,* etc.

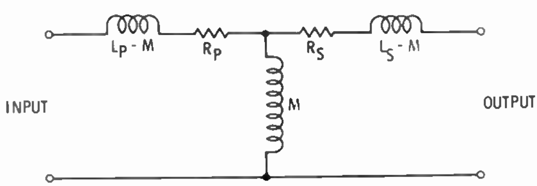


Fig. 15. A more complete equivalent circuit of a basic transformer.

We have seen that leakage inductance can be considered as an inductance in series with either the primary or secondary lead. Other losses, such as hysteresis, eddy-current, and copper losses can be considered as a resistance in series with the primary or secondary lead. Therefore, a more precise equivalent circuit can be drawn for the basic transformer, as shown in Fig. 15. Note that there is an IR drop across R_p and R_s when a current demand is placed on the secondary. In other words, the resistive loss causes a reduction in output voltage in addition to the reduction caused by the IX_L drop across the leakage reactance.

Hysteresis Loss

Theoretically, hysteresis loss is energy spent in overcoming the friction between the molecules of iron as they move backward and forward with the change of direction of flux. Some believe that it

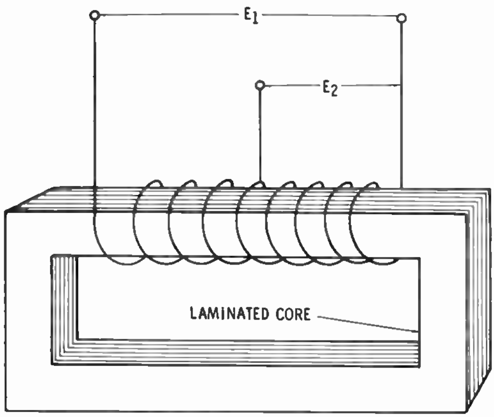


Fig. 16. Typical autotransformer arrangement. E_1 is the primary voltage and E_2 is the secondary voltage for a step-down voltage ratio.

is the natural resistance of the metal to the flow of flux and that the molecules of iron do not move backward or forward.

Eddy-Current Loss

This type of loss is the energy spent in the heating action of the induced currents in the iron core by the varying flux. Voltages are induced in the core by the alternating flux and these voltages produce eddy currents that represent energy subtracted from the input energy.

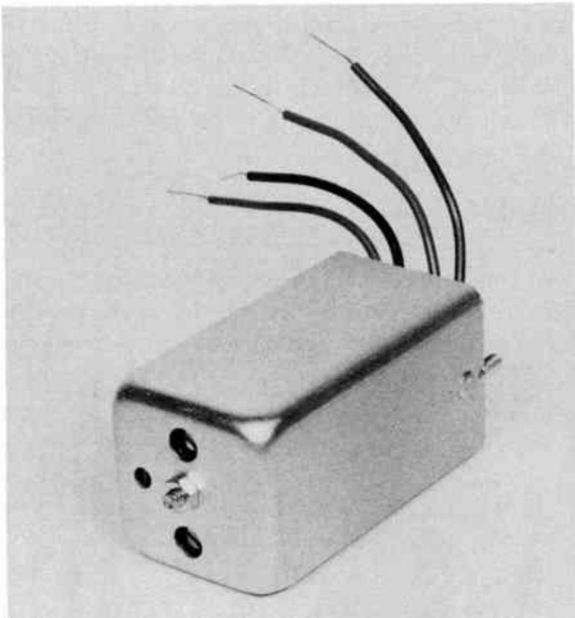


Fig. 17. Transformer designed for use at intermediate radio frequencies.

Copper Loss

This varies directly with the square of the current due to the load of the transformer. The total copper loss in the transformer is $(I_1^2 \times R_1)$ of the primary plus $(I_2^2 \times R_2)$ of the secondary.

Magnetic-Leakage Loss

When the magnetic lines of force flow through the core, some of them do not interlink both coils, thus causing an inductive resistance or counter electromotive force in the primary coil, which is not transmitted to the secondary coil. This then causes a loss of voltage analogous to the resistance loss in the primary winding.

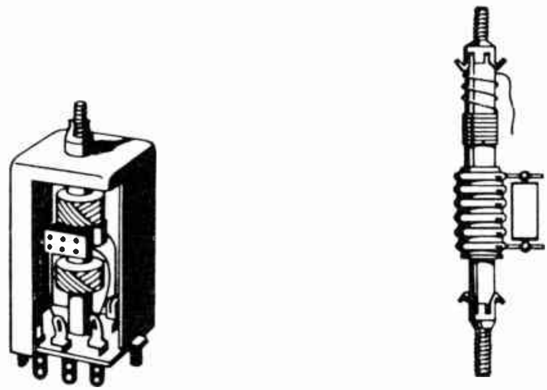
TRANSFORMER EFFICIENCY

Because of the relatively small power involved in radio transformers, there is no urgent need for high efficiency. Generally a transformer that is 80% efficient is satisfactory.

The efficiency of a transformer may be written in the form of an equation as follows:

$$\text{Efficiency} = \frac{\text{output of secondary}}{\text{output of secondary} + \text{transformer losses}}$$

When the core loss is small, the transformer has a high efficiency on light loads. When the core loss is equal to the copper loss, the transformer has a high efficiency on full load or overload.



Courtesy Stancor Electronics, Inc.

(A) Shielded type. (B) Unshielded type.

Fig. 18. Two types of permeability-tuned transformers.

The efficiency of a transformer may also be written:

$$\text{Efficiency} = \frac{\text{output in watts of secondary}}{\text{input in watts of primary}}$$

AUTOTRANSFORMERS

The autotransformer is sometimes used in audio-frequency amplifier couplings, and in connection with battery chargers, bell-ringing transformers, etc.

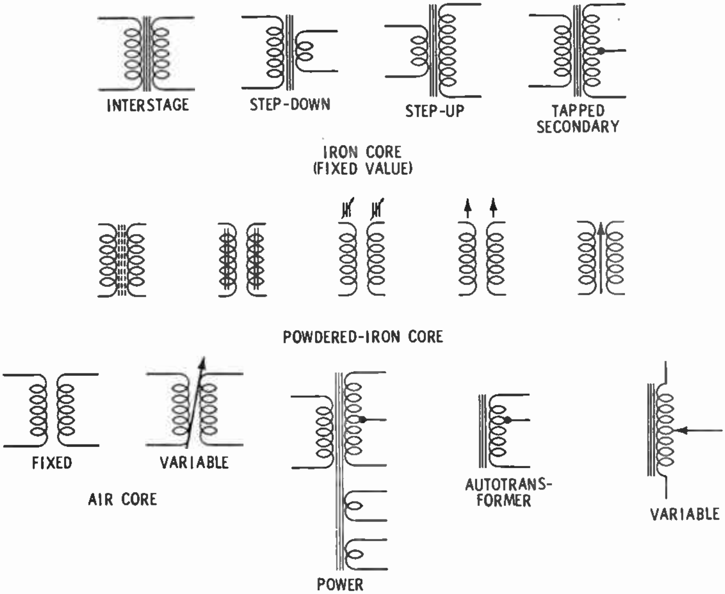


Fig. 19. Schematic symbols for transformers.

Principally the autotransformer consists of one coil tapped at one or more points (Fig. 16), dividing it into parts. Any given part can be used as the primary or secondary. The ratio depends upon the number of turns in each part and can be a step-up or step-down ratio.

Because of its simplicity, this form of transformer is economical to build, but is hazardous on high voltage and should be used only for small ratios of transformation. The transformation at low ratios is accomplished partly by transformer action; however, at higher transformation ratios, more and more of the power is transferred by regular transformer action and less by direct conduction.

RADIO-FREQUENCY TRANSFORMERS

In addition to the fixed-inductance, iron-core transformers discussed so far, there are air-core types and those which employ adjustable iron cores. Fig. 17 shows an example of a transformer designed for use at the intermediate radio frequencies. This type of transformer is generally used in conjunction with trimmer capacitors across the primary and secondary windings to form a tuned transformer that will couple signals of a predetermined frequency to another stage while discriminating against all other signals.

Fig. 18 shows two examples of transformers which use adjustable powdered-iron cores to vary their inductive characteristics. The transformer shown in Fig. 18A is enclosed in a can which acts as a shield; the transformer in Fig. 18B is unshielded. Transformers of this type are referred to as permeability-tuned transformers and may or may not be employed in resonant, or tuned, circuits. Some of the schematic symbols representing the various types of transformers are shown in Fig. 19.

SUMMARY

A transformer consists of two or more coils which couple energy from one circuit to another by means of electromagnetic induction. Two types of induction are present in any transformer—mutual induction and self-induction. Mutual induction is the property of two circuits, situated in such a manner with respect to each other that a current in one circuit sets up a magnetic field which is linked with the other circuit. Self-induction is the property of a single circuit whereby a current flowing sets up a magnetic field which links with the circuit, inducing an emf.

When the magnetic field of one circuit is linked to another circuit, the two are said to be coupled. The amount of coupling between circuits depends on their proximity, their relative positions, and the medium through which the magnetic flux must travel.

A transformer does not generate power; it merely transfers it from one circuit to another, usually with a change in voltage. A step-up transformer is one in which the output voltage from the secondary is higher than the input voltage to the primary. Transformers for use in low-frequency circuits normally have a laminated iron core to provide maximum coupling between the primary and secondary. Transformers for use in the radio-frequency range often have a core of a nonmagnetic material in order to minimize losses and thus improve efficiency. Powdered-iron cores are also used in some high-frequency circuits to provide maximum coupling with improved efficiency.

Losses in transformers are from several sources. The major sources of loss are hysteresis, eddy currents, I^2R, and magnetic leakage. Careful design and quality materials can reduce these losses to a minimum.

An autotransformer consists essentially of only one winding, tapped at one or more points to give either a step-up or step-down ratio. This type of transformer is economical to build, but should only be used for small ratios of transformation.

REVIEW QUESTIONS

1. What is the primary purpose of a transformer?
2. What is mutual induction?
3. What is self-induction?
4. Define coupling.
5. What type of core is usually used in a transformer for low-frequency application?
6. Why is an air-core often used in transformers for RF application?
7. What are eddy currents and how can they be reduced?
8. What is copper loss?
9. Draw the schematic symbol of an iron-core transformer that has two secondary windings.
10. How does an autotransformer differ from a conventional transformer?

Chapter 10

Vacuum Tubes

A vacuum tube in its simplest form is usually a glass or metal envelope containing a number of elements designed to perform specific functions in connection with the transmission and reception of radio signals. There are many types of vacuum tubes, and they vary not only physically but also in electrical characteristics. Fig. 1 illustrates some of the different types of vacuum tubes. One of the more recent designs is an extremely compact version known as a *nuvistor*. The internal construction of one such device is shown in Fig. 2.

The general purpose of a vacuum tube is to detect and amplify radio waves, to change alternating current into direct current, to produce oscillations or rapid electrical pulsations, to change an electric current of one degree of pulsation to that of another, and for innumerable other purposes.

The materials used for housing the elements of a vacuum tube may be glass, metal, ceramic, or sometimes a combination of these materials.

VACUUM-TUBE OPERATING PRINCIPLES

In any electronic tube, minute electrical charges called electrons jump from a metallic surface (usually heated), in a vacuum, to an-

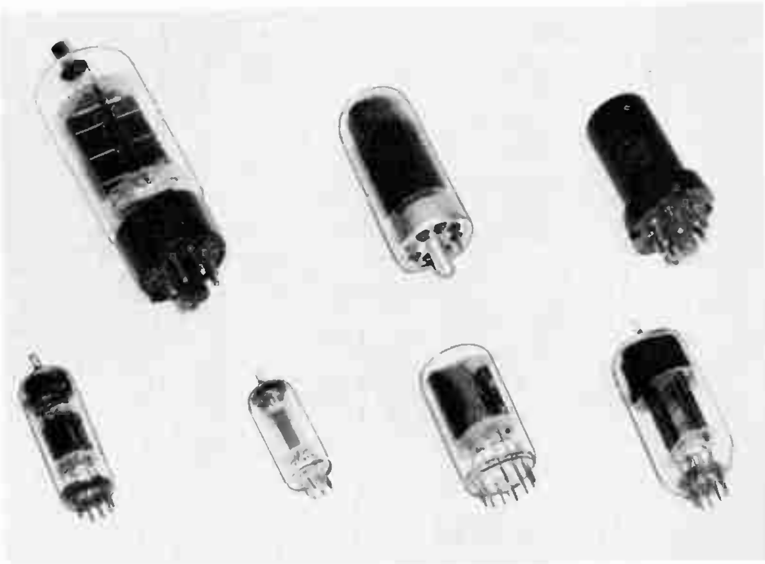


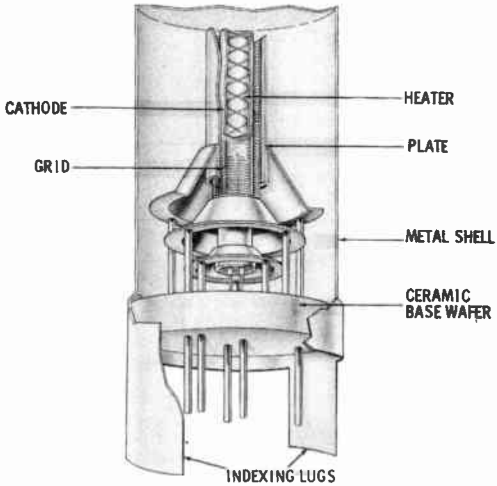
Fig. 1. Various types of vacuum tubes.

other metallic surface and cause current to flow between the two when connected together as shown in Fig. 3. This current flow is always in one direction only—never in the reverse.

To produce such a flow of electrons, which constitutes an electric current, the following fundamental requirements must be obtained:

1. There must be a continuous source of supply voltage for the *cathode* which produces the current flow.
2. The cathode must be maintained at the high temperature necessary for the dissipation of electrons from it.
3. To produce this continuous flow of electrons, a force must be supplied to transfer them through the vacuum.

Now, since the electrons consist of infinitely small negative charges of electricity, it is evident that they will be attracted to a body that is positively charged and repelled by a body that is negatively charged.



Courtesy Radio Corporation of America.

Fig. 2. Internal construction of a typical nuvistor vacuum tube.

Hence, if a second element (anode) is added within the vacuum enclosure and is maintained at a positive potential with respect to the cathode, it will attract the negatively charged electrons.

In its simplest form, therefore, a vacuum tube consists of two electrodes—a cathode and an anode (sometimes referred to as filament and plate—the former emitting or discharging the electrons and the latter acting as a collector of electrons. A vacuum tube hav-

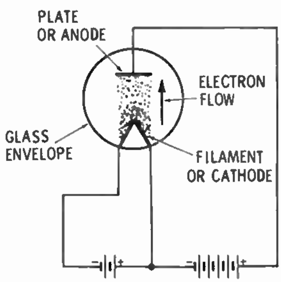


Fig. 3. The flow of electrons in a vacuum tube.

ing only these two elements is called a *diode* or two-electrode vacuum tube.

Electron Emission

The phenomenon whereby electrons can be driven out of a conductor by heating it, as in the case of a radio vacuum tube, is called *thermionic electron emisison*, or simply *electron emission*.

Electron emission, also known as the Edison effect, was discovered by the famous inventor in his early experiments with the incandescent lamp sometime prior to 1890. Edison observed that when a metal plate was sealed inside a lamp bulb so that it was between the two sides of the carbon filament, but electrically insulated from the filament, an electric current would flow through a galvanometer connected between the outside terminal of the metal plate and the positive terminal of the filament. When the galvanometer was connected between the negative terminal of the filament and the outside terminal of the plate the current flow stopped.

Although the phenomenon was known at this early date, its availability could not be utilized, due to the absence of the vacuum tube. It was only after the discovery of the vacuum tube by Professor J. A. Fleming and Dr. Lee de Forest that this great invention could be made serviceable.

The emission of electrons from a conductor may be accelerated by increasing the temperature of the conductor. Once free, most of the emitted electrons make their way to the plate, but others return to the cathode, repelled by the cloud of negative electrons immediately surrounding the cathode. This cloud of electrons surrounding the emitting cathode is known as the *space charge*.

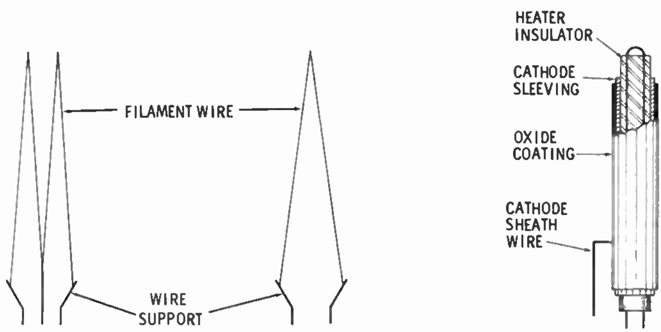
In tubes in which the electron velocity is high, some of the electrons that reach the plate may strike it with sufficient force to dislodge electrons already on the plate. The dislodging of electrons from the plate by other fast-moving electrons is called *secondary emission*.

A vacuum tube consists of a cathode, which supplies electrons, and one or more additional electrodes, whose function it is to control and collect these electrons, all mounted in an evacuated envelope. This envelope may consist of a glass bulb or it may be the more compact and efficient metal shell. In recent years, ceramic envelopes have even been employed.

The outstanding properties of the vacuum tube lie in its ability to control almost instantly the motion of millions of electrons supplied by the cathode. Because of its almost instantaneous action, the vacuum tube can operate very efficiently and accurately at electrical frequencies far above those obtainable by mechanical means.

Function of the Cathode

When a metal becomes hot enough to glow, the agitation of the electrons becomes sufficiently great to enable a certain number of them to break away from the metal. It is this action that is utilized in the radio tube to produce the necessary electron supply. A cathode is that part of a vacuum tube which supplies the electrons that are essential for its operation. All heated cathodes in vacuum tubes are universally heated by electricity. The method of heating the cathode may be used to distinguish between the different forms.



(A) Directly heated. (B) Directly heated. (C) Indirectly heated.

Fig. 4. Various types of cathodes.

The simplest form of a cathode is a wire or ribbon (Figs. 4A and B) heated directly by the passage of current through it. Radio tubes having such filaments for cathodes are sometimes referred to as filamentary tubes to distinguish them from tubes having indirectly heated cathodes.

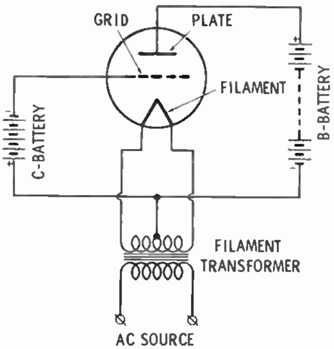


Fig. 5. Diagram of connections to a triode using a filament transformer.

A common arrangement of an indirectly heated cathode is shown in Fig. 4C. Here the cathode consists of a cylindrical metallic sleeve, usually of nickel, coated with a mixture of barium and strontium oxides. This oxide coating is used because of its ability to greatly increase the electron emission at normally used temperatures.

A lead wire from the cathode sheath is carried out to an external terminal on the tube in order that the cathode may be maintained at any desired potential.

The heater wire usually consists of tungsten or a similar metal and may be in the form of a spiral or, as in Fig. 4C, in the form of a hairpin threaded through holes in a ceramic insulator. Tubes having cathodes of this type are referred to as heater-type tubes.

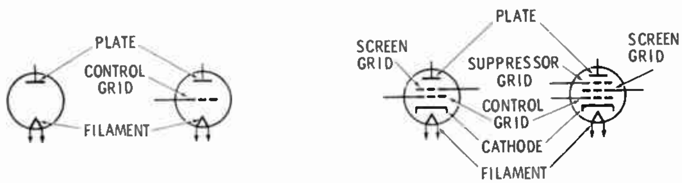
The heater may be operated from either direct or alternating current. The one disadvantage of using alternating current for the filaments of tubes used in audio-frequency circuits is that it may introduce objectionable hum in the output. This hum can usually be reduced somewhat by connecting the plate and the grid circuits to the midpoint of the secondary of the transformer (Fig. 5). Generally, however, it is not recommended to use AC in the filament of tubes used in the early stages of high-gain amplifiers.

CLASSIFICATION OF TUBES

Tubes are usually classified according to the number of electrodes present. For example, a two-element tube is called a *diode*, a three-element tube is a *triode*, and so on to *tetrodes* and *pentodes*. A pentode therefore is a tube having five elements (see Fig. 6). Tubes may also be classified according to whether there is high vacuum, gas, or an element that vaporizes within the envelope of the tube.

Diodes

From the foregoing it is evident that electrons are of no value in a tube unless they can be controlled or made to work according to



(A) Diode. (B) Triode. (C) Tetrode. (D) Pentode.

Fig. 6. Vacuum tube schematic representation.

a predetermined schedule. The very simplest form of tube consists of two electrodes—a cathode and a plate—and is most often referred to as a diode, which is the family name for two-electrode tubes.

In common with all tubes, the electrodes are enclosed in an evacuated envelope with the necessary connections projecting through airtight seals. The air is removed from the envelope to allow free movement of the electrons, to prevent injury to the emitting surface of the cathode, and to prevent rapid burnout of the tube filament. If the cathode is heated, electrons leave the cathode surface and form a cloud in the space around it. Any positive electric potential within the evacuated envelope will offer a strong attraction to the electrons.

In a diode, the positive potential is applied to the second electrode, known as the anode, or plate. The potential is supplied by a suitable electrical source connected between the plate terminal and the cathode terminal, as seen in Fig. 7. Under the influence of the positive plate potential, electrons flow from the cathode to the plate

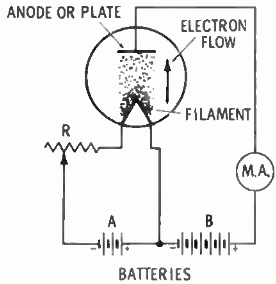


Fig. 7. Diode connections.

and return through the external plate-supply circuit to the cathode, thus completing the circuit. This flow of electrons is known as the plate current and may be measured by a sensitive current indicator such as a galvanometer.

The Diode as a Rectifier—It is obvious that under no conditions can the current flow from the plate to the cathode. As far as the current is concerned the tube is a one-way path. That is, current will flow only from cathode to anode. Increasing the positive potential on the plate will increase the flow of electrons from the cathode to the plate and consequently increase the current flow in the plate circuit, but if the plate is made negative instead of positive it will repel the electrons and no current will flow. Therefore, the di-

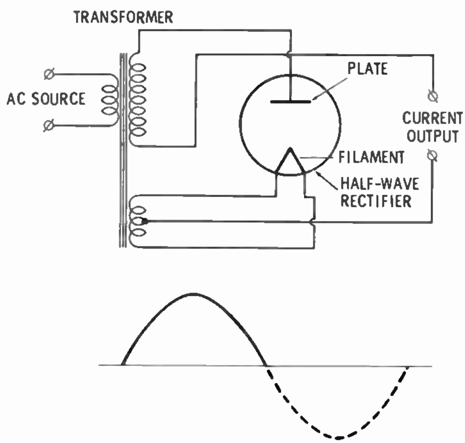


Fig. 8. A half-wave rectifier circuit.

ode acts as an electrical valve that will permit current to flow in one direction but not in the other. It is this characteristic of the diode that has been utilized as a means of converting or rectifying alternating current into direct current.

The diode is commonly used as a signal rectifier or detector in a radio receiver and as a power rectifier to convert alternating current into direct current. Diode rectifiers may have one plate and one cathode or one or more cathodes and two plates. When only one plate is employed, the tube is referred to as a half-wave rectifier (see Fig. 8). In this circuit, current can flow only during one-half of the alternating-current cycle and that half is the one that makes the plate positive with respect to the cathode.

Full-Wave Rectifier—If two plates and one or more cathodes are used in the same tube, current may be obtained during both

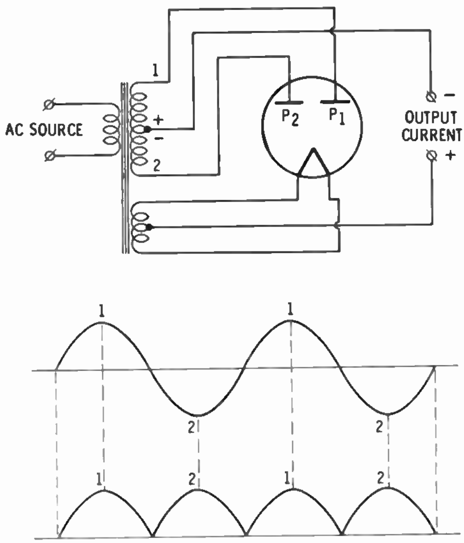


Fig. 9. A full-wave rectifier circuit.

halves of the alternating-current cycle as shown in Fig. 9. The tube is then called a full-wave rectifier. In this circuit, the voltage at the center tap of the high-voltage secondary winding is zero with respect to terminals 1 and 2. During the period when terminal 1 is positive, terminal 2 will be negative.

Plate P_1 will draw current while plate P_2 is idle and vice versa. In this manner both the positive and the negative halves of the alternating-current cycle are utilized, and the resulting output current consists of a series of unidirectional pulses with no spacing between them as shown in the lower part of Fig. 9. These unidirectional pulses may be further smoothed out by insertion of filters consisting of inductive and capacitive reactances connected to the output terminals of the rectifying system.

Space-Charge Effect—Not all of the electrons emitted by the cathode reach the plate. Some return to the cathode while others remain for a brief period in the space between the cathode and plate thereby forming a space charge. This charge has a repelling action on other electrons which leave the cathode and impedes their passage to the plate. The extent of this action and the amount of space charge depend on the cathode temperature and the plate potential.

Plate-Voltage Versus Plate-Current Relationship of a Diode—The higher the plate potential, the less is the tendency for electrons to remain in the space-charge region and repel others. This effect may be noted by applying increasingly higher plate voltages to a tube operating at a fixed heater or filament voltage. Under

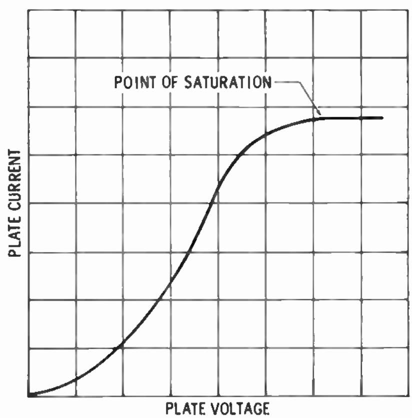


Fig. 10. Characteristic curve of a diode.

these conditions, the absolute maximum number of available electrons is fixed; but below this limit, increasingly higher plate voltages will, as previously stated, succeed in attracting a greater proportion of the free electrons.

Beyond a certain plate voltage, however, additional plate voltage has little effect in increasing the plate current. The reason is that all of the electrons emitted by the cathode are already being attracted to the plate. This maximum current is called *saturation current,* and because it is an indication of the total number of electrons emitted, it is also known as the emission current (see Fig. 10).

Tubes are sometimes tested by measurement of their emission current. In this test, however, it is generally not feasible to measure the full value of emission because this value would be sufficiently large to cause a change in the tube's characteristics or to damage the tube. For this reason, the test value of current in an emission test is less than the full emission current. However, this test value is larger than the maximum value which will be required from the cathode during normal tube operation. The emission test, therefore, indicates whether the cathode of the tube can supply a sufficiently large number of electrons for satisfactory operation of the tube.

Triodes

The triode or three-electrode tube is principally a two-electrode tube in which a third electrode, called the *grid,* is placed between the plate and the cathode (Fig. 11).

The grid usually consists of a fine wire mesh extending the full length of the cathode. The spaces between the turns of the wire constituting the grid are comparatively large so as not to impair the passage of electrons from the cathode to the plate.

Grid Function—The function of the grid is to control the plate current. By maintaining the grid at a negative potential, it will repel electrons and will, to some degree, neutralize the positive or attractive force exerted upon them by the positive plate. Hence, a stream of electrons will flow from the cathode to the plate, although smaller than it would be if the negative grid had not been present. Now if the grid is made less negative, it follows that its repelling effect will be reduced and more current will be permitted to flow to the plate.

Similarly, if the grid is again made more negative, its repelling force will increase and the current to the plate will correspondingly decrease (see Fig. 12). If the grid is made sufficiently negative, the plate current can be cut off completely.

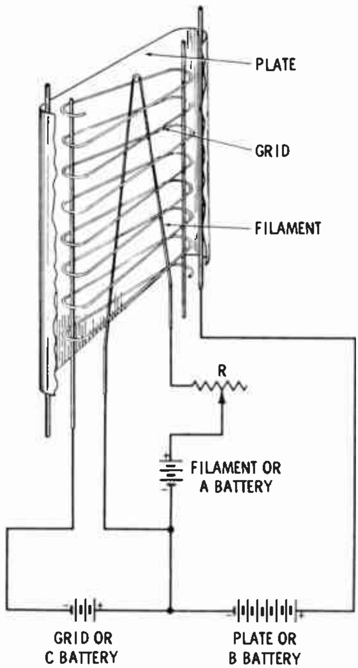
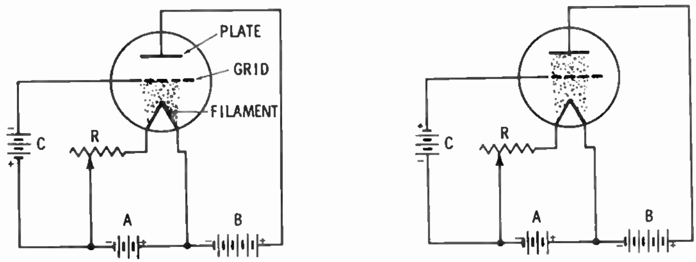


Fig. 11. Triode connected to batteries.

From the above, it follows that when the potential of the grid is varied in accordance with some desired signal, the plate current will vary in a corresponding manner. Because the grid is assumed at all times to be at a negative potential with respect to the cathode, it cannot collect electrons and so a very small amount of energy will be sufficient to vary its potential exactly in accordance with the input signal.

Capacitance Effect—In a triode, the grid, plate, and cathode form what is called an electrostatic system—that is, each electrode



(A) Grid negative.

(B) Grid positive.

Fig. 12. Effect of grid polarity on plate current.

acts as the plate of a small capacitor. The capacitive values exist between the grid and plate, plate and cathode, and grid and cathode (see Fig. 13).

These capacitances are usually referred to as "interelectrode capacitances." It might also be pointed out that the capacitance between the grid and plate is of the utmost importance, because in high-gain, radio-frequency amplifier circuits, this capacitance may act to produce undesired coupling between the input circuit (the circuit between the grid and cathode) and the output circuit (the circuit between the plate and the cathode). The effect of this coupling can cause instability and oscillation.

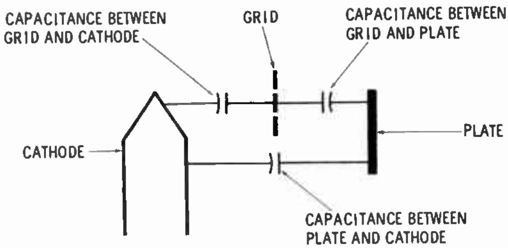


Fig. 13. Interelectriode capacities in a triode.

Tetrodes

The undesirable capacitance between the grid and the plate in the triode can be decreased by inserting an additional electrode, known as a *screen grid*, between the grid and the plate, as shown in Fig. 14. With the addition of this fourth electrode, the tube is accordingly referred to as a *tetrode*.

The Screen Function—The position of the screen between the grid and the plate gives it the function of an electrostatic shield between them, thus reducing the capacitance between the two.

The effectiveness of this shielding action is further increased by inserting a bypass capacitor between the screen and the cathode. Therefore, by means of this screen and bypass capacitor, the grid-to-plate capacitance is very small.

The screen has another desirable effect in that it makes plate current almost independent of plate voltage over a certain range. The screen is operated at a positive voltage (although somewhat less than the plate) and, therefore, attracts electrons from the cathode.

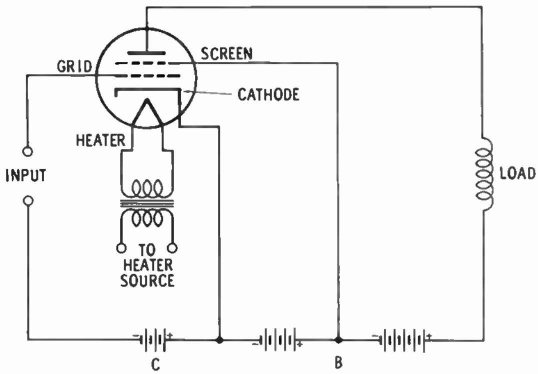


Fig. 14. Connection of electrodes in a tetrode.

However, because of the comparatively large spaces between wires of the screen, most of the electrons drawn to the screen pass through it and go on to the plate. Hence, the screen supplies an electrostatic force that aids in pulling electrons from the cathode to the plate.

At the same time, the screen shields the electrons between the cathode and screen from the plate so that the plate exerts very little electrostatic force on electrons near the cathode. Therefore, the plate current in a screen-grid tube depends to a great degree on the screen voltage and very little on the plate voltage. This holds true only as long as the plate voltage is higher than the screen voltage.

The fact that plate current in a screen-grid tube is largely independent of plate voltage makes it possible to obtain much higher amplification with a tetrode than with a triode. The low grid-to-plate capacitance makes it possible to obtain this high amplification without plate-to-grid feedback and resultant instability.

Pentodes

It has previously been mentioned that when high-velocity electrons strike the plate they may dislodge other electrons. In diode and triode tubes this is generally no problem since there is no positive electrode other than the plate to attract them. These vagrant electrons, therefore, are eventually drawn back to the plate.

Emission from the plate caused by bombardment of the plate by electrons from the cathode is referred to as secondary emission since its effect is secondary to the original cathode emission.

In the case of the previously discussed screen-grid or tetrode tube, the proximity of the positive screen to the plate offers a strong attraction to these secondary electrons, and more markedly so if the plate voltage is lower than the screen voltage. This results in lowering of the plate current and limits the permissible plate-voltage swing for tetrodes.

To overcome the effects of secondary emission, a third grid, called the *suppressor grid*, is inserted between the screen and plate. This grid, usually connected directly to the cathode, repels the relatively low-velocity secondary electrons back to the plate without obstructing to any appreciable extent the regular plate-current flow. Larger undistorted outputs therefore can be secured from the pentode than from the tetrode.

Pentode-type screen-grid tubes are used as high-gain RF and AF voltage amplifiers since the pentode resembles the tetrode in having a high amplification factor. Pentode tubes also are suitable as AF power amplifiers, having greater plate efficiency than triodes and requiring less grid-voltage drive to obtain maximum output. In audio power pentodes, the function of the screen grid is chiefly that of accelerating the electron flow rather than shielding. In radio-frequency (RF) voltage amplifiers, the suppressor grid, in eliminating the secondary emission, makes it possible to operate the tube with the plate voltage as low as the screen voltage. This cannot be done with tetrodes.

Pentodes used as audio-frequency power amplifiers have inherently greater distortion (principally odd-harmonic distortion) than triodes. The output rating usually is based on a total distortion of 10%.

The Beam-Power Tube

In this tube a different method is used for suppressing secondary emission. The tube (Figs. 15 and 16) contains four electrodes, a cathode, grid, screen and plate respectively. The spacing between the electrodes is such that secondary emission from the plate is suppressed without the suppressor found in the pentode.

Because of this method of spacing the electrodes, electrons traveling to the plate slow down when the plate voltage is low, the velocity being almost zero in a certain region between the screen and the plate. In this region the electrons form a stationary cloud—a space charge. The effect of this space charge is to repel secondary electrons emitted from the plate, and thus cause them to return to the plate.

An added advantage of the beam-power tube is the low current drawn by the screen. The screen and the grid consist of wires wound in a spiral in such a way that each wire of the screen is shaded from the cathode by a grid wire. Because of this alignment

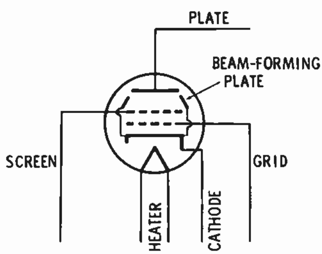
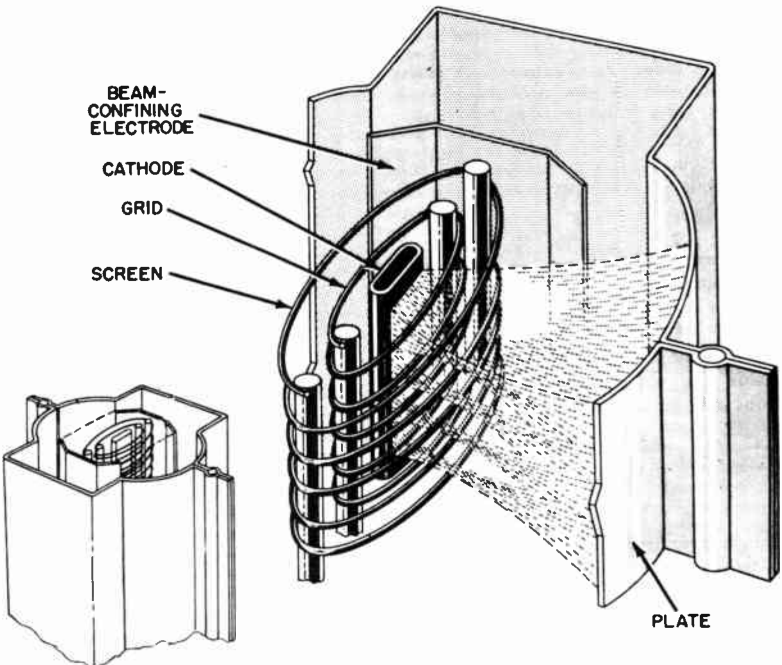


Fig. 15. Schematic representation of a beam-power tube.

of the screen and the grid, the electrons travel in sheets between the wires of the screen so that very few of them flow to the screen. Because of the effective suppressor action provided by the space charge and because of the low current drawn by the screen, the beam-power tube has the advantage of high power output, high sensitivity and efficiency.

Multipurpose Tubes

During the early stages of tube development and application, tubes were essentially of the so-called general-purpose type; that is, a triode was used as a radio-frequency amplifier, an intermediate-frequency amplifier, an audio-frequency amplifier, an oscillator or a detector. It is obvious that with such a diversity of applications, one type did not meet all requirements to the best advantage.

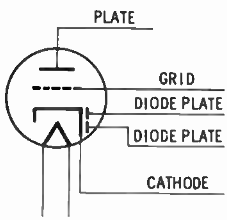


Courtesy Radio Corporation of America.

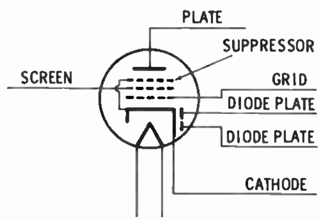
Fig. 16. Internal structure of a beam-power tube.

At present a myriad of tube types have been designed for almost every conceivable electronic application. Among the simplest and most important in radio receiver circuits are the full-wave rectifier, containing two separate diodes of the power type in one envelope, and the twin triode, consisting of two triodes in one envelope. There are many more with complex combinations of three and even four equivalent tubes within a single envelope (pentode and two diodes, triple diode, etc.).

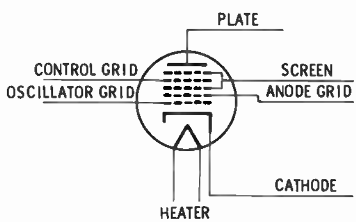
To add the functions of diode detection and automatic volume control to that of amplification, a number of types are made in which two small diode plates are placed near the cathode, but not in the amplifier portion of the structure. These types are known as duplex-diode triodes or duplex-diode pentodes, depending upon the type of amplifier section incorporated.



(A) Duo-diode triode.



(B) Duo-diode pentode.



(C) Pentagrid converter.

Fig. 17. Schematic representation of multipurpose tubes.

Another type is the pentagrid converter, a special tube designed to serve as both oscillator and first detector in superheterodyne receivers. There are five grids between the cathode and plate in the pentagrid converter; the two inner grids serve as control grid and plate of a small oscillator triode, while the fourth grid is the detector control grid. The third and fifth grids are connected together to form a screen grid which shields the detector control grid from all other tube elements. The pentagrid converter eliminates the need for special coupling between the oscillator and detector circuits.

The conventional schematic representation of these tubes is shown in Fig. 17. Another type of tube consists of a triode and pentode in one envelope, for use in cases where the oscillator and first detector are preferably separately coupled. Still another type consists of a pentode with a separate grid for connection to an external oscillator circuit. This "injection" grid provides a means for introducing the oscillator voltage into the detector circuit by electronic means.

Tetrodes and pentodes used as RF voltage amplifiers are made in two types known as sharp cutoff and variable-mu, or super-control, types. In the sharp-cutoff type, the amplification factor is practically constant regardless of grid bias up to the point of plate-current cutoff; while in the variable-mu type, the amplification factor decreases gradually as the negative bias is increased. The purpose of this design is to permit the tube to handle large signal voltages without distortion in circuits that employ grid-bias control to vary the amplification. The variable-mu type is employed to reduce interference from stations on frequencies near that of the desired station by preventing cross-modulation. Cross-modulation is modulation of the desired signal by an undesired one, and is practically the same thing as detection. The variable-mu type of tube is a poor detector in RF circuits, hence cross-modulation is reduced by its use.

SUMMARY

The general purpose of a vacuum tube is to detect and amplify radio waves, to change AC to DC, to produce oscillations or pulsations, and for many other purposes in electronic circuits.

The principle of operation of a vacuum tube depends on a continuous supply of voltage to the cathode in order for it to produce a current flow, the cathode must be maintained at a temperature high enough to release electrons from its surface, and a force supplied to transfer the electrons through the vacuum.

A cathode heated by a supply voltage furnishes electrons which are attracted to a second element called the anode. Thus, an electron flow is established. This flow is always in one direction —from the cathode to the anode (plate). This type of tube is known as a diode. A third element positioned between the cathode and anode can be used to control the electron flow. A small variation of voltage on this third element, called a grid, can cause a large variation in the electron flow. Thus, amplification can take place.

Other elements can be added to provide other functions in regard to the electron flow, making possible greater amplification, specialized control, or other desired results. Tubes with multielement construction are called tetrodes, pentodes, duo-diodes, diode-triodes, etc.

REVIEW QUESTIONS

1. Name three basic functions of a vacuum tube.
2. What is the direction of electron flow in a vacuum tube?
3. What is space charge?
4. What is secondary emission?
5. What are the main functions of a diode?
6. What is the purpose of the grid in a triode vacuum tube?
7. What is the purpose of a screen grid in a vacuum tube?
8. What is the purpose of a suppressor grid in a vacuum tube?
9. Give an example of a multipurpose vacuum tube.
10. What method is used to vary the amplification in certain types of vacuum tubes?

CHAPTER 11

Semiconductor Diodes

A semiconductor diode is a solid-state device that is used to control the flow of electrical current. However, unlike the components discussed so far, the semiconductor possesses somewhat different characteristics. Its closest relative is the vacuum-tube diode. Semiconductor diodes can be employed in almost any application in which a vacuum-tube diode is used and, in fact, in some instances where a tube cannot be used.

ADVANTAGES OF SOLID-STATE COMPONENTS

Solid-state semiconductors have several distinct advantages over vacuum tubes. First of all they do not require a filament for operation; therefore, they consume less operating power, and subsequently less heat is generated. Heat can be damaging to other components, so it is desirable that it be kept to a minimum. Solid-state components are also much smaller as a general rule and operate more efficiently than vacuum tubes. Because of these advantages, the use of semiconductor components in electronic equipment has been on the upswing in recent years.

PHYSICAL AND ELECTRICAL CHARACTERISTICS

All semiconductor diodes are constructed of a material such as selenium, silicon, or germanium which, when properly treated, has the ability to permit electron flow in one direction but essentially none in the other. Thus, a semiconductor acts as a conductor to electrons flowing in one direction, but as an insulator to electron flow in the opposite direction. From this it becomes apparent that a semiconductor diode performs the same function as a diode vacuum tube, the only difference being that the semiconductor device is composed of solid materials rather than individual elements enclosed in a vacuum. Some semiconductors are composed of a single material, whereas others use two different materials to form a junction. These materials, which have been specially treated (usually impurities are added), are known as P- and N-type semiconductors.

There are two basic classes of semiconductor diodes. One is referred to as a signal diode and is used in circuits where the power requirements are low; these devices are not designed to withstand heavy current. Some of the more common uses of signal diodes are in detectors, discriminators, AFC (automatic frequency control) circuits, etc. The second class of semiconductors is a more rugged version designed to handle higher currents and is referred to as a power diode. These are used primarily as rectifiers in power-supply circuits.

Both classes of semiconductors operate on the same principle; however, it is the type of semiconductive material and the physical construction that affect the electrical characteristics of the device. Signal diodes (often referred to as crystal diodes) generally employ a material such as germanium, whereas the higher-current devices generally employ silicon as the semiconductor. Fig. 1 shows several types of crystal diodes.

The simplest and oldest form of semiconductor is the metallic rectifier. A metallic rectifier presents a high resistance to the flow of current through it in one direction and a comparatively low resistance to the flow of current through it in the opposite direction. Thus, if an alternating voltage is applied to the terminals of a single

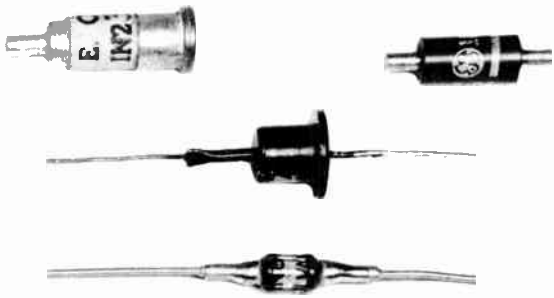


Fig. 1. Typical examples of crystal diodes.

rectifier, current will flow easily in one direction, but practically not at all in the other direction. The current flow is actually a pulsating DC current since it flows for a half cycle only, during each cycle of the applied AC voltage (Fig. 2).

The unidirectional conductivity possessed by the junction of various combinations of different solids is the basis of metallic

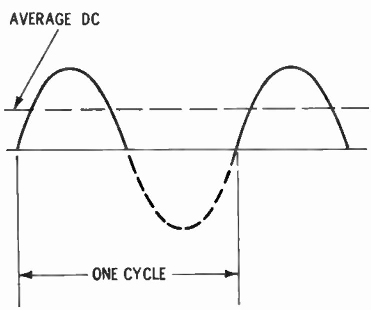


Fig. 2. The result of passing alternating current through a metallic rectifier.

rectifiers. Selenium and silicon are generally used as the semiconductor, although other materials such as copper oxide and magnesium may be used instead.

In the selenium type of rectifier (Fig. 3) the basic materials are selenium, aluminum, and a low-melting-point alloy. In the manufacturing process, aluminum base plates are prepared by chemical etching and are electroplated with a thin layer of nickel. The undercut etch serves as a mechanical means of bonding the selenium layer to the base plate during the subsequent pressing operation.

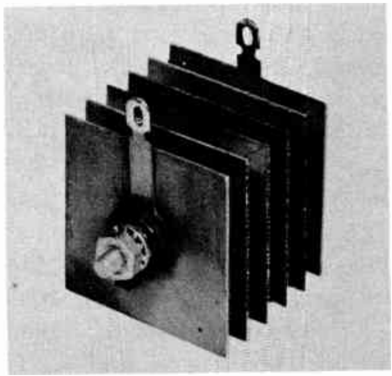


Fig. 3. A selenium rectifier.

The nickel plating governs crystal growth and orientation in the selenium layer.

High-purity selenium is then sprinkled over the nickel-plated base plate in fine powder form and is then subjected to high temperature and pressure in hydraulic presses with electrically heated platens. After the power-press operation, the selenium rectifiers are placed in ovens for heat treatment which completes the crystallization process. Here the selenium is completely converted to a metallic form and the crystals are arranged to cause rectification.

During the heating process, the temperature is exceedingly critical, since a one-percent deviation could cause poor crystallization and consequently a poor rectifier cell. This heat treatment also forms a very thin "barrier layer" on the selenium and it is believed that current rectification is accomplished in this layer.

Selenium rectifiers are used alternately with copper-oxide rectifiers for alternating-current rectification. Typical applications include radio and television receivers, business machines, communications equipment, battery chargers, electroplating equipment, etc.

Since selenium rectifiers are thermally as well as electrically rated devices, it is important that the rectifier stack be located away from all heat sources such as resistors, tubes, transformers, ballasts or any other heat-radiating components.

In larger installations, forced-air cooling is quite often used as a means of dissipating heat. Thus, for example, a rectifier that is rated at 10 amperes with normal convection cooling can be operated at 25 amperes if sufficient cool air is passed across the cells. Also, to decrease the effects of very high ambient temperatures, forced air is often used to allow higher percentages of normal rating. In all cases, however, manufacturers' recommendations should be adhered to.

The efficiency of conversion in selenium rectifiers is relatively high, or on the order of 90% in three-phase, full-wave circuits and 70% in single-phase, full-wave circuits (to be discussed later). The nonlinear characteristics of selenium rectifiers contribute to high efficiency even at large overload factors.

By the very nature of their construction (two metals separated by a semiconductor), selenium rectifiers have a considerable amount of inherent capacity. This capacity, 0.1 to 0.15 microfarad per square inch of rectifying area, limits the frequency at which rectifiers can be used. The practical limit varies between 1,000 and 15,000 hertz, depending on cell size and electrical requirements. In general, for applications that require small values of direct current, the maximum practicle frequency is 15,000 hertz. The limit is 1,000 hertz when relatively large DC loads are involved.

Operation of selenium rectifiers at frequencies above the practical limit results in a sharp reduction of the rectification ratio and efficiency due to increased reverse current. Selenium rectifiers can be overloaded with respect to their current output under momentary or cyclic condition without serious damage. A prolonged overload, however, such as that produced by a short circuit, will damage or destroy the rectifier. Thus, it is important that proper circuit protection in the form of fuses or other devices is used, and that proper precautions are observed to locate and correct the trouble before power is applied to the rectifier.

Exceeding the voltage rating is more serious than current overloads. A potential in excess of the rectifier rating may cause a breakdown across the selenium layer, and while a selenium rectifier is "self-healing" to a certain extent, prolonged over-voltage conditions can cause rectifier failure.

The copper-oxide and magnesium type rectifiers will not be discussed here for two reasons. First of all, except for the semiconductive material employed, their construction and electrical characteristics are similar to those of the selenium rectifier.

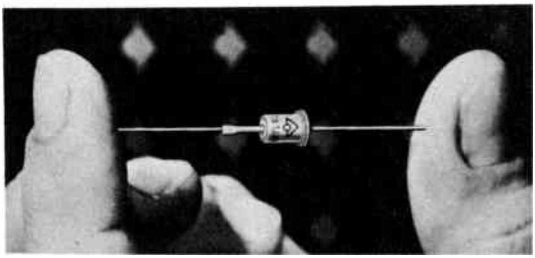


Fig. 4. A silicon diode with flexible wire leads.

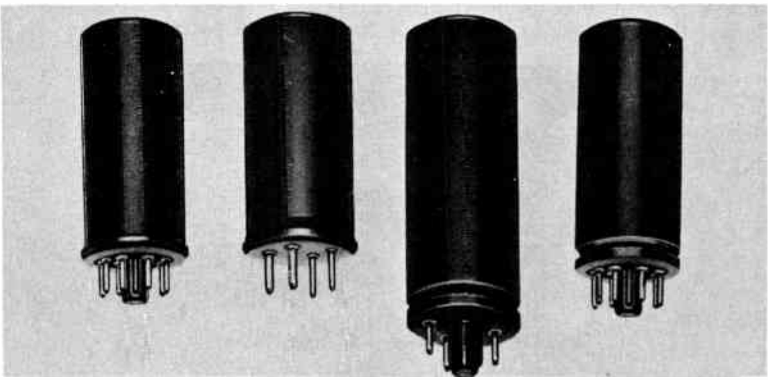
Secondly, except in special applications, the copper-oxide and magnesium type rectifiers are seldom used in modern radio equipment. In fact, selenium rectifiers which were once used quite extensively in radio receivers and in some television sets are rapidly approaching obsolescence.

Silicon rectifiers are now replacing the once popular selenium type in much of today's electronic equipment. These silicon devices have considerable power handling capacities and are much smaller physically than selenium rectifiers with equivalent electrical ratings.

Courtesy Sarkes Tarzian, Inc.

Fig. 5. Silicon rectifiers designed to fit in a clip-type holder.

Like other components discussed previously, silicon diodes appear in a variety of forms. Some, like the one in Fig. 4, have flexible wire leads and must be soldered into the circuit. Others are made in the form of a cartridge (Fig. 5) and fit into a clip-type holder somewhat like a fuse holder. There are even some silicon diodes that are constructed in a cylinderical container with pins similar to those of a vacuum tube (see Fig. 6). Units of this type



Courtesy Sarkes Tarzian, Inc.

Fig. 6. Silicon rectifiers designed to fit into tube sockets.

need only to be plugged into a tube socket which is wired to provide the proper circuit connections.

SPECIAL-ACTION DIODES

In addition to those devices which provide the normal semiconductor action, there are several others that have electrical characteristics that are quite different.

Zener Diode

This type of diode is known as the zener, avalanche, or breakdown diode. In this type of diode the current is switched through it quite rapidly whenever the applied voltage is increased. This action is refered to as avalanche breakdown and is a nondestructive breakdown caused by the cumulative multiplication of carriers which produces a regenerative effect. The transit time of electrons in the zener diode is on the order of a trillionth of a second.

Silicon Controlled Rectifier

Another type of semiconductor is the silicon controlled rectifier. This device is constructed of alternate layers of P- and N-type material as shown in Fig. 7. As you can see, it has three connecting terminals rather than the normal two. This three-junction

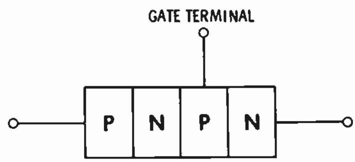


Fig. 7. Basic construction of a silicon controlled rectifier.

semiconductor acts as an open circuit to electron flow until an appropriate gate signal is applied to the third terminal. When this occurs the device is triggered into conduction and from then on operates as a conventional semiconductor diode. The action of this rectifier is similar to that of a thyratron tube.

Tunnel Diode

This semiconductor device is composed of a junction of P- and N-type material to which a large amount of impurity has been added. As the voltage across this diode is increased, the current through it first increases, then decreases, and finally increases again. The region where the current is reduced as the voltage across it rises is called the negative-resistance region. The tunnel diode can be used as an amplifier and oscillator.

POLARITY IDENTIFICATION

Polarity must be observed when semiconductor diodes are connected into a circuit. Connecting a diode backwards can damage or ruin the unit. In signal circuits where crystal diodes are generally employed, it is more likely that improper connection of the diode will cause the circuit to be inoperative rather than ruining the rectifier. However, connecting a solid-state rectifier with reversed polarity can cause a breakdown in the properties of the semiconductor material. When this occurs the material will have reduced resistance to the flow of current in the reverse direction. The ratio of forward to reverse resistance will, of course, then be dependent on the degree of damage to the semiconductor.

Fig. 8. Various methods of indicating the polarity of semiconductor devices.

Fig. 8 shows several methods of indicating the polarity of a semiconductor diode. A black stripe around one end designates that end as the cathode or negative terminal. If the arrow-bar symbol is painted on the diode, remember that the arrow points in the direction opposite that of the electron flow. In other words,

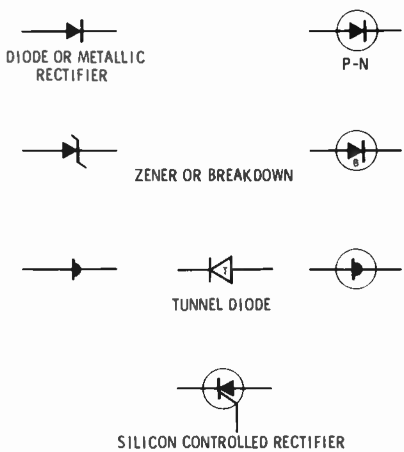


Fig. 9. Common schematic symbols for semiconductors.

the arrow points toward the negative end. Some diodes will have the abbreviation "Cath" printed on the cathode end or it may be marked with the letter K or C. Other diodes use either a plus or minus sign to indicate polarity. Fig. 9 shows some of the most common schematic symbols used to represent the various diode semiconductor devices. Notice that in each instance a bar representing the cathode is used to indicate polarity.

SUMMARY

Semiconductor diodes are solid-state devices used to control the flow of electrical current. Their purpose is no different than vacuum tubes, but the method by which they accomplish their purpose is different. Solid-state diodes have no filament so require less operating power with less heat generated, are smaller than a comparable vacuum tube, and operate more efficiently.

Semiconductor diodes are constructed of materials such as selenium, silicon, or germanium, and have the property of allowing current to flow quite freely through them in one direction, but permitting practically none to flow in the opposite direction.

The two basic classes of semiconductor diodes are signal diodes and power diodes. The power diodes are designed to handle higher currents than the signal diodes. Selenium rectifiers are of the power type of diodes, but have been largely made obsolete by silicon diodes which are more efficient and much smaller than selenium units with equivalent ratings.

Solid-state diodes having characteristics considerably different than normal semiconductor action include the zener diode, silicon controlled rectifier, and tunnel diode. Each has special characteristics that makes it valuable for certain specific applications.

Polarity of solid-state devices must be observed to prevent permanent damage to them. Thus, all semiconductor devices are marked in some way to indicate their polarity.

REVIEW QUESTIONS

1. Can a semiconductor diode usually be used for the same application as a vacuum tube?

2. Name two advantages of a semiconductor diode as compared to a vacuum tube.
3. What are the two basic classes of semiconductor diodes?
4. What is another name often given a signal diode, and list two applications for this type of device?
5. What is a metallic rectifier? Give an example.
6. Is a copper-oxide rectifier classified as a solid-state device?
7. What causes the frequency-limiting characteristic of selenium rectifiers?
8. Which is the most damaging to a selenium rectifier, exceeding the voltage rating or current rating?
9. What is the major disadvantage of a copper-oxide rectifier?
10. How many terminals does a silicon controlled rectifier have?

CHAPTER 12

Transistors

The transistor, sometimes termed the "mighty midget" because of its minute size, is primarily a three-electrode crystal device which, when properly connected in a circuit, will provide many of the services formerly delegated to the familiar vacuum tube.

ADVANTAGES OVER TUBES

The development of the transistor has made possible many new types of electronic equipment, some of which use both transistors and vacuum tubes and others that use transistors exclusively.

Transistors offer several advantages over vacuum tubes. First of all they are much smaller than tubes and, therefore, make possible more compact radio equipment. Moreover, transistors do not require filaments or heaters for thermonic emission as tubes do, hence they draw far less current and produce very little heat. This is a most desirable feature especially in regard to portable radio equipment where current drain must be kept to a minimum for maximum battery life. The battery-powered transistor pocket radio has become as common in recent years as the television receiver.

THEORY OF OPERATION

The semiconductor material in most transistors employed in radio and audio equipment is either germanium or silicon. Semiconductors, as the term implies, fall in a category between good conductors and good insulators. The semiconductor material is not used in its pure state. Controlled amounts of certain impurities are added which, by imparting certain conduction properties to the material, produce what is known as a doped semiconductor.

The doping material (impurity) may be one of two general types:

1. Donor impurity—donates electrons to the semiconductor. Donor impurities produce N-type semiconductors.
2. Acceptor impurity—accepts electrons from the semiconductor material. Acceptor impurities produce P-type semiconductors.

The primary difference between P and N material is in the method by which current flows. In N-type material, current flow is by electrons; in P-type material, current flow is by holes.

Just as vacuum tubes can be classified into low-power and high-power types, so can transistors. For example, Fig. 1 shows a low-power transistor, and Fig. 2 shows a power-type transistor. We will find that transistors are also classified into low-frequency (audio-frequency) types and high-frequency (radio-frequency) types. Various other subclasses are also of importance to the radioman, as explained subsequently.

Electrons and Holes

Electron is a familiar term associated with electronics and current flow. Current flow through wires, tubes, and other components is generally accepted to be by electrons, which are negatively charged particles. The term hole is fairly new to electrons and has a meaning opposite from the electron. Hole denotes a positive charge, or the lack of an electron—just as the term vacuum denotes the lack of air.

To describe the foregoing more fully, we must touch briefly on the atomic structure. Atoms are made up of a nucleus surrounded by rings of electrons. Each ring of a particular atom consists of a specific number of electrons. The electrons in the outer ring lie in a band termed the valence band (Fig. 3). A discrete

Courtesy Raytheon Co.

Fig. 1. A low-power transistor.

Courtesy Clevite Corp.

Fig. 2. A power-type transistor.

level of energy in this band provides the force that binds all the electrons in the valence band of one atom to the electrons in the valence bands of other atoms and makes up the crystal structure (Fig. 4).

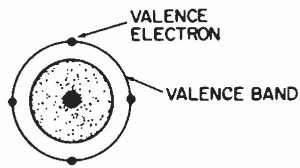


Fig. 3. Exaggerated sketch of an atom, showing the various parts.

If we could add atoms with five valence electrons to the structure shown in Fig. 4, the material would then contain free electrons that would not be held by a valence band. This addition can be performed in semiconductors by adding a donor impurity, which produces an N-type semiconductor. The electrons (negative charges) not bound in the crystal structure can now be used as current carriers. In N-type material, the electrons are called majority carriers because the majority of the current flow will be by electrons. This statement presupposes that current can flow by holes, and this supposition is correct. The holes are minority carriers in N-type semiconductors.

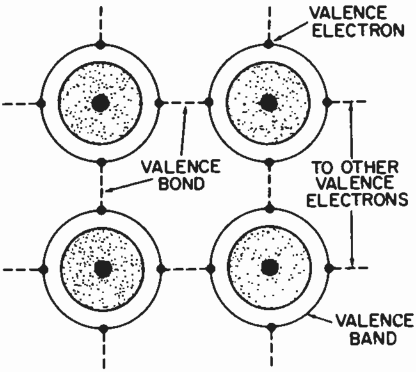


Fig. 4. Composition of the crystal structure from atoms.

Just as we can add a donor impurity that donates electrons to the semiconductor material, we can add an acceptor impurity that accepts electrons. Thus, we have produced a P-type semiconductor. In the P-type semiconductor, we have atoms that lack an electron in the valence band. This lack of an electron is termed a hole, or positive charge. The hole, being the lack of an electron in the valence band of an atom, does not move out of this band; therefore, conduction takes place in the valence band. This action can occur in solids only (such as P-type semiconductors); it does not apply to vacuum-tube theory. Because the majority of current flow in P-type semiconductors is by holes, the holes are the majority carriers and the electrons are the minority carriers.

To understand this theory, remember that (1) an electron is a negatively charged particle which will be attracted by and will move toward a positive charge, and (2) the hole has a positive charge which will be attracted by and will move toward a negative charge.

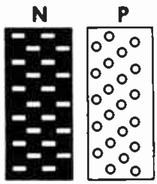
An electron leaving the valence band will leave a hole in the valence band, and an electron-hole pair will be formed. The electron and the hole will have equal charges but opposite polarities. If an electron fills a hole in the valence band, the charges will be canceled.

The main points to remember are that electrons are negatively charged particles and that holes are positive charges. Both can move and therefore can be current carriers. In N-type semiconductors, the electrons are the majority carriers; in P-type semiconductors, the holes are the majority carriers.

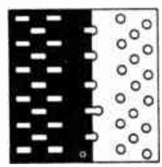
Junction of P and N Semiconductors

Transistor operation normally is based upon the action of the carriers at the junction of P and N materials. A pictorial method of describing the action of the carriers at a junction will probably be the easiest to follow. For this purpose, the blocks labeled N and P in Fig. 5A will represent the doped semiconductor materials. The N material is shown as having electrons as majority carriers, and the P material is shown as having holes as majority carriers.

In the N material or the P material, a net charge balance is maintained by the even distribution of majority carriers throughout



(A) Two types of semiconductor materials and their associated carriers.



(B) Action that takes place when a junction is produced.

(C) Battery showing polarity of charge at junction as a result of the union of N and P materials.

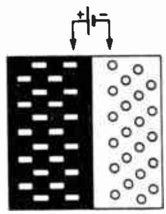


Fig. 5. Action of the carriers at a junction.

the material. It must be recognized that the majority carriers are bound into the crystal structure of the semiconductor. The material itself has no charge, and current will not flow between two types of material if they are just placed in physical contact. The term junction implies that the materials are bound together at the molecular level by a process such as fusion or melting.

When P and N semiconductors are formed together to produce a junction, the majority carriers near the function move toward each other and cancel out (Fig. 5B).

Because of this canceling action at the junction, a charge has now been created between the semiconductor materials. Since some of the majority carriers (electrons in the N-type and holes in the P-type) have been effectively canceled, the material at the junction assumes a positive charge in the N semiconductor material and a negative charge in the P semiconductor material. Remember as previously noted, the majority carriers were bound in the crystal structure and, before the junction was formed, there was an even distribution of these carriers in the semiconductor materials. Therefore, the material by itself has a zero net charge.

The electrons in the N material now are repelled by the negative charge in the P material, and the holes (positive charges) are repelled by the positive charge in the N material. These majority carriers therefore maintain positions back from the junction. The charge and its polarity at the junction are represented by the battery in Fig. 5C. This charge, or potential, is extremely small—in tenths of a volt—but does produce an effective potential hill or barrier to the passage of the current carriers. To pass from one side of the junction to the other, the electron or hole must gain energy equal to this potential hill.

The sources of external energy that can move the carriers across a junction may be radiation in the form of heat, light, or X rays; or the source may be a more usual one, like a voltage supply.

Forward and Reverse Bias

The PN junction acts as a one-way valve, or rectifier, to the flow of current. There is through the junction a forward, or low-resistance direction, and a reverse, or high-resistance direction. Current flowing in the low-resistance direction is called forward bias; current flowing in the high-resistance direction is called reverse bias.

The potential hill at the PN or NP junction, represented by the battery at the junction in Fig. 5C, must be overcome before current can flow. When a battery is connected so that it aids or increases the potential hill at the junction, the carriers are pulled farther away from the junction (Fig. 6). The minus terminal of the battery attracts the holes to the right, and the positive terminal of the battery attracts the electrons to the left. Such a reverse-biased junction can have a DC resistance reading in the megohm region.

As the applied voltage is increased, the potential hill increases, and the resistance of the junction also increases. Unlike a resistor, the reverse-biased junction increases its resistance as the voltage increases.

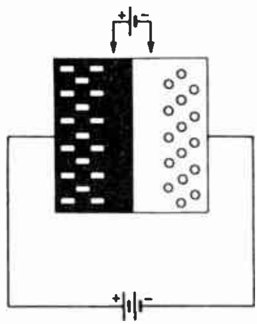


Fig. 6. Result of connecting a battery to aid, or increase, the potential hill (reversed biasing).

The resistance of a reverse-biased junction depends upon the applied voltage. The current through a reverse-biased jucntion is relatively constant. As the voltage across a resistance is changed, the current changes. With a junction diode, however, the reverse-bias voltage produces a resistance change, but the current remains nearly the same. This condition can be shown by the Ohm's law formula $I = E/R$. Thus, if E (voltage) increases across a resistor and if the resistance is constant, I (current) will increase. If E increases and if the resistance increases proportionately (as it does in the junction diode), then I will remain constant.

The forward biasing of a junction will reduce the potential hill. When a battery with opposite polarity from that of the potential hill is applied to the junction, the carriers are moved up to the

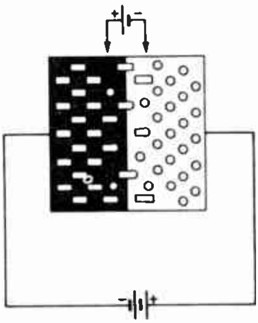


Fig. 7. Result of connecting a battery to reduce the potential hill (forward biasing).

junction (Fig. 7). Holes and electrons now flow across the junction. This action results in a current flow in the external circuit. Another way of describing this action is by saying that the battery will inject excess holes in the P material by removing electrons and will inject electrons into the N material.

The forward bias is different from the reverse bias because the voltage necessary to overcome the potential hill is rather small; but once this potential is reached, the current has little opposition. As current increases, the resistance of the junction decreases. The applied voltage remains nearly the same. (A small rise in voltage is necessary to overcome the resistance of the semiconductor material.)

THE JUNCTION TRANSISTOR

The transistor is composed of an emitter E, a base B, and a collector C. The arrangement in Fig. 8 is for an NPN transistor with an N-type emitter and collector and a P-type base. Notice

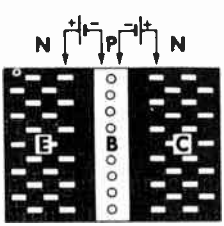
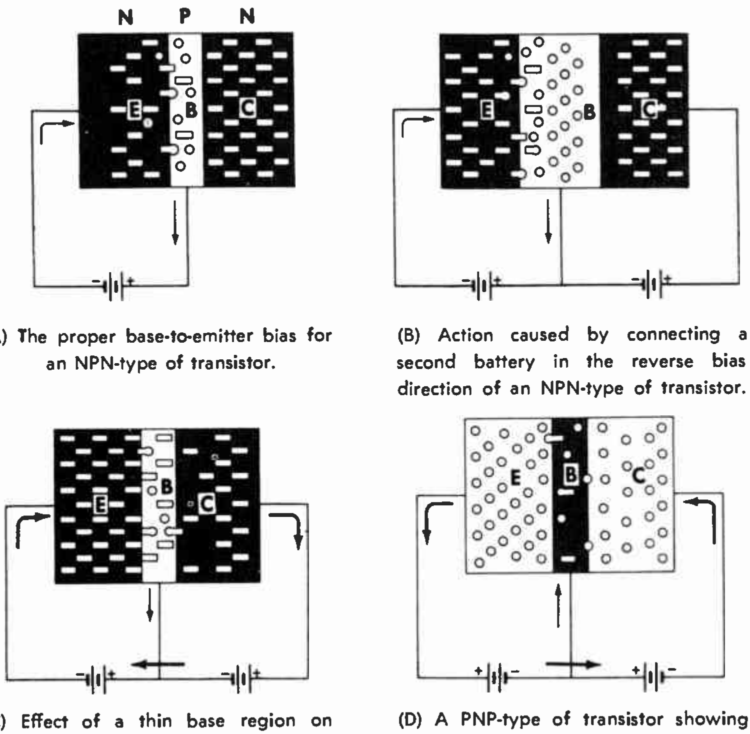


Fig. 8. Arrangement of an NPN-type of transistor.

that the base region of the transistor is drawn thin in comparison to either the emitter or the collector regions. There is a reason for this thin base region: it affects both the majority and the minority carrier action at the junctions.

The proper base-to-emitter bias for an NPN transistor is shown in Fig. 9A. When the base-to-emitter battery is connected in the forward direction, the majority carriers are forced up to the junction, and a current flow is produced between the base and the emitter. The holes move into the N material, and the electrons move into the P material. Recombination takes place at the junction, but the combining of electrons and holes can also take place after the carriers have passed this barrier. The existence of such



(A) The proper base-to-emitter bias for an NPN-type of transistor.

(B) Action caused by connecting a second battery in the reverse bias direction of an NPN-type of transistor.

(C) Effect of a thin base region on transistor action.

(D) A PNP-type of transistor showing reversed action.

Fig. 9. The effect of forward and reverse biasing of a transistor.

minority carriers (electrons in this example) in the base region is of prime importance to the operation of a transistor.

When free electrons exist in the emitter region of an NPN transistor, they are majority carriers; but when these same electrons cross the barrier into the base region, they are considered minority carriers. These electrons eventually combine with holes in the base region unless some field of force intervenes.

In Fig. 9B, a second battery is connected to the transistor. This battery is connected in the reverse-bias direction and has thus caused the carriers to move away from the base-to-collector junction. A wide base region permits all of the electrons from the emitter to recombine with holes in the base region. In this situation we actually have two diodes, one forward biased and one reverse biased; and no transistor action takes place.

In Fig. 9C, the base region has been made thin. The electrons forced into the base region by the forward bias at the emitter-to-base junction are now attracted by the positive charge of the N-type material at the junction of the collector and base. A large number of electrons now traverse the base region and reach the collector before recombination takes place. A small number of electrons and holes do recombine in the base region to produce a current in the base-to-emitter circuit.

Current Control

The forward bias or the injection of carriers into the base region controls the amount of current that will flow in the collector circuit. Increasing or decreasing the electron flow into the base region of an NPN transistor will increase or decrease the electrons available to the collector circuit. For a PNP transistor, the availability of holes to the collector is controlled by the injection of holes into the base from the emitter.

The forward bias of the emitter-to-base junction provides energy to the carriers on each side. Because of the energy added to the carriers, they can pass over the potential hill more easily. In other words, because the height of the potential hill has been effectively reduced, the carriers can pass more readily. Incidentally, the potential hill does not decrease to zero. As the potential hill gets smaller, the number of recombinations increases to maintain a barrier. If more carriers cross the junction, more minority carriers will be available in the base region or will be available to the collector.

The collector current depends upon the number of available minority carriers in the base region. Increasing the collector voltage does not increase the number of available carriers. Therefore, the collector current will remain relatively constant as the collector voltage changes.

The height of the potential hill between the emitter and the base is determined by the emitter-to-base bias. The height of the potential hill also determines the collector current. Decreasing this hill increases the available carriers, and increasing the hill decreases the available carriers. Thus, the collector current can be controlled, although amplification is not necessarily produced.

Amplification and Gain

Amplification and gain, whether they be of power, current, or voltage, are measures of the difference between the input and output. The transistor can perform as an amplifier in various circuit configurations, and in each, the basic operation of the transistor itself will remain the same.

The input circuit of a transistor is associated with the injection of carriers into the base region. The output circuit is associated with the flow of carriers from the emitter to the collector. The larger portion of the current flow is from emitter to collector, and only a small current will flow between emitter and base. Circuits like the one in Fig. 10 can be used to demonstrate this effect.

In this circuit, meter M1 will indicate the bias current or the current flow between the base and emitter. Meter M2 will indicate the collector current. When resistance R1 is changed, the current in M1 will change, but the current change in M2 will be much larger. A small change in the base current has produced a larger change in the collector current.

The voltage drop across resistor R_1 will be small, not greater than the voltage of battery B_1. The voltage across resistor R_2 will be much larger, particularly if the voltage of battery B_2 is larger. In this circuit, then, a voltage gain has been realized.

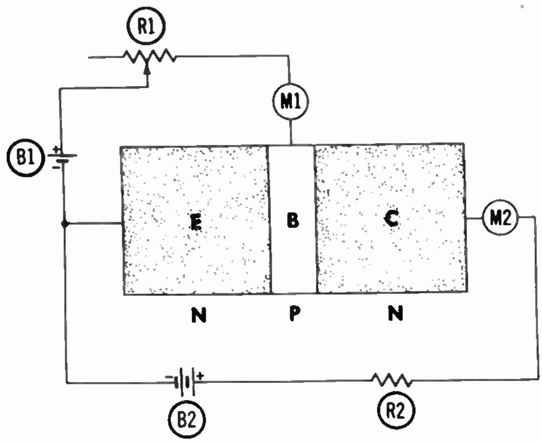


Fig. 10. Circuit illustrating basic operation of the NPN-type of transistor as an amplifier.

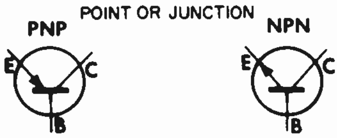
In practice, the circuitry can be arranged to produce either voltage or current gain, or both; but in either case, the basic operation of the transistor remains the same.

BASIC TRANSISTOR CIRCUITS

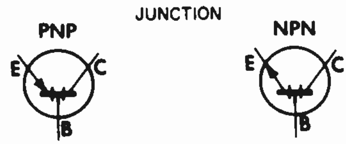
The circuit symbols for the PNP and NPN transistors are shown in Fig. 11. The symbols in Fig. 11A are generally accepted, and can be used either with or without the enclosing circle. The other symbols in Figs. 11B and 11C are less used, but will be encountered from time to time.

The arrow on the emitter lead is the only difference between the PNP and the NPN symbols, as shown by Fig. 11. The arrow also indicates the direction of hole flow and the location of the negative supply terminal.

On all symbols for solid devices, the direction indicated by the arrow is the direction of hole flow. This procedure also has been adopted for solid-state diodes and rectifiers.



(A) Most widely-used symbols.



(B) Lesser-used symbols.

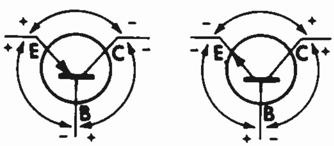
(C) Seldom-used symbols.

Fig. 11. Commonly accepted transistor symbols.

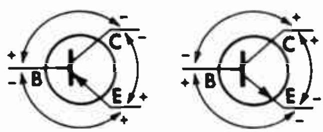
Polarity of Terminals

The polarity of voltage applied to the PNP transistor is the opposite of that applied to the NPN. In Fig. 12, the PNP and NPN symbols are shown with the relative polarity of voltage that exists between each of the terminals.

The transistor can be operated in three circuit configurations—common base, common emitter, and common collector. The configurations are also referred to as grounded base, grounded emitter, and grounded collector. The term "common" or "grounded" re-



(A) Common base.



(B) Common emitter.

(C) Common collector.

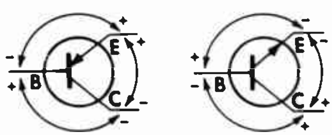


Fig. 12. The polarities of transistor voltages in the three circuit configurations.

fers to the element that is common to both the input and the output circuits. In Fig. 12A, the symbols are positioned in common-base configurations. The input is applied between the emitter and the base, and the output appears between collector and base.

In Fig. 12B, the emitter is the common terminal. The signal is applied to the base terminal, and the output is taken from the collector.

Fig. 12C shows the common-collector configuration, which is also referred to as an emitter follower. The base is the input terminal, and the emitter is the output terminal. This configuration is the least popular of the three configurations. It is used primarily to match a high impedance to a low impedance.

The polarity of voltages applied to the terminals of the NPN transistor is the same for each of the three configurations; only the points of input and output are changed. The polarity of voltages applied to the NPN transistor is the exact reverse of the polarity applied to the PNP types.

Two simple rules can be employed to remember the three transistor configurations:

1. The base must be one terminal of the input circuit.
2. The collector must be one terminal of the output circuit.

TRANSISTOR BIAS

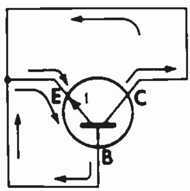
The bias of a diode junction has been described as the flow of current or the application of voltage in a forward or reverse direction (forward or reverse bias). The bias of a transistor is the voltage applied to, or the current flowing between, the emitter and base. This bias determines the operating characteristics of the transistor, and can be considered as being either current bias or voltage bias, or a combination of both. The term used depends upon which one best describes the circuit being considered.

The current bias of a transistor will vary from a few microamperes to a few hundred microamperes. The bias voltage will seldom exceed a maximum of one volt, and part of this voltage is made up of the IR drop through the semiconductor material of the emitter and base. Most transistor specifications will list the transistor bias in terms of current flow in the base circuit.

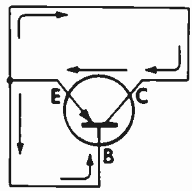
The forward current at the emitter-to-base junction controls the current flow between the emitter and collector. Increasing the base current increases the current from the emitter to the collector. Decreasing the base current decreases the current between the emitter and collector. The arrows in Fig. 13 indicate the direction of electron flow in NPN and PNP transistors. The emitter current is equal to the base current plus the collector current.

Common-Emitter Biasing

The circuit most often encountered is the common-emitter configuration. The common-emitter circuit has a distinct bias ad-



(A) NPN electron flow.



(B) PNP electron flow.

Fig. 13. Direction of electron flow in transistors of opposite conduction types.

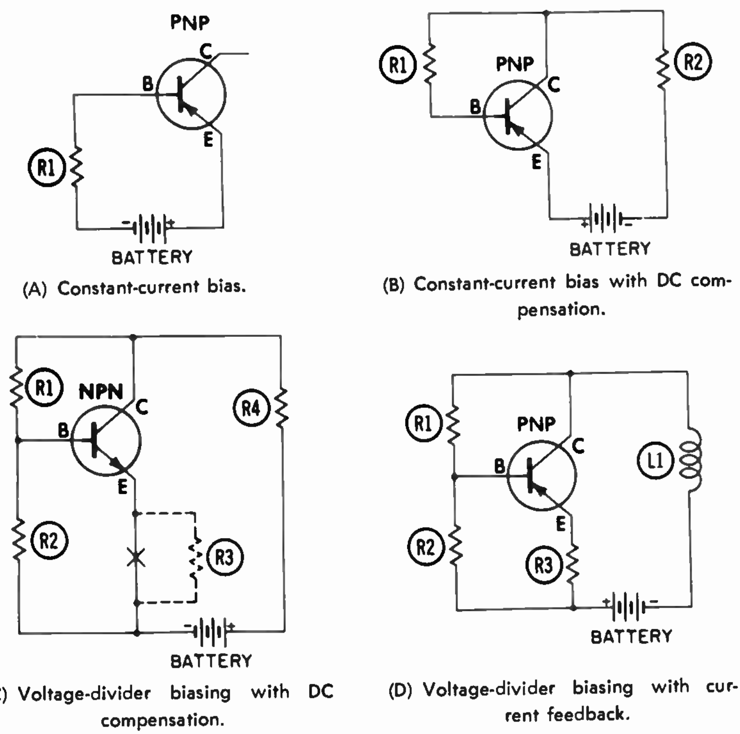
vantage in that one battery will supply both bias in the emitter circuit and power in the collector circuit.

Various biasing arrangements are shown in Fig. 14. The circuit of Fig. 14A provides a constant-value bias current. Resistance R_1 is much larger than the base-to-emitter resistance. The battery voltage will produce a given current flow through resistor R_1, and any change in base-to-emitter resistance will have almost no effect upon the current. This is a constant-current method of biasing a transistor.

If the characteristics of the transistor change or if a new transistor with different characteristics is substituted, the same amount of current will not provide the proper operating point. For most applications, the circuit must be so designed that variations within the transistors themselves or variations between the same types will not have a detrimental effect upon circuit operation.

Figs. 14B, C, and D show biasing arrangements that provide DC compensation for transistor variations. In Fig. 14B, resistor R_1 is connected from collector to base. Increased collector current will lower the voltage at the collector because of the increased drop across collector load R_2. The reduced voltage at the collector reduces the bias; and as a result, the collector current decreases. This action tends to stabilize the circuit and permits wider-tolerance components to be used.

In Figs. 14C and 14D, a voltage-divider arrangement provides a proper bias condition. Resistor R_3, in series with the emitter, provides current feedback. When the load resistance is large, the



(A) Constant-current bias.

(B) Constant-current bias with DC compensation.

(C) Voltage-divider biasing with DC compensation.

(D) Voltage-divider biasing with current feedback.

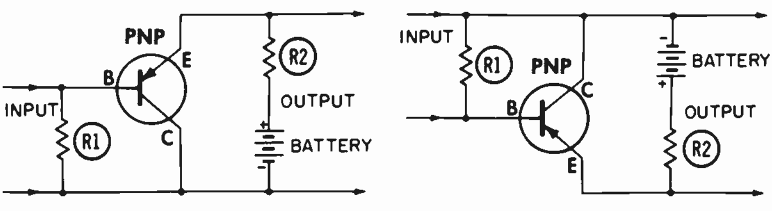
Fig. 14. Methods of biasing common-emitter circuits.

current change through R_3 is small. In Fig. 14D, the load is shown as an inductor. Because there is little DC voltage drop in this circuit, R_3 now becomes important in maintaining the operating characteristic of the stage. Current feedback is particularly useful in stabilizing the RF and IF stages of transistor radios.

Emitter resistor R_3 in Fig. 14C causes the emitter to follow changes in the collector current. As the collector current increases, the emitter voltage level rises, moving closer to the potential on the base. This decrease in potential difference between base and emitter reduces the bias current and tends to return the transistor to its correct operating characteristic.

Common-Collector (Emitter-Follower) Biasing

The common-collector circuits in Figs. 15A and 15B are identical. In the circuit in Fig. 15A, the emitter, which is the output terminal, is at the top right. In the circuit in Fig. 15B, the collector is at the top right in the conventional manner. Resistor R_1, the base-to-emitter junction, and load resistor R_2 form a series load across the battery. The collector-to-emitter path and resistor R_2 form another series circuit. Because input current and output current both flow through load resistor R_2, it is common to both circuits. Increased current flow in the collector will move the emitter potential nearer to the base potential. The increased IR



(A) Emitter shown at top. (B) Emitter shown at bottom.

Fig. 15. Method of biasing common-collector circuits.

drop across R_2 will reduce the current through resistor R_1 and through the base-to-emitter junction. The reduction in bias current will prevent large current changes from taking place in the collector.

This emitter resistor is the load resistor, and current feedback is nearly 100%. The emitter-follower circuit is extremely stable.

Common-Base Biasing

The common-base circuit requires two voltage-supply points or two batteries, one for power and one for biasing. In Fig. 16, resistor R_1 and battery A give the correct operating bias. The bias

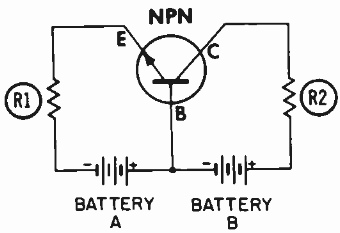


Fig. 16. Biasing common-base circuits.

current from battery A flows through resistor R_1, the emitter, the base, and back to the battery. The output current path is from battery B through battery A, resistor R_1, the emitter, the collector, load R_2, and back to the battery. In this circuit, the input and output currents differ only by the amount of bias current flowing in the base.

The emitter and collector circuits are practically independent from each other, although the same current flows in both. The input current is moved by battery A, and the output current is moved by battery B. The collector current through resistor R_1 provides a current feedback that tends to stabilize the transistor stage. Higher temperatures will increase both the collector current and the voltage drop across R_1; thus the bias current will be reduced. This action tends to return the transistor to its proper operating point.

AMPLIFICATION

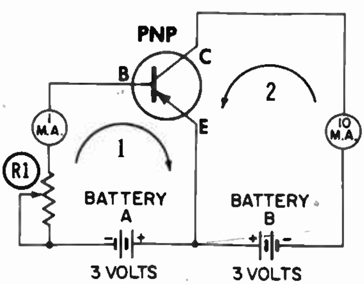
The meaning of amplification can be extended to cover a great deal of territory. For instance, a relay that requires only a small wattage for its operation can control hundreds of watts by simply closing or opening contacts. Relay action, even though an on-off sequence, can be considered as being amplification. Transistors can be made to perform as on-off switches at low speeds or at speeds in excess of those obtainable mechanically.

The change generally referred to as amplification is a constant but smooth change of signal that is reproduced in its entirety. The term "amplification" includes signals that are increased or decreased in voltage, current, or power, or in any combination of these units. Amplification for any one stage may be as high as $\times$ 1,000 or as low as $+$ 3, and even less than one ($<$ or $\times$ 0.85).

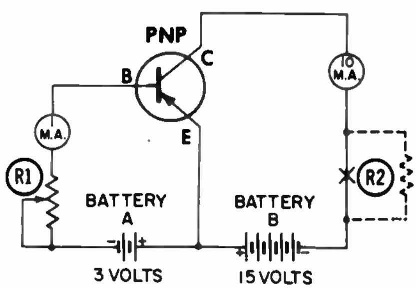
Amplification is an expression of the difference between the input and the output signals of a circuit or of a series of circuits. Amplification is equal to the output current or voltage level divided by the input current or voltage level, but is also equal, in the case of AC, to the change in output level divided by the change in input level.

Common-Emitter Amplifier

In the common-emitter circuit of Fig. 17A, the input (bias battery A) and the output voltage source (battery B) are equal in voltage. This arrangement establishes the levels of current flowing in the input (1) and output (2) circuits. A variable resistor R_1, which sets the bias current at 1 milliampere, is employed.



(A) With a 3-volt collector supply.

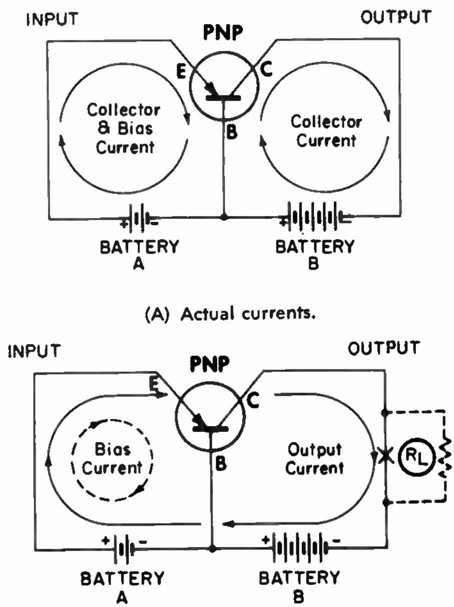


(B) With a 15-volt collector supply.

Fig. 17. The common-emitter amplifier.

With a static current gain of ten, the collector current will be 10 ma. This action is termed a static current gain because both the input and the output have static values. One milliampere of current in the input controls ten milliamperes in the output. If the input current is reduced to 0.8 ma and if the output current drops to 8 ma, the change will be 2 ma in the output divided by 0.2 ma in the input, or an AC current gain of 10.

In Fig. 17B, supply battery B has been changed to 15 volts, and the collector current remains at 10 ma. (The current in the collector circuit is relatively independent from the collector voltage.) A resistance R_2 can be inserted into the collector circuit to produce an IR drop. This voltage will vary as the input varies, and a voltage gain will be produced. Because of the small voltage necessary to change the base current, the voltage amplification can be quite high. Voltage gains over 100 are not unusual for a transistor amplifier.



(A) Actual currents.

(B) Currents as they might be considered.

Fig. 18. Current paths in a common-base amplifier.

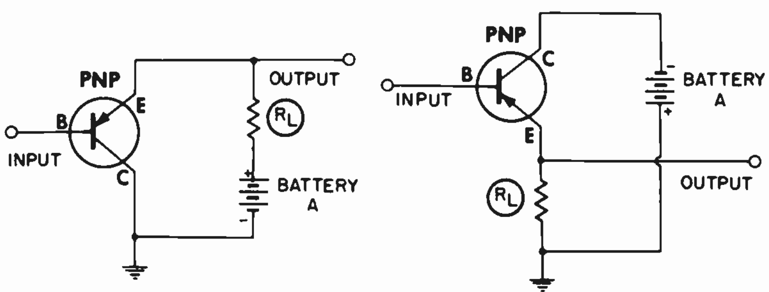
Common-Base Amplifier

The current gain of the common-base circuit is about 0.98. This is a gain of less than one because more current flows in the input circuit than in the output circuit (Fig. 18A).

The current in the input circuit is composed of the output current plus the bias current. The output current (in either circuit) is collector current only. Observe that the base lead theoretically has two collector currents of opposite polarity; actually, these currents cancel each other and leave only the bias current flowing in the base lead.

The current paths of Fig. 18A can thus be described as shown in Fig. 18B, in which the output current flows in both circuits. Although the same current flows in both circuits, it must be considered as being two currents, the input current and the output current.

The collector current is controlled by the amount of bias or signal current impressed across the emitter-to-base junction. The impedance of the collector circuit will be determined by the collector supply voltage, and an increased supply voltage will increase the output impedance. A load, such as resistor R_L inserted into the output circuit in Fig. 18B, will have an IR drop (collector current × resistance) across it that will be greater than the voltage which moves this same amount of current in the input circuit. A voltage gain is thus realized from input to output.



(A) Basic amplifier.

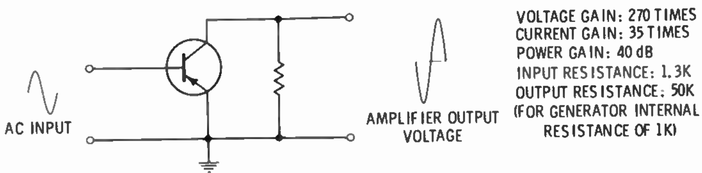
(B) Amplifier with collector ungrounded.

Fig. 19. The common-collector amplifier.

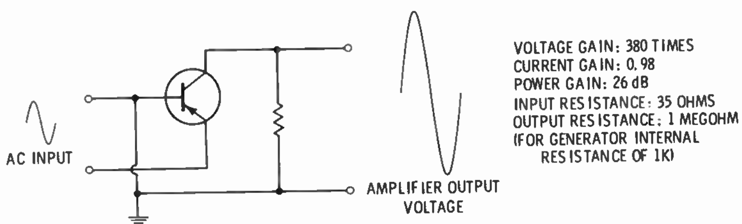
Common-Collector (Emitter-Follower) Amplifier

Fig. 19A shows the basic circuit for a common-collector amplifier. The input signal is applied to the base and collector, and the output is taken from the emitter and collector.

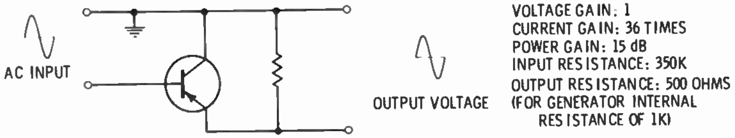
Fig. 19B shows that the output lead is separated from the input lead by the emitter-to-base junction. The voltage between the emitter and the base will change only about 1 volt between collector cutoff and full conduction; therefore, the voltage of the output signal will remain almost the same as the voltage of the input signal, but the current flow in the output circuit will be much greater than the current flow in the input circuit.



(A) Common emitter.



(B) Common base.



(C) Common collector.

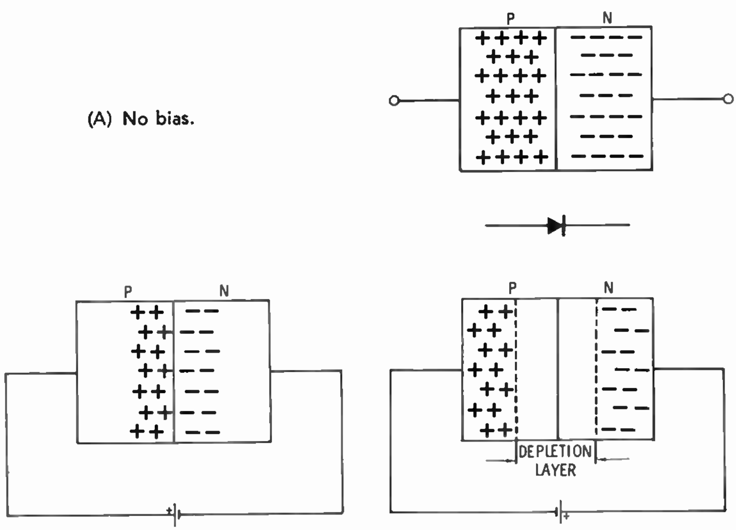
Fig. 20. Transistor circuit parameters.

The circuit is called an emitter follower because of the action of the emitter. As the input voltage on the base of the transistor in Fig. 19B becomes more negative, the current flow in the transistor increases. This increased current flow produces a larger voltage drop across emitter resistor R_L. Thus, the changes in the emitter voltage tend to follow the changes in the base voltage.

The emitter follower has a current gain close to that of the common emitter; but, because there is no voltage gain, the power gain is much less. The main advantages of this circuit are the very high input and very low output impedances, which make this circuit useful as an impedance-matching device.

SUMMARY OF TRANSISTOR AMPLIFIER CHARACTERISTICS

Fig. 20 presents a summary of transistor amplifier characteristics. Observe that the CB configuration has the highest voltage gain, the CC configuration has the highest current gain, and the highest



(A) No bias.

(B) Forward bias.

(C) Reverse bias.

Fig. 21. PN junction characteristics.

power gain is provided by the CE configuration. The CC configuration is used to obtain maximum input resistance, while the CB configuration is used to obtain maximum output resistance. Note that the CE configuration provides phase reversal from input to output, while the CB and CC configurations do not.

FIELD-EFFECT TRANSISTORS

Field-effect transistors are used in various high-quality receivers. The FET has certain features that make it superior to conventional transistors in various applications. An FET has a very high input impedance, comparable to that of a vacuum tube, which is in sharp contrast to the low input impedance of conventional transistors. A field-effect transistor has three electrodes, called the *drain,* the *gate,* and the *source;* these are comparable respectively to the plate, grid, and cathode of a vacuum tube. We will find that the characteristics of the FET are quite similar to those of triode tubes.

To analyze the operation of the FET, let us start with a simple junction diode shown in Fig. 21. With no bias applied, electrons and holes are uniformly distributed throughout the N and P material. Forward bias causes charge carriers to flow to the junction, where they neutralize and permit conduction of forward current. On the other hand, reverse bias sweeps the charge carriers away from the junction, and the resulting depletion layer operates effectively as an insulator to prevent conduction of current.

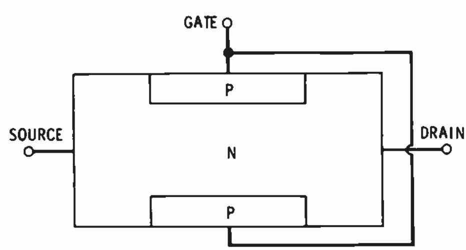


Fig. 22. N-channel junction FET.

Fig. 22 shows a cross section of an N-channel junction FET. A positive voltage is applied to the drain, and a negative control voltage is applied to the gate. When the gate voltage is zero, current conduction occurs from the source to the drain, as shown in Fig. 23. However, an increasing negative voltage on the gate reduces the current because the depletion layer restricts the current as it becomes larger. In normal operation, the gate is reverse-biased, so that the operation is quite similar to that of a triode tube. A P-channel junction FET operates in the same manner, except that the bias voltages are reversed. This is the same distinction that is observed in PNP and NPN junction transistors.

Another type of FET, called the MOSFET, is designed so that at zero gate voltage, drain-current conduction either will or will not

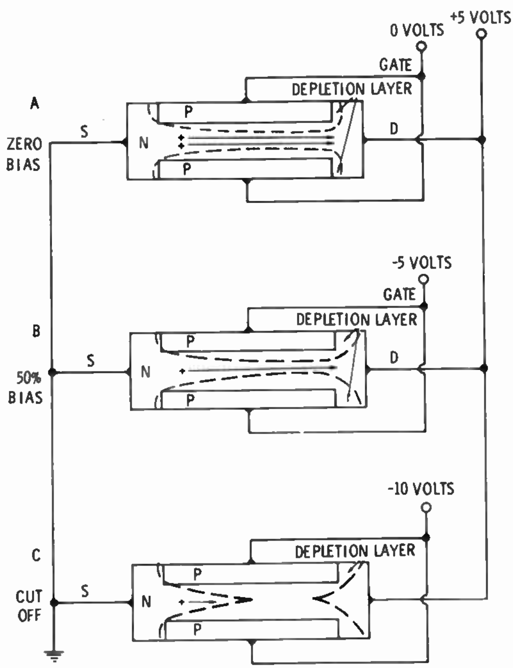
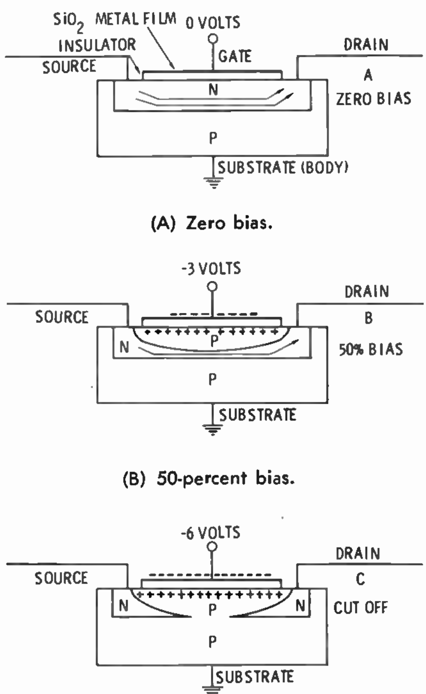


Fig. 23. Effect of bias on J-FET.

occur. If a MOSFET permits current flow at zero gate voltage, it is called a *depletion* type; on the other hand, if current flow is stopped at zero gate voltage, it is called an *enhancement* type. Fig. 24 shows the cross section of a depletion-mode MOSFET (N-channel version). Note that is has an additional connection called the substrate, which is usually connected to ground. "Channel" terminology derives from the fact that when the device is conducting, a channel of N-type material occurs between the N-type drain and the source. The basis of MOSFET operation is the capacitance formed by the metal gate, the silicon-dioxide insulator, and the silicon semiconductor.



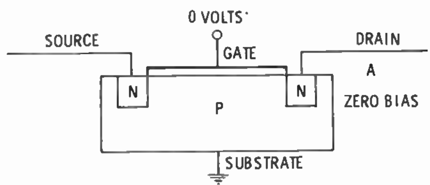
(A) Zero bias.

(B) 50-percent bias.

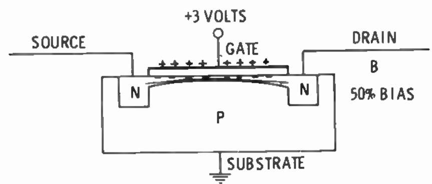
(C) Cutoff.

Fig. 24. N-channel depletion MOSFET.

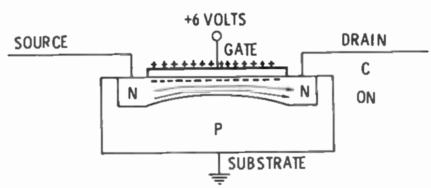
Since an ideal capacitor conducts no direct current, the gate electrode has zero leakage current whether a positive or a negative signal voltage is applied. On the other hand, the grid of a triode tube draws current when driven positive. When the gate voltage is zero, as shown in Fig. 24A, the existing N-channel conducts electrons from the source to the drain. If a negative gate voltage is applied, the MOS capacitor charges. This causes holes to be drawn toward electrons on the gate, thus forcing electrons out of the N-channel, as shown in Fig. 24B. Because the channel is now smaller, less current flows from source to drain. If sufficient negative voltage is applied to the gate, enough electrons are forced out of the channel to produce pinch-off, as shown in Fig. 24C. An NPN junction is formed, but it does not conduct current because the PN junction is reverse-biased.



(A) Zero bias.



(B) 50-percent bias.



(C) On.

Fig. 25. N-channel enhancement MOSFET.

The enhancement type of MOSFET (Fig. 25) operates in an opposite manner. When the gate voltage is zero, there is no current-conducting channel. On the other hand, when the gate is positive, electrons are drawn toward the gate, which sets up an N-channel. Current then flows from source to drain in accordance with the value of positive gate voltage that is applied. Since the input impedance to the gate is extremely high, static electricity of strong stray fields can build up enough voltage to damage an FET when it is not connected into a circuit. Therefore, the leads are usually shorted until the FET is ready to be connected.

INTEGRATED CIRCUITS

Integrated circuits represent an important direction in semiconductor technology. Integrated and monolithic circuits are integral solid-state units that contain transistors, resistors, semiconductor diodes, and sometimes capacitors. The components of an

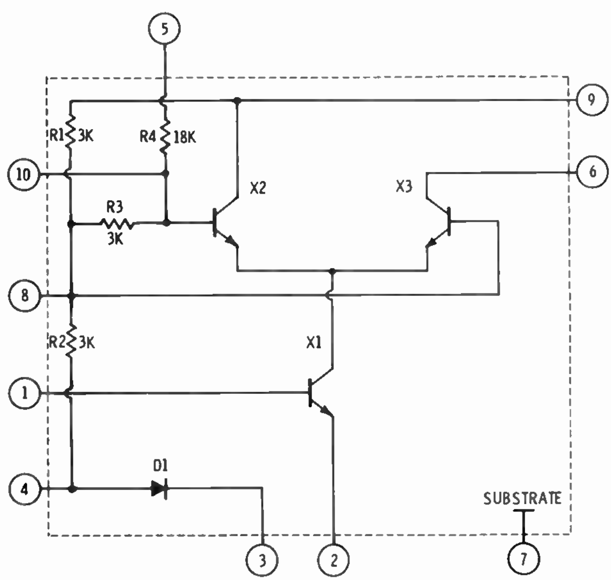


Fig. 26. An integrated amplifier package.

integrated circuit are formed simultaneously during manufacture. This technique tends to introduce factors that are not present when a circuit is wired with separate components. Fig. 26 shows the configuration of an integrated amplifier. The transistors in an integrated circuit are similar to conventional transistors, but more capacitance is involved because of the compact construction.

Resistors used in an integrated circuit are basically semiconductor material, which is temperature-dependent to a greater extent than an ordinary composition resistor. Therefore, it is advantageous to employ circuits that are based on resistance ratios rather than on absolute resistance values. In other words, the tolerance of an integrated resistor is greater than the usual tolerance of a composition resistor. Dependence on resistance ratios makes it desirable to use more than one transistor in a stage, as seen in

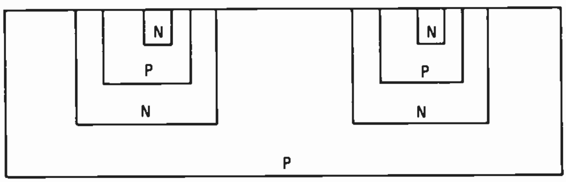
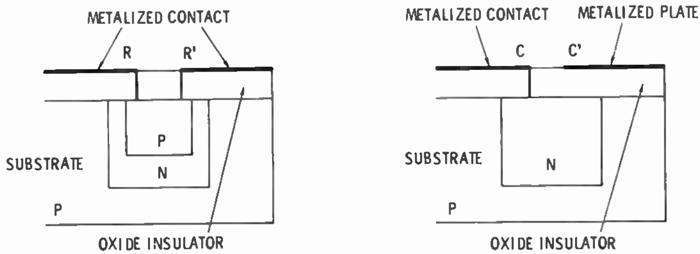


Fig. 27. A pair of NPN transistors diffused into a P-type substrate.

Fig. 26. This arrangement provides stable IC operation, although resistive values tend to drift. Advantage is taken of the fact that the percentage of drift will be practically the same for each resistor.

An integrated circuit is typically manufactured from a silicon wafer of P-type substance. If a pair of N-type regions are diffused into the P-type substance at separate places, a pair of diodes is formed. The P-type material that is common to these diodes is called the *substrate*. This substrate provides electrical isolation between the two N-type regions. Next, if a P-type region is diffused into each of the N-type regions, the base of a transistor is formed. Finally, if another N-type region is diffused into each of the P-type regions, a pair of transistors is formed, as shown in Fig. 27. Note that the P-type substance provides electrical isolation between the two transistors. Metallized contacts are made to the electrodes of the transistors.



(A) An integrated resistor.

(B) An integrated capacitor.

Fig. 28. How integrated resistors and capacitors are formed.

In Fig. 27, the upper N-type regions are emitters, the interleaved P-type material forms bases, and the lower N-type regions are collectors. To form a resistor, the upper N-type region is not used; instead, a pair of separate contacts is made to the P-type substance. The amount of resistance provided by the P-type substance depends on its length, width, and depth. The lower N-type regions serve to provide electrical isolation between the P-type resistor and the substrate. When capacitors are to be formed, only the initial N-type region is used. An oxide layer is employed as the dielectric. Cross sections of an integrated resistor and of an integrated capacitor are shown in Fig. 28.

SUMMARY

A transistor is primarily a three-electrode solid-state device which will provide many of the services that a vacuum tube can provide. Some of the advantages of transistors over vacuum tubes are their smaller size, greater reliability, greater efficiency, and production of much less heat.

Transistors are constructed of one of two major materials—silicon or germanium. They are further classified as to one or the other of two main types—PNP or NPN. The electrodes of a transistor are connected to the base, collector, and emitter. These correspond approximately to the elements in a triode vacuum tube in this way —base (grid), collector (plate), and emitter (cathode).

The amplification taking place in a transistor is commonly that of current amplification as opposed to voltage amplification in a vacuum tube. The transistor can be operated in three circuit configurations—common base, common emitter, and common collector. The term "common" (also called "grounded") refers to the element that is common to both the input and output circuits.

REVIEW QUESTIONS

1. Name three advantages that transistors have over vacuum tubes.
2. What are the two major materials used in producing transistors?
3. Define a hole as applied to transistor theory.
4. Do electrons and holes travel in the same direction through a transistor?
5. Define forward bias.
6. Is the emitter positive or negative with respect to the base in a properly connected NPN transistor?
7. Draw the symbol for a PNP transistor.
8. Electron flow is from collector to emitter in a properly connected transistor. Is the transistor a PNP or an NPN type?
9. What configuration would be most useful to match a high-impedance circuit to a low-impedance circuit?
10. What is an integrated circuit?

CHAPTER 13

Speakers and Microphones

A very close relationship exists between speakers and microphones—so close, in fact, that a speaker can be made to perform the same function as a microphone. The function of both of these devices is to convert one form of energy into another. A microphone converts mechanical energy into electrical energy and a speaker does just the opposite.

SPEAKERS

Speakers convert audio-frequency currents into sound waves. In order to accomplish this, the speaker must be designed in such a way that it will cause the varying electric currents to set a diaphragm into motion.

The vibration of the diaphragm in turn sets the surrounding air molecules into motion. The vibration of this comparatively large volume of air produces sound, which the ear receives and the brain sometimes appreciates.

The efficiency of a speaker is defined as the ratio of the useful acoustical power radiated to the electrical power supplied.

Speakers generally consist of two main parts, namely, the driving unit that changes the varying audio-frequency currents into mechanical vibrations and the diaphragm itself which acts in conjunction with the driving unit to produce a corresponding vibration of the air molecules.

Classification of Speakers

Speakers may be divided into the following general classes, depending upon the principle involved in the operation of the driving unit, namely:

1. Dynamic (including permanent magnet and electromagnetic types).
2. Electrostatic (also called capacitor speaker).

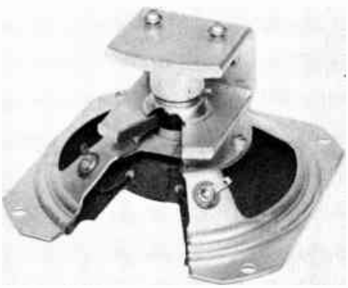
Other types of speakers including magnetic, balanced armature, induction, metal strip, and piezoelectric have been used in past years. In this discussion, however, we will be concerned only with those speakers previously mentioned.

Dynamic Speakers — The dynamic, or moving coil, speaker consists primarily of the following parts:

1. Frame.
2. Either a permanent magnet or an electromagnet.
3. Voice coil.
4. Cone (also referred to as a diaphragm).

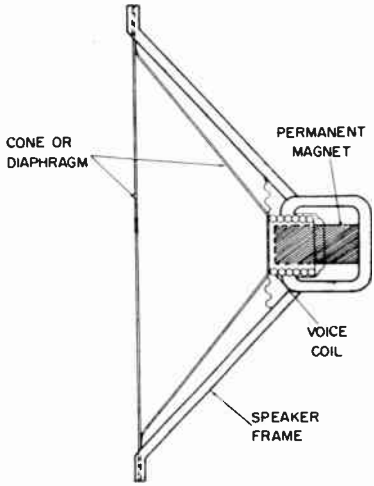
Fig. 1 shows a typical permanent-magnet (PM) dynamic speaker and its internal construction. Fig. 2, on the other hand, illustrates the physical characteristics of another type of dynamic speaker. This one uses an electromagnet instead of a permanent magnet and is commonly referred to as an electrodynamic speaker.

In the dynamic speaker, the magnet produces a strong magnetic field across the air gap in which the voice coil is inserted. The signal current from the audio output terminals of the device to which the speaker is connected flows through the voice coil, causing an interaction between the fixed magnetic field and the changing field around the voice coil. It is this interaction between the fields that causes movement of the voice coil and the speaker cone to which it is attached. These movements, which correspond to the audio signal, produce sound. Thus, the speaker translates variations of the signal current into corresponding sound variations.



Courtesy Quam Nichols Co.

(A) Physical appearance.



(B) Construction features.

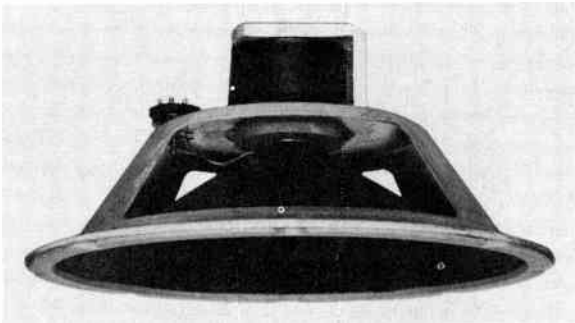
Fig. 1. A typical PM dynamic speaker.

Electrostatic Speakers—Electrostatic speakers (also called capacitor speakers) consist essentially of two parts: namely, two plates, one which is stationary and one which is free to vibrate, and a dielectric separating the plates. These are assembled as shown in Figs. 3 and 4. The diaphragm consists of a thin layer of metal sprayed on the rubber dielectric and is the vibrating plate.

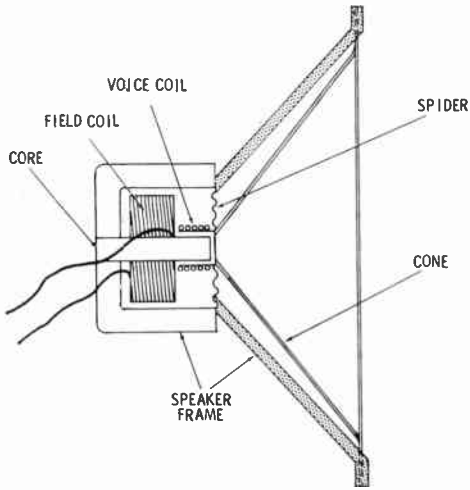
The electrostatic speaker operates on the well-known principle of electrostatic attraction and repulsion, in that two bodies of similar charges of electricity repel each other, whereas two opposite charges attract each other.

When a polarizing voltage is applied to the plates, a steady electric field is built up; superimposed upon this is the audio-frequency electrostatic field. This causes an attraction and repulsion between the two plates, producing oscillations in the free plate corresponding to the audio-frequency impulses.

The back or stationary plate in the commercial types of electrostatic speakers usually consists of stiff metal such as copper, iron



(A) Physical appearance.



(B) Construction features.

Fig. 2. An electrodynamic speaker. Notice that this speaker has an electromagnet instead of a permanent magnet.

or aluminum. The back plate is usually perforated with slots in order to prevent compression of air between the two plates. Fig. 5 shows the schematic symbols for the various types of speakers.

Speaker Baffles

In a cone-type speaker, the cone is driven backward and forward in the same manner as a piston by the action of the impressed

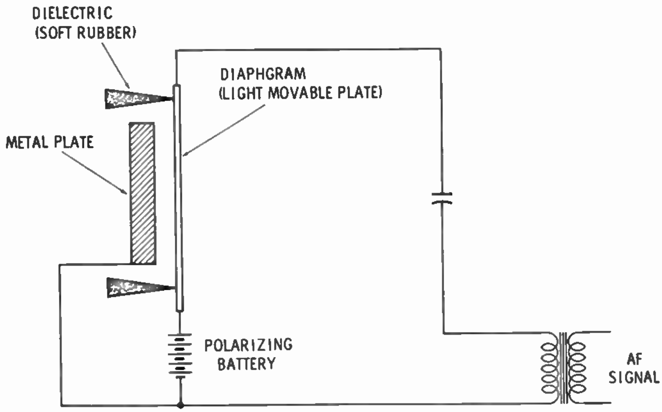


Fig. 3. Electrostatic speaker showing circuit connections.

audio-frequency signal. This constant movement displaces a certain amount of air, and it is this displaced air that generates the sound that is heard.

When the air is pushed forward by the forward motion of the cone, a partial vacuum is created in back of the cone. The displaced air in the front then encounters very little resistance and

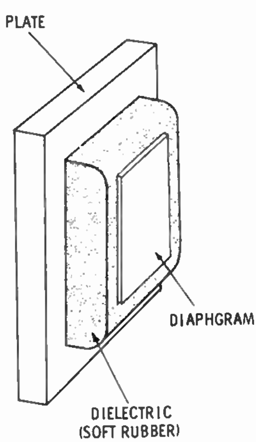


Fig. 4. Elements of an electrostatic speaker.

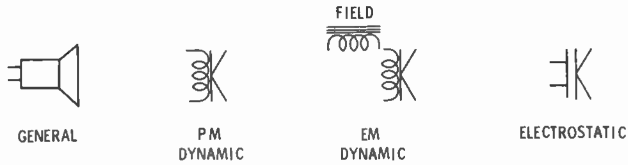
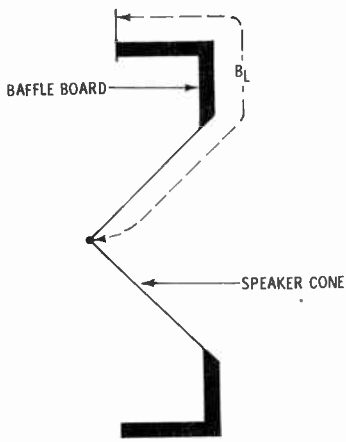


Fig. 5. Schematic symbols for speakers.

hence flows rapidly to fill the vacuum at the rear of the cone created by the forward thrust.

If these air movements were allowed to cancel each other completely, there would be no air movements and hence no sound waves would be created. The method used to delay these rapid movements is to increase the path of air travel by means of a baffle board surrounding the cone as shown in Fig. 6.

Fig. 6. A speaker baffle.



The amplitude of air movement from a speaker, however, is relatively low, and, at least theoretically, sound waves are produced only in the air very close to the moving cone. This is true for low, but not for high frequencies.

Thus, in practice an unbaffled speaker will reproduce high tones, but will lack almost entirely all low tones, due to the neutralization already described.

The purpose of the baffle is to delay the flow of the air creating the sound waves by an artificial lengthening of the path of its travel. A baffle can be anything that will lengthen the air path from the cone center to the rear of the cone.

Calculation of Baffle Length — By recalling that the speed of sound is 1,130 feet per second in air, it is possible to calculate the minimum baffle length for a certain frequency.

If B_L denotes the baffle length in feet, and f is the frequency of the sound wave, then:

$$B_L = \frac{1}{4} \times \frac{1130}{f} = \frac{282.5}{f}$$

or, expressed in a nonmathematical form, the baffle length in feet is equal to one quarter the wavelength of the note to be reproduced.

Example: Assuming 40 cycles as the lowest tone to be reproduced by a speaker, what is the minimum baffle length required?

Solution: Substituting the numerical values in the equation we obtain:

$$B_L = \frac{282.5}{40} \text{ or 7 feet (approximately)}$$

In a similar manner the baffle lengths for low-frequency cutoffs, below which a speaker will not reproduce sound, are as follows:

Lowest frequency to be reproduced	*Baffle length from cone center in feet*
100	2.825
60	4.708
40	7.006
30	9.417
20	14.125

Since the tone corresponding to the lowest frequency of various instruments is approximately 20 cycles per second, it follows that for its reproduction, baffles of considerable length must be created.

MICROPHONES

The function of a microphone is to convert sounds into equivalent electrical impulses. This can be accomplished in a number of ways and is reflected in the operating principles of various types of microphones.

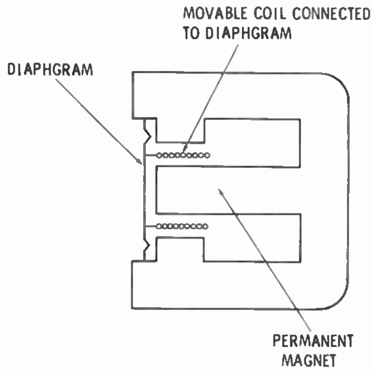


Fig. 7. Basic construction of a dynamic microphone.

Dynamic Microphones

The dynamic, or moving-coil, type of microphone is widely used and operates on the same principle as the dynamic speaker. With the microphone, however, the process is reversed. The basic construction of a dynamic microphone is illustrated in Fig. 7. As you can see, the diaphragm is attached to a coil. The latter is centered within the air gap of a permanent magnet, and is movable within the fixed magnetic field. When sound waves cause the diaphragm to vibrate, a corresponding movement of the coil is produced. This movement cuts the lines of force within the magnetic field, thereby inducing a current in the coil. This current is the equivalent of the mechanical vibration or sound entering the microphone.

Crystal and Ceramic Microphones

Another common microphone type uses a crystal element as its voltage-producing device. Some time ago, early experimenters found that certain crystalline substances, in their natural state, exhibit an electrical charge when subjected to a physical strain. Later it was found that the opposite effect also held true. This is known as the piezoelectric effect, meaning "pressure electricity." There are a number of materials having such properties, two of which

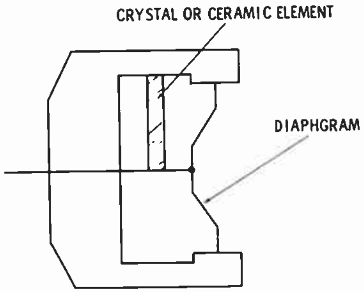


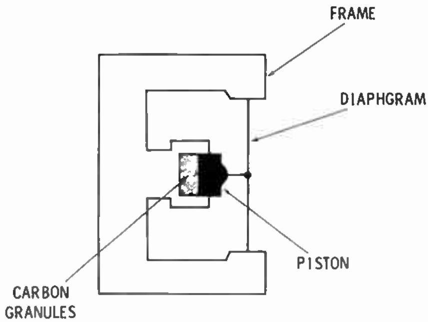
Fig. 8. Basic construction of a crystal and ceramic microphone.

are Rochelle salt and quartz. Fig. 8 shows the basic construction of a crystal microphone. Some types of ceramics can be used in place of the crystal, and the principle of operation is practically the same.

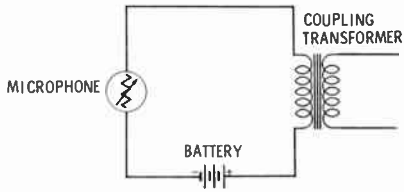
From the diagram you will notice that the diaphragm is physically linked with the crystal or ceramic element. When the diaphragm is set in motion by air waves, it places a physical stress on the element, causing a corresponding AC voltage to be produced. Crystal elements have a relatively high voltage output but are adversely affected by excessive heat. Prolonged exposure to temperatures above 120° F. can ruin a crystal. Ceramic, however, is essentially unaffected by wide ranges of temperature or humidity.

Carbon Microphones

Unlike the previous microphones which generate their own voltage, the carbon microphone requires an external source of power. Instead of producing its own current, it merely varies an existing current. The basic construction of a carbon microphone is illustrated in Fig. 9A and the equivalent circuit is shown in Fig. 9B. As you can see, it operates on the variable-resistance principle. The primary element of this microphone is a small container filled with carbon granules.



(A) Basic construction.



(B) Equivalent circuit.

Fig. 9. Principles of a carbon microphone.

Connections are made to the carbon in such a way that it is placed in series with the microphone leads. Attached to the diaphragm is a small piston-like device which is designed to exert physical pressure on the carbon granules. Before the microphone will operate, its external leads must be connected in series with a DC source and the primary winding of an appropriate transformer (Fig. 9B).

Solid carbon is a relatively good conductor; however, in granular form it is somewhat resistive. The amount of resistance it offers depends on how closely associated the individual particles are. Therefore, by varying the pressure on the carbon granules, the resistance is likewise varied. With no sounds entering the microphone, the current flowing in the circuit is steady. However, sounds cause the diaphragm to vibrate, and the piston-like plunger produces a corresponding change in pressure on the carbon particles. This, in turn, varies the resistance of the carbon (in series with the current) and results in similar variations in the flow of current through the microphone transformer. These variations are then coupled to an amplifier circuit where they are handled like any other microphone signal.

Magnetic Microphones

A magnetic microphone (also called reluctance microphone) is one whose operation is dependent on variations in the reluctance of a magnetic circuit. The most popular version of the magnetic microphone is the variable-reluctance type. It is somewhat similar in operation to a dynamic microphone except that it uses a stationary rather than movable coil. This coil is wound around the center leg of an armature which is attached, at the top, to the frame of the unit. A drive pin is used to connect the center leg to the diaphragm as shown in Fig. 10. The outer legs of the armature are evenly spaced between the poles of the permanent magnet, and are held in place with nonmagnetic shims.

When no sounds are entering the microphone, the diaphragm is at rest. Under this condition the center leg of the armature is held

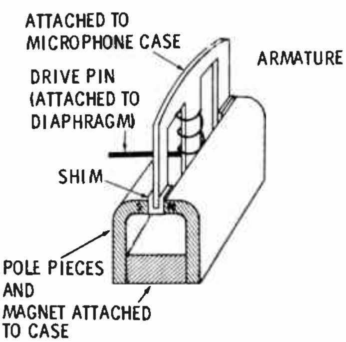


Fig. 10. Basic construction of a variable-reluctance microphone.

midway between the pole pieces. Therefore, in this position the magnetic lines of force follow a path directly across the gap through the ends of all the legs.

When the center leg is set into motion by sound waves, it causes a voltage to be induced in the coil. At the instant a sound wave moves the center leg of the armature toward the north pole piece, it causes a concentrated flow of magnetic lines through the center leg (following the path of least resistance) and through the outer legs to the south pole piece. When the center pole is moved closer to the south pole, the magnetic lines of force follow a path up through the outer legs and down through the center to the south pole, thereby reversing the path taken by the lines of force. It is these changes in reluctance that cause a signal voltage to be induced in the coil.

SUMMARY

Speakers and microphones are basically similar in many respects. A speaker can, and in many applications does, perform the same function as a microphone. The function of both devices is to convert one form of energy into another—a speaker converts electrical energy into mechanical (sound) energy while a microphone does just the opposite.

Speakers are divided into permanent-magnet, electromagnetic, and electrostatic types. The most common is the permanent-magnet type. In order to perform efficiently, a speaker must be baffled in some way. Baffles take many forms.

Microphones convert sound into corresponding electrical impulses. The common types of microphones are the dynamic, crystal, ceramic, magnetic, and carbon types. The modern telephone uses a carbon microphone.

REVIEW QUESTIONS

1. What is the function of a speaker?
2. What is the function of a microphone?
3. Name an application where a speaker is used as a microphone.
4. What is the principle difference between a permanent-magnet type of speaker and an electromagnetic type?
5. Why is a baffle necessary in order for a speaker to reproduce sound faithfully?
6. What is the most common type of microphone in use today?

7. What is the source of electrical generation in a dynamic microphone?
8. What is the source of electrical generation in a crystal microphone?
9. What is one of the disadvantages of a crystal microphone that can cause damage to the unit?
10. Does a carbon microphone generate electricity?

CHAPTER 14

Basic Electronic Circuits

Every piece of electronic equipment, regardless of how complex it appears, is nothing more than an accumulation of basic circuits. When each circuit is considered separately the complexity no longer exists. Now that each of the basic electronic components has been discussed separately in previous chapters, we will consider their functions in actual circuits.

All electronic circuits can be broken down into one of three basic classes, namely rectifiers, amplifiers, and oscillators. There are many variations of the basic designs; however, once you understand the principles of operation of the basic circuits, any deviation from them will not be difficult to comprehend.

RECTIFIERS

The word rectify means to change something and that is just what a rectifier circuit does—it changes an alternating current flow into a pulsating form of direct current. Rectifiers were mentioned only briefly in previous chapters in connection with vacuum tubes and semiconductor devices. From that discussion, you will recall that electrons will flow from the cathode to the anode of a diode vacuum tube when it is connected as shown in Fig. 1. When an AC voltage is applied to the plate of a diode rectifier (Fig. 2) it pro-

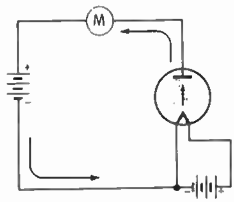


Fig. 1. Circuit connections for current flow through a diode vacuum tube.

duces a pulsating DC output. In this circuit the only time the tube will conduct is when the plate is positive with respect to the cathode and this only occurs during one-half of each cycle. Thus, the alternating current applied to the tube is rectified (changed) into a form of direct current. This particular circuit is referred to as a half-wave rectifier since it deals with only half of the AC cycle.

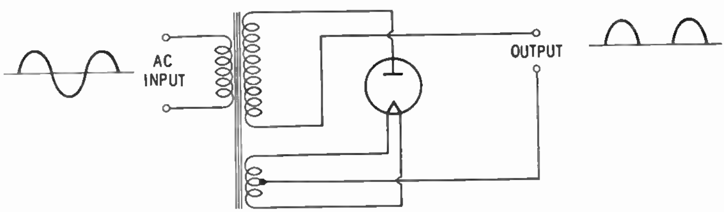


Fig. 2. Basic half-wave rectifier circuit.

The circuit in Fig. 3, however, employs a tube with two anodes and is connected in such a way that conduction occurs during both halves of the AC cycle. An arrangement such as this is known as a full-wave rectifier. Notice from the output that although this tube

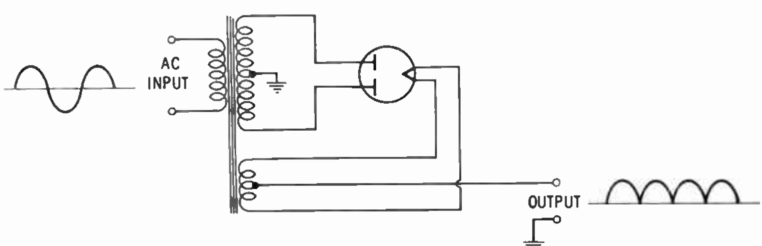


Fig. 3. Full-wave rectifier circuit.

conducts during each half of the AC cycle, all conduction is still from the cathode to the anode and the current flow is only in one direction. In other words, on one-half of the AC cycle one plate will be positive and the other will be negative. Conduction will then occur between the cathode and positive plate. On the next half cycle, tube conduction is between the cathode and the opposite plate. Therefore, each plate conducts alternately and produces the pulsating output shown in Fig. 3. (Rectifier circuits and rectification are discussed at great length in Chapter 15.)

Detectors

Another form of rectifier employed in radio receivers is known as a detector. Unlike the power-supply rectifier, detectors handle only signal currents. The function of the detector is to demodulate, or separate, the audio component from the radio-frequency carrier. This action can be accomplished by any one of several types of detector circuits. In all of these circuits, detection is accomplished by rectifying the modulated signal and filtering or bypassing the RF component. The type of circuit employed depends on the signal to be detected, its strength, the gain required, and the amount of distortion that can be tolerated. Fig. 4 shows the circuit action of a diode detector.

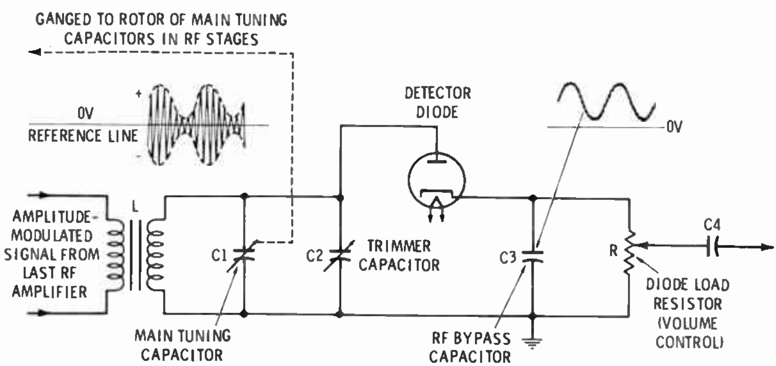


Fig. 4. Circuit action of a diode detector.

Some detector circuits not only detect the signal but also serve the additional function of providing what is known as automatic volume control (AVC). Fig. 5 shows one of the most popular detector-AVC circuits used in AM radio receivers.

Known as a half-wave diode detector this circuit operates as follows: The modulated signal is coupled to the detector by means of T1. This signal is developed between the plate of V1 and ground. V1 conducts when the input RF signal applied to the plate is positive. The resultant current flow develops a voltage across load resistors R1 and R2. C3 and C4 have a low reactance at radio fre-

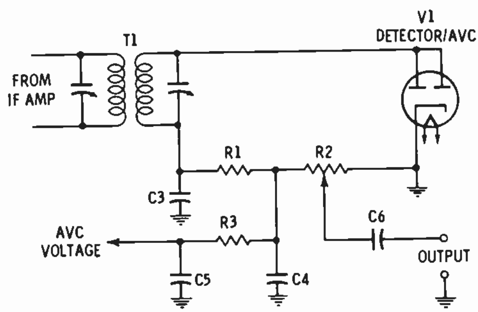


Fig. 5. A typical detector/AVC circuit.

quencies and therefore bypass the RF currents to ground. R2 is a potentiometer whose function is to control the amount of audio signal fed to the succeeding stage. In a receiver this resistance is termed the volume control.

The DC voltage developed across R2 is also passed through a filter network comprised of C4, R3, and C5, which serves to remove the audio component. The resultant output is a DC control voltage that varies with the strength of the incoming signal. This voltage is applied to the grids of one or more receiver stages preceding the detector and serves to control the bias of these stages to maintain a constant audio output for signals of varying intensity. In other words, as you tune a receiver without AVC from a weak station to a strong one, the increase in signal strength causes the stronger station to "blast" through the speaker. With AVC, however, the stronger carrier develops more AVC voltage and the tubes are biased to compensate for this increase. The result is that both stations will be heard with nearly equal intensity. With AVC the audio output tends to remain constant despite variations in signal strength. The signal itself will automatically either increase or decrease the bias so that the output voltage of the detector will be fairly constant.

AMPLIFIERS

The function of an amplifier is to produce as an output an enlarged reproduction of the essential features of its input. The amplifying device may be either a vacuum tube or a transistor. Looking first at the vacuum-tube amplifier, examine the basic amplifier circuit in Fig. 6. If the grid were not present in this tube, the amount of current flowing between the cathode and the plate would be determined primarily by the positive voltage applied to the plate. With fixed filament and plate voltages, the current flowing through the vacuum tube will be of constant value. As this current flows through the plate resistor (R1) it produces a voltage drop across it. As you learned previously, the amount of voltage developed across a resistor is determined by the value of the resistance and the

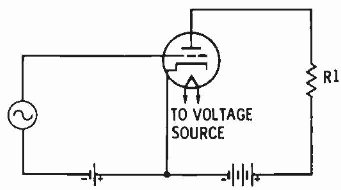


Fig. 6. Basic amplifier circuit.

amount of current passing through it. Under the present condition let us assume that 15 volts DC appears across R1. At the same time assume that an increase of 50 volts on the plate results in a voltage drop of 25 volts across R1, an increase of 10 volts. This is one way of changing the plate current.

Now consider what occurs when the grid is present in the tube. There are now two ways in which the plate current can be increased. One way is to increase the plate voltage as just mentioned.

A more practical way, however, is to hold the plate voltage constant and vary the grid voltage. Since the grid is closer to the cathode it has more control over the amount of electron flow than the plate. With no voltage applied between the grid and cathode, the plate current will produce the same voltage drop (15 volts) across R1 as in the previous example. If, however, the grid is made positive it will increase the plate current. By the same token electron flow will be reduced if a negative voltage is applied to the grid. Say

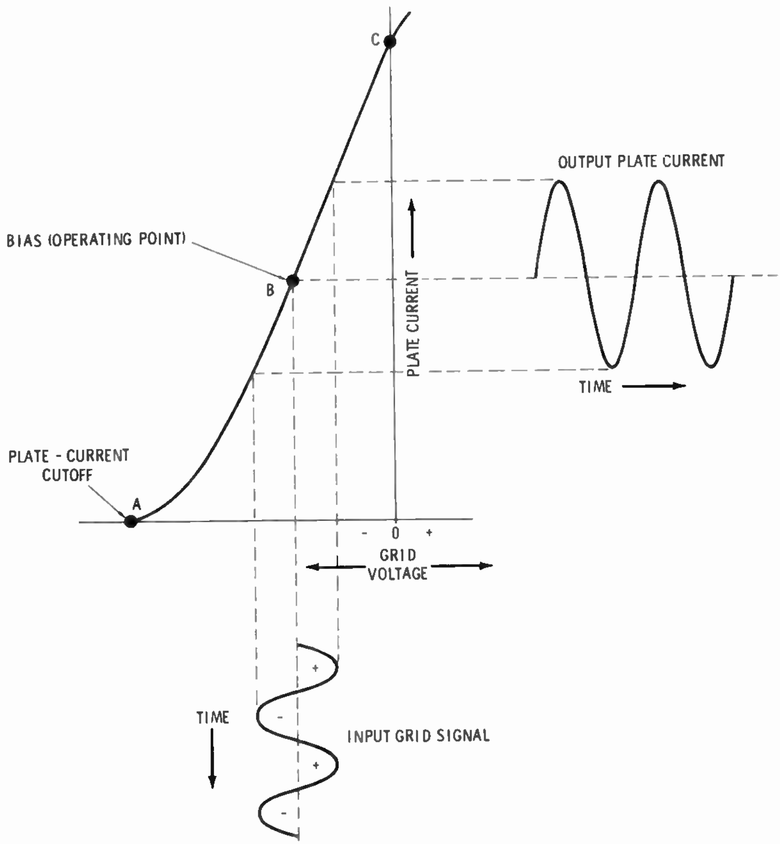


Fig. 7. Characteristic curve with class-A operation.

that a potential of plus 1 volt on the grid of the tube produces a sufficient increase in plate current to develop 25 instead of 15 volts across R1. This means then that a 1-volt change in voltage at the grid will produce the same increase in voltage across R1 as would result from increasing the plate potential 50 volts. This would be an amplification factor of 10 (1 volt at the grid produces a change of 10 volts in the plate circuit). A visualization of this process is seen in Fig. 7.

Grid Bias

Grid bias is a constant DC potential which is applied between the grid and cathode of a vacuum tube to establish an operating point. The operating characteristics of a vacuum tube can be plotted as a curve like that shown in Fig. 8. This is commonly referred to as the grid-voltage-plate current (E_g-I_p) characteristic

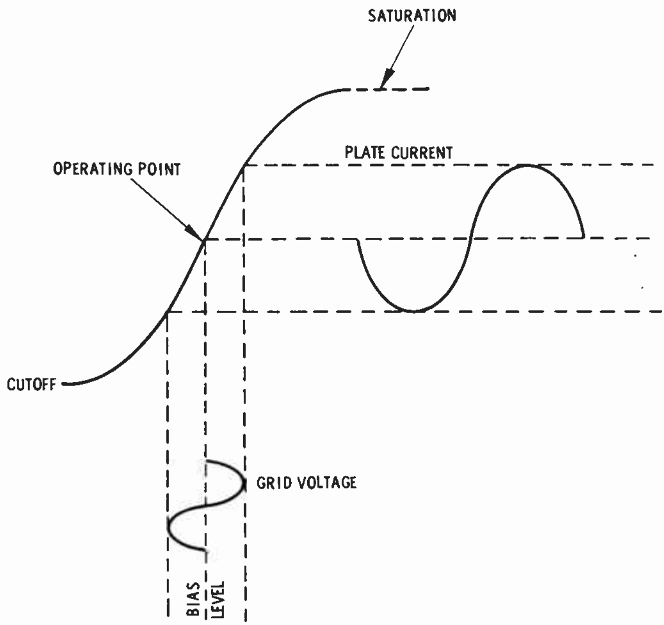


Fig. 8. Characteristic curve of a vacuum tube.

curve. As you can see, the bias level establishes the operating point in such a way that variations in grid voltage produce larger but identical variations in plate current. This is accomplished by biasing the tube to operate over the linear portion of its E_g-I_p curve. The upper roll-off of the curve indicates the point of saturation. This is a condition whereby further increases in plate voltage no longer produce an increase in plate current. This roll-off point is also referred to as the knee of the curve. The lower bend in the curve represents plate-current cutoff.

To illustrate how grid bias affects tube operation consider the curve in Fig. 9. Here the tube is biased near cutoff. As you can

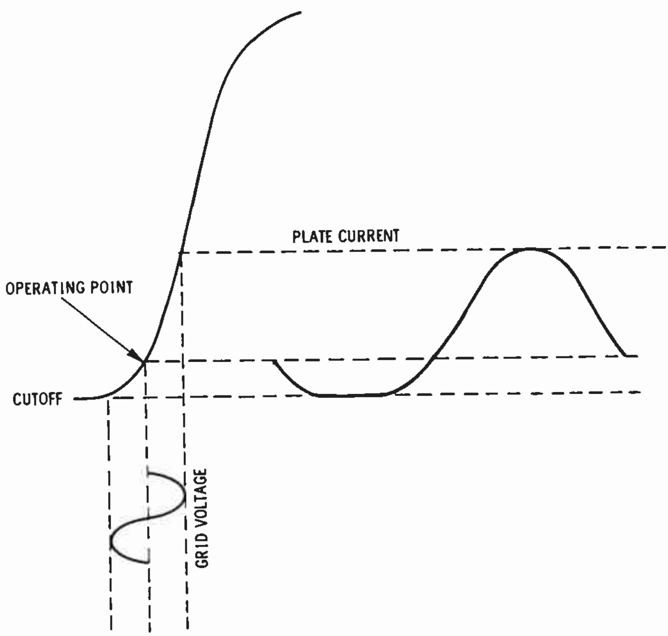


Fig. 9. The effect of biasing a tube near the cutoff point.

see, the tube no longer operates over the linear portion of the curve and the result is distortion of the amplified signal.

Amplifier Classes

The point at which the grid bias is fixed (the bias potential) on the E_g-I_p curve of an amplifier determines the class of operation. If the tube is biased for operation over the linear portion of the curve, the stage is termed a class-A amplifier. In class-A operation, the waveshape of the output voltage is the same as that of the input voltage applied to the grid.

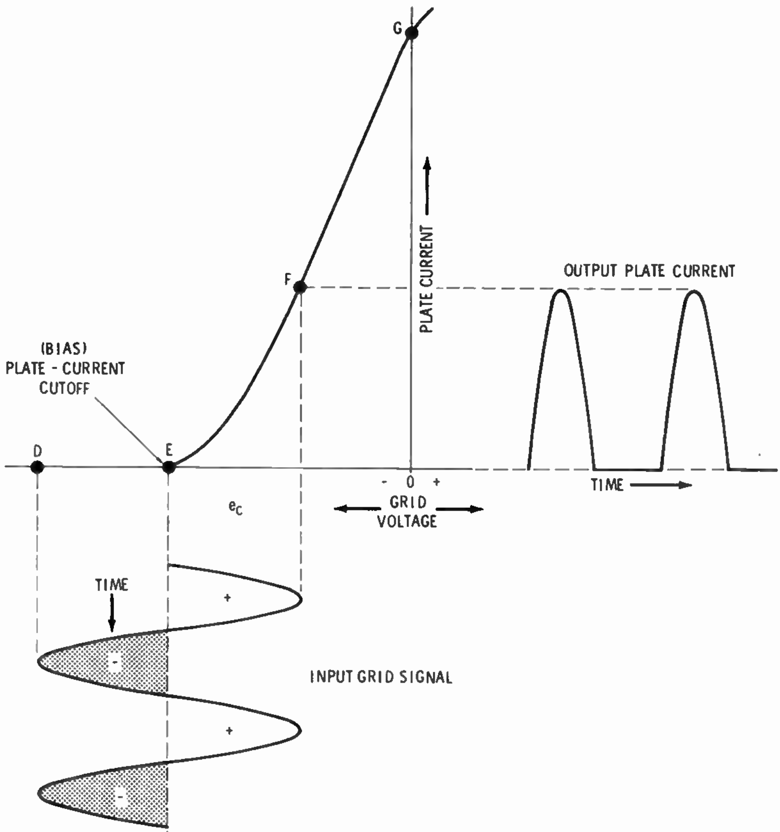


Fig. 10. Characteristic curve with class-B operation.

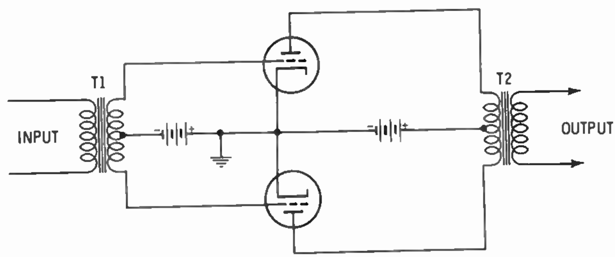
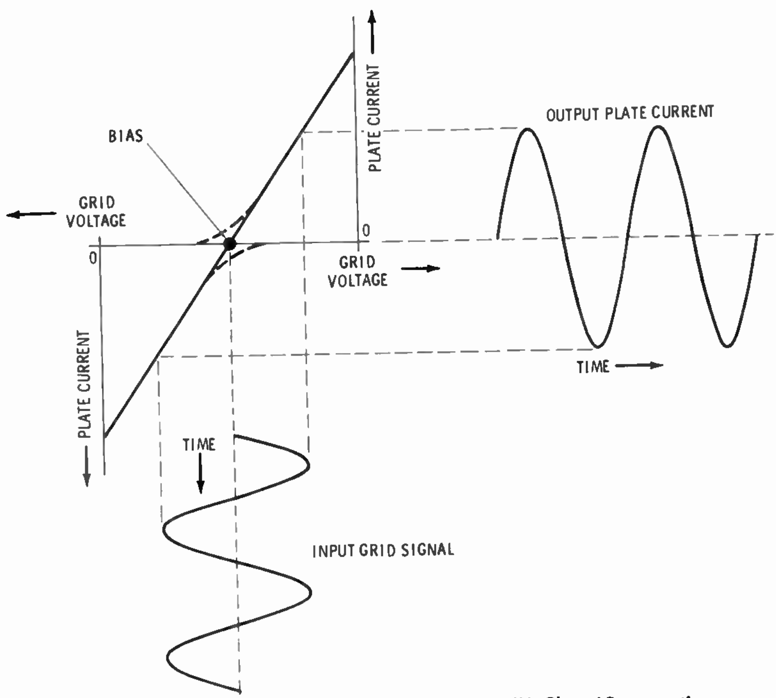


Fig. 11. A basic class-B push-pull amplifier circuit.

A class-B amplifier is one that is biased at the cutoff point (Fig. 10). Here plate current flows only when the signal makes the grid positive with respect to the cathode. This class of operation is often



(A) Class-AB_1 operation. (B) Class-AB_2 operation.

Fig. 12. Dynamic characteristic of two tubes in class-B push-pull operation.

employed in push-pull amplifier circuits designed to deliver relatively high power output. A basic circuit of this type is shown in Fig. 11. With this arrangement, the grids and plates of the tubes are connected to opposite ends of a balanced circuit. Therefore, when an AC voltage is applied to transformer T1, it causes the grid of one tube to swing in a positive direction while the grid of the other swings negative. On the next half cycle, the opposite action occurs. This means that the voltages and currents of one tube are 180° out of phase with those of the other. The driving voltage (measured between the two grids) required for operation of this circuit is twice that of a single-tube amplifier. (See Fig. 12.) If the push-pull stage is employed as a power amplifier, twice the driving power will be consumed. The push-pull circuit is referred to as a double-ended stage while a circuit using one tube is termed single-ended.

When a push-pull amplifier is biased at a potential higher than normal for class-A operation but less than the cutoff value required for class-B, it is said to be operating in class AB. There are further variations of this class, designated AB_1 and AB_2. In a class

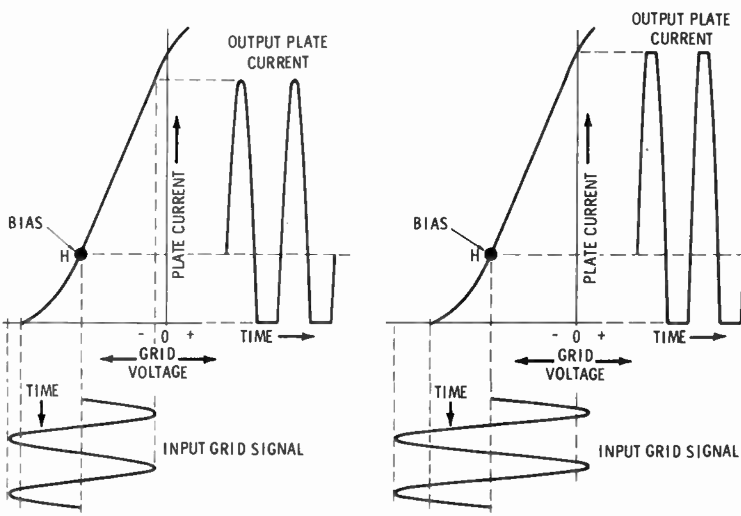


Fig. 13. Dynamic characteristic with class-AB operation.

AB_1 amplifier, the grids are never driven positive with respect to the cathode. In class AB_2 operation, however, the grids are driven positive for a brief portion of the input cycle if the signal is large. A visualization of this process is seen in Fig. 13.

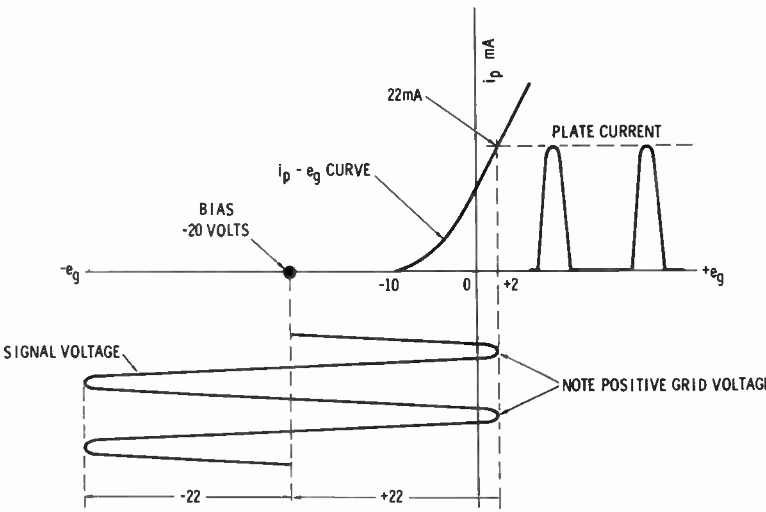


Fig. 14. Class-C operation.

In class-C operation the tube is biased appreciably beyond the cutoff point, so that the plate current is zero when no signal is applied to the grid. When a signal is present, plate current flows during considerably less than one-half of the input cycle. At no time, however, does grid current flow (the grid never goes positive). Fig. 14 depicts class-C operation.

Reactance Considerations in Interstage Coupling

In a low-frequency amplifier where resistance, capacitance, or choke-capacitance coupling is employed between stages, it is necessary to guard against an excessive voltage drop across the coupling capacitor at the lowest frequency the capacitor will be handling. The total available voltage passed on to the second stage is a matter which is easily analyzed by the aid of vectors, which also give the phase angle of this voltage.

Fig. 15 depicts ordinary resistance-capacitance (RC) coupling. Assuming that the alternating component of the voltage developed across the plate resistance is E volts, this potential difference is set

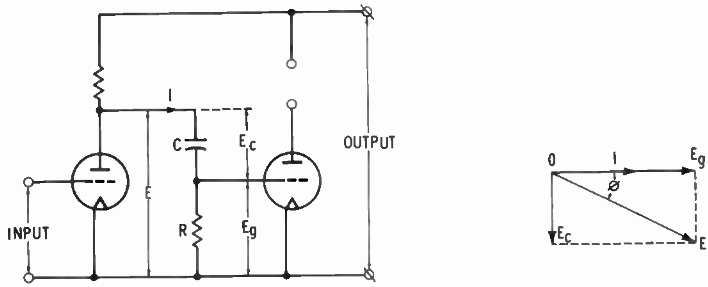


Fig. 15. Interstage coupling with vector diagram.

up between the ends of coupling circuit CR as shown. Suppose that the grid leak (R) has a resistance of 0.5 megohm, and that the capacity of the coupling capacitor is 0.01 microfarad. Assuming that 50 hertz represents the lowest frequency to be amplified, the reactance of the capacitor at this frequency is:

$$\frac{1}{2\pi fc} = \frac{10^6}{2\pi\, 50 \times 0.01} = 318{,}000 \text{ ohms or } 0.318 \text{ megohm}$$

Now, since R and C are in series, there is only one current and so the current vector of Fig. 15 is drawn in position first, this being denoted by O-I of an arbitary length.

In the circuit diagram of Fig. 15 the voltage required to drive the current through the capacitor is denoted by E_c and that through the grid leak by E_g. What is required is the mathematical ratio of E_g to E.

By Ohm's law, $E_g = IR$ volts in phase with I. Its numerical value cannot be found yet because I is not known, but the vector O-E_g can be drawn parallel to O-I and its length made proportional to resistance R. Since R is 0.5 megohm, O-E_g could conveniently be made 5 inches long.

The current passed by the capacitor leads the voltage across it by a quarter of a cycle, and the voltage E_c will therefore lag the current by this amount. Hence the vector O-E_c is drawn at right angles to O-I in the position shown in Fig. 15, and its length is made proportional to the reactance of the capacitor to the same scale as O-E_g.

Since the capacitor reactance at 50 hertz is 0.318 megohm, O-E_c will have to be 3.18 inches, using the same scale as before. Now the total voltage (E) across the coupling circuit must be equal to the vector sum of E_c and E_g. If the rectangle O-E_c-E-E_g is completed as shown, O-E will represent the total available voltage to the same scale.

The length of OE will clearly be:

$$\sqrt{\text{O-}E_g{}^2 + \text{O-}E_c{}^2} = \sqrt{5^2 + 3.18^2} = 5.92 \text{ inches.}$$

Thus, the ratio of E_g to E is $\frac{5}{5.92} = 0.844$, so that 84.4% of the available signal voltage is passed to the succeeding tube at 50 hertz, which represents a fairly high efficiency. Incidentally, the actual value of voltage E would be $0.592 \text{ I} \times 10^{-6}$ volts so that the impedance of the coupling circuit is 0.592×10^{-6} ohm or 0.592 megohm. It can be shown that the efficiency of the coupling is equal to its power factor. A pictorial summary of stage operation is seen in Fig. 16.

OSCILLATORS

The third type of circuit in electronic equipment is the oscillator. This is a circuit which electronically generates an alternating current, the frequency of which is determined by the values of certain components employed. Basically it is nothing more than an amplifier circuit with a portion of the output signal fed back to the input with the proper amplitude and phase relationship. Oscillators produce the RF carrier signals for the transmission of intelligence through space, make possible the heterodyne principles of radio reception, and have countless other applications. The oscillator is

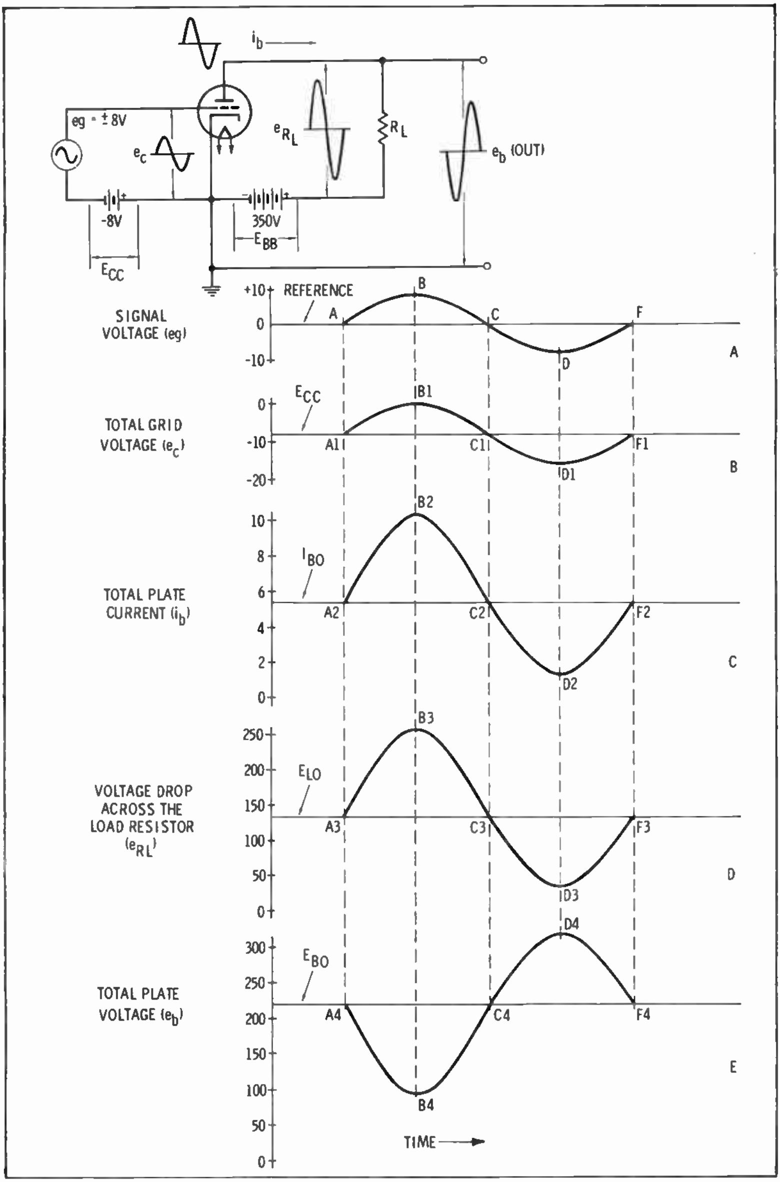


Fig. 16. Waveforms in a triode amplifier circuit.

self-sustaining in its operation due to the fact that it requires no external signal source, merely the normal supply voltages.

Fig. 17 shows one type of oscillator using what is known as a "tickler coil." In this circuit L1 and C1 determine the frequency of oscillation. The resonant frequency can be varied by adjusting C1, which is variable.

Mutual coupling between coils L3 and L1 is utilized to permit feedback from the plate to the grid circuit. The values of the LC combination (L1-C1) in the grid circuit determine the frequency of oscillation and C2 couples the signal to the grid. The resonant frequency, the frequency at which the circuit oscillates, can be changed by varying the value of C1, which is adjustable.

The correct bias for this stage is provided by the voltage drop across R1, while C3 serves to bypass the alternating current around the plate power supply. The AC output of the circuit is taken from L2, which is mutually coupled to L1.

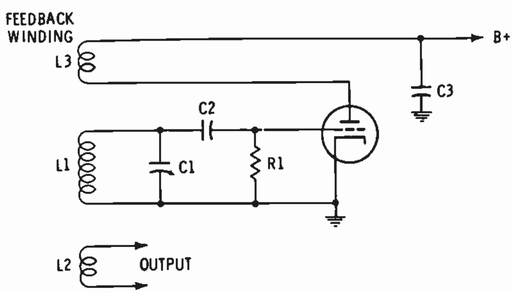
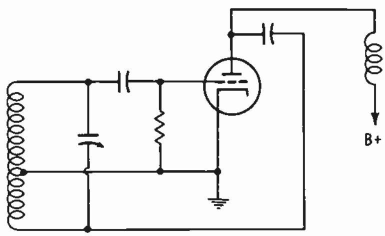


Fig. 17. "Tickler coil" oscillator circuit.

Circuit operation is as follows: When the circuit is excited (by applying operating voltages), an increasing plate current flows through L3 causing a voltage to be induced in L1. This voltage drives the grid of the tube more positive by charging capacitor C2. When the grid becomes sufficiently positive with respect to the cathode, any further increase in grid voltage will no longer cause the plate current to increase. At this instant one-half of the AC cycle has been completed. The constant plate-current flow through L3 results in a constant magnetic field, and since there is no variation in the magnetic lines of force at this time, no voltage is induced in L1. Therefore, capacitor C2 starts to discharge through R1. When this happens, the grid-to-cathode voltage begins to decrease from its high positive value and subsequently the plate current decreases. This decrease in plate current causes the magnetic field around L3 to collapse, inducing a voltage once more into L1. This time, however, its polarity is reversed. Now capacitor C2 is charged to a high negative value and plate current ceases. By this time there is no longer a magnetic field around L3 and therefore no voltage is induced in L1. Capacitor C2 begins to discharge, the grid becomes less negative, and once again the tube begins to conduct with increasing value, causing the entire cycle of operation to be repeated.

Fig. 18. Basic Hartley oscillator circuit.



All oscillator circuits operate on the principle just described; however, there is a considerable variation in methods of feedback, etc. Another basic oscillator known as the Hartley is shown schematically in Fig. 18. This is one of the simplest self-excited oscillators. Its distinguishing feature is the tapped coil used to obtain the feedback necessary for oscillation. As you can see the coil is connected between the grid and the plate. The tap, generally located nearer the plate end of the coil, is connected either directly or through a capacitor to the cathode of the tube. There are many variations even in the basic oscillator types.

Another popular circuit is the Colpitts oscillator shown in Fig. 19. In this circuit the feedback required for oscillation is obtained by dividing the tuned circuit into two parts. This division is accomplished by means of a capacitive voltage divider comprised of C_1 and C_2 connected in series across L_1. You will notice that this

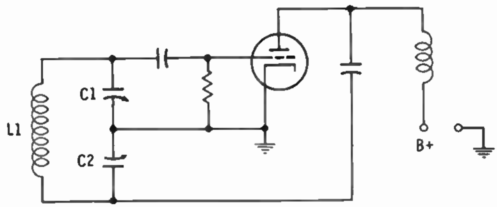


Fig. 19. Colpitts oscillator circuit.

oscillator circuit operates on the same principle as the Hartley except that the capacitance is tapped rather than the inductance.

Another interesting oscillator is the ultra-audion shown in Fig. 20. This oscillator works on the same capacitive-divider principle as the Colpitts; however, the capacitors do not exist as separate components. Here, the grid-to-cathode and grid-to-plate interelectrode capacitances of the tube itself form the voltage divider. This makes the feedback ratio entirely dependent on the characteristics of the tube, and the frequency stability is subject to all the heating effects of the tube elements. Adjustment of the feedback in this circuit is only possible by adding a variable capacitor of the proper value between the grid and cathode, grid and plate, or both.

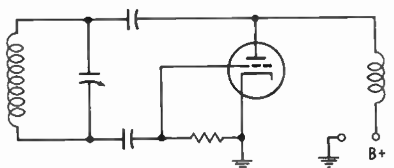


Fig. 20. Ultra-audion oscillator circuit.

BASIC TRANSISTOR CIRCUITS

Transistor amplifier circuits differ considerably from the familiar vacuum-tube circuits. At the same time there is a reasonable amount of similarity between the two. There are three possible circuits in which a tube can be connected. The transistor also has three circuit configurations which conform to the three vacuum-tube configurations. The comparisons are shown in Fig. 21. For

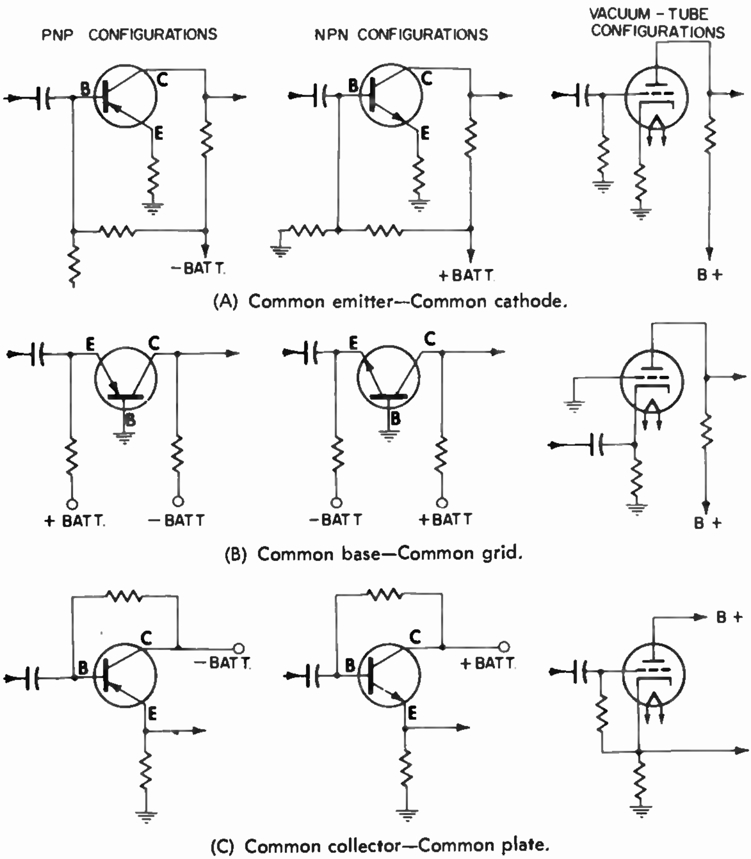


Fig. 21. Transistor circuits and their vacuum-tube counterparts.

each vacuum-tube configuration there are two transistor configurations, one for the PNP type and one for the NPN type.

The transistor circuit in Fig. 21A is a common-emitter circuit, which is used almost exclusively for most amplification purposes, just as the common- or grounded-cathode vacuum-tube circuit is also used extensively. The remaining circuit forms in Fig. 21 are used for more special applications, such as impedance matching to and from transmission lines or in place of matching transformers

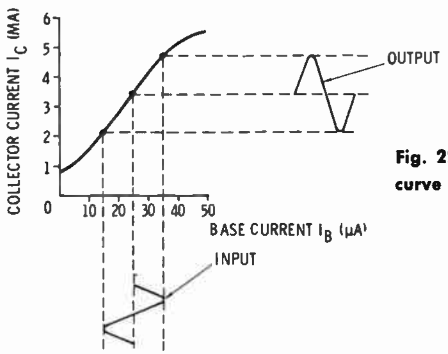


Fig. 22. Dynamic transfer characteristic curve showing linear (class-A) operation.

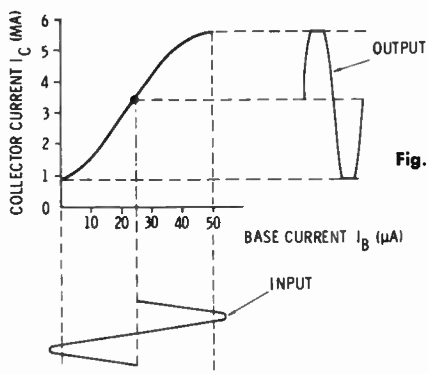


Fig. 23. Dynamic transfer characteristic curve showing overdriving.

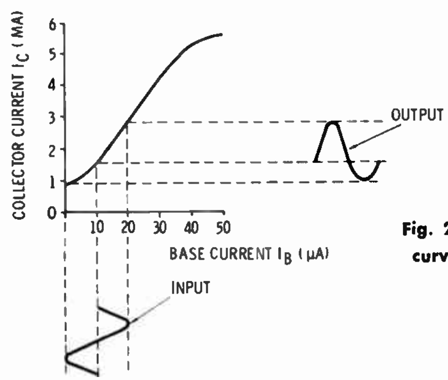


Fig. 24. Dynamic transfer characteristic curve showing nonlinear operation.

between amplifier stages. A visualization of normal class-A operation in the CE configuration is seen in Fig. 22. If the transistor is overdriven, the peaks of the output waveform become flattened, as shown in Fig. 23. An incorrect bias voltage causes compression of one-half cycle of the output waveform, as depicted in Fig. 24.

AMPLIFIER CIRCUIT RECOGNITION

A familiar tube circuit can be redrawn into another form that will be almost unrecognizable. The circuits used with the transistor can be even more unfamiliar. First, the circuits are new; and second, they can be arranged in two ways, with a PNP transistor and with an NPN transistor.

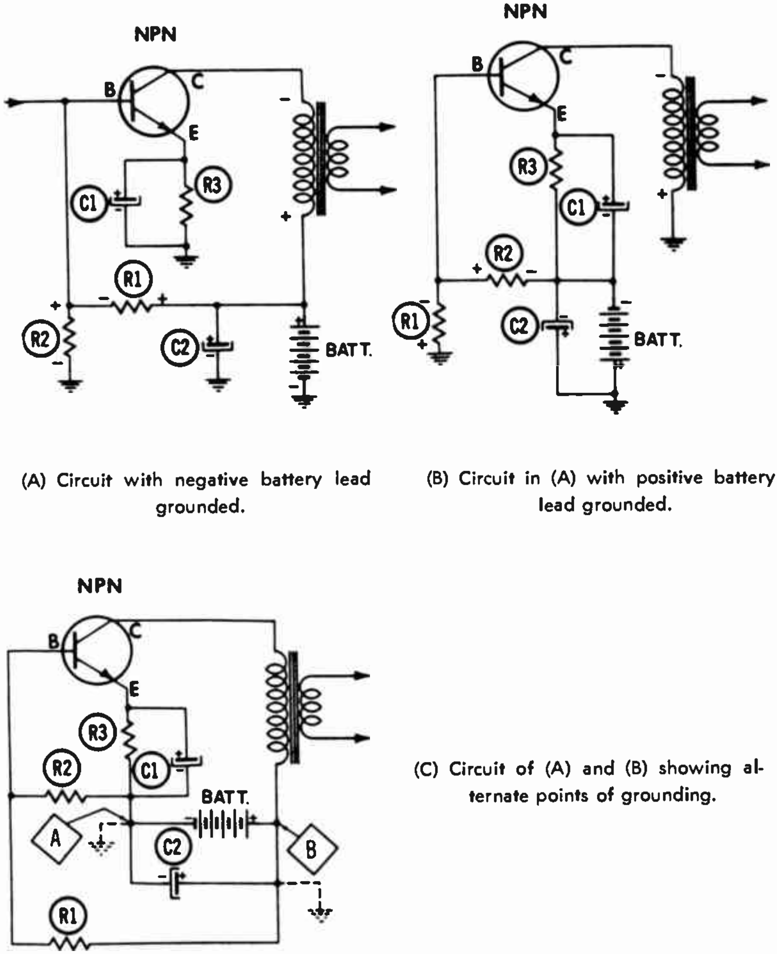
If the common-emitter circuit is drawn as in Fig. 25A, and if an NPN transistor is used, the circuit will closely conform to what we are accustomed. The positive battery terminal is connected to the collector. Bias is obtained from the tapped bleeder made up of resistors R_1 and R_2. The bias current must be obtained from the positive battery terminal through R_1.

This same circuit can be rearranged to look like Fig. 25B. The grounding of the battery terminal is the only difference between this circuit and the one in the previous paragraph. The same circuit is reproduced in Fig. 25C without a ground reference. Point A is grounded in Fig. 25A, and point B is grounded in Fig. 25B. The operation is the same in either case.

If a PNP transistor is used in this circuit, two drawings can again be made, one with the positive terminal grounded, as in Fig. 26A, and one with the negative terminal grounded, as in Fig. 26B.

Compare the PNP circuit with the NPN circuit and notice that the current is reversed in all of the components. Therefore, all of the electrolytic capacitors must be reversed when the transistors are changed from PNP to NPN.

With the vacuum tube, the interchange of current and voltage polarities between PNP and NPN transistors did not exist. Because of this interchange in the transistor, circuits that have no parallel in vacuum-tube circuitry can be produced. Nevertheless, the cir-



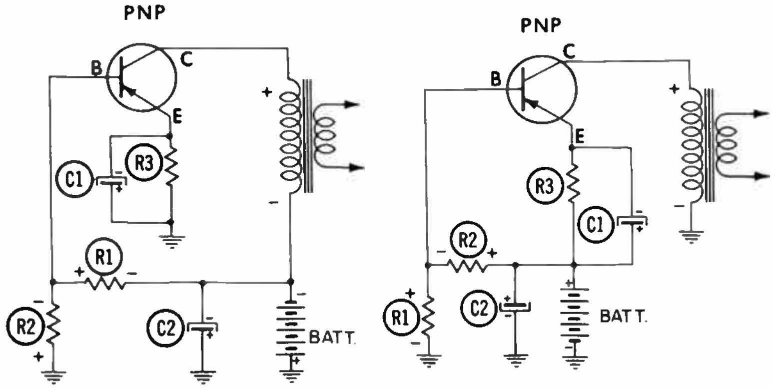
(A) Circuit with negative battery lead grounded.

(B) Circuit in (A) with positive battery lead grounded.

(C) Circuit of (A) and (B) showing alternate points of grounding.

Fig. 25. A common-emitter amplifier circuit showing different grounding points.

cuits of transistor equipment are quite similar in many respects to the circuits in vacuum-tube equipment.



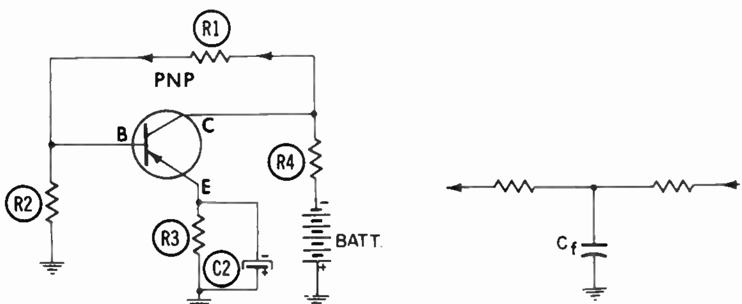
(A) Positive battery terminal grounded. (B) Negative battery terminal grounded.

Fig. 26. A common-emitter amplifier using a PNP transistor.

Input and Bias

A signal can be coupled to a transistor stage in a number of ways. Each stage is designed for a particular purpose; and the efficiency of the coupling, the biasing of the stage, the amount of gain desired, and the component cost are all considered.

The most efficient system of coupling a signal to a transistor is with a transformer that will provide a correct impedance match be-



(A) A circuit which accomplishes biasing and feedback simultaneously. (B) A frequency selective network which replaces R_1 in (A).

Fig. 27. Bias stabilization and signal feedback.

tween the signal source and the transistor. Although the transformer may be the most efficient, it has certain drawbacks, such as cost, weight, and frequency response. Because of the high gain of the transistor, a less efficient coupling system can be used and there is a wide variety of these from which to choose.

Signal Feedback

An arrangement for providing feedback in a single transistor stage is shown in Fig. 27A. Resistor R_1 biases the transistor and, at the same time, becomes part of a feedback system for the signal. The signal at the collector is impressed across resistors R_1 and R_2 and part of the output signal is applied to the transistor base.

The signal at the collector is 180° out of phase with the signal on the base, and the feedback now is degenerative. Resistor R_1 can be replaced by a network like the one shown in Fig. 27B. If the values of the capacitor and the resistors are varied, the feedback can be made frequency selective. If capacitor C_f is made large, the signal can be bypassed to ground and no signal feedback will take place. However, the DC bias stabilization will still be maintained.

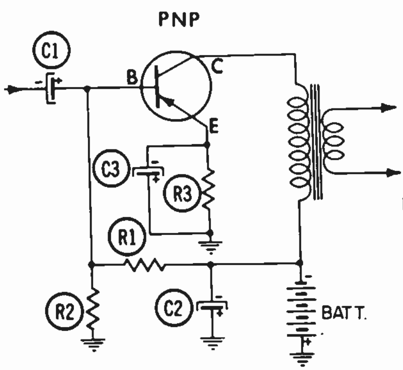


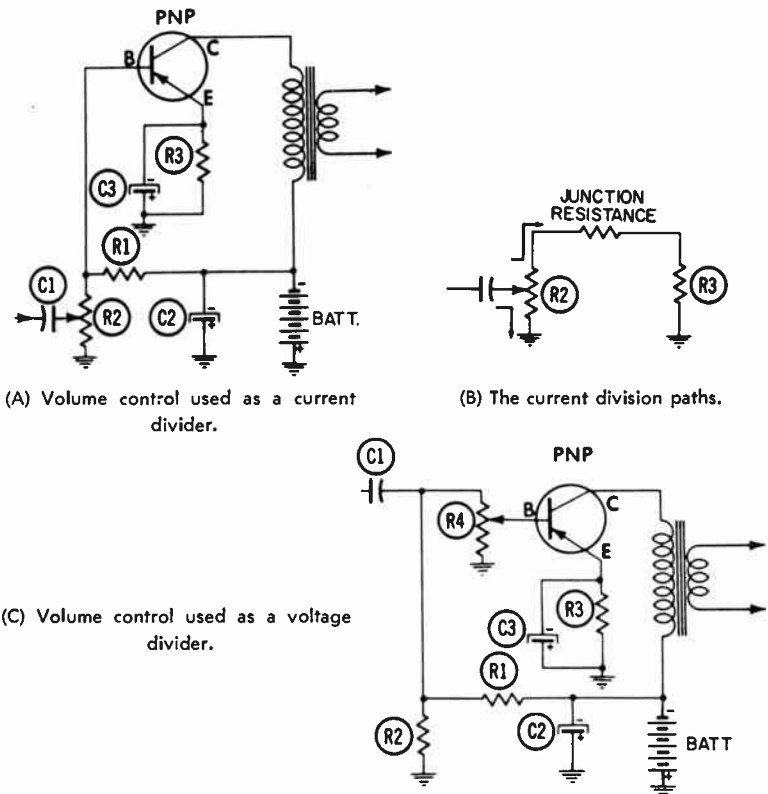
Fig. 28. A very common RC-coupled amplifier circuit.

The collector-to-base feedback of the signal is used principally in amplifiers designed to produce a particular frequency response, such as phonograph preamplifiers and high-fidelity sound systems.

Coupled Amplifiers

The input circuit in Fig. 28 is used more in audio amplifiers than probably any other circuit. This is an RC coupled input with an electrolytic capacitor to block the DC voltage from the previous stage. The capacitances of the electrolytics in such transistor stages range from 1 mfd to 100 mfd. Such high capacitance is needed to pass audio frequencies in a low-impedance circuit.

Coupling capacitor C_1 in Fig. 28 may be connected in either polarity, depending on whether the DC voltage at the take-off point of the preceding stage is positive or negative with respect to the voltage on the base of the transistor.



(A) Volume control used as a current divider.

(B) The current division paths.

(C) Volume control used as a voltage divider.

Fig. 29. Different types of volume-control circuits.

Fig. 29A is an RC-coupled stage in which R_2 is part of the bias network and acts as the volume control. The resistance of R_2 becomes a current divider for the incoming signal. The signal current is divided into two paths, as shown in Fig. 29B.

The volume control in Fig. 29C is a voltage-divider type. The signal is developed as a voltage across resistor R_4. Moving the slider changes the signal voltage at the transistor base and, at the same time, also changes the bias of the transistor. The signal level and the bias change simultaneously (less signal and less bias) and cause less battery power to be consumed on low volume than on high volume.

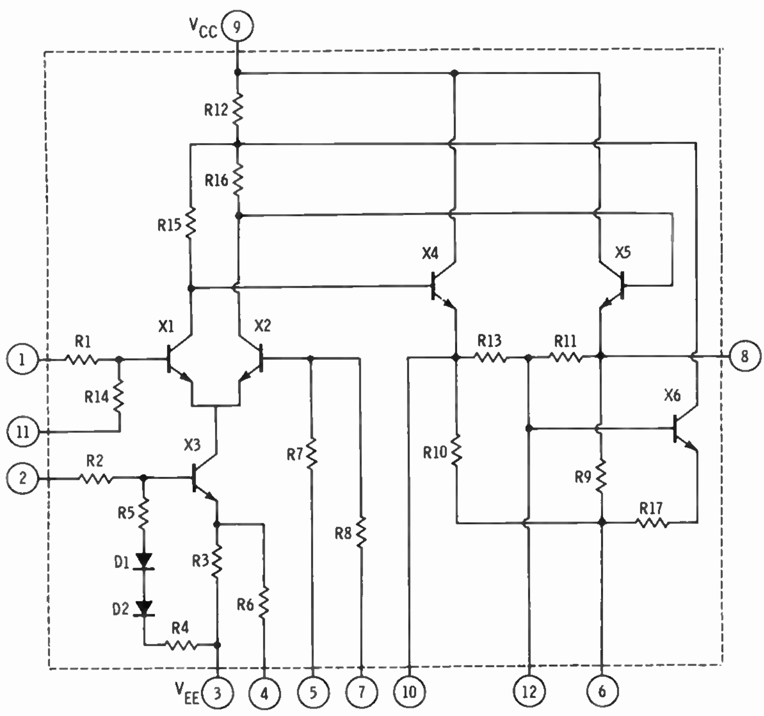


Fig. 30. Schematic diagram of the RCA CA3007 audio driver.

Fig. 30 shows the circuit for a typical integrated audio driver. This is a balanced differential circuit arrangement, which provides

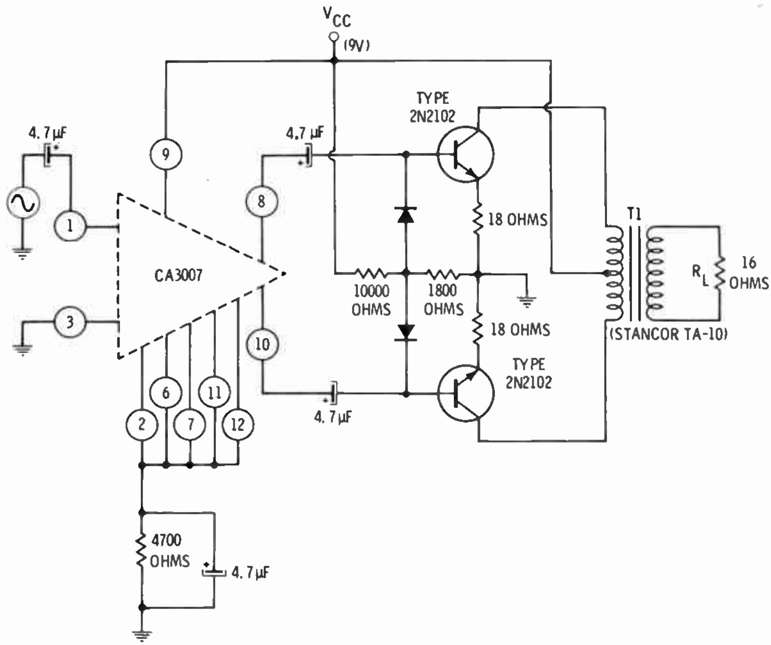


Fig. 31. The RCA CA3007 used as an audio driver for a 30-milliwatt audio amplifier.

for a single-ended input (or differential input) and push-pull output. Single-ended input is used in conventional receiver applications. The input stage of the IC comprises the differential pair of transistors X_1 and X_2; these transistors operate as a phase splitter, and provide some gain. In turn, the push-pull output signals from X_1 and X_2 are fed to the emitter followers X_4 and X_5. This is also a differential pair. Transistor X_3 operates as a constant-current unit. Transistor X_6 is part of a DC feedback loop which stabilizes the operating point of the amplifier.

Fig. 31 shows how the IC is used as a single-supply audio driver in an amplifier. This amplifier is rated for an audio power output of 30 milliwatts, with an input of 6.5 millivolts rms. Fig. 32 shows how the IC is used as an audio driver in a DC-coupled 300-mw

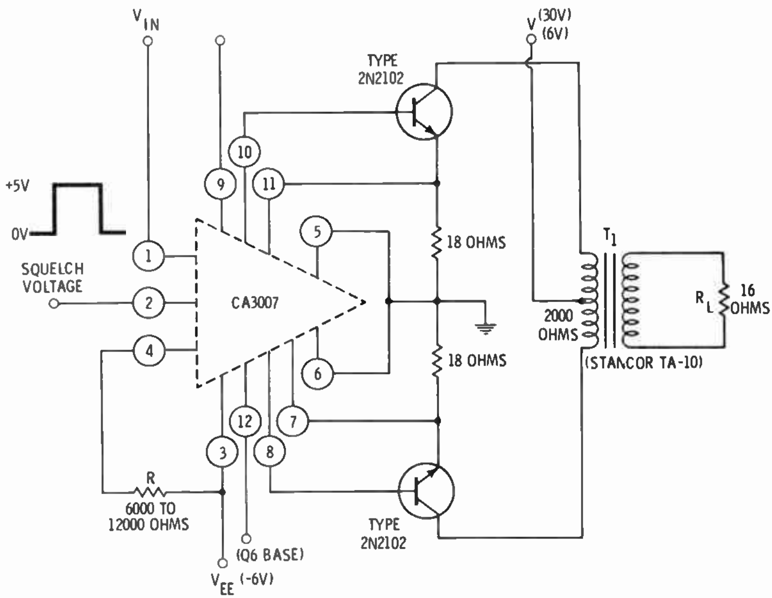


Fig. 32. The RCA CA3007 used as an audio driver for a direct-coupled 300-milliwatt audio amplifier.

amplifier. This arrangement lends itself to operation with a squelch (muting) function, if desired. The distortion of the amplifier is quite low, and varies from 0.95% to 1.27% from low-level to high-level output.

Transformer-Coupled Amplifiers

The transformer is used for coupling when high efficiency and proper impedance matching are important. However, the transformer is more expensive than the resistors and capacitors necessary to couple two amplifier stages. Often, special transformers are required to obtain the desired frequency response.

Many functions, such as accurately matching the output impedance of one transistor stage to the input of the next, are fullfilled extremely well by the transformer. With good matching, the maximum gain of the transistors can be approached.

A good example of transformer impedance matching between amplifier stages is the audio-amplifier and power-output stages of a hybrid auto radio. The diagram of such a circuit is shown in Fig. 33. The audio amplifier is a vacuum tube with a rather high output impedance, and the output stage is a power transistor with a very low input impedance. The difference between the two impedances is so great that, without the transformer T_1 (or some form of impedance-changing device), the tube cannot provide adequate drive signal to the base of the transistor. Transformer T_2 in the collector circuit of the transistor is used to match the collector impedance to the speaker impedance.

Direct-Coupled (DC) Amplifiers

The main advantage of DC-coupled amplifiers is that they eliminate transformers and coupling capacitors. These latter two devices tend to limit the frequency response of an amplifier. The DC amplifier will amplify signals from zero frequency to the high limit imposed by the amplifying device (transistor or tube) and by the associated wiring. In other words, direct coupling is quite a desirable feature in an amplifier.

Because high-voltage DC supplies are needed, direct coupling has never been very popular in vacuum-tube circuitry. Each stage

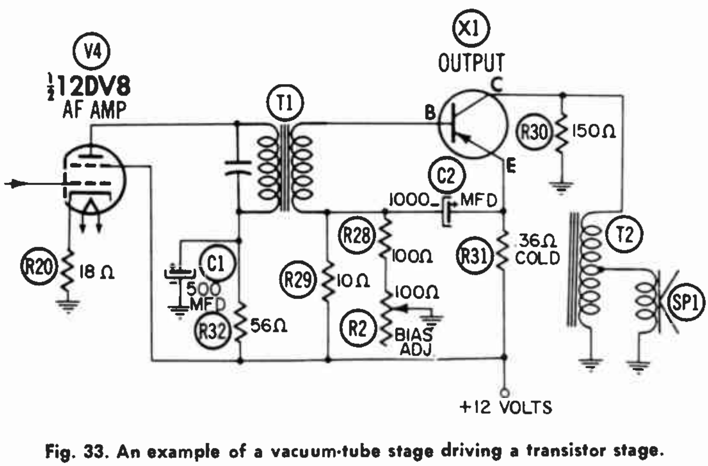


Fig. 33. An example of a vacuum-tube stage driving a transistor stage.

must have a higher supply voltage than that of the preceding stage; thus, the final signal must have an extremely high DC component.

The ideal system would be to have a small DC change above and below a given reference level, amplify this changing voltage, and end up with an amplified change that still swings above and below the original reference point.

A transistor can operate as a DC amplifier. A simplified version of a DC amplifier using PNP and NPN transistors is shown in Fig. 34. The arrows indicate the direction of electron flow.

The single battery supplies the power to all of the DC-coupled transistors in Fig. 34. Transistor X_1 is biased from the bleeder circuit of R_1 and R_2. The bias of transistor X_2 is controlled by the current flow through the collector of X_1. Similarly, X_3 is biased by the current through X_2.

Any current change at the first transistor is amplified greatly at the last stage. This high amplification is a property of the transistor DC amplifier. However, high amplification is also a detriment because transistors are temperature sensitive; therefore, any change in conduction due to a change in temperature will also be greatly amplified. A high-gain DC amplifier must have some system of compensating for temperature changes.

The circuit in Fig. 35 is the audio portion of a transistor portable receiver. Audio amplifier X_4 is direct-coupled to output transistor X_5. Transistor X_4 is biased near cutoff to permit only a small cur-

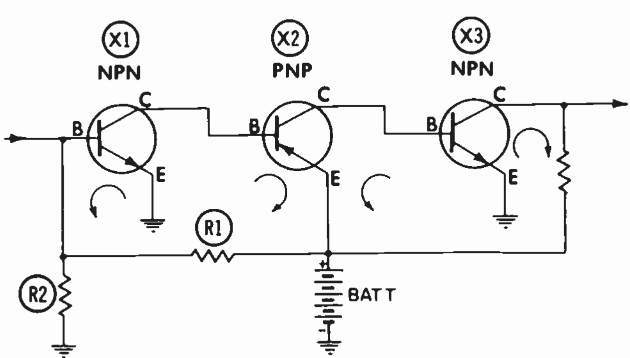


Fig. 34. A simplified DC amplifier.

rent to flow in the collector of X_4 and in the base of the following stage. This current provides the bias for output transistor X_5.

The volume control not only controls the signal level, but acts as a divider for the bias current. The signal and bias are increased or decreased simultaneously; and at zero signal setting, the output transistor is cut off. This system provides a saving in battery current because the amount of current used depends upon the volume setting.

Transistor X_4 operates as the detector and first audio amplifier. The transistor is biased near cutoff; therefore, practically no current flows between the base and emitter. The base-to-emitter junction

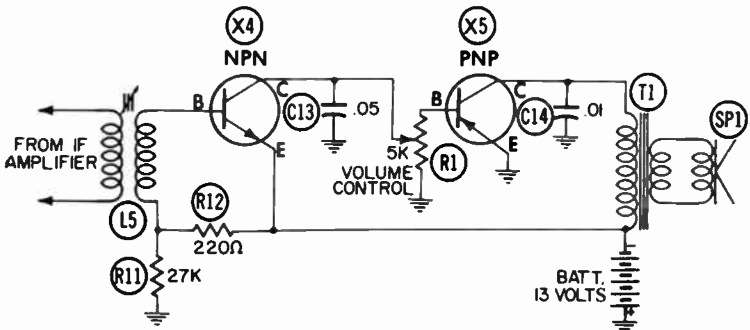


Fig. 35. A DC-coupled amplifier employed in a receiver.

acts as a diode and blocks the current flow on the negative swing of the IF signal, but conducts on the positive swing. These current pulses are amplified in the collector circuit. The RF is bypassed to ground by the .05-mfd capacitor C_{13}, leaving an audio signal with an amplitude great enough to drive the output stage and speaker of the receiver.

Remember that a transistor, unlike a vacuum tube, may be biased by a part or by all of the output current of another transistor. This is particularly true of the DC-coupled amplifier.

This method of biasing is used particularly where both PNP and NPN transistor types are contained in the same piece of equipment.

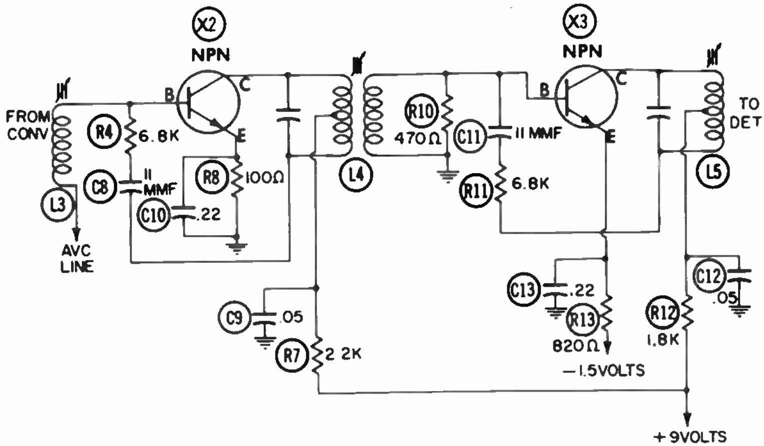


Fig. 36. An IF amplifier with single-tuned transformers.

RF and IF Amplifiers

The RF or IF amplifier employs transformer coupling between stages. The impedance match from one stage to the next is of prime

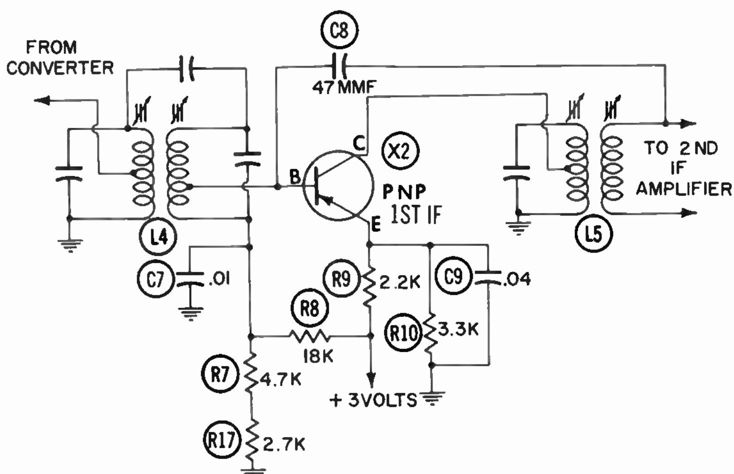


Fig. 37. An IF amplifier with double-tuned transformers.

importance; for this reason the IF transformers of a transistor radio are quite different from those in vacuum-tube receivers.

The IF amplifier circuit shown in Fig. 36 incorporates a tapped-primary IF transformer, single-slug tuning, low-impedance untuned secondary, and feedback to the base.

The impedances of tuned circuits are high compared to the collector and base impedances. The former are matched by using a tapped-primary IF transformer. Only a portion of the total impedance of the tuned circuit exists from collector to ground. A secondary winding must have even lower impedance, since it must drive the base of a common-emitter circuit. Untuned secondary windings are normal in transistor receivers, although some double-tuned (primary and secondary) IF transformers will be encountered.

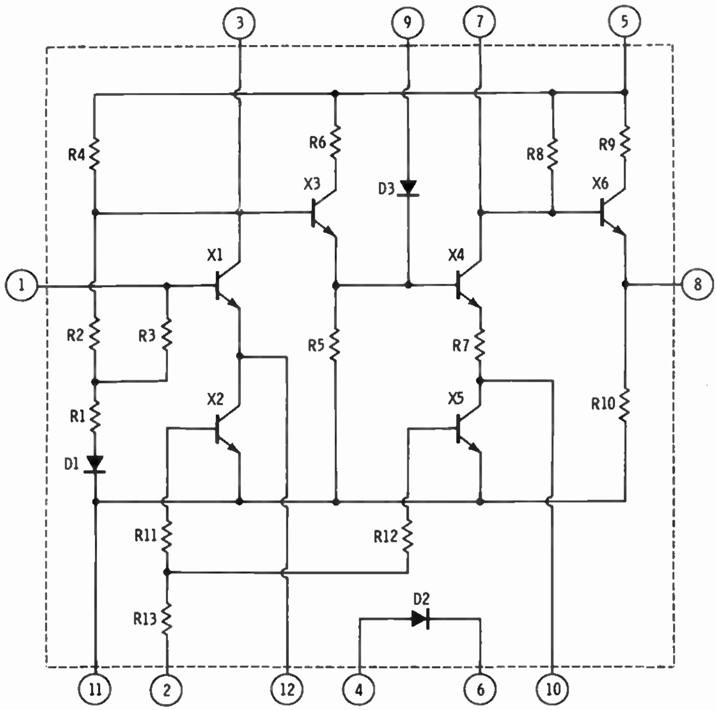


Fig. 38. Schematic diagram of the RCA CA3021 integrated circuit.

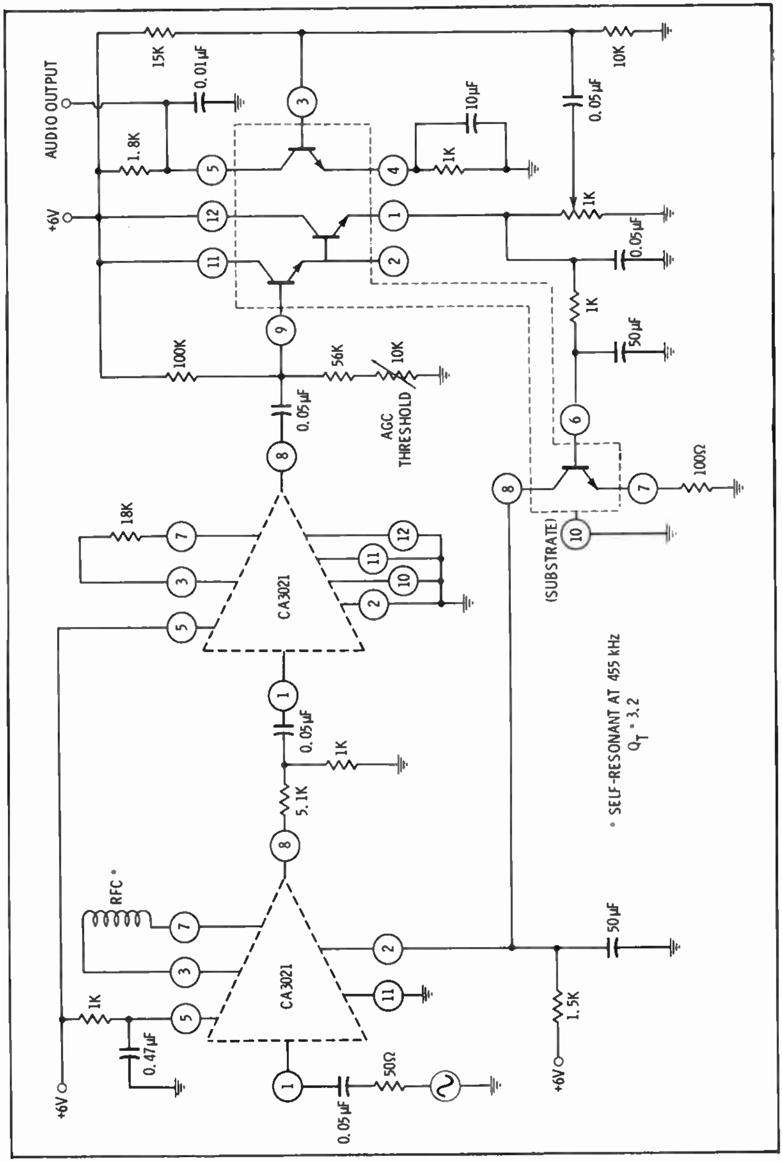


Fig. 39. Connections of the RCA CA3021 IC in a 455-kHz amplifier.

Table 1. Db Expressed as Power and Voltage (or Current) Ratios

Power Ratio	Voltage Ratio	− db + ← →	Voltage Ratio	Power Ratio
1.000	1.0000	0	1.000	1.000
.9772	.9886	.1	1.012	1.023
.9550	.9772	.2	1.023	1.047
.9333	.9661	.3	1.035	1.072
.9120	.9550	.4	1.047	1.096
.8913	.9441	.5	1.059	1.122
.8710	.9333	.6	1.072	1.148
.8511	.9226	.7	1.084	1.175
.8318	.9120	.8	1.096	1.202
.8128	.9016	.9	1.109	1.230
.7943	.8913	1.0	1.122	1.259
.6310	.7943	2.0	1.259	1.585
.5012	.7079	3.0	1.413	1.995
.3981	.6310	4.0	1.585	2.512
.3162	.5623	5.0	1.778	3.162
.2512	.5012	6.0	1.995	3.981
.1995	.4467	7.0	2.239	5.012
.1585	.3981	8.0	2.512	6.310
.1259	.3548	9.0	2.818	7.943
.10000	.3162	10.0	3.162	10.00
.07943	.2818	11.0	3.548	12.59
.06310	.2512	12.0	3.981	15.85
.05012	.2293	13.0	4.467	19.95
.03981	.1995	14.0	5.012	25.12
.03162	.1778	15.0	5.623	31.62
.02512	.1585	16.0	6.310	39.81
.01995	.1413	17.0	7.079	50.12
.01585	.1259	18.0	7.943	63.10
.01259	.1122	19.0	8.913	79.43
.01000	.1000	20.0	10.000	100.00
10^{-3}	3.162×10^{-2}	30.0	3.162×10	10^{3}
10^{-4}	10^{-2}	40.0	10^{2}	10^{4}
10^{-5}	3.162×10^{-3}	50.0	3.162×10^{2}	10^{5}
10^{-6}	10^{-3}	60.0	10^{3}	10^{6}
10^{-7}	3.162×10^{-4}	70.0	3.162×10^{3}	10^{7}
10^{-8}	10^{-4}	80.0	10^{4}	10^{8}
10^{-9}	3.162×10^{-5}	90.0	3.162×10^{4}	10^{9}
10^{-10}	10^{-5}	100.0	10^{5}	10^{10}

sized portable receivers because of the added weight and size. One double-tuned transformer may be used in a receiver, between the mixer and the first IF amplifier, to provide a greater degree of isolation between the oscillator and the first IF stage than a single-tuned transformer will provide.

A double-tuned IF transformer is shown in Fig. 37. Both the primary and the secondary are tapped at impedance points that will match the collector of the converter to the base of the first IF stage. Double-tuned transformers are not generally used in the personal-

An IC unit used in a 455-kHz IF amplifier is shown in Fig. 38. Transistors X_1, X_3, X_4, and X_6 are connected as a pair of DC-coupled CE/CC amplifiers, and provide a voltage gain of approximately 60 db. A db chart is given in Table 1. Fig. 39 shows how the IC units are connected for two stages of 455-kHz IF amplification. The RF feedback choke is self-resonant at 455-kHz. For precise bandwidth control (such as 10 kHz), a tuned IF transformer may be used to couple the signal source to the first IC unit.

SUMMARY

All electronic equipment, regardless of its complexity, is made up of basic circuits. Considering each circuit separately, the complexity disappears. Also, all electronic circuits are one of three basic types—a rectifier, an amplifier, or an oscillator.

Rectifiers are used to change AC into some form of pulsating DC. Detection is a form of rectification in which AC signal voltages are changed to variable DC. Automatic volume control (AVC) is one of the functions performed by a detector circuit.

Amplifiers produce an output which is larger than their input. Thus, weak signals can be built up to a useful level. There are three main classes of amplifier operation—class-A, class-B, and class-C. Each finds a useful application in modern circuits.

Oscillators electronically generate an alternating current at a frequency determined by certain components in the circuit. An oscillator is basically an amplifier with a portion of its output fed back to the input at the proper amplitude and phase relationship.

REVIEW QUESTIONS

1. Name the three basic classes of electronic circuits.
2. Define a rectifier.
3. Give two applications of rectifier circuits in an AM radio.
4. What is the primary function of an amplifier circuit?
5. What is grid bias?
6. Define a class-B amplifier.
7. Define an oscillator.
8. Give an application of an oscillator circuit in an AM radio.
9. What is one feature of a Colpitts oscillator that makes a schematic of this type of circuit easy to recognize?
10. What is the main advantage of a direct-coupled transistor amplifier?

CHAPTER 15

Power-Supply Circuits

The function of a power supply is to deliver all of the operating voltages necessary to power one or more pieces of electronic equipment. It may be relatively simple, consisting of one or more DC batteries; or it may be complex, having a number of diode vacuum tubes or semiconductor diodes and various transformers, choke coils, capacitors, and resistors. A power supply may deliver a single voltage of a higher or lower value than the primary power source or it may be required to provide a number of different voltage and current values. Most AC power supplies using a power transformer are designed to deliver at least one value of high-voltage DC plus one or more values of low-voltage AC much lower than that supplied to the transformer primary.

The high-voltage DC is used to supply the plates of the vacuum tubes with the proper positive potential, and the low-voltage AC powers the tube filaments (in the case of cathode-type tubes). When tubes using the filament as the cathode are employed (except as a rectifier in power-supply circuits), the filaments must also be supplied with DC; otherwise, undesirable hum voltages will be passed along to other circuits.

RECTIFIER TUBES

Rectifier tubes are generally divided into two classes—the half wave and the full wave. In modern AC systems, however, the latter is most commonly employed. In the half-wave rectifier circuit (Fig. 1), only one-half of the current wave is utilized, whereas in the full-wave rectifier (Fig. 2), both halves of the wave are utilized.

It is also possible to connect two half-wave rectifier tubes in such a way as to obtain full-wave rectification.

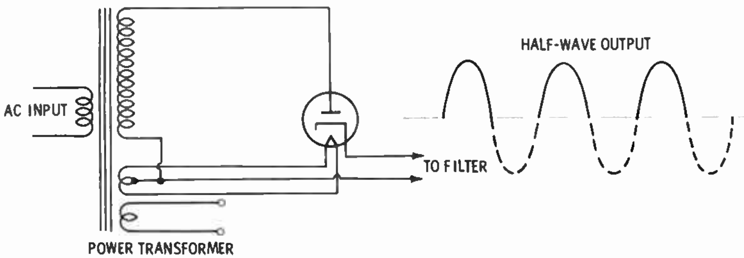


Fig. 1. A half-wave rectifier circuit.

Since the full-wave rectifier produces twice as many impulses, its output is considerably easier to filter into the desired smooth direct current.

There have been two general types of rectifier tubes used: (1) The high-vacuum type, in which the conduction is purely by means of the electron stream from the cathode to the plate, and (2) those in which a small quantity of mercury has been introduced after the tube has been evacuated. In the latter type, part of the mercury vaporizes when the cathode reaches its operating temperature, and during the part of the cycle in which the rectifier is passing current, the mercury vapor is broken down into positive and negative ions. The ions decrease the normal resistance of the plate-cathode circuit and the voltage drop in this type is less than in the high-vacuum types.

As a result of this lower voltage drop, the power loss (I^2R) is lower, and the efficiency of the mercury-vapor rectifier is higher than the high vacuum type. Despite its advantages, the mercury-vapor tube is no longer used in radio receivers. It is, however, used quite frequently in high-voltage power supplies for radio transmitters.

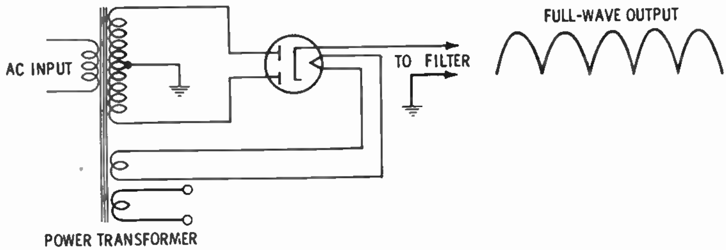


Fig. 2. A full-wave rectifier circuit.

SOLID-STATE RECTIFIERS

As mentioned previously, the present trend is toward the use of solid-state rectifiers, such as germanium or silicon. Because of this the following examples of rectifier circuits will include these devices. These same circuits apply to vacuum-tube rectifiers except that a source of filament power must be provided.

Rectifiers may be connected in various ways depending upon the direct-current power requirements for a certain application. When rectifiers are connected in single- and three-phase circuits, they are termed:

1. Half wave.
2. Bridge.
3. Center tap.

Half-wave rectification is generally used in applications that require small amounts of power. The ripple frequency is the same as the supply frequency, and the ripple component is large since the

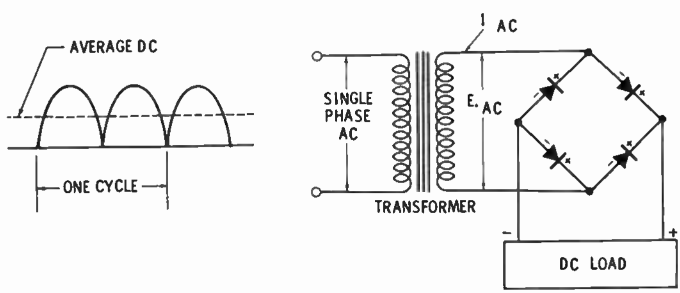


Fig. 3. A full-wave-bridge rectifier circuit.

rectifier conducts only during one-half of the input cycle as noted previously in Fig. 1.

Equipment using this form of rectification usually requires a special transformer design because of the unidirectional flow of DC current through the secondary.

The bridge single-phase rectifier (Fig. 3) is popular because it offers flexibility of design, full-wave rectification, and a ripple frequency that is twice the power-line frequency. It also offers high efficiency and utilization of an economical transformer design. Its field of application covers every phase of electronic and electrical design.

The center-tap, single-phase rectifier (Fig. 4), in common with the single-phase, bridge type, has a high ripple frequency and is

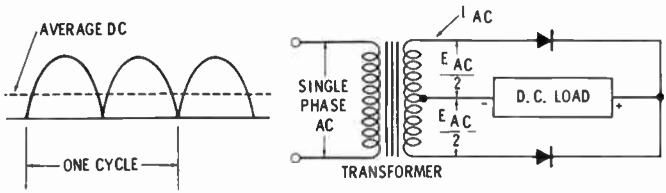


Fig. 4. Rectifier connections in a center-tapped, single-phase circuit.

highly efficient. The transformer design, however, is more complicated.

The three-phase, half-wave rectifier circuit shown in Fig. 5 is used primarily in low-voltage, high-current applications. The output ripple frequency is three times the source frequency, and the

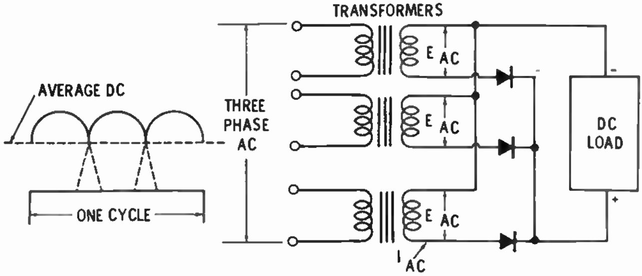


Fig. 5. A three-phase, half-wave rectifier circuit.

load ripple component is approximately 20 percent. The three-phase, half-wave rectifier is commonly used in commercial electroplating applications that may require thousands of amperes of current.

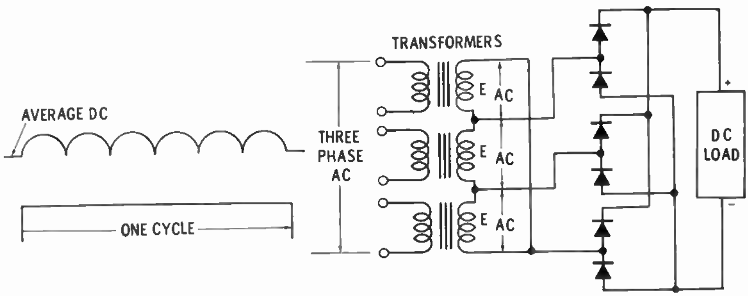


Fig. 6. A three-phase-bridge rectifier circuit.

The three-phase bridge rectifier shown in Fig. 6 supplies one of the most economical and useful circuits where DC power requirements are high and efficiency is an important factor. Here the ripple frequency is six times the source frequency and the load ripple component is only 4.5%. In most applications filtering is not required. Popular applications include aircraft motor starters, electrolysis equipment, large power supplies, and arc-welding equipment.

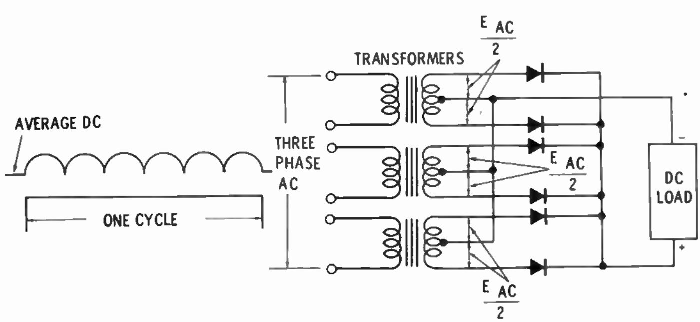


Fig. 7. A center-tapped, three-phase rectifier circuit.

The three-phase, center-tap circuit (Fig. 7) is generally used where the DC voltage requirements are low and load current requirements are high. Special transformer design is required to provide a six-phase secondary.

FILTER SYSTEMS

The primary function of the filter system is to smooth out the remaining ripples or pulsations in the voltage received from the rectifier.

Smoothing filters are comprised of capacitors and filter chokes; however, in some instances resistors are used in place of the choke coils. Filters are generally classified as choke input or capacitor input depending on whether a choke or a capacitor follows the rectifier output. Figs. 8 and 9 show a choke-input and capacitor-input filter, respectively.

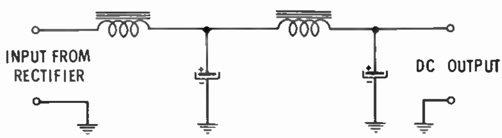


Fig. 8. A choke-input filter.

If a capacitor-input type is used, consideration must be given to the instantaneous peak value of the AC input voltage. This peak voltage is two times the root mean square (rms) value as obtained by an AC voltmeter. Hence, filter capacitors, especially the input capacitor, should be of a rating high enough to withstand the instantaneous peak voltage if breakdown is to be avoided.

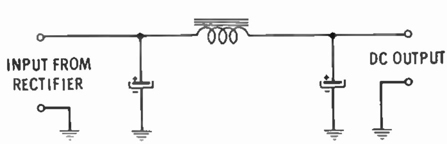


Fig. 9. A capacitor-input filter.

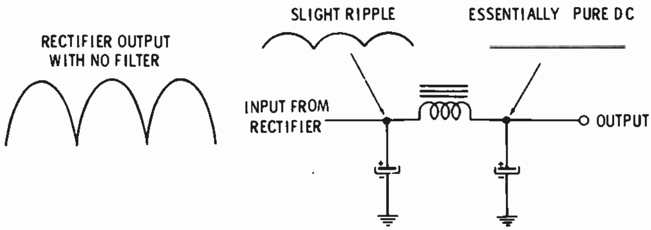


Fig. 10. Smoothing action of a power-supply filter.

When the choke-input type is used, the available DC output voltage will be somewhat less than with the capacitor-input type for a given AC plate voltage; however, in the later type improved regulation together with lower peak current will be obtained.

The basic action of the filter is shown in Fig. 10. The input capacitor charges up to the peak value of the pulse from the rectifier. Following the pulse is a drop in voltage; however, the filter capacitor remains charged at the peak voltage value. By the time this charge begins to diminish (due to current being drawn by the load connected to the supply) the next pulse arrives and recharges the capacitor. The result of this action is that the ripple voltage is greatly reduced. The choke coil provides further smoothing action and the output filter capacitor, which performs in the same manner as the input capacitor, delivers an essentially pure DC voltage (the ripple can never be reduced to absolute zero). The filter shown in Fig. 10 is referred to as a single-pi filter. When additional filtering is required, a two-pi filter (which merely consists of a duplicate circuit connected in series) is employed.

VOLTAGE DIVIDERS AND BLEEDERS

The function of a voltage divider is to provide several different voltage values from a single output. The principal method in each system is to lower the voltage by means of one or more resistors inserted in the circuit. When one resistor is utilized, it is generally tapped at suitable intervals, as shown in Fig. 11. The voltage divider shown here also serves as a bleeder resistor. The bleeder has two major functions: (1) It bleeds off the charge on the filter ca-

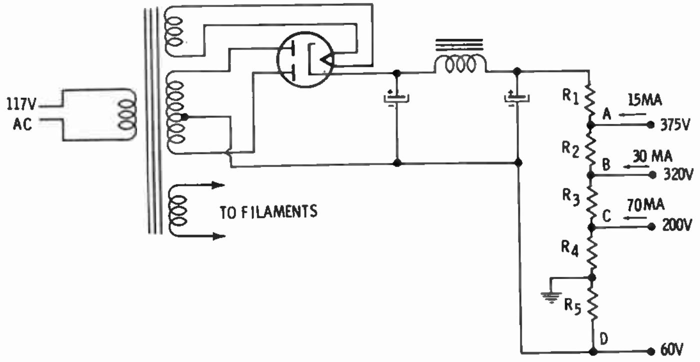


Fig. 11. A voltage divider network.

pacitors when the set is turned off, and (2) it improves the voltage regulation by providing a minimum load of constant value.

Before discussing bleeder resistors, however, let us see how to calculate the values of resistance necessary to drop a desired amount of voltage.

Example: Assume that the power supply shown in Fig. 11 has 450 volts across its output terminals and that the required voltages and currents are as follows:

1. 375 volts at 15 ma.
2. 320 volts at 30 ma.
3. 200 volts at 70 ma.
4. Minus 60 volts at zero current.

Solution: To compute the resistance values in a voltage divider, a bleeder current must be known or assumed. A current of .01 ampere is common.

The first step in computing resistance values is to find the value of R_1. To produce 375 volts at circuit A, R_1 must have an IR drop of 75 volts. Flowing through R_1 are the currents in all of the circuits plus the bleeder current; this totals 0.125 ampere. Using Ohm's law:

$$R_1 = \frac{E_1}{I_1} = \frac{75}{0.125} = 600 \text{ ohms}$$

Resistor R_2 must drop 65 volts and has a current of .01 + .03 + .07 = .110 ampere.

Again, by Ohm's law:

$$R_2 = \frac{E_2}{I_2} = \frac{65}{.110} = 590 \text{ ohms}$$

Resistor R_3 must drop 120 volts and has a current of .08 ampere.

Again by Ohm's law:

$$R_3 = \frac{E_3}{I_3} = \frac{120}{.08} = 1{,}500 \text{ ohms}$$

Resistor R_4 must drop 200 volts and has only the bleeder current flowing through it.

Using Ohm's law:

$$R_4 = \frac{E_4}{I_4} = \frac{200}{.01} = 20{,}000 \text{ ohms}$$

Resistor R_5 must drop 60 volts and has the sum of all the currents, or .125 ampere, flowing through it. By Ohm's law:

$$R_5 = \frac{E_5}{I_5} = \frac{60}{.125} = 480 \text{ ohms}$$

Bleeder Resistors and Their Uses

It is common practice to connect a bleeder resistor across a power supply to obtain a more stable output—that is, to improve the voltage regulation. However, this is often accomplished without any fundamental knowledge of how a bleeder resistor actually works and how its exact size may be calculated.

Voltage regulation may generally be defined as the change in potential with a change in the load or current consumed. Voltage regulation is an important consideration in power supplies for radio receiving circuits because the current may change with signal intensity, line-voltage fluctuation, etc., and it is highly desirable and often imperative that the voltage remain constant.

A problem of this kind may best be studied by considering the arbitrary condition existing in the simple filter system of a power supply, shown in Fig. 12.

In this circuit, E is a source of constant voltage. Choke C has a DC resistance of 1,000 ohms. E_L is the potential supplied to load R_L, which may be the palte circuit of a receiver. Switch S applies or removes the load.

It is assumed that the load is such that it requires 100 ma at 1,000 volts for the most efficient operation, which according to Ohm's law gives R_L a resistance of 10,000 ohms. R_b is a 10,000-ohm bleeder resistor which at first is not connected.

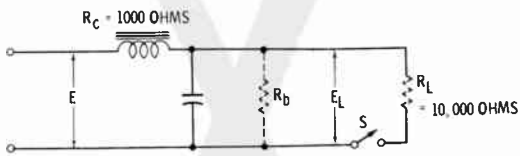


Fig. 12. Application of a bleeder resistor across a power supply.

If R_L draws a current of 100 ma, the drop through choke C will be 100 volts, and E, therefore, must be 1,100 volts in order that load voltage E_L shall provide the 1,000-volt potential.

However, with the switch open, the no-load voltage (E_L) will be the same as E, or 1,100 volts. When switch S is closed, this 1,100-volt potential will momentarily be applied to the load but will drop almost immediately to the required potential of 1,000 volts. In other words, the change in voltage with the change in load has been a drop from 1,100 volts to 1,000 volts or a voltage regulation of 100 volts.

Assuming that R_b is also connected in the circuit, it is evident that as R_b also draws current, the drop through R_c will be increased. Hence if E_L is to be maintained at 1,000 volts, the source voltage will also have to be increased. With E_L at 1,000 volts and R_L and R_b at 10,000 ohms each, the current drain through the circuit will be 200 ma and the drop across C will be 200 volts. Therefore, the voltage at E will have to be raised to 1,200 volts.

It is evident that the no-load voltage (switch S being open) will no longer be the total voltage at E, but instead the voltage drop across R_b. This may be easily calculated by using Ohm's law.

The bleeder current through R_b will be $\frac{E}{R_c + R_b}$ or 0.109 ampere; the voltage drop across R_b (or the no-load voltage) will be $I \times R_b = 0.109 \times 10{,}000$ or 1,090 volts. Since the no-load voltage is 1,000 volts, the change due to regulation will be 90 volts, or an improvement of 10 volts over conditions when the bleeder is not employed.

It will be observed that the improvement in regulation obtained by using a bleeder resistor is not as much as might be expected. While the conditions in the above problem have been arbitrarily assumed, similar arithmetical treatment will apply to actual cases encountered in equipment.

It is evident that the lower the value of the bleeder resistor, the greater the regulating effect, but at the same time the lower will be the available voltage. The bleeder is essentially a wasteful proposition and particularly so when its value is made sufficiently low to secure any real degree of regulatory effect. However, a bleeder of even say 100,000 ohms will be effective in preventing excessively high potentials which could damage tubes and other components under no-load conditions.

POWER-SUPPLY TYPES

Radio power supplies generally fall into one of three categories:

1. The AC supply, which operates from alternating current only.
2. The DC supply, which operates from direct current only.
3. The AC/DC supply, which will operate from either AC or DC power.

AC Power Supplies

This is the type of power supply that has been discussed in previous examples. It generally consists of a power transformer, a tube or solid-state rectifier, and a filter, such as those shown in Figs. 8 and 9.

The purpose of the power transformer is to supply a high voltage to the rectifier for rectification of the alternating current and to supply the heaters or filaments with the required voltage and current. After the high-voltage AC from the transformer secondary is rectified, it is fed to the filter network where it is smoothed out to almost pure DC as described previously.

Voltage-Doubler Circuit—Another type of AC circuit is the voltage doubler. As its name implies this circuit makes it possible to obtain twice the AC input voltage without the need for a power transformer. The circuit shown in Fig. 13 represents a typical volt-

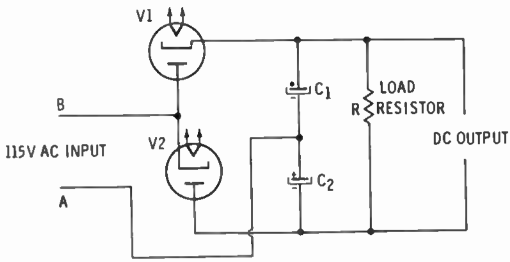


Fig. 13. A voltage-doubler circuit using vacuum tubes.

age doubler without a power transformer, although a power transformer may be employed if the voltage requirements demand it.

The action that takes place within this circuit is briefly as follows: During the half cycle when terminal B is positive with respect to A, rectifier V_1 is conducting and capacitor C_1 is being charged. The two capacitors are connected in series with respect to load resistor R, which results in the doubling of the voltage appearing across this resistor. This is because the charges across the indi-

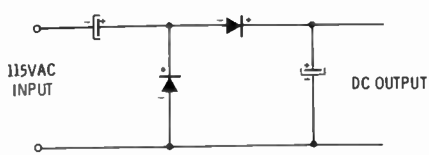


Fig. 14. A voltage-doubler circuit using semiconductor diodes.

vidual capacitors are added. Fig. 14 shows a similar voltage-doubler circuit using semiconductor diodes.

DC Power Supplies

Practically all modern radio equipment (except battery operated) is designed to operate from an AC power source. However, there are certain localities in which direct current is furnished and hence the radio equipment used in those localities must be designed for operation with a DC power supply.

Obviously, since DC is practically pure, no rectifier is required. All that is necessary is a filter system which serves to smooth out any slight remaining ripples. Filament power in these supplies is generally dropped to the desired value by means of resistors, or else the tube filaments are connected in series so that the full value of DC voltage may be divided among them.

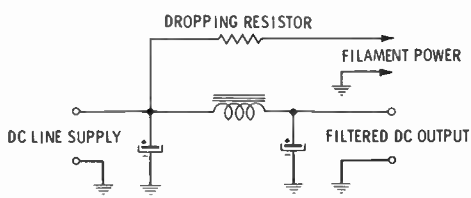


Fig. 15. One type of filter arrangement for a DC power supply.

The filaments may be arranged either in series or parallel. However, if they are connected in series, all tubes must have the same current rating. The disadvantage in both cases is a considerable amount of power dissipation in the form of heat. Fig. 15 shows a conventional filter for a DC power supply.

There are several other types of DC power supplies that are very common. The simplest DC supply, of course, is the common dry-cell, mercury, and nickel-cadmium batteries used in practically all portable radios. Some of the portable models still employ vacuum tubes, but the majority use transistors, since they permit more compact construction and require less operating power.

Another common type of power supply, known as the DC-to-DC converter, has been used extensively in automobile radio receivers. This circuit (Fig. 16) converts the relatively low-voltage DC of the car battery into the higher-voltage DC required for operation of the radio receiver. In order to do this, however, the DC must first be converted into a form of AC so that the transformer can provide the proper step-up action. The high-voltage output of the transformer secondary is then rectified and filtered in the conventional manner.

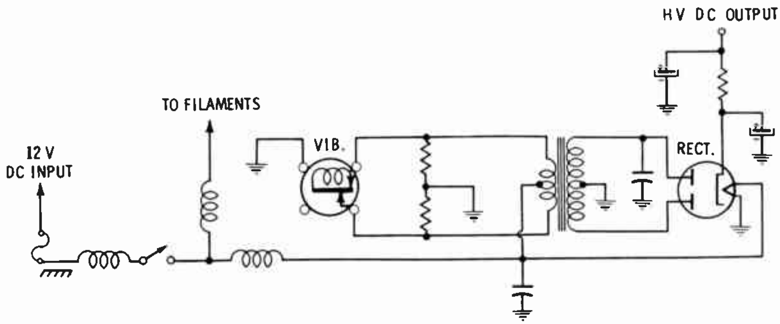


Fig. 16. A DC-to-DC converter using a vibrator.

From the diagram you will notice that the filaments are supplied directly from the primary DC source. This same voltage is applied to the vibrator which produces a mechanical switching action that alternately reverses the flow of current through the primary winding. This, in turn, produces the stepped-up AC voltage in the secondary.

Rapidly replacing the vibrator power supply is one using transistors (Fig. 17). In this circuit the DC current is switched back and forth electronically rather than mechanically as in the case of the vibrator supply. This switching action is produced by the two transistors which cause the DC to alternately reverse its direction. This alternating current is stepped up by the transformer and, in turn, is filtered in the usual manner. The transistor power supply requires less power for operation and is much more efficient than the vibrator type.

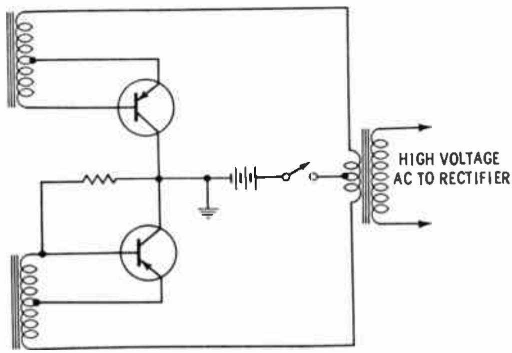


Fig. 17. A transistorized power-supply circuit.

AC-DC Power Supplies

The third type of power supply is known as the AC/DC, or universal, power supply. Used primarily in the less expensive table-model radios, phono amplifiers, and similar devices, this supply will operate equally well from either a 117-volt AC or DC power source. This type of circuit is both practical and economical because of its versatility and because it requires fewer electronic components and less physical space than the average AC power supply.

Fig. 18 shows a typical AC/DC power supply of the type employed in a small table-model radio. As you can see, no power transformer is required. The AC line voltage is rectified in the usual

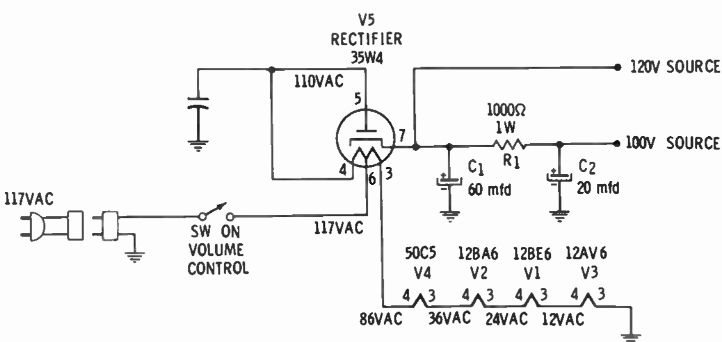


Fig. 18. A typical AC-DC power-supply circuit.

manner by V_5 and is subsequently filtered by the combination of C_1-R_1-C_2. It is a common practice in power supplies of this type to use a resistance, such as R_1, in the filter in place of a choke coil. B+ voltage for the receiver circuits is taken off at the points indicated, and all tube filaments are connected in series. The line voltage is divided among the tubes in proportion to their specific voltage rating.

There are a number of variations in AC/DC power supplies; some are more elaborate than others, etc., but basically their theory of operation is the same.

SUMMARY

The function of a power supply is to deliver all of the operating voltages necessary to power one or more pieces of electronic equipment. A power supply may be relatively simple, consisting of one or more batteries, or it may be much more complex, with a number of diodes, transformers, chokes, capacitors, and possibly vacuum tubes or solid-state devices.

AC power supplies are either the half-wave or full-wave variety. The type depends on the requirements of the equipment to be powered and on the cost factor. Rectifier tubes used in power supplies are normally of the vacuum type, but for units where the current demand is greater, mercury-vapor or other types of gaseous tubes may be used.

The modern trend in power supplies is toward the use of solid-state rectifiers such as germanium, silicon, or selenium. The advantage of solid-state devices over tubes is their smaller size and a source of filament power is unnecessary.

The rectified AC in a power supply must be filtered to reduce or remove the ripple frequency that is present. This is accomplished by means of chokes (inductors), capacitors, and resistors. These components may be used individually or in combination to achieve the desired reduction in the ripple.

Many power supplies are designed to furnish two or more output voltages. When this is the case, a network of resistors (or a single tapped resistor) is used to provide different voltages. This part of a power supply is called a voltage divider or bleeder. It serves also to discharge the filter capacitors in the power supply when the equipment is turned off. In addition, the bleeder also improves the voltage regulation of the unit.

REVIEW QUESTIONS

1. What are the two general types of AC power supplies?
2. What is the ripple frequency of a full-wave bridge rectifier operating from a 60-Hz source?
3. What advantage do solid-state rectifiers have over tube rectifiers?
4. What is the ripple frequency of a three-phase, half-wave, rectifier circuit?
5. Is the output voltage of a choke-input filter higher or lower than that of a capacitor-input filter?
6. Draw the schematic diagram of a single-pi filter.
7. What are the two major functions of a bleeder resistor?
8. What are the principle components in an AC power supply?
9. What is a common application for an AC/DC power supply?
10. What is the purpose of a vibrator-type power supply?

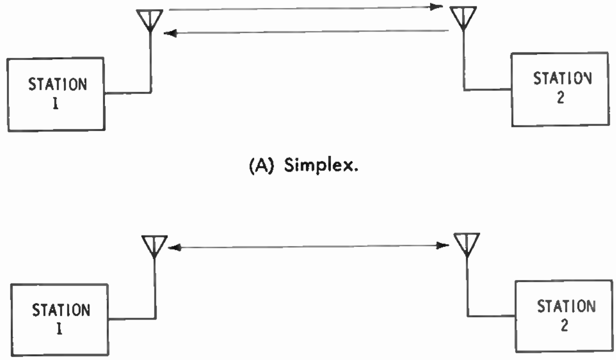
CHAPTER 16

Radio Transmitting and Receiving Principles

Radiocommunications is made possible by the radiation and reception of electromagnetic energy. This energy is produced by a radio transmitter, delivered to the antenna system where it is radiated into space, and finally is picked up by the receiver, which converts it into a form of energy that can be heard and understood.

SIMPLEX AND DUPLEX OPERATION

There are two basic methods or radiocommunications—one-way and two-way. One-way communications is generally referred to as broadcasting and may involve the transmission of either audio signals as in the case of radio broadcasting or both audio and video signals as in telecasting. In two-way radiocommunications, both stations are designed to transmit as well as receive. Fig. 1 shows two methods of communicating by means of two-way radio. One method is known as simplex operation and the other, duplex. With simplex (Fig. 1A) station 1 transmits while station 2 listens. At the completion of the transmission, station 2 can transmit back to station 1. However, at no time can the transmitting station hear the other station. In short, simplex operation permits communications



(A) Simplex.

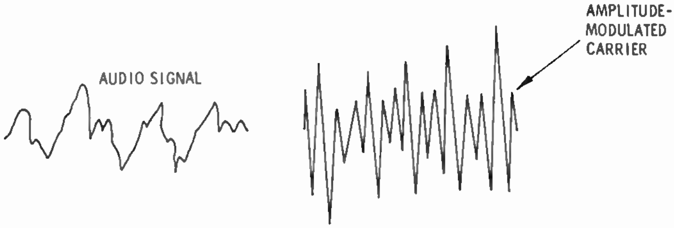
(B) Duplex.

Fig. 1. Methods of two-way radio operation.

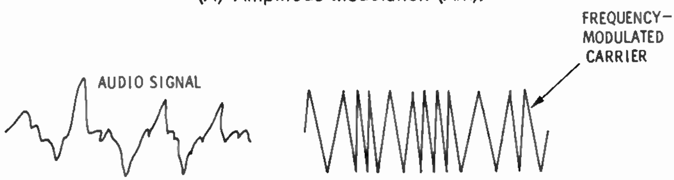
between two stations in only one direction at a time and is generally associated with push-to-talk switches, voice-operated relays, or some other automatic or manual method of switching from the receive to the transmit mode. With duplex operation (Fig. 1B), communications are permitted in both directions at the same time. Here, the transmitting station can be interrupted by the receiving station. This type of operation is similar to that employed in a regular telephone system such as that in the home.

MODULATION CHARACTERISTICS

The two basic types of modulation currently employed in radiocommunications are amplitude modulation (AM) and frequency modulation (FM). With AM, the frequency of the carrier wave remains constant, but the amplitude is varied in accordance with the modulating signal (audio signal originating at the microphone). This action is illustrated in Fig. 2A. With the second method of modulation (FM), the audio signal causes the frequency to vary in accordance, but here the amplitude remains constant (Fig. 2B). Actually there are slight variations in the amplitude of an FM signal due to noise pulses, etc.; however, these variations are reduced by one or more limiter stages before the signal is detected. One of



(A) Amplitude modulation (AM).



(B) Frequency modulation (FM).

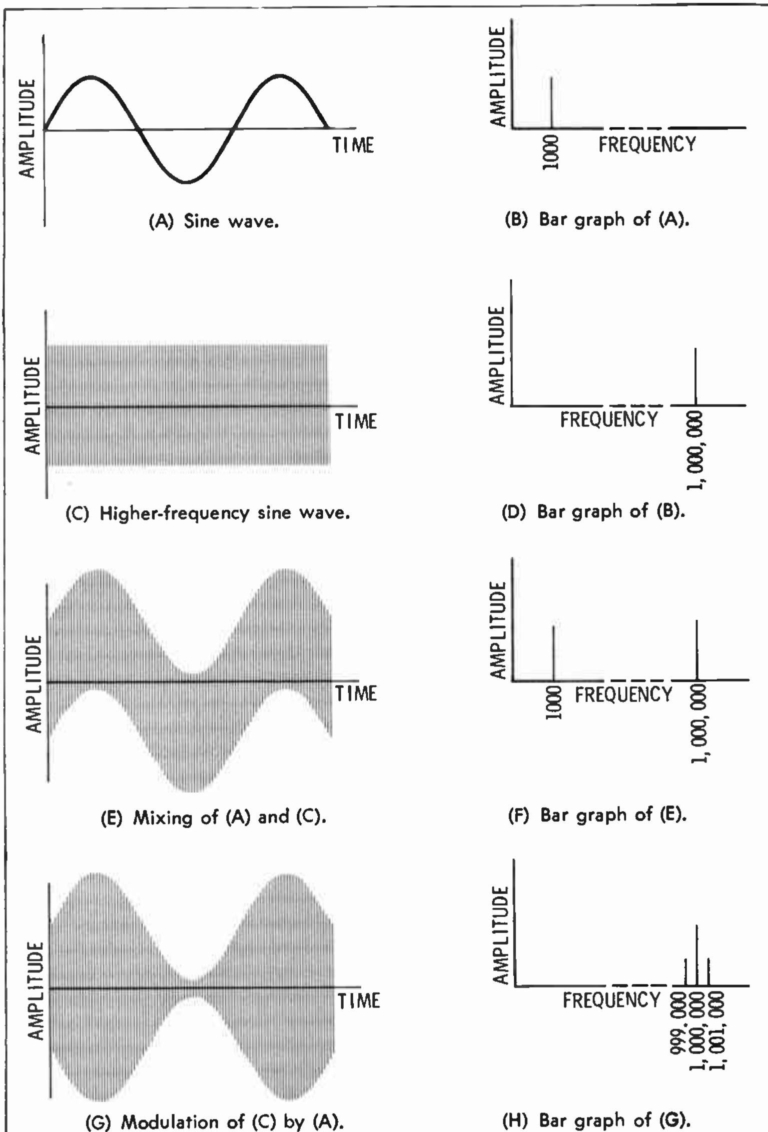
Fig. 2. Two types of modulation presently employed in radiocommunications.

the chief advantages of FM over AM is the freedom from noise interference. Pulse-type noise generally affects the amplitude rather than the frequency of radio signals.

It is important for us to understand the modulation process. The development of amplitude modulation is depicted in Fig. 3. Observe that when a low-frequency sine wave is mixed with a high-frequency sine wave, no new frequencies are generated. On the other hand, when a low-frequency sine wave amplitude-modulates a high-frequency sine wave, the low-frequency sine wave disappears and two new frequencies, called *sideband frequencies,* appear. In this example, the lower sideband frequency is 999 kHz, and the upper sideband frequency is 1001 kHz. Frequency modulation also results in the generation of new (sideband) frequencies. However, details of the FM process are reserved for later discussion.

RADIO SYSTEMS

As stated, there are two types of radio systems, namely two-way and broadcasting. The operating principles of the radio equipment



(A) Sine wave.

(B) Bar graph of (A).

(C) Higher-frequency sine wave.

(D) Bar graph of (B).

(E) Mixing of (A) and (C).

(F) Bar graph of (E).

(G) Modulation of (C) by (A).

(H) Bar graph of (G).

Fig. 3. Waveforms and their bar graphs.

are the same in both cases; however, the broadcasting system is generally more complex.

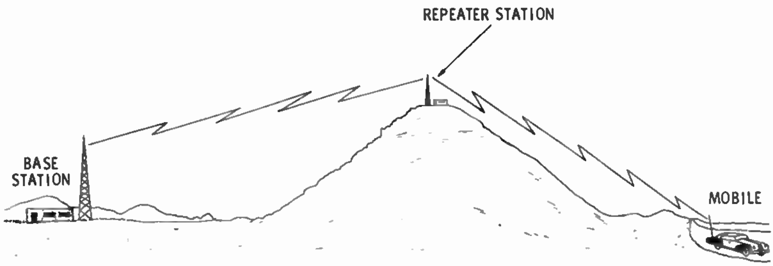


Fig. 4. Two-way radio system using repeater station to extend coverage.

Two-Way Systems

Two-way radio systems generally consist of a single base station and one or more mobile units. The system is designed to permit direct radiocommunications between these units within a specified area. The area of coverage is dependent on a number of factors including such things as transmitter power, surrounding terrain, type of antenna, etc. When communications are desired over a greater distance than the radio equipment is designed to provide or when intervening terrain may block the radio signals, one or more repeater stations may be employed (Fig. 4). The function of the repeater (as its name implies) is to receive the signals from the base station, amplify them, and then retransmit these signals to the mobile units, another repeater, or another base station. The retransmitting of the original radio signal from the repeater may be either instantaneous or delayed, depending on the desired type of operation. With a repeater station the area of coverage can be increased and reliable communications can be obtained between two points despite obstructions.

Broadcast Systems

In a regular broadcasting setup the transmitter itself is usually some distance from the studio. It may be several hundred feet from the control room or miles away. In most cases the main studios are situated within the city while the transmitter is located either on the outskirts of town or in a rural area. Fig. 5 shows the arrangement used in a typical broadcasting station. Here the program is originating "live" at the studio. The audio signal is fed from the microphone through the control console where it is amplified. It is then fed via telephone lines to the transmitter location where it receives additional amplification before it is superimposed on the transmitter

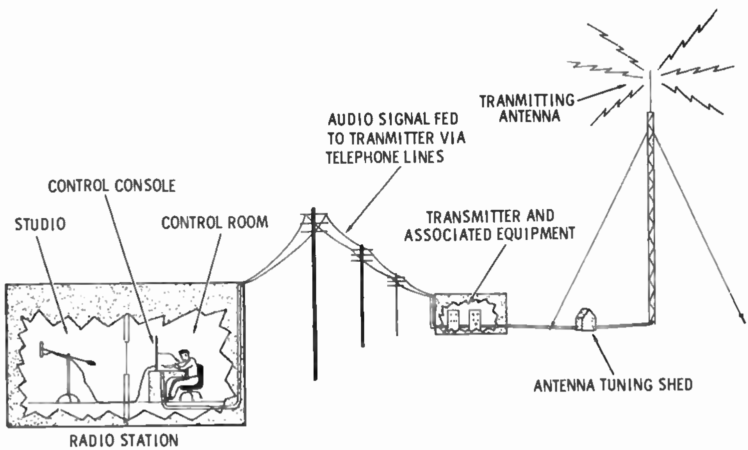


Fig. 5. Hookup of a typical radio broadcasting station.

carrier signal. The transmitter output is then routed through appropriate RF cables to a small building located near the base of the antenna structure. This building houses the antenna tuning equipment and other devices associated with the radiation of RF energy. This is the last control point before the RF signal is fed to the antenna and radiated into space.

An engineer is generally present at the transmitter site at least some part of each day. The transmitter may be put on the air at this location but usually it is operated by remote-control from the studio. Programs originating in other cities and coming in over the network are received over telephone lines and are routed through the control board in the same manner as a live program.

Special programs such as church services and other forms of remote broadcasts are either linked to the studio by means of telephone lines or radioed directly. Many stations now employ a radio relay link between mobile units or a remote site.

SHORT-WAVE RECEPTION

Short waves permit reception of radio signals at much greater distances than can be accomplished with the longer waves regularly employed by commercial broadcasting stations. Generally a radio program received at a frequency above 1,605 kHz is classed as short-wave reception, and the transmitting and receiving of radio waves above 1,605 kHz is termed short-wave communication.

Short-wave communications are at present carried on at frequencies up to thousands of megahertz (a small fraction of one meter). Frequencies with wavelengths less than one meter are called microwaves.

The problems introduced in the design of equipment by the attempt to raise the limitations of high frequencies can best be appreciated by speaking in terms of wavelengths.

The wavelength determines directly, in the same units, the approximate maximum physical size which the equipment to produce that frequency may attain. This results from the fact that the greatest speed at which energy may be sent along an electrical circuit is the same as that of electromagnetic energy in space—the velocity of light, or approximately 300,000,000 meters per second.

In practical circuits, however, inductance and capacitance lower the speed of electrical energy and this speed is never attained. From this it follows that the circuits then must be smaller in extent than the wavelengths and the tubes themselves will be very small physically.

Wavelength and Frequency

Since electromagnetic energy and flux lines move with the velocity of light (approximately 186,300 miles or 300,000,000 meters per second), the wavelength of this energy at a given frequency can be found by the formula

$$\text{wavelength (in meters)} = \frac{300{,}000{,}000}{\text{frequency (in hertz)}} \tag{1}$$

$$\text{or frequency (in hertz)} = \frac{300{,}000{,}000}{\text{wavelength (in meters)}} \tag{2}$$

From the formula it is apparent that the shorter the wavelength, the higher the frequency.

For example, if the wavelength is one meter, the corresponding frequency is 300,000,000 hertz, 300,000 kilohertz, or 300 megahertz.

Example: What are the frequencies for wavelengths of 5, 25 and 100 meters?

Solution: Substituting 5 in formula (2)

$$\text{Frequency} = \frac{300{,}000{,}000}{5} = 60{,}000{,}000 \text{ hertz,}$$

$$= 60{,}000 \text{ kilohertz, or } 60 \text{ megahertz}$$

Similarly, substituting 25 and 100 in formula (2), 12 and 3 megahertz, respectively, are obtained.

Distance Ranges of Various Wavelengths

All radio-wave transmission occurs by the propagation of either a ground wave (along the ground) or a sky wave (reflected or refracted from the Kennelly-Heaviside layer), or by both means.

Radio waves are subject to absorption both in the ground and in the ionized upper atmosphere. Ground-wave absorption generally increases with the frequency and is reasonably constant with time over a given path at a given frequency; it varies for earth of different conductivity and dielectric constant.

Sky-wave absorption, however, is not constant with time, frequency, and path; it appears to be maximum in the broadcast band 550-1,600 kilohertz), decreasing with a change in frequency in either direction.

During the daytime this absorption of the sky wave is so great that there is practically no sky-wave reception from frequencies somewhat below and above the broadcast band; the specific limits, however, vary with the seasons. Therefore, sky-wave propagation in the daytime is only noticeable in the lower- and higher-frequency ranges. At night, however, sky-wave propagation takes place at all frequencies except extremely high ones.

Other Factors Affecting Sky-Wave Propagation

Sky-wave propagation is also materially influenced by the condition and changes in ionization of the Kennelly-Heaviside layer.

Daily variation of daylight and darkness in the path of the waves, and other factors such as latitude, season of the year, and magnetic and solar disturbances have been found to influence the ionization characteristics.

Long-Distance Reception

High-frequency reception at great distances is due entirely to the sky wave. However, above a certain frequency (which may be as low as 4,000 kilohertz), no appreciable portion of the sky-wave radiation is reflected back from the Kennelly-Heaviside layer in a certain zone surrounding the transmitter.

In the area bounded by the inner edge of this skip zone, the signals appearing at a receiver may be composed of both the ground and sky waves, the latter being appreciable on frequencies up to approximately 6,000 kilohertz in the summer and 12,000 kilohertz in the winter. The sky-wave intensity in this area is ordinarily much less at night than in the day. The outer boundary of the skip zone is commonly referred to as the skip distance. This distance increases with the frequency and varies daily and seasonally. Beyond the skip distance, the sky-wave radiation is received with useful intensity.

Reception on higher frequencies (above 12 megahertz) is generally more satisfactory during the day than at night; on frequencies below 6 megahertz, however, the reverse is true.

Except in rare instances, frequencies above 12 megahertz can be heard only when daylight exists over the path between the transmitting station and the receiver. It has also been found that frequencies from 6.4 to 15 megahertz are received best when either (but not both) the transmitter or receiver is located in an area where night prevails.

The time of the day must also be taken into consideration in high-frequency reception. For example, when it is 8:00 P.M. in New York and 7:00 P.M. in Chicago, it is 9:00 A.M. in Melbourne; 1:00 A.M. the next day in London, and 2:00 A.M. the next day in most of Europe. During those hours, of course, the European broadcasting stations are seldom operating. Hence on the American continent, tuning for stations in Europe must be done during the afternoon or early evening. Australian stations, however, will be received in the early morning.

In addition, the season of the year also affects reception. Better reception on the high frequencies may generally be expected during the summer months and better reception at 6 megahertz and above during the winter months.

Because reception at the higher frequencies is generally affected very little by atmospheric noise or static, good results may be obtained in midsummer even during a thunder storm. The same, however, is not true of so-called man-made static produced by such things as electric fans, mixers, etc., which create far more interference on high frequencies than they do on the lower broadcast frequencies.

As an example of the effect of time, day, and season of the year on high-frequency transmission, assume that you are in New York and that the time is 1:00 P.M. in midsummer and that you tune in a station in Chicago on approximately 15 megahertz (20 meters wavelength). Also assume that this station transmits a continuous program and that your receiver is left tuned in. Several hours later, the signal will begin to fluctuate excessively and finally will fade out entirely or become unintelligible. This can be accounted for by the fact that, in midsummer, the skip distance is approximately 400 miles at noon and increases to 2,500 miles at midnight. Chicago is approximately 600 miles from New York and is one hour later in time; therefore, some few hours after noon, in Chicago, the skip distance will have so increased that reliable reception on 15 megahertz cannot be obtained in New York.

It is also well to note that in midwinter, the skip distance for 15 megahertz is approximately 900 miles at noon and becomes infinity at midnight—showing that reliable reception could not be effected at this frequency between Chicago and New York. Therefore, if you were located in New York, you could become accustomed to receiving a 15-megahertz program from Chicago at noon during the summer. As winter approached, the period of time during which reliable communication could be effected would decrease until at no time could a signal be heard. The reverse would be true the following spring.

SUMMARY

Radiocommunications take place by the radiation (transmission) and reception of electromagnetic energy. There are two basic methods involved—one-way and two-way. The broadcast of radio and television to the general public is an example of the one-way method. Police radiocommunications is an example of the two-way method. The two-way method is further divided into either simplex or duplex operation. With simplex operation, communication can take place in only one direction at a time between two stations. Duplex operation permits communications in both directions at the same time.

Two basic types of modulation are currently employed in radiocommunications—amplitude modulation (AM) and frequency modulation (FM). In amplitude modulation, the radio carrier frequency remains constant but the amplitude varies in accordance with the modulating signal originating at the microphone or TV camera. In frequency modulation, the amplitude of the radio carrier frequency remains constant but the frequency varies in accordance with the modulating signal.

Short-wave communications take place at frequencies up to thousands of megahertz. The characteristics at these frequencies permit much greater distances to be spanned by the radio waves. Sky-wave radiation is responsible for the increased distance.

REVIEW QUESTIONS

1. Define simplex operation.
2. Name the two basic types of modulation currently in use.

3. Explain the characteristics of a frequency-modulated radio wave.
4. What is the chief advantage of FM over AM?
5. Above what frequency is generally classed as short-wave?
6. What are frequencies with wavelengths less than one meter called?
7. State the formula for determining frequency if the wavelength is known.
8. What is a sky wave?
9. State two factors affecting long-distance reception of radio waves.
10. What is skip distance?

CHAPTER 17

Radio Transmitters

Transmitters are generally much simpler than receivers. In fact, a single tube connected as an RF oscillator can serve the purpose. Such a circuit is shown in Fig. 1. This transmitter uses a beam-power tube and is capable of operating with a power input (plate voltage times plate current) of 25 watts. There is no provision in this circuit for modulating the carrier; however, a key jack is provided in the cathode circuit to permit the sending of CW (continuous waves). This is the term given code transmission when the carrier, or continuous wave, is broken up into dots and dashes to form the International Morse code. No carrier is produced with this circuit until a ground for the cathode circuit is provided through the contacts of the key. At the receiving station the interrupted carrier beats with a local RF signal to produce an audio tone that can be deciphered. (This oscillator is referred to as a beat-frequency oscillator (BFO). Additional circuitry would be required to modulate the carrier produced by the transmitter in Fig. 1.

This particular transmitter employs a crystal-controlled circuit although a variable-frequency oscillator (VFO) could just as easily be used. The purpose of the crystal, of course, is to maintain good frequency stability, which is important in a transmitter. The crystal determines the operating frequency of the transmitter; however, slight changes in this frequency can be made by adjusting variable

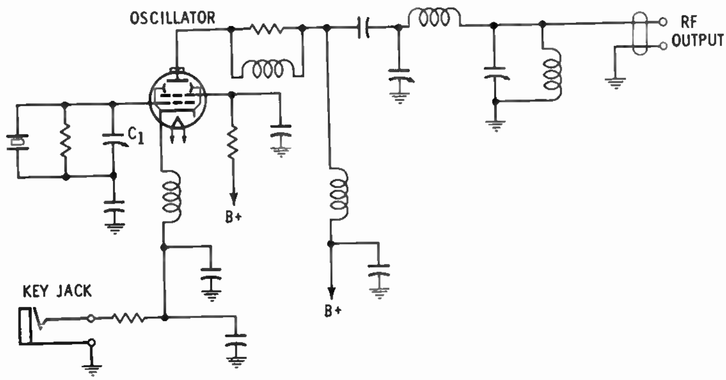


Fig. 1. A simple tube-type radio transmitter.

capacitor C_1 which is connected directly across the crystal. This makes it possible to compensate for slight variations in crystal frequency and component values which may cause "off-frequency" operation.

When a circuit such as this is made variable in frequency, several steps must be taken to assure good frequency stability. First of all, it is important that the supply-voltage values be constant, and to accomplish this, a regulated power supply is generally employed. With this type of supply the voltage tends to remain constant de-

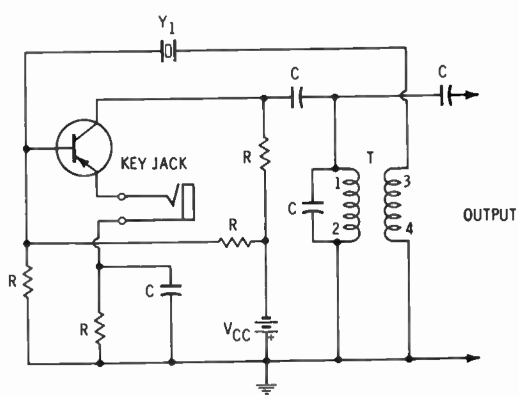


Fig. 2. A simple transistor-type radio transmitter.

spite variations in load current. Another measure to insure frequency stability involves the use of temperature-compensated components. Component values normally vary with changes in temperature and such variations cannot be tolerated in oscillators of this type. Capacitors in particular are troublesome in this respect.

Fig. 2 shows a circuit for a simple transistor radio transmitter.

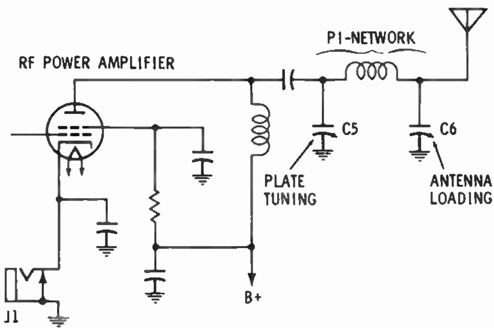


Fig. 3. An RF power amplifier stage using a pi-network to couple the signal to the antenna.

RF POWER AMPLIFIERS

Although an oscillator by itself can serve as a transmitter, it is generally followed by other stages such as the RF power amplifier shown in Fig. 3. This circuit uses a pi-network to couple the RF signal to the antenna. Other methods of coupling (link, for example) can also be employed; however, the pi-network is one of the most common in use because it enables the RF output stage to match a wide range of impedance values. Furthermore, the pi-network rejects spurious harmonic frequencies which are very undesirable, especially in the final RF stage of a transmitter. This is one of the major objections to using a power-oscillator transmitter. Oscillators generally produce a number of harmonics in addition to the desired frequency and if these harmonics are not suppressed, they can interfere with other stations.

Parasitic Oscillations

Parasitic oscillations within an RF power amplifier (PA) stage can also produce undesired harmonics unless proper precautions are taken. One of the most common methods of preventing parasitics is by inserting a parasitic choke in the plate and/or grid lead of the amplifier as shown in Fig. 4. This choke may consist of a resistor-coil combination as shown, or it may consist of a coil only.

RF Amplifier Adjustments

The plate circuit of a transmitter power amplifier is designed to tune to the desired operating frequency (carrier frequency). In the circuit of Fig. 3, plate tuning is accomplished by adjustment of C_5. At resonance, *maximum* RF energy is transferred to the antenna

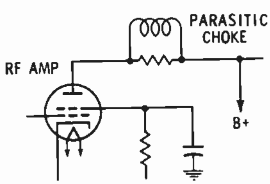


Fig. 4. A parasitic choke in the plate lead of an RF power amplifier.

and *minimum* plate current flows in the RF amplifier. Capacitor C_6 in this circuit is the antenna-loading adjustment, which determines the amount of signal coupled to the antenna. In adjusting a circuit of this type, C_6 is first adjusted for minimum loading. The plate circuit is tuned for resonance as indicated by a dip in the plate current. The jack in the cathode leads is provided so that an ammeter can be connected for tuning purposes. The plate circuit is tuned for minimum current as indicated by the meter and then the antenna loading is increased. Once again the plate-tuning capacitor (C_5) is adjusted for a minimum current indication. Alternate adjustments of C_5 and C_6 are made in this manner until the proper degree of loading is obtained. This occurs when the final adjustment of the plate-tuning capacitor produces a "dip" at the correct current value for the tube. "Off-resonance" tuning can cause enough plate current flow to destroy the tube within a few minutes or even seconds. Under this condition the tube plate becomes red hot, the amount of

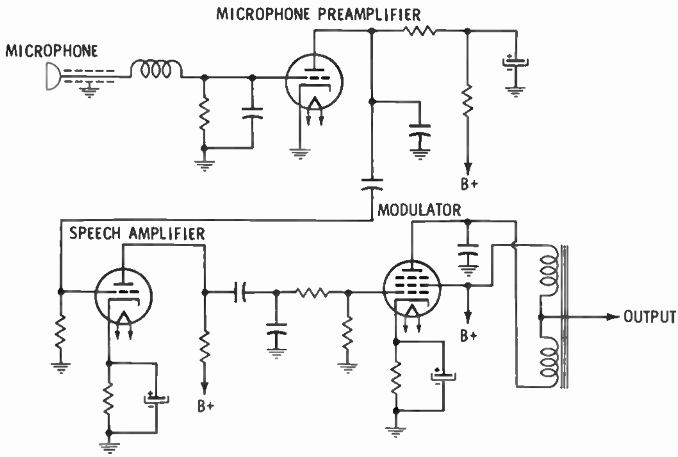


Fig. 5. One type of audio modulator circuit.

heat being dependent on how far the circuit is tuned off resonance. Excessive plate current will also flow if the antenna does not reflect the correct load impedance to the circuit.

MODULATORS

The function of the modulator is to superimpose the desired audio signal on the carrier. Before the microphone signal can perform this function, however, it must first be amplified. Fig. 5 shows a simple modulator circuit used in an AM transmitter.

The audio signal produced by the microphone is fed to the grid of the microphone preamplifier tube. Next it is coupled to another triode where it receives additional voltage amplification. It is then fed to the modulator itself where the required amount of power amplification is obtained. It should be pointed out that this is the *modulator* stage and not the modulated stage. The modulation process itself occurs in the final RF amplifier of the transmitter.

To understand how the carrier is amplitude modulated, refer to Fig. 6. Here the modulator and RF power amplifier shown previously are shown interconnected. As you can see, the carrier produced by the transmitter oscillator is applied to the grid of the RF amplifier tube. With no modulation present, the carrier is merely given one final boost in amplification by this stage and is then radi-

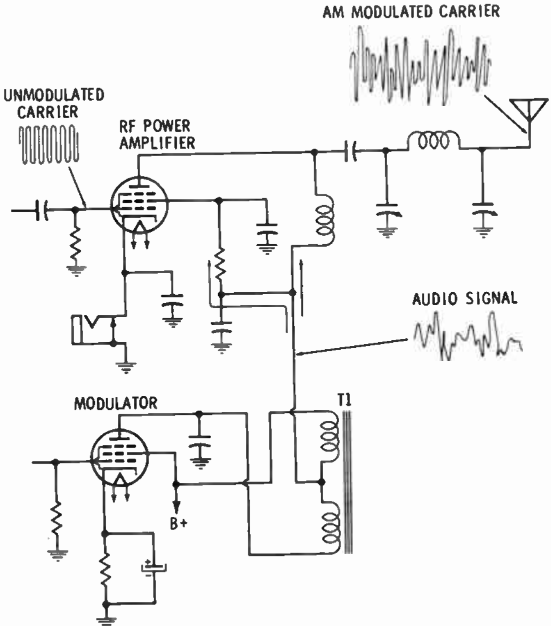


Fig. 6. A transmitter PA stage using plate modulation.

ated from the antenna. When modulation is present, however, the audio signal appearing in the plate circuit of the modulator flows through transformer T1. It is from this transformer that the screen and plate of the RF power amplifier receive B+ voltage. Therefore, the audio variations in the plate circuit of the modulator stage produce corresponding variations in the plate and screen supply voltages of the RF power amplifier. This, in turn, causes the carrier wave to vary above and below its normal amplitude in accordance with the audio signal. The output of the RF amplifier then becomes an amplitude-modulated carrier. The method just described is known as plate modulation, although the audio signal is applied to

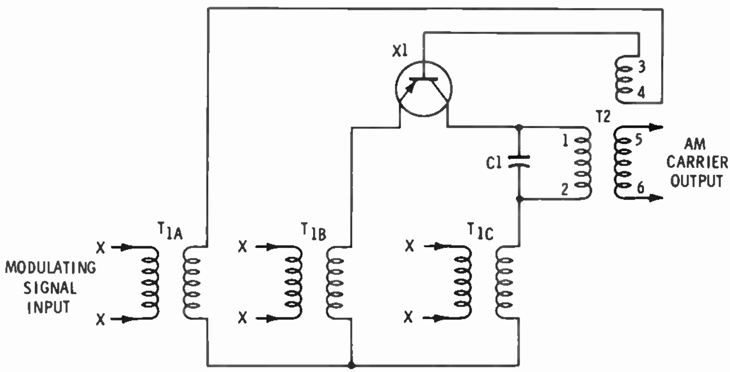


Fig. 7. Methods of injecting an amplitude-modulating signal into an oscillator circuit.

the screen as well. This is done to provide more effective control over plate current.

Plate modulation is by no means the only method in use, although it is about the most popular. Modulation can also be accomplished by applying the audio signal to one or more grids of the power amplifier tube or to its cathode. It is then generally referred to according to the element involved—for example, cathode modulation, screen-grid modulation, etc.

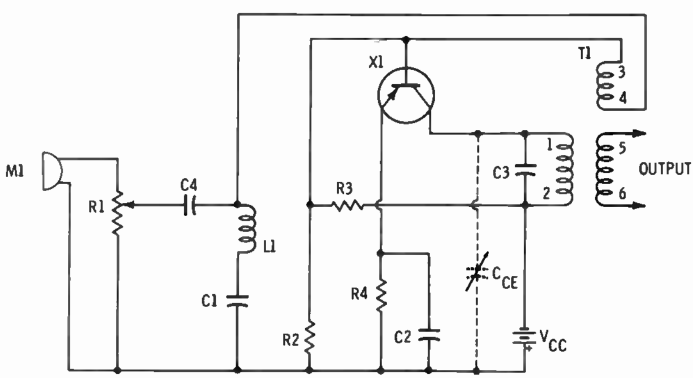


Fig. 8. An amplitude-modulated oscillator with base injection.

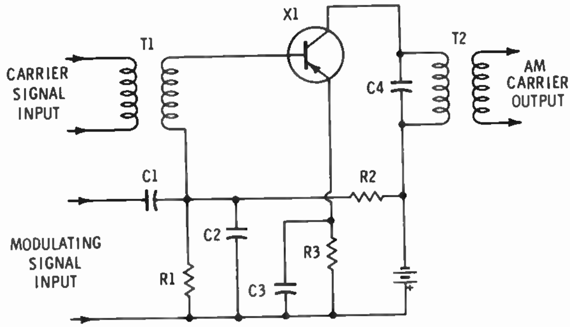


Fig. 9. An amplitude-modulated amplifier with base injection.

Fig. 7 shows three ways of injecting an amplitude-modulating signal into a transistor oscillator circuit. Thus, a transistor oscillator can be amplitude-modulated with base injection as shown in Fig. 8. A transistor RF amplifier can also be amplitude-modulated with base injection as depicted in Fig. 9. The circuit seen in Fig. 10 is suitable for amplitude-modulation of an RF amplifier with emitter injection. Or, an RF amplifier can be amplitude-modulated with collector injection, as shown in Fig. 11.

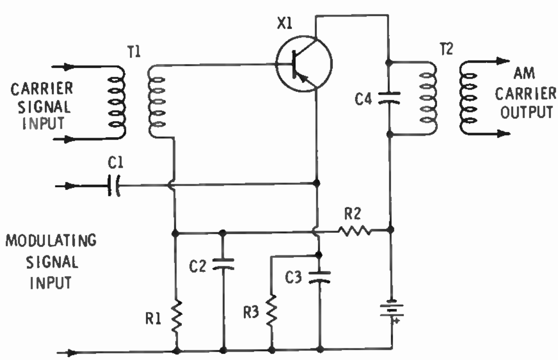


Fig. 10. An amplitude-modulated amplifier with emitter injection.

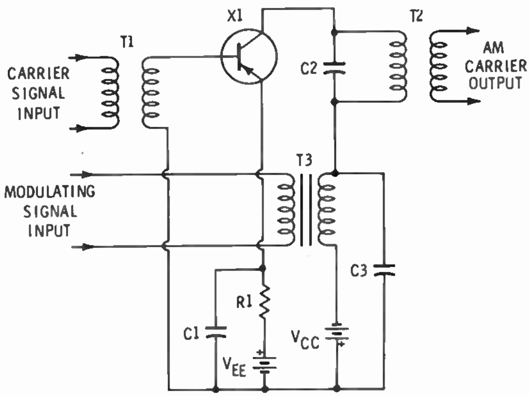


Fig. 11. An amplitude-modulated amplifier with collector injection.

Reactance Modulator

One of the simplest methods of achieving frequency modulation is through the use of a reactance-modulator circuit like the one shown in Fig. 12. The operating principle of this circuit is such that it acts as a variable capacitance or inductance when properly connected to the tuned circuit of an oscillator stage. A reactance modulator can be used in conjunction with either a crystal-controlled or a free-running oscillator circuit. From the circuit you will see that the grid of the modulator is connected across the oscillator tuned circuit through resistor R_1 and capacitor C_2. The value of R_1 is made high in comparison with the reactance of the modulator-

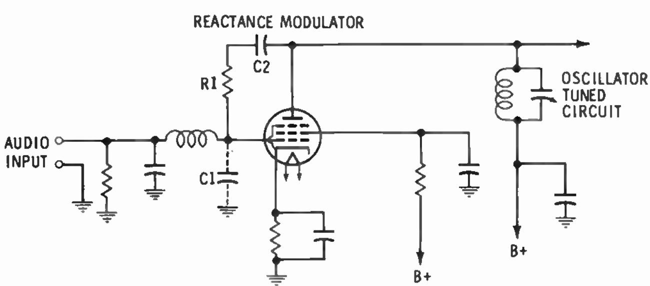


Fig. 12. Reactance modulator used to produce frequency modulation.

circuit input capacity (represented by C_1), and RF current flowing through R_1 and C_1 is essentially in phase with the RF voltage appearing across the oscillator tank circuit. The voltage across C_1, however, lags this current by 90°. The RF plate current in the modulator stage is in phase with the grid voltage and therefore is 90° behind the current through C_1 (it lags the voltage across the oscillator tuned circuit). This results in a lagging current being drawn through the tuned circuit and has the same effect as connecting an additional inductance across the tuned circuit. The frequency increases in proportion to the lagging current in the plate circuit of the modulator stage. When an audio signal is applied to the input terminals, it produces corresponding variations in RF plate current.

FREQUENCY MULTIPLIERS

Frequency multipliers are stages designed to deliver an output signal whose frequency is a multiple of the input frequency. Multipliers can be made to double, triple, or quadruple the input frequency. Actually, they can be designed to select almost any harmonic, i.e., seventh, eighth, etc., although in actual practice, they are seldom made to multiply more than four or five times. When higher frequencies are required, additional multiplier stages are generally used. Depending on the operating frequency desired, a transmitter may employ a single multiplier stage or it may employ several. As the order of harmonics selected becomes higher, the output of each stage drops off. Thus, it is more practical to use two frequency multipliers that triple rather than a single stage that multiplies six times.

Frequency multipliers are used in both AM and FM radio transmitters and may be thought of as amplifiers having an output circuit tuned to some multiple of the input signal. Some multipliers have tuned plate circuits only, while others have both tuned input and output circuits. The grid, or input, circuit is usually tuned to the output frequency of the preceding stage.

When used in an AM transmitter, the frequency multiplier serves two primary functions—to amplify the signal applied at its input and to deliver at its output an identical signal of higher frequency.

With FM, however, the frequency multiplier serves an additional function. It not only multiplies the input signal, but also the amount of frequency deviation, thereby effectively strengthening the audio modulation. Obviously this characteristic lessens the requirements on the modulator stage of an FM transmitter.

Consider the block diagram of the FM transmitter in Fig. 13. Here the oscillator operates on the fundamental frequency of 1641.406 kHz. Acting as a quadrupler, the first frequency-multiplier stage selects the fourth harmonic of the oscillator signal (6565.624 kHz). At the same time this stage multiplies the frequency deviation by four also. Thus, the frequency variations above and below the normal unmodulated value are four times greater at the output of the first quadrupler than at the output of the modulator stage. A similar action occurs in the second quadrupler. The following stage serves as a frequency doubler as well as the driver. The final RF stage operates as a straight-through amplifier tuned to the same frequency as the driver, and although it could also act as a multiplier, this is not generally done. In the example shown here (Fig. 13), the 1641.406-kHz crystal frequency is multiplied 32 times by three stages in order to derive the desired output of 52.525 mHz (this will be the frequency after a slight adjustment of the oscillator frequency).

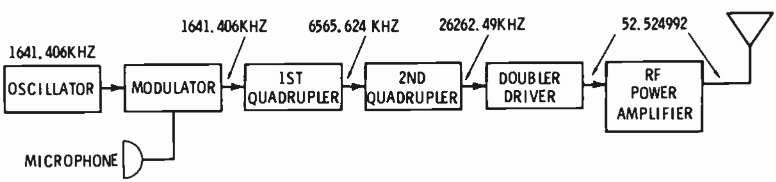


Fig. 13. Block diagram of an FM transmitter using frequency multipliers.

In general, frequency modulation produces more sideband frequencies, which means that an FM transmission usually requires a greater bandwidth than an AM transmission. In frequency modulation, the *deviation* of the carrier denotes the number of cycles that the carrier is swung above and below its resting frequency. As indicated in Fig. 14, the ratio of the deviation to the modulating

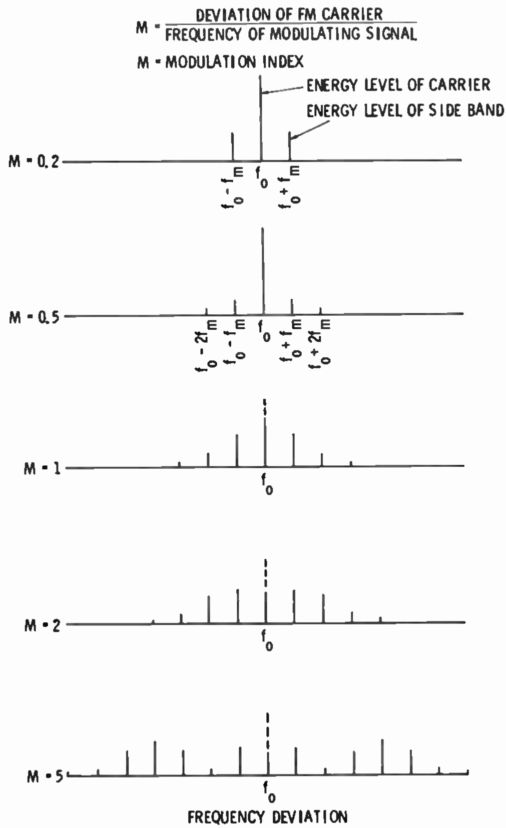


Fig. 14. Sidebands in frequency-modulated waves.

frequency is called the *modulation index.* Any modulation index can be used that might be desired. If the modulation index M is 0.2, narrow-band FM (NFM) results. We observe that the significant sidebands in NFM occupy the same bandwidth as in amplitude modulation. On the other hand, if M = 5, there are seven times as many significant sidebands, and the transmission bandwidth is seven times as great as for an AM transmission. A large modulation index is desirable to minimize the signal-to-noise ratio of the received signal.

Note that, although an infinite number of sidebands are theoretically generated in frequency modulation, not all of these sidebands are significant. Any sideband frequency that has an amplitude less than the prevailing noise level can obviously be ignored. In commercial FM broadcasting, the sidebands occupy a frequency spread of 75 kHz on either side of the resting carrier frequency. That is, the transmission bandwidth is 150 kHz.

BUFFER AMPLIFIERS

In addition to the circuits already discussed, some transmitters employ what is known as a buffer or buffer amplifier. Actually this is nothing more than an intermediate RF amplifier which serves to isolate the effects of one stage from another. For example, in a three-stage CW transmitter, the buffer would be situated between the oscillator and RF power amplifier and would not only isolate these two stages but also provide amplification of the oscillator output. In some transmitters the frequency multiplier also serves as the buffer, in which case it is referred to as a buffer/multiplier.

CLAMPERS

Insufficient driving voltage at the grid of the RF power amplifier will cause excessive plate current that can ruin the tube. The function of the clamper circuit is to protect the final amplifier should the grid drive fail. Usually the RF power amplifier controls the action of the clamper and the clamper in turn protects it. In one arrangement, the cathode of the clamper tube is connected to ground and the plate is connected to the screen grid of the final RF amplifier where it receives its voltage. The grid of the clamper is common to the grid of the final amplifier; thus, the bias developed at the RF amplifier grid keeps the clamper cut off. If grid excitation at the final ceases, however, the absence of grid bias on the clamper causes this tube to conduct heavily, thereby lowering the screen voltage on the RF amplifier tube and reducing the plate current to a safe value. Clamper circuits are not employed in all transmitters.

SUMMARY

Radio transmitters are generally much simpler than receivers. A simple oscillator can be used as a transmitter. When such a transmitter is turned on and off it produces an interrupted CW signal. By proper timing, this on-off procedure can produce a code which can convey intelligence. In order to prevent the frequency of the transmitter from changing, a crystal ground to the correct thickness can be used to stabilize the oscillator.

The output of the oscillator is seldom strong enough for transmission over any appreciable distance, so amplifiers are used to strengthen the oscillator output. These are called RF power amplifiers.

In order to transmit an audio signal (speech, music, etc.), it is necessary to modulate the oscillator frequency. Modulation is merely a process of changing certain characteristics of the oscillator frequency. If the amplitude is changed at an audible rate, the transmitter is said to be amplitude modulated. If the frequency is changed at an audible rate, it is frequency modulated.

Frequency multipliers are often used in a transmitter when it is desirable to have an output frequency substantially higher than the oscillator frequency. Multipliers deliver an output whose frequency is some multiple of the input frequency.

REVIEW QUESTIONS

1. What is the simplest form of a tube-type transmitter?
2. What is CW?
3. What is a VFO?
4. Would it be possible to have a crystal-controlled VFO?
5. What is parasitic oscillations?
6. What is the purpose of an RF power amplifier in a transmitter?
7. What is a buffer amplifier?
8. What is modulation?
9. How does FM differ from AM?
10. Is plate current in an RF power amplifier maximum or minimum at resonance?

CHAPTER 18

Radio Receivers

The function of a receiver is to select and amplify the desired radio signals, separate from them the intelligence originally transmitted, and to convert this intelligence into sounds that can be heard and understood. A radio receiver can be very simple or it can be quite complex. The most basic type of receiver is the crystal set shown schematically in Fig. 1. Here the desired station is selected by tuning the L_1-C_1 combination to resonance at that frequency. The signal is then demodulated by the crystal detector, and the resultant audio component is converted into sound waves by the headphones. Since the days of the crystal set, a number of receiver circuits have been developed, including such types as the regenerative and superregenerative, tuned radio frequency (TRF) and the

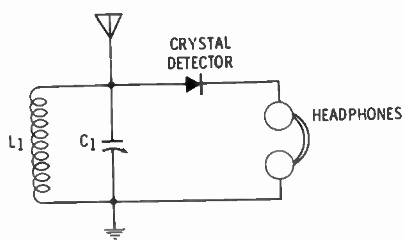
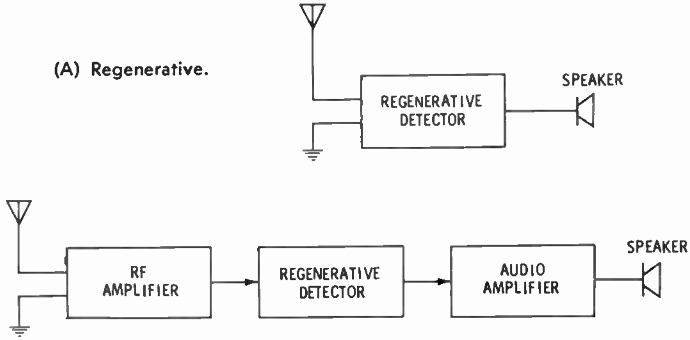


Fig. 1. A basic crystal set.

currently popular superheterodyne receiver circuit. Fig. 2 shows block diagrams of two regenerative-type receivers.



(B) Tuned-radio-frequency regenerative.

Fig. 2. Block diagrams of two regenerative-type receivers.

A radio signal intercepted by an antenna might have an amplitude in the order of only millionths of a volt (several microvolts), and a power of only "one" micromicrowatt. This extremely small amount of electrical energy must then be amplified without objectionable distortion to a power level of approximately 1 watt in order to operate a speaker satisfactorily. Thus, the radio receiver must provide a power amplification of 10^{12} times in this example.

RECEIVER PERFORMANCE CHARACTERISTICS

Receiver performance characteristics are determined by a number of factors, several of which are selectivity, sensitivity, fidelity, and stability.

By definition, the selectivity of a receiver is its ability to discriminate between signals of various frequencies. The sensitivity of a receiver is the minimum signal voltage input required to produce a specified output. The fidelity is the response through the audio-frequency range required for a given type of receiver. The stability of a receiver, on the other hand, is its ability to maintain the selected frequency as the receiver warms up.

Selectivity

As mentioned previously, selectivity is that characteristic of a receiver which determines its ability to tune in a desired signal while rejecting all others. Receiver selectivity is determined with the aid of an RF signal generator which makes it possible to impress RF potentials of known frequency on the input of a radio receiver.

There are various methods of carrying out this test, although the one generally used is to impress a small potential on the input of the receiver and note the output, and then to vary gradually the fre-

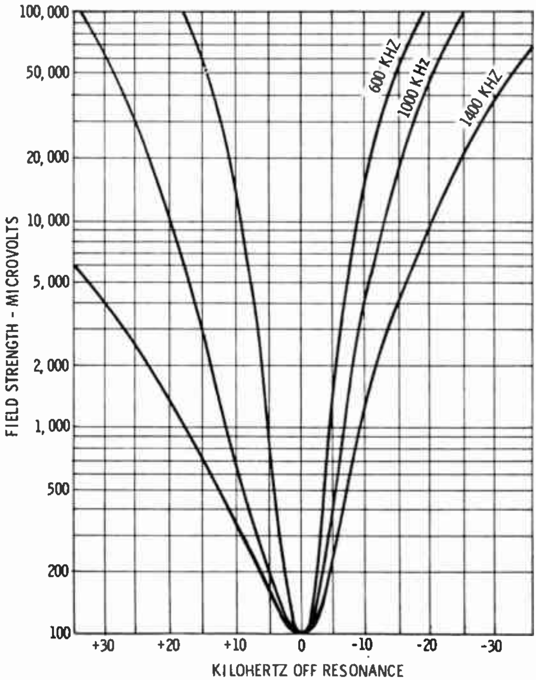


Fig. 3. Selectivity curve of a typical radio receiver.

quency of the RF generator, and at the same time adjust the potential supplied to the receiver input so as to maintain the same output.

In this manner a set of figures will be obtained, indicating how the output of the receiver falls off at either side of the frequency to which it is tuned. The more rapidly the output falls off, the better is the selectivity of the receiver.

However, the receiver's selectivity is closely allied with its fidelity. Hence, if the selectivity is too great, the sidebands are suppressed and the fidelity is impaired. A typical selectivity curve is shown in Fig. 3.

Curves such as this may be plotted at various points through the broadcast band to determine the selectivity characteristics of a receiver.

The selectivity of a receiver is stated in terms of *bandwidth.* With reference to Fig. 4, bandwidth is defined as the number of cycles between the 70.7% maximum voltage points on the curve. Conventional AM broadcast receivers have a typical selectivity of 10 kHz.

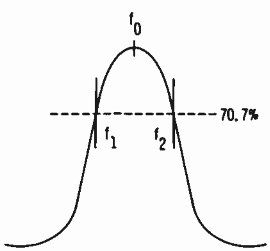


Fig. 4. Bandwidth is measured between the 70.7% maximum voltage points.

Sensitivity

The sensitivity of a receiver is expressed as a measure of the voltage (or power) that must be applied at the input to produce a specified standard output voltage (or power). For AM broadcast receivers, the sensitivity is defined as the RF carrier voltage, modulated 30% at 400 hertz, which when applied to the input of the receiver through a standard artificial antenna will develop .5 watt output in a resistive load connected in place of the speaker. This measure of sensitivity is expressed in microvolts. Fig. 5 shows a sensitivity curve for a typical radio receiver.

Fidelity

Fidelity is the term used to indicate the accuracy of reproduction, at the output of a radio receiver, of the modulation impressed on the RF signal applied to the input of the receiver under test. The fidelity of a given receiver is generally determined by setting up the receiver to be tested and impressing on its input an RF signal modulated at 30%, the input signal having a value such that the normal output is obtained.

Next the frequency of the modulating signal is varied (the percentage of modulation being held constant) over the entire audio-frequency band, and the output power at each frequency is noted. From the data so obtained, a curve can be charted showing how the audio-frequency output power from the set varies with the frequency applied. The fidelity characteristics of a typical radio receiver are plotted in Fig. 6.

Such curves are conducted at various radio frequencies—for example, at 600, 1,000 and 1,500 kilohertz in the broadcast band—so that the variation of fidelity can be determined.

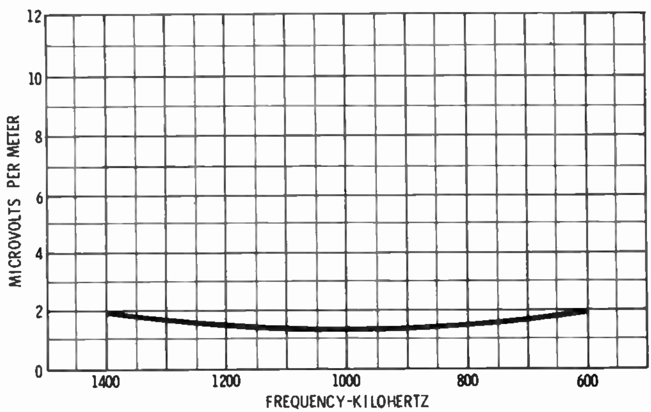


Fig. 5. Sensitivity characteristics of a typical radio receiver.

In this manner it is possible to obtain information regarding the characteristics of the RF-amplifier system. It is obvious that if the

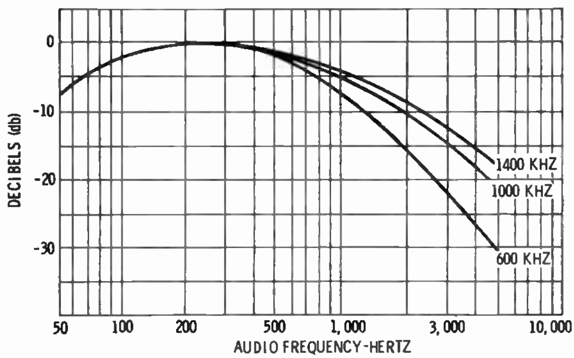


Fig. 6. Fidelity characteristics of a typical broadcast receiver.

system tunes too sharply at some point in the broadcast band, the sidebands will be suppressed partially and this will show up on the curve as a falling off in response at the higher audio frequencies.

When a test of this type is made, it is essential that the source of the audio-frequency voltage used to modulate the RF input signal be quite pure (free from harmonics). Generally the total harmonic output from the AF oscillator should not exceed 5%.

AMPLIFIER CLASSIFICATION

As mentioned previously in the discussion of basic electronic circuits, there are four basic classes of amplifier service. This classification depends primarily on the fraction of the input cycle during which the plate current is expected to flow under rated full-load conditions. The term cutoff bias used in the following definitions is the value of grid bias at which plate current is a small, insignificant value or is zero.

Class-A

A class-A amplifier is one in which the grid bias and alternating grid voltages are such that plate current flows at all times.

Class-A voltage amplifiers find their application in reproducing grid-voltage variations across an impedance or resistance in the plate circuit. These variations are essentially of the same form as the input-signal voltage impressed on the grid, but of increased amplitude. This is accomplished by operating the tube at a suitable grid bias so that the applied grid-input voltage produces plate-current variations proportional to the grid swings. Since the voltage variation obtained in the plate circuit is much larger than the voltage at the grid required to produce it, amplification of the signal is obtained.

Class-A power amplifiers find their chief application as output amplifiers in audio systems, radio receivers, and public-address systems, where relatively large amounts of power are required.

In the above applications, large output power is of more importance than high-voltage amplification. Therefore, gain possibilities are sacrificed in the design of power tubes to obtain this greater power-handling capability.

Class-AB

A class-AB amplifier is one in which the grid bias and alternating grid voltages are such that plate current in a specific tube flows for somewhat more than one-half of the cycle but less than the entire cycle.

Class-B

A class-B amplifier is one in which the grid bias is approximately equal to the cutoff value so that the plate current is approximately zero when no input grid voltage is applied. In this class of amplifier, the plate current flows for approximately one half of each cycle when the alternating grid voltage is applied.

Class-B power amplifiers employ two tubes connected in push-pull. These tubes are biased so that the plate current is almost zero when no signal voltage is applied to the grids. Because of this low value of no-signal plate current, class-B amplification has the same advantage as class-AB, in that a large power output can be obtained without excessive plate dissipation. The difference between class-B and class-AB is that, in class-B, plate current is cut off for a larger portion of the negative grid swing.

Class-C

A class-C amplifier is one in which the grid bias is appreciably greater than the cutoff value. In this class of operation, the plate current in each tube is zero when no alternating grid voltage is applied; plate current flows in a tube for appreciably less than one half of each cycle when the alternating grid voltage is applied.

Push-Pull

A push-pull amplifier arrangement is frequently used in receivers for supplying more power to the speaker than is ordinarily obtainable from one- or two-stage audio amplifiers. Another advantage of the push-pull amplifier is that it eliminates some of the distortion existing in ordinary amplifiers due to the nonlinear characteristics of the tube.

By observing the circuit in Fig. 7, we see that this is a balanced circuit—that is, the cathode returns are made to the midpoint of the input and output devices.

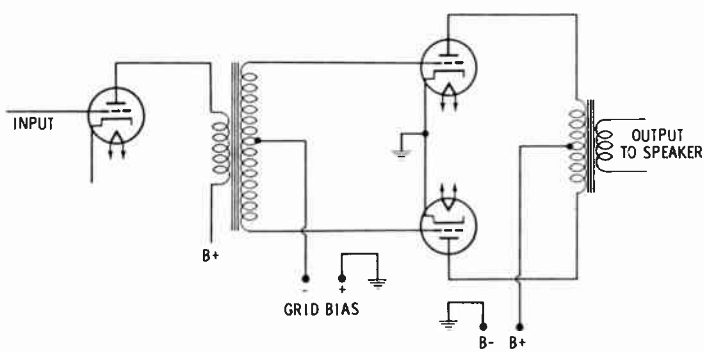


Fig. 7. A push-pull amplifier circuit. This type of amplification requires two identical tubes in the stage.

An AC current flowing through the primary winding of the input transformer will cause an AC potential to be induced in the secondary. The voltages at the ends of the winding will be opposite in polarity with respect to the center connection. Hence, it will be found

Fig. 8 shows the circuit for a typical transistor push-pull amplifier. Two transistors are used as audio drivers, and two more are used in a push-pull configuration. The included frequency-response shows that the amplifier has reasonably uniform response from 100 Hz to 10 kHz. Maximum power output is 0.4 watt, and is accompanied by 10% distortion. If the power output is reduced to 0.1 watt, the distortion is only 5%.

that the grid of one tube goes positive at the same instant that the grid of the other goes negative. The plate current in one tube is increasing while the plate current of the other tube is decreasing. It is from this characteristic that the name "push-pull" has been derived.

Although ordinary amplifier tubes can be utilized in this type of amplifier, it is often desirable to use special power tubes that have a high amplification factor.

RADIO-FREQUENCY AMPLIFIERS

Radio-frequency (RF) amplification is used to increase the amplitude of weak radio signals received from the antenna. There are three general methods for coupling one stage to another—resistance coupling, impedance coupling, and transformer coupling.

Resistance-Coupled

In this type of amplifier (Fig. 9), a high resistance is utilized for the interstage coupling. The advantage of using this type of coupling in an amplifier is its simplicity and the fact that the amplification can be made very uniform over a rather wide range of frequencies. It is these characteristics that have made resistance coupling useful in radio circuitry.

The function of the blocking capacitor is to prevent the plate potential of one stage from being impressed on the grid of the next stage.

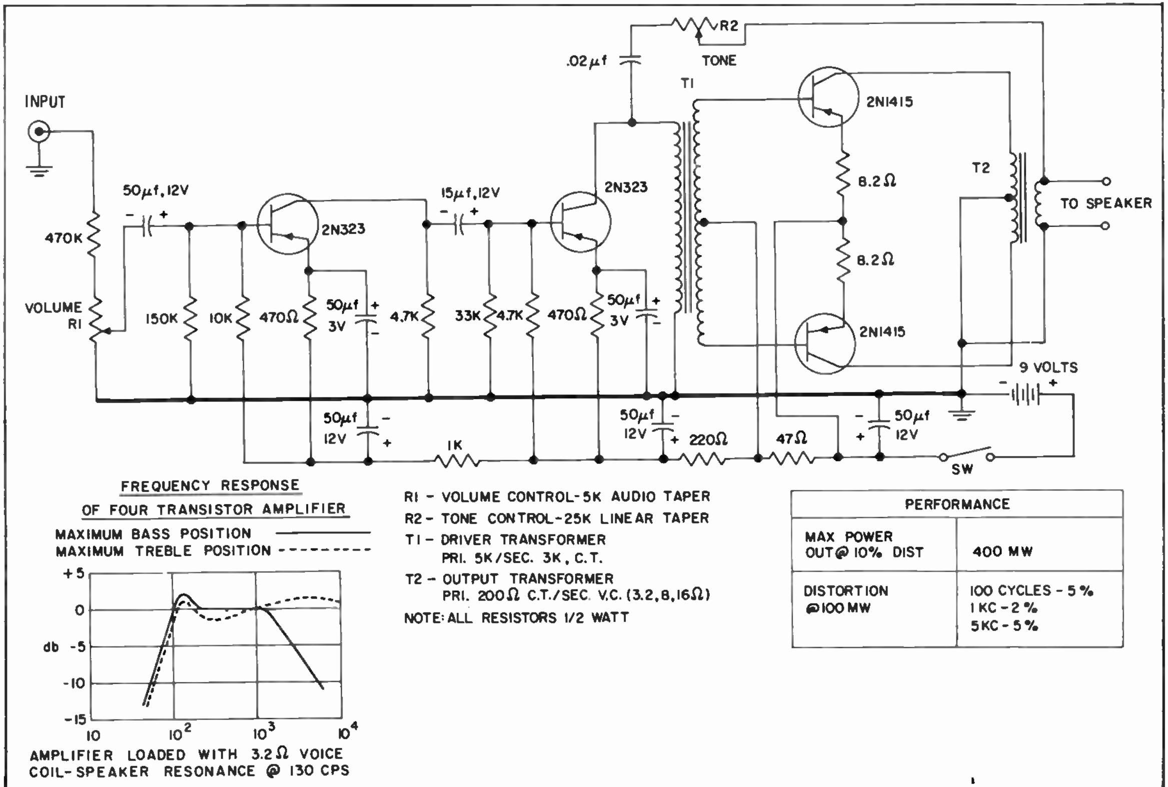


Fig. 8. A push-pull transistor amplifier circuit.

Courtesy General Electric Company

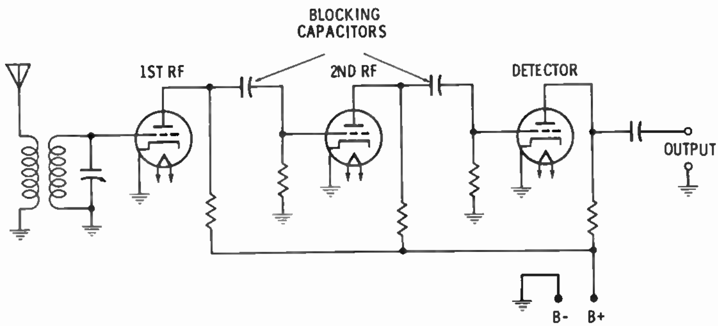


Fig. 9. A typical two-stage resistance-coupled RF amplifier.

Resistance-coupled RF amplifiers find their chief usefulness at comparatively low radio frequencies, such as from 20 kHz to 100 kHz. This type of amplifier is practically useless at high radio frequencies, such as 1 mHz. The reason for this is that the tubes have interelectrode capacitances, and the circuit has stray capacitance. Thus, the shunt capacitive reactances become so small at high radio frequencies that the signal is almost entirely bypassed to ground, resulting in a loss instead of a gain.

Impedance-Coupled

The method of connection for impedance coupling is shown in Fig. 10. Impedances L_1 and L_2 are in the form of autotransformers; R_1 and R_2 are grid leaks that may range in value from 250,000 to 500,000 ohms.

Fig. 11 shows the circuit for a two-stage transistor RF amplifier. The amplified RF output is applied to a detector (not shown in the diagram). This circuit differs basically from the circuit shown in Fig. 10 in that the impedance L_3-R_6 is tuned, in addition to tuning of L_1-L_2. Thereby, full gain is provided at any frequency within the AM broadcast band.

Transformer-Coupled

In this method of coupling, air-core transformers with a one-to-one ratio are most commonly used. However, at very low frequencies, it has been found advantageous to use step-up transformers.

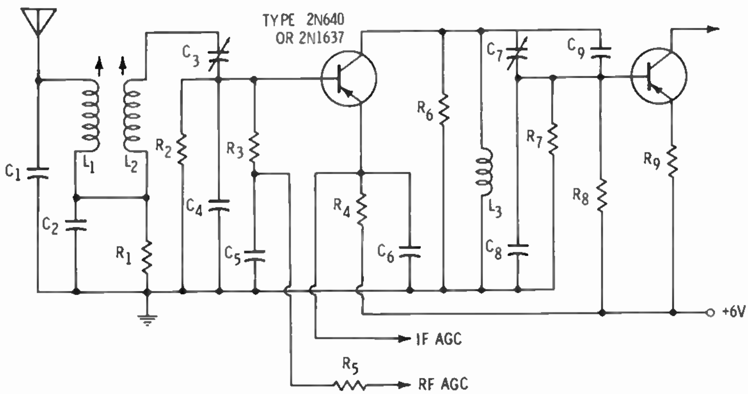


Fig. 10. A transistor "front-end" for a radio receiver.

Fig. 12 shows the coupling arrangement used in a three-stage RF amplifier.

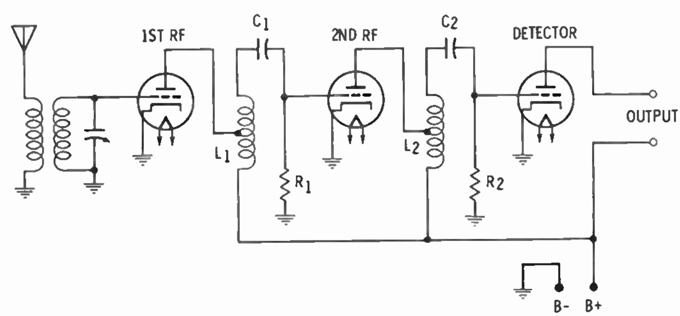


Fig. 11. A two-stage impedance-coupled RF amplifier.

Effect on Selectivity

As previously explained, the selectivity of a receiver is defined as its ability to discriminate between signals of various frequencies. This ability among other factors is affected by the total number of stages in the receiver as well as the selectivity of each of the individual stages.

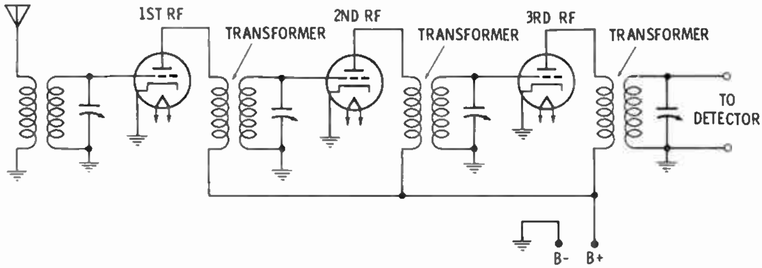


Fig. 12. A three-stage transformer-coupled RF amplifier.

The influence of the number of stages upon the selectivity can best be understood by referring to Fig. 13, which represents the selectivity characteristics of several RF stages. Curve 1 represents the selectivity of a single RF stage. At a point 5,000 hertz off resonance, the circuit gives 84% of the amplification at resonance; and at 10,000 hertz off resonance, the amplification has dropped to 66% of the resonance amplification.

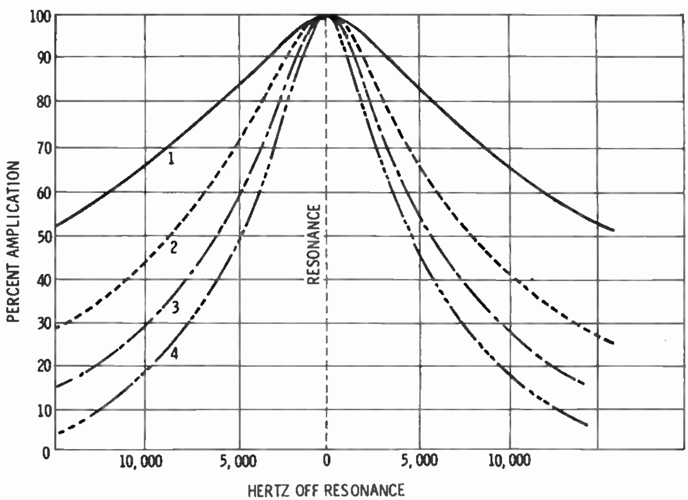


Fig. 13. How several stages of RF amplification increase the selectivity of a receiver by reducing undesired signal strength.

Assume that another stage is added having exactly the same characteristics as that of the first. Now selectivity curve No. 2 indicates the resultant response. If at a certain point off resonance, the first stage reduced the amplification factor to 84%, then the second stage would reduce the amplification to 84% of what came through the first stage. With four stages of RF amplification, a point 5,000 hertz off resonance would introduce a final amplification of only 49% of the resonant frequency.

Analyzing the result further, at a point 5,000 hertz off resonance the amplification of the first stage is 84%; that of the second stage .84 × .84 or 73%; that of the third stage .84 × .84 × .84 or 61%; and finally the amplification of the fourth stage .84 × .84 × .84 × .84 or only a little better than 51%.

Since a radio signal includes modulation frequencies up to 5,000 hertz off center frequency, it is evident that a radio-frequency amplifier having four such stages would cause considerable sideband suppression with consequent signal distortion and unintelligible speech.

REGENERATIVE CIRCUITS

The term "regenerative" is applied to any detector circuit with coupling provided between the plate and oscillatory grid circuit. A tube connected in such a manner performs simultaneously the functions of a detector and an oscillator.

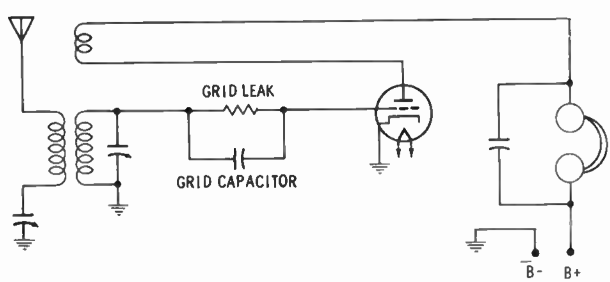
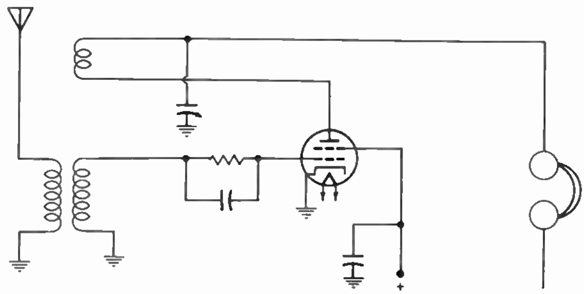
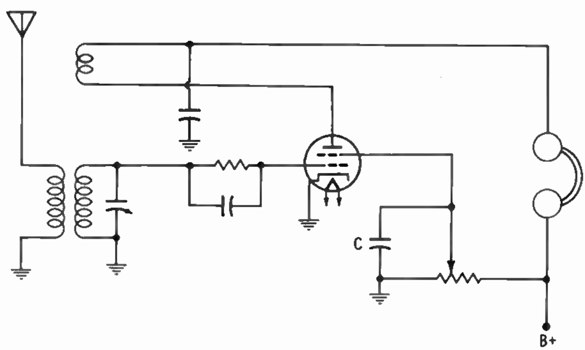


Fig. 14. A regenerative circuit.



(A) Variable capacitor.



(B) Variable resistor.

Fig. 15. Two methods of regeneration control.

A typical regenerative circuit is shown in Fig. 14. The various methods for controlling the amount of feedback, or regeneration, in receivers utilize such things as potentiometers, ticklers, variable capacitors, etc. Fig. 15 shows two ways in which regeneration may be controlled by means of a screen-grid detector. In Fig. 15A, the regeneration control is a variable capacitor having a maximum capacity of 100 or 150 mmf. It acts as a variable bypass between the low-potential end of the tickler coil and the cathode of the tube. If the bypass capacity is too small the tube will not oscillate, while increasing the capacity will cause oscillations to start at a certain value of capacity.

This method of regeneration control is very smooth in operation, causes relatively little detuning of the received signal and, since the voltage on the screen grid of the tube is fixed, permits the detector to operate at its most sensitive point. The sensitivity of a screen-grid detector depends to a great extent on maintaining the screen-grid voltage in the vicinity of 30 volts.

In Fig. 15B, regeneration is controlled by changing the mutual conductance of the detector tube through varying its screen-grid voltage. The regeneration control is usually a potentiometer with a total resistance of 50,000 ohms or more. This circuit causes more detuning of the signal than the one in Fig. 15A. Furthermore, unless the variable regeneration control is bypassed by a large value capacitor (approximately 1 mfd), a certain amount of noise is likely to be produced. In Fig. 15A, capacitor C may be .5 mfd or larger. In the circuit of Fig. 15B, it is necessary to adjust the number of turns on the tickler coil to make the tube just start oscillating with about 30 volts on the screen grid for maximum sensitivity.

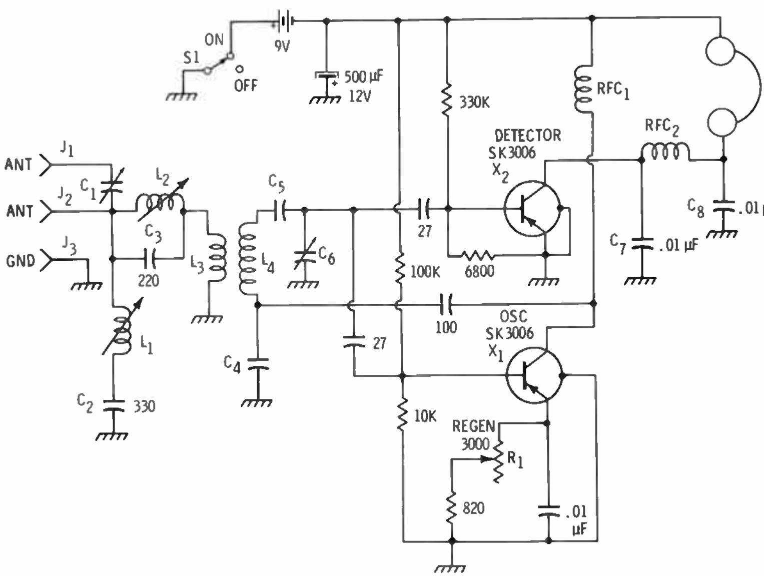


Fig. 16. A simple transistor regenerative receiver.

Both methods shown here may be applied to triode detectors, although these tubes have been largely superseded as detectors by the more sensitive tetrode and pentode tubes. To use the method shown in Fig. 15B for a triode, the regeneration control should be placed in series with the plate of the tube and it need not be used as a voltage-divider, but simply as a series variable resistor. It can also be used as a series resistor when controlling a tetrode tube. Another type of regeneration control, more suitable for lower radio frequencies, employs a variable resistance across the feedback portion of the RF circuit.

Fig. 16 shows the circuit for a simple transistor regenerative receiver. In this arrangement, a separate transistor is used to provide regeneration (or oscillation). This provides better quality reception and minimizes distortion due to overload on strong signals. Regeneration is controlled by varying the bias on the feedback transistor X_1. This circuit is designed for short-wave reception and is operated from a dipole antenna, as explained in a later chapter. L_1, L_2, C_1, and C_2 are connected as wave traps to eliminate or minimize interference from broadcast-frequency signals.

FREQUENCY CONVERSION

Frequency conversion is based on the simple electrical principle that when two different frequencies are combined in a suitable detector, there is produced a third frequency (termed the beat or in-

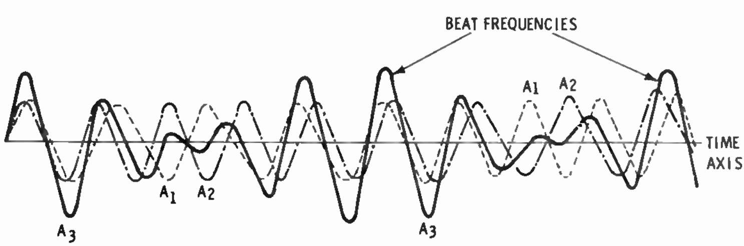


Fig. 17. How beat frequencies are generated. Observe how frequencies A_1 and A_2 are alternately in and out of phase with each other. The frequency with which these two are in phase is equal to the difference between their frequencies.

termediate frequency) that is equal to the difference between or the sum of the two original frequencies.

Thus, if an amplifier is designed for 130 kilohertz, and it is desired to receive a broadcast signal of 1,500 kilohertz, all that is needed is to supply a locally generated frequency either 130 kHz higher or 130 kHz lower than the received signal of 1,500 kHz.

The combination of the received broadcast signal and the locally generated signal produces a beat note, or intermediate frequency, equal to the difference between them, or 130 kHz. This action is illustrated in Fig. 17.

DETECTION

RF amplification in a radio occurs before the radio signals reach the detector circuit. The function of the detector is to demodulate the RF wave before it reaches the audio stage.

In the receiver it is desired to reproduce the original AF modulating wave from the modulated RF wave. In other words, the objective is to recover the original audio signal that was superimposed on the transmitted wave. The stage in the receiver in which this function is performed is called the demodulator or detector stage.

A number of different detector circuits have been employed over the years, several of which will be considered here. Fig. 18 shows a typical diode-detector circuit. The action of this circuit when a modulated RF wave is applied is illustrated in Fig. 19. The RF voltage applied to the circuit is shown in a light line; the output

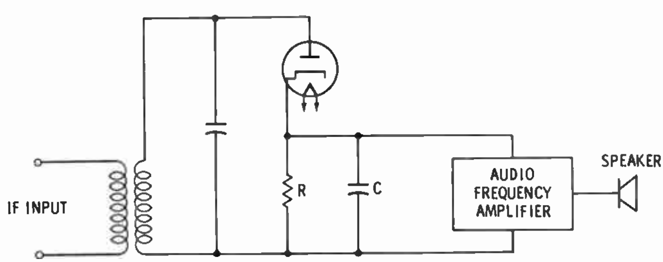
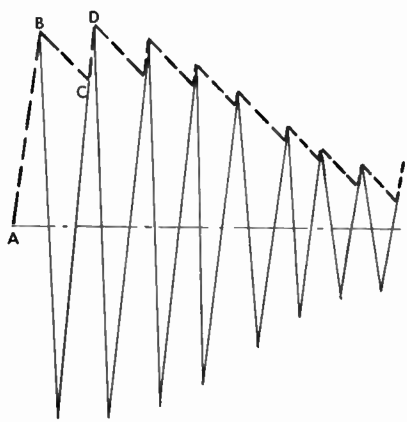


Fig. 18. A diode-detector circuit.

voltage across capacitor C is indicated by the heavy line. Between points a and b on the first positive half cycle of the applied RF voltage, the capacitor C charges to the peak value of RF voltage.

As the applied RF voltage falls away from its peak value, the capacitor holds the cathode at a potential more positive than the voltage applied to the anode. Capacitor C thus temporarily cuts off current through the diode. While the diode current is cut off, the capacitor discharges from b to c, through diode load resistor R. When the RF voltage on the anode again rises high enough to exceed the potential at which the capacitor holds the cathode, current flows again and the capacitor charges up to the peak value of the second

Fig. 19. Diode-detector characteristics.



positive half cycle at d. In this way, the voltage across the capacitor follows the peak value of the applied RF voltage and thus reproduces the AF modulation.

The curve representing the voltage across capacitor C as shown in Fig. 19 is somewhat jagged. However, this jaggedness, which represents an RF component in the voltage across the capacitor, is exaggerated in the illustration. In an actual circuit the RF component of this voltage is negligible. Hence, when the voltage across capacitor C is amplified, the output of the amplifier reproduces the speech or music originating at the transmitting station.

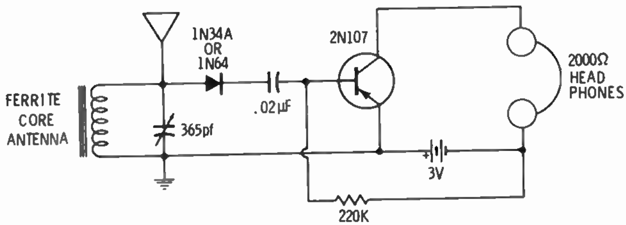


Fig. 20. A one-transistor receiver.

Fig. 20 shows the circuit diagram for a semiconductor diode detector, followed by a transistor audio amplifier. If desired, a transistor can be used for detection, as seen in Fig. 21. The advantage of a transistor detector over a semiconductor diode detector is the additional gain provided by the transistor.

The diode method of detection has the advantage over other methods in that it produces less distortion. The reason is that its dynamic characteristic can be made more linear than that of other detectors. It also has certain disadvantages in that it does not amplify the signal, and it draws current from the input circuit, thereby reducing the selectivity of the input circuit. However, because the diode method of detection produces less distortion and because it permits the use of simple automatic volume control (AVC) cir-

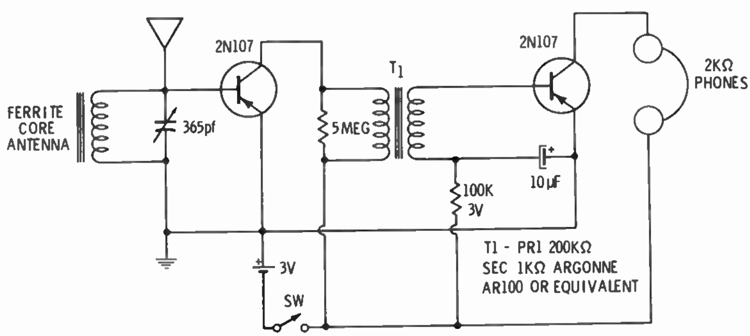


Fig. 21. A two-transistor receiver.

cuits without the necessity for an additional voltage supply, the diode method of detection is most widely used in broadcast receivers.

Another detector circuit, called a diode-biased circuit, is shown in Fig. 22. In this circuit, the triode grid is connected directly to a tap on the diode-load resistor. When an RF signal voltage is applied to the diode, the DC voltage at the tap supplies bias to the

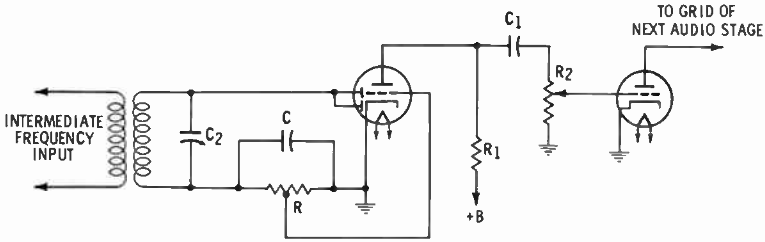


Fig. 22. A diode-biased detector circuit.

triode grid. When the RF signal is modulated, the AF voltage at the tap is applied to the grid and is amplified by the triode. The advantage of this circuit over the self-biased arrangement shown in Fig. 23 is that the diode-biased circuit does not employ a capacitor between the grid and the diode-load resistor, and consequently does not produce as much distortion of signals having a high percentage of modulation.

However, there are restrictions on the use of the diode-biased circuit. Because the bias voltage on the triode depends on the average amplitude of the RF voltage applied to the diode, the average amplitude of the voltage applied to the diode should be constant for all values of signal strength at the antenna. Otherwise there will be different values of bias on the triode grid for different signal strengths and the triode will produce distortion.

This restriction means, in practice, that the receiver should have a separate automatic volume control system. With such an AVC system, the average amplitude of the signal voltage applied to the diode can be held within very close limits for all values of signal strength at the antenna.

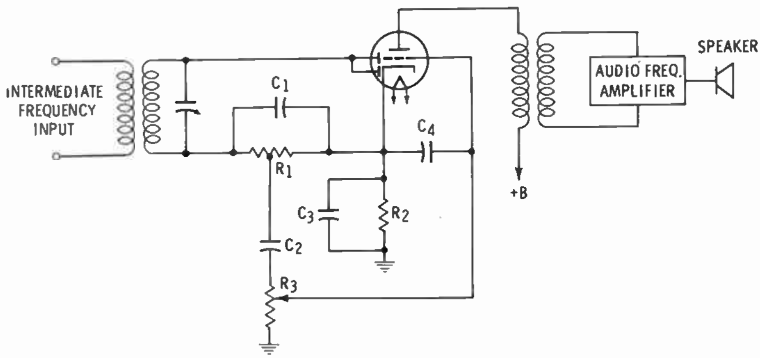


Fig. 23. A typical diode-detector circuit using a duplex-diode tube. R_1 is the diode-load resistor. In a typical circuit, R_1 may be tapped so that 80% of the total AF voltage across it is applied to the volume control. This reduces audio distortion and improves the RF filtering.

The tube used in a diode-biased circuit should be one that operates at a fairly large value of bias voltage. The variations in bias voltage are then a small percentage of the total bias and hence produce small distortion.

In the grid-bias detector circuit shown in Fig. 24, the grid is biased almost to cutoff—that is, operated so that the plate current is practically zero with no signal applied to the grid. The bias

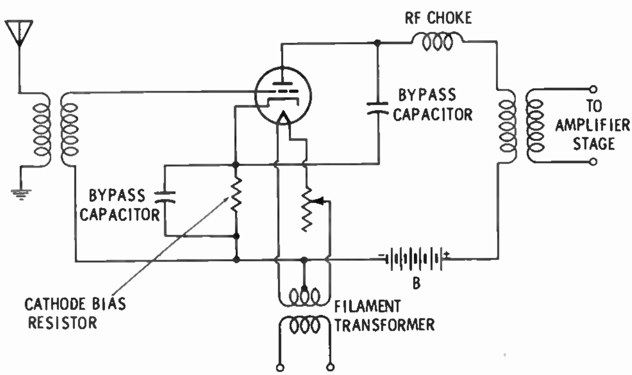


Fig. 24. A grid-bias detector circuit.

voltage can be obtained from a cathode-bias resistor or a bleeder tap on the B+ power supply. Because of the high negative bias, only the positive half cycles of the RF signal are amplified by the tube. The signal is, therefore, detected in the plate circuit.

The advantages of this method of detection are that it amplifies the signal besides detecting it, and that it does not draw current from the input circuit.

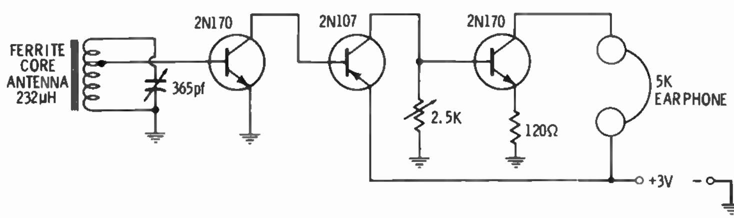


Fig. 25. A three-transistor receiver.

Fig. 25 shows the circuit for a base-bias transistor detector with a two-stage DC coupled audio amplifier. In this arrangement, the base-emitter bias voltage on the detector transistor is zero volts. A small improvement in sensitivity can be obtained by using a very small forward bias on the base. The first audio transistor is forward-biased for class-A operation by the emitter current which flows through the base to the collector of the detector transistor. The second audio transistor is forward-biased by the voltage drop across the 2.5K variable resistor (volume control).

The grid-leak and capacitor method, shown in Fig. 26, is somewhat more sensitive than the grid-bias method and provides its best results on weak signals. In this circuit, there is no negative DC bias voltage applied to the grid. Hence, on the positive half cycles of the RF signal, current flows from grid to cathode. The grid and cathode thus act as a diode detector, with the grid-leak resistor as the diode-load resistor and the grid capacitor as the RF bypass capacitor.

The voltage across the capacitor then reproduces the AF modulation in the same manner as has been explained for the diode de-

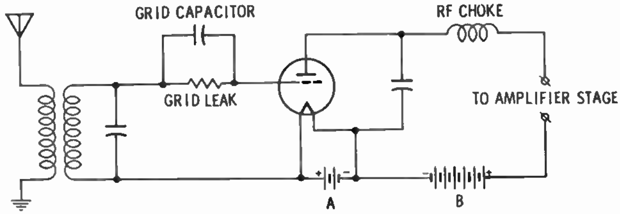


Fig. 26. A grid-leak and capacitor detector circuit.

tector. This voltage appears between the grid and cathode and is amplified in the plate circuit. The output voltage thus reproduces the original AF signal.

In this detector circuit, the use of a high-resistance grid leak increases selectivity and sensitivity. However, improved AF response and much better stability are obtained with lower values of grid-leak resistance.

TUNED-RADIO-FREQUENCY (TRF) CIRCUITS

The word "tuned" in this connection simply means that the circuit is brought into resonance with the desired signal. A tuned RF circuit is one in which the radio-frequency-amplifier circuits may be tuned to the desired wavelength by adjusting the inductance, the capacity, or both, although the usual method of tuning is by means of a variable capacitor in parallel with the secondary of the RF transformer. Fig. 27 illustrates the principle of a tuned-radio-frequency circuit.

Reflex Circuits

The reflex circuit is only one of several circuits developed for the purpose of reducing the number of tubes required in a multi-stage receiver. The use of this circuit, however, with the versatility and relative inexpensiveness of the modern vacuum tube has become largely obsolete; however, it will be discussed here because of the electronic principles involved and because many transistor receivers are using it. A typical reflex circuit is shown in Fig. 28.

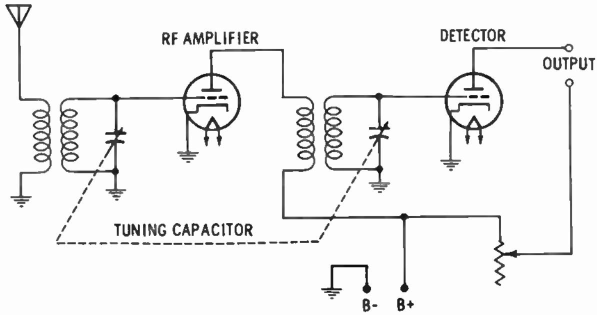


Fig. 27. The principle of a TRF receiver.

In this circuit the vacuum tube is made to perform the dual functions of both radio- and audio-frequency amplification.

The incoming signal is amplified at radio frequency, rectified by a detector, and then amplified at audio frequency using the same

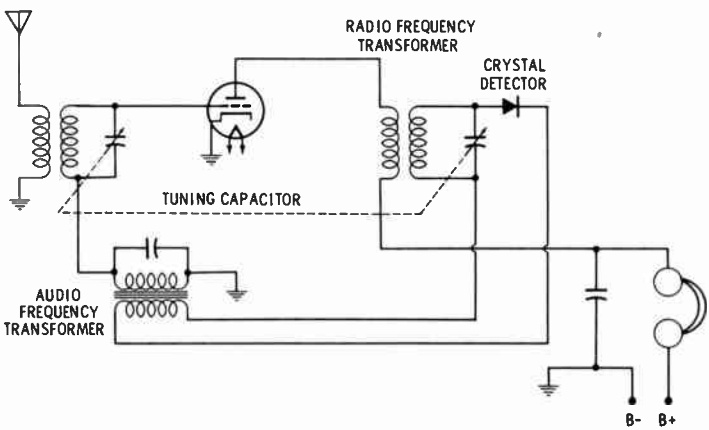


Fig. 28. A typical reflex circuit.

tube. Or, if so desired, the circuit values can be chosen so that the stage can function as a radio-frequency and intermediate-frequency amplifier.

It can readily be understood that to construct a stage that will first amplify the signal at the IF and then further amplify it after it has been rectified and converted into an audio frequency signal requires a very careful choice of circuit constants, because not only must the circuit elements present the proper load at both audio and intermediate frequencies but also filters must be inserted to separate the frequencies so as to prevent feedback.

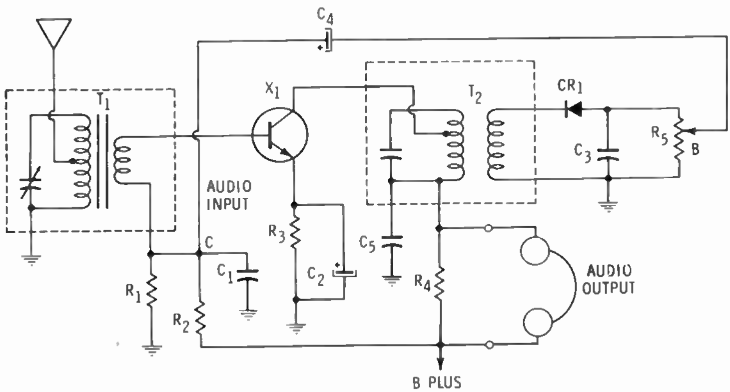


Fig. 29. A transistor reflex circuit.

A transformer reflex circuit is shown in Fig. 29. The incoming RF signal is first amplified by TR_1, and then detected by X_1. The detected signal is then coupled back to the base of X_1, thereby providing audio amplification. The amplified audio signal drops across R_4 and the earphones. If the earphones have a suitable value of DC resistance, R_4 may be omitted. R_5 operates as a volume control.

FREQUENCY CONVERTERS

The function of the frequency converter in a superheterodyne receiver is to convert the RF signal to an intermediate frequency.

Before the incoming signal is fed to the IF amplifiers, it must be converted to a lower frequency. To obtain this change in frequency, a frequency-converting system consisting of a local oscillator and a mixer circuit is commonly employed. In the mixer tube, the incoming RF signal and the RF signal produced by the local oscillator are mixed (heterodyned) to produce in the plate circuit a signal having, in addition to the original frequencies, the sum and difference frequencies.

Generally the output circuit of the mixer stage is provided with a tuned circuit adjusted to select only one beat frequency—that frequency which is equal to the difference between the incoming (received) signal frequency and the oscillator frequency. It is this selected output frequency that is known as the intermediate frequency or, in abbreviated form, IF. The signal output of the mixer is held constant (at the IF value) regardless of the frequency of the signal being received. This is accomplished by synchronizing the tuning of the oscillator and preselector circuits.

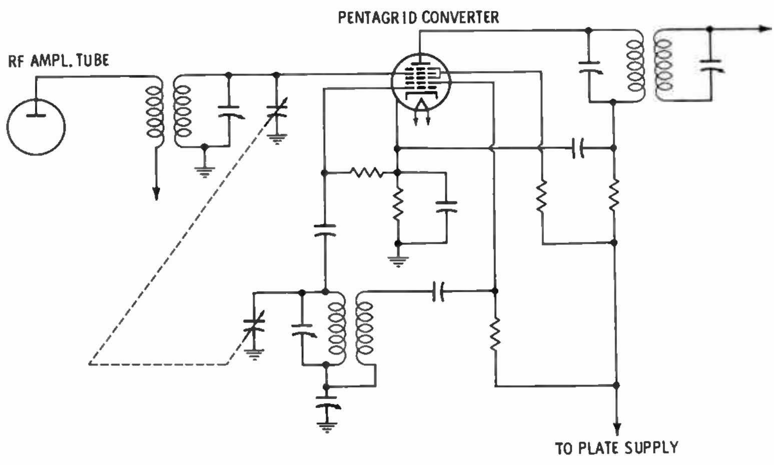


Fig. 30. A pentagrid converter tube employed as an oscillator-mixer in a superheterodyne receiver.

The first method of frequency conversion widely employed before the availability of tubes especially designed for this purpose, employed as the mixer tube either a triode, a tetrode, or a pentode. In this method the oscillator and the incoming signal are applied to

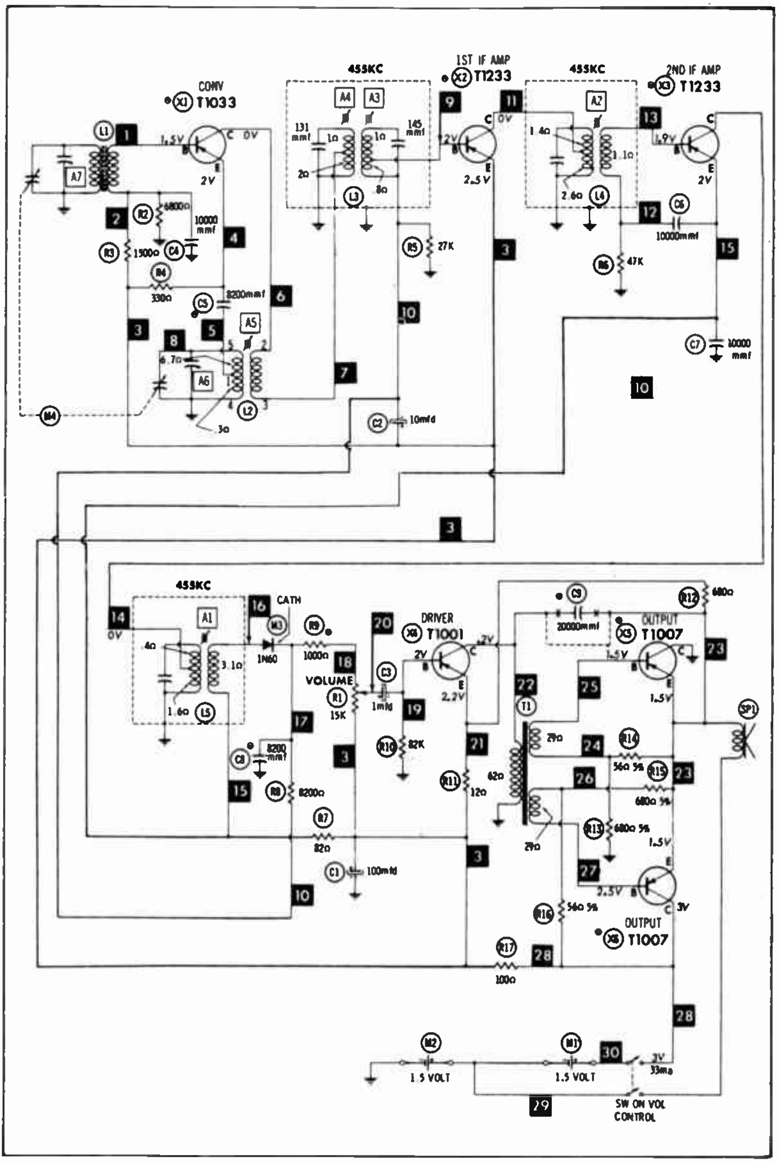


Fig. 31. A transistor superheterodyne receiver.

the same grid. The coupling between the oscillator and mixer circuits is obtained by means of inductance or capacitance.

A second method employs a tube which is especially designed for this type of service known as the pentagrid converter tube. (See circuit in Fig. 30.)

In this tube the oscillator and frequency mixer are combined, with coupling between the oscillator and mixer circuit provided by means of the electron stream within the tube.

A third method of frequency conversion uses a circuit identified as the pentagrid mixer. It has two independent control grids, and is used with a separate oscillator tube. In this circuit, the incoming RF signal is applied to one of the control grids and the oscillator signal is applied to the other grid of a tube with two control grids.

In the case of transistor radio receivers, a triode transistor is often employed as an oscillator-mixer, as shown in Fig. 31. Feedback is provided by L_2 from the collector to the emitter of transistor X_1. Thereby an oscillatory signal is generated for mixing with the incoming RF signal. The RF signal is applied to the base of transistor X_1. In turn, a 455-kHz beat signal is developed at the collector. This IF signal is picked off by L_3 and fed to the IF amplifier section.

AUDIO-FREQUENCY AMPLIFIERS

An audio-frequency amplifier is employed to increase the strength (amplitude) of the signals after leaving the detector tube, but before the signal is fed to the speaker.

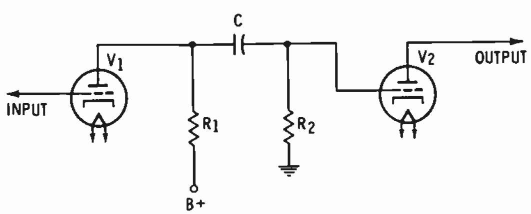


Fig. 32. A resistance-coupled AF amplifier.

There are three general methods of audio-amplifier coupling whereby one stage of an audio-frequency amplifier may be connected to the following stage, identified as:

1. Resistance coupled.
2. Impedance coupled.
3. Transformer coupled.

Resistance-Coupled

Here, as in the previously discussed RF amplifier coupling, a resistance is employed in the interstage coupling, as shown in Fig. 32. The function of the blocking capacitor C is that of insulating the grid of the tube from the high positive potential of the plate supply. In order to prevent the grid from accumulating a negative charge, a high-resistance leakage path is introduced through grid resistor R_2, the size of which depends upon the value of the grid-to-cathode resistance of the tube.

When a signal potential is received from the detector, a current is generated through coupling resistor R_1 in the plate circuit of the first tube. These variations of plate voltage are reduced by blocking capacitor C and are impressed on the input circuit of the second tube. Finally the grid-voltage variations applied to the second tube cause corresponding variations of the plate potential which are, in turn, impressed on the input circuit of the final audio stage.

Resistance coupling of the audio-frequency stages offers the advantages of good response at low audio frequencies. However, this increases the possibility of trouble from a common plate-voltage supply. This is due to the fact that the bypass capacitors are ineffective at very low audio frequencies and hence the common voltage supply acts as coupling between the stages. This gives rise to a low-frequency form of oscillation.

Impedance-Coupled

The impedance-coupled audio amplifier is similar to the resistance-coupled amplifier just described except that, in place of the resistance, an inductance is employed (see Fig. 33).

The effect of the blocking capacitor is similar to that described for the resistance-coupled amplifier.

Transformer-Coupled

In the amplifier stages shown in Fig. 34, the coupling is made by means of a transformer consisting of two windings—one primary and one secondary. The voltage gain received with this type of coupling is largely defeated due to the fact that it is not linear for all

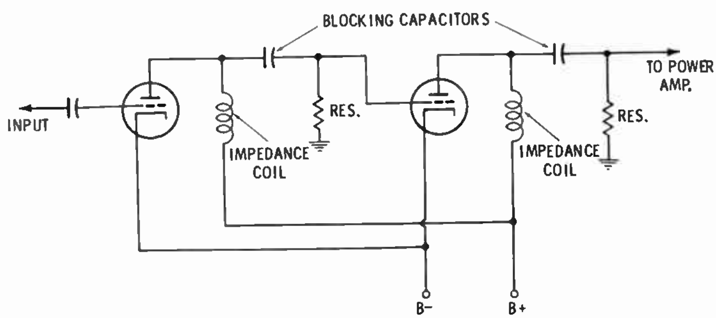


Fig. 33. An impedance-coupled AF amplifier.

frequencies. This frequency distortion is caused largely by the distributed capacity existing between the windings of the transformer, and an additional form of distortion known as harmonic distortion is caused by saturation of the iron core in the transformer.

Now that receivers have been discussed from the point where signals enter the RF stages to the point where the audio is recov-

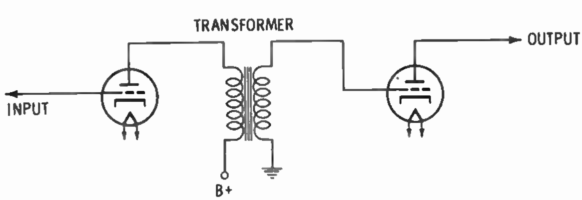


Fig. 34. Interconnection of a transformer-coupled AF amplifier.

ered frcm the transmitted wave, refer to Fig. 35 for an overall picture of the various stages in a superheterodyne receiver and their progressive effects on radio signals entering at the antenna and emerging from the speaker.

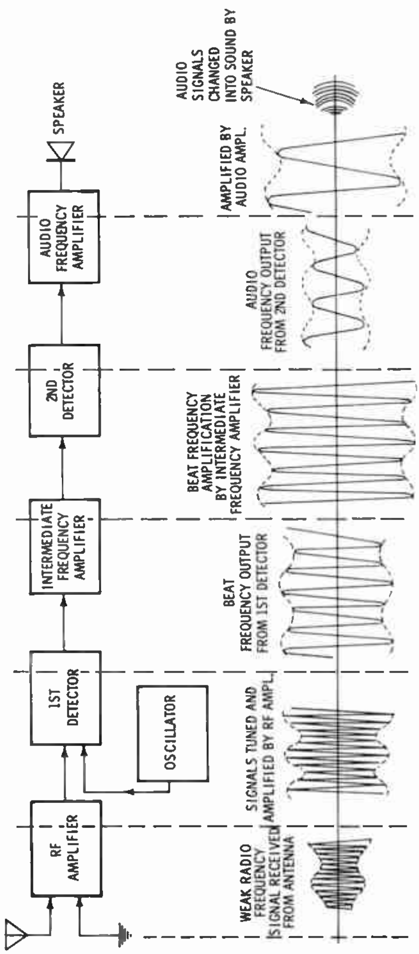


Fig. 35. Combination diagram showing arrangement of the different stages of a typical superheterodyne receiver, with charts indicating how the radio signals are modified by each unit.

FM RECEIVER PRINCIPLES

In the AM system of reception, most interfering noises affect the amplitude of the signals. Therefore, receivers designed to receive amplitude-modulated signals also receive a considerable amount of radio interference.

Frequency-modulated signals received on receivers designed exclusively for such reception give greater freedom from interference.

The advantages in reception when using frequency modulation are:

1. Freedom from static interference.
2. A greatly extended frequency range. (See Fig. 36.)

The main difference between the amplitude- and frequency-modulated receiver is apparent from the block diagrams in Fig. 37. As you can see, both types may have an RF amplifier stage, the primary function of which is to provide adequate selectivity and voltage gain.

A converter stage, consisting of a single tube functioning as mixer and oscillator, or two separate tubes performing these functions, is common to both circuits.

Intermediate-Frequency Amplifiers

Although an intermediate-frequency amplifier of one or more stages is employed in both AM and FM receivers, the IF amplifier in a frequency-modulated receiver differs from that of an amplitude-modulated receiver by reason of its wide-band characteristics. It must amplify a wide band of frequencies.

In an amplitude-modulated receiver, the IF amplifier is designed to reject a signal more than 10 to 15 kHz from that to which the amplifier is tuned, whereas the IF amplifier in a frequency-modulated receiver is designed to pass a signal, without appreciable attenuation, as much as 100 kHz or more on either side of the frequency to which the IF transformers are aligned.

There are various methods employed to obtain this bandwidth. In some instances, the primary and secondary windings are overcoupled to broaden the response curve.

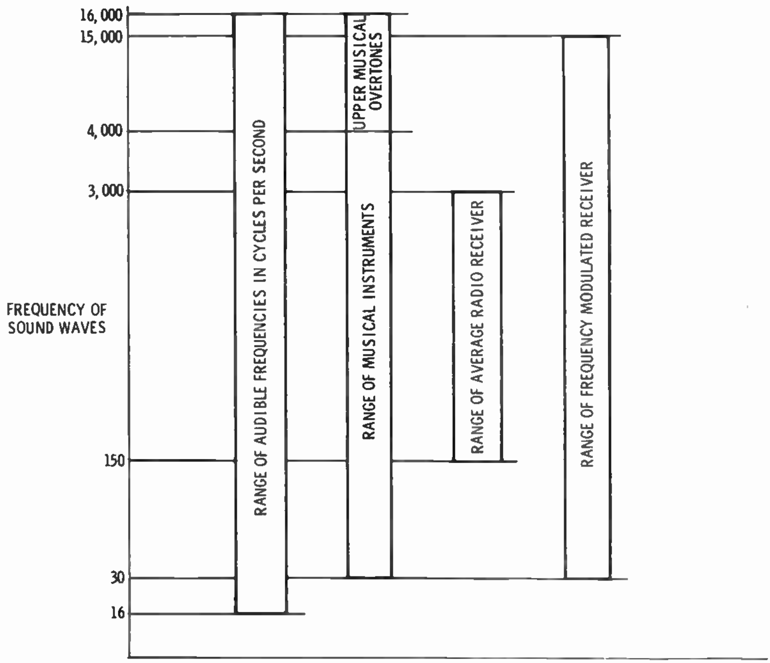
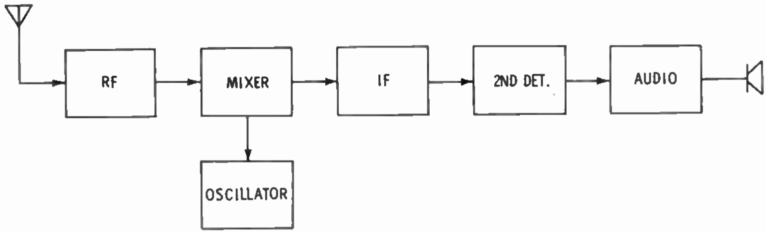


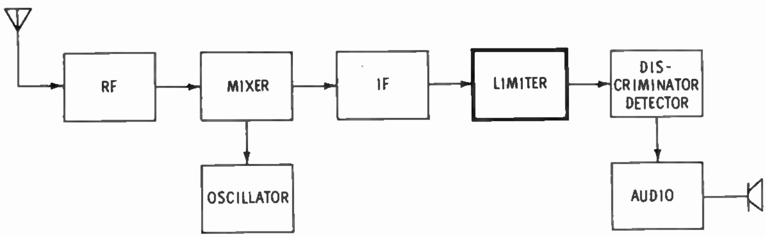
Fig. 36. Comparative tone coverages of average AM and FM receivers.

The great majority of frequency-modulation receivers, however, employ shunt resistors, to load either or both the primary and secondary windings to obtain the required 150- to 200-kHz bandwidth. In some of the early receivers, as well as several frequency-modulation adapters, both the primaries and secondaries of the IF transformers were shunted by resistors as shown in Fig. 38.

The values of these shunt resistors vary with each receiver model, and depend upon transformer design and degree of loading required in each case to secure the bandspread. Resistor values from 10,000 to 50,000 ohms are most commonly used for this purpose.



(A) Amplitude modulation.



(B) Frequency modulation.

Fig. 37. Block diagrams showing sequence of stages in AM and FM receivers.

Limiters

Again referring to the block diagram in Fig. 37B, a limiter stage is shown. This is essentially an intermediate-frequency stage and consists of one or two amplifier tubes so arranged as to deliver constant-amplitude output regardless of wide variation in input-signal amplitude.

The tubes employed as limiters are usually of the pentode type, having sharp cutoff characteristics, and are operated at low plate and screen voltages, so that plate-current cutoff occurs with relatively small grid bias or signal input.

Normal signal input will swing the grid voltage considerably above and below the linear portion of the characteristic curve of the tube.

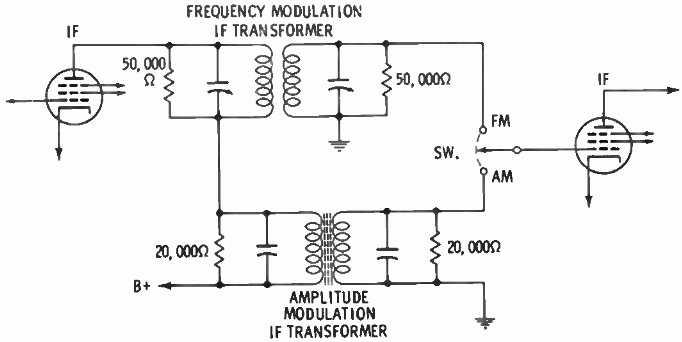


Fig. 38. Use of resistive loading to broaden response characteristics.

Positive peaks beyond the range of the limiter tube will be clipped by grid-bias limiting, whereas negative signal peaks will be clipped due to plate-current cutoff. In this manner, variations in the signal which are greater than the operating limits of the tube are clipped and have no effect on plate current.

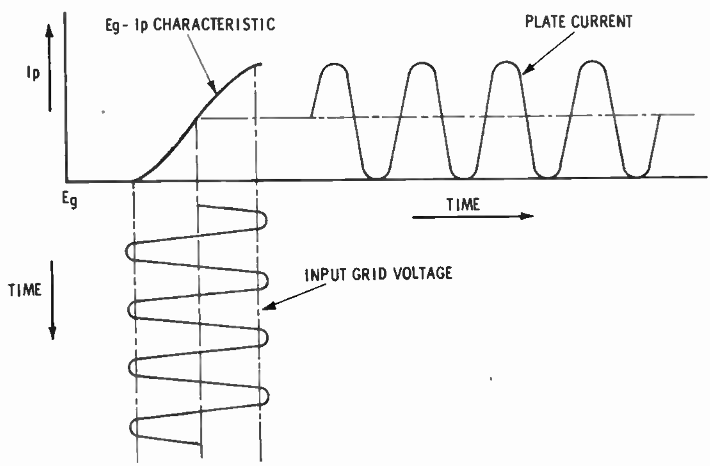


Fig. 39. Action of limiter in clipping modulation peaks beyond linear portion of the characteristic curve.

Since static and noise disturbances primarily produce amplitude changes in the signal, as do tube noises, the clipping of amplitude variations removes the disturbing effects but leaves the frequency-modulated signal unaltered. This action is illustrated in Fig. 39.

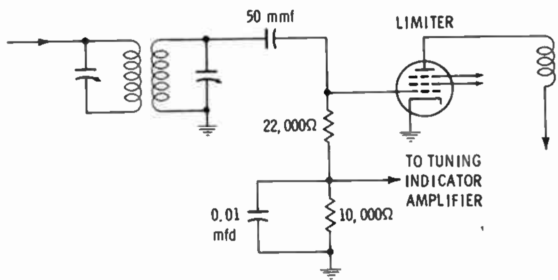


Fig. 40. One type of limiter used in FM receivers.

For complete noise elimination, it is essential that the signal voltage appearing at the limiter grid be sufficiently strong to swing the grid bias to plate-current cutoff and saturation points.

Limiter tubes are generally operated at zero bias or with a small bias voltage. The limiter circuit shown in Fig. 40 is repre-

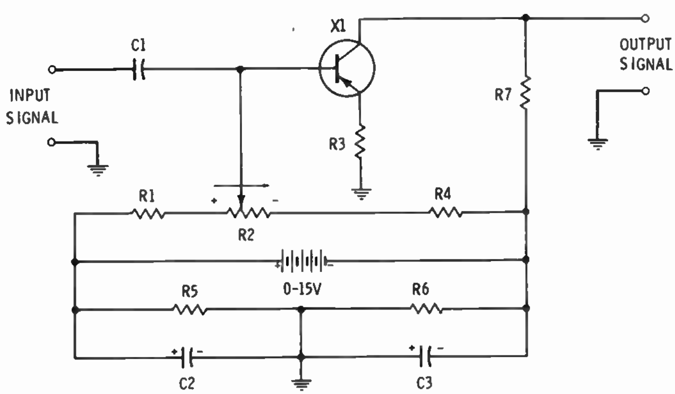


Fig. 41. A transistor triode limiter.

sentative of those used in some FM receivers. Fig. 41 shows a transistor triode limiter circuit. Another limiter circuit is shown in Fig. 42, in which the load resistance is connected to the secondary return, the tube being supplied with a small initial negative bias.

The limiter circuit in Fig. 43 shows a low-value resistor connected in series with the limiter load resistor so that an indicating meter may be conveniently connected. The circuit in Fig. 44 shows how two tubes may be arranged in cascade to operate more efficiently as limiters.

FM Detectors

The last significant difference between the amplitude-modulation and frequency-modulation receivers concerns the second detector, or demodulator.

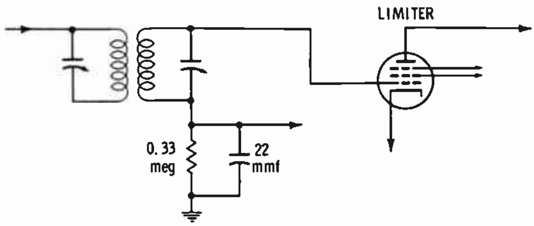


Fig. 42. Another type of limiter circuit employed in FM receivers.

In frequency-modulation receivers one of two types of detector circuits is generally employed, namely the Foster-Seeley discriminator or the ratio detector. The Foster-Seeley discriminator (Fig. 45) consists of a push-pull diode detector in which opposing voltages developed across load resistors are equal and opposite so long as the carrier frequency remains at the intermediate frequency.

The resultant voltage across the two load resistors from Point A to ground is zero and no audio voltage is developed. When the signal impressed upon the discriminator transformer is frequency modulated, phase changes as a result of both magnetic and capacitive coupling will unbalance the voltage drops across the load re-

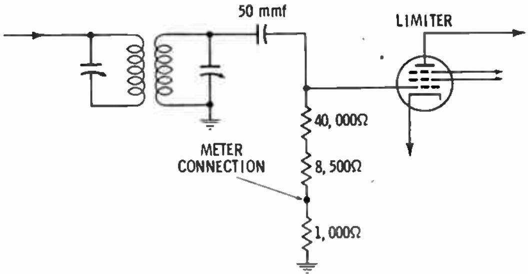


Fig. 43. A limiter circuit in which an indicating meter may be connected.

sistors as the frequency varies above and below the intermediate frequency with modulation.

The resultant voltage measured across both diode load resistors will then be equal to the difference between the voltages developed across each, and will vary in polarity from point A to ground as the

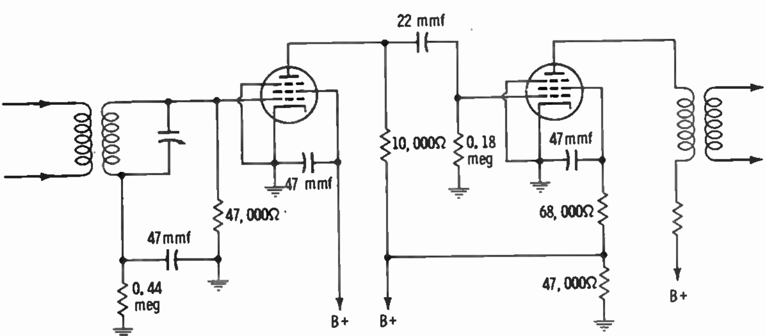


Fig. 44. A dual limiter circuit.

modulation swings the frequency higher and lower than the resting or resonant frequency. The degree of modulation, or frequency swing, determines the magnitude of the voltage. The voltage developed across the load resistors is the equivalent of the audio signal impressed on the transmitted carrier wave.

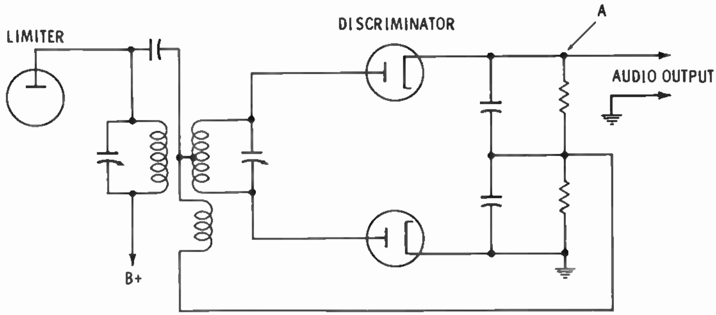


Fig. 45. A Foster-Seeley discriminator.

The ratio-detector circuit (Fig. 46) appears somewhat similar to the Foster-Seeley discriminator except that the polarity of one of the diodes is reversed. L_1 and L_2 in this circuit comprise an IF transformer with secondary L_2 being center tapped. More commonly it is referred to as the discriminator transformer. An inherent characteristic of the ratio detector is its ability to cancel amplitude variations appearing in the received signal. Because of this feature no limiter stage is required ahead of the detector, as is the case with the discriminator. You will also notice that unlike the discriminator, the ratio detector has a different take-off point for the audio signal and an additional capacitor (C_6) is employed. The function of C_6 (generally referred to as the stabilizing capacitor) is to keep the total rectified voltage constant despite rapid variations in the incoming signal.

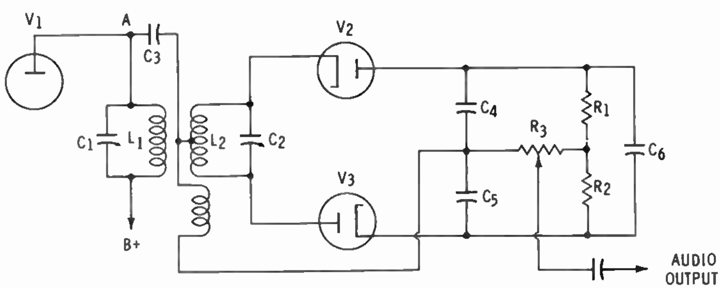


Fig. 46. A ratio detector.

In operation the RF voltages applied to the diodes are the vectorial sum of the primary voltages at point A and the half of secondary L_2 connected to the diode involved. The phase relation is such that, as the frequency of the signal increases, the RF voltage at one diode increases. At the same instant the RF voltage on the other diode decreases. As the frequency of the signal decreases the opposite condition exists. The rectified DC voltages appearing across resistors R_1 and R_2 are equal to the AC voltages across the diodes to which they are connected. Variations in the phasing of the voltages due to frequency deviations in the received signal produce varying DC voltages across C_4 and C_5. These in turn result in a varying current through R_3 and, hence, develop the desired audio signal across this resistor. The instantaneous sum of the voltages across C_4 and C_5 must at all times equal the fixed voltage across C_6. In other words it is the ratio of the voltages across capacitors C_4 and C_5 that varies and not the sum.

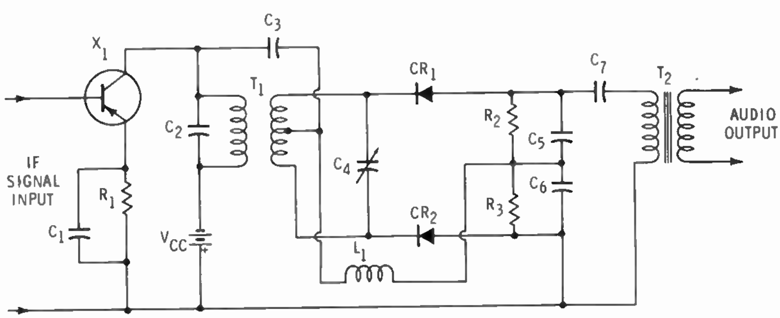


Fig. 47. A transistor IF amplifier and discriminator stage.

Fig. 47 shows the circuit for a semiconductor discriminator. It is seen that this configuration is essentially the same as shown in Fig. 45 for a tube arrangement. We will also find the *slope detection* process employed occasionally. A typical slope-detector circuit is depicted in Fig. 48. Note that L_1 and C_2 are tuned so that the center frequency of the incoming FM signal falls on the side of the frequency-response curve. This side-tuning operates to

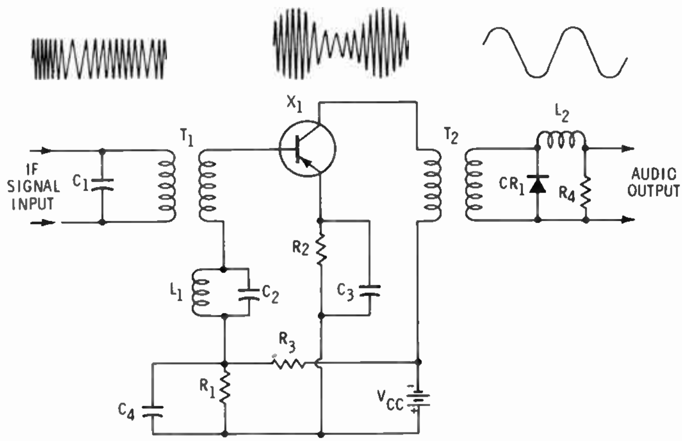


Fig. 48. A transistor slope detector and diode detector.

change the FM signal into an AM signal. In turn, the output from transistor X_1 is fed to a conventional diode detector CR_1. The detector output is the AM wave envelope.

AUTOMATIC FREQUENCY CONTROL

Tuning an FM receiver to the desired signal is more critical than tuning an AM receiver. Since the frequency-modulated signal is quite wide in comparison with AM signals, it is easy to tune to some point on either side of the center frequency, and the signal will sound fine on low-level signals. On stronger signals, however, the frequency deviation will increase and distortion will occur due to the fact that the receiver is tuned so that only a portion of the signal is within the bandpass. The automatic frequency control system (abbreviated AFC) is designed to correct automatically for slight misadjustments in tuning. AFC is used primarily with FM receivers; however, it can be used with AM receivers.

The action of the automatic frequency control circuits in superheterodyne receivers is such that any mistuning by the listener or any frequency drift in the set after it has been properly tuned is automatically corrected by the incoming signal itself.

In most instances a DC voltage proportional to the frequency of the IF signal is taken off at the detector and is applied to the oscillator stage (Fig. 49). This control voltage varies when the IF frequency varies above and below the proper value. Intermediate frequencies which are too low and thoses which are too high produce a corresponding voltage, the value of which depends upon the direction of frequency departure from a prescribed intermediate frequency. This DC voltage is applied to the reactance stage, which in turn causes a shift in frequency of the local oscillator so as to bring the IF signal to very nearly the correct frequency. Since the production of this DC voltage is due to departure from the resonant or

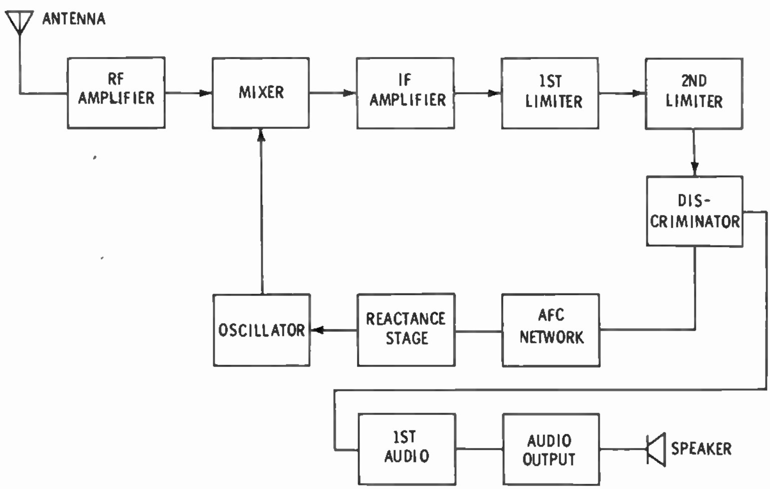


Fig. 49. Block diagram of a superheterodyne FM receiver with automatic frequency control.

center frequency of the IF system, the correction cannot be strictly complete. However, in the system described, a correction ratio of more than 100 to 1 is feasible. In other words, when the dial of the receiver is mistuned 100 kHz for the received signal, the automatic correction may be made to bring the actual IF signal frequency to within only 100 hertz of resonance in the IF system.

The use of AFC on the short-wave bands is extremely helpful in making the tuning operation easier. The tuning control has to be moved only until the frequency is close enough to resonance to permit the AFC circuit to make the necessary correction. Short-wave stations are thus spread out on the dial, making them easier to locate and easier to hold.

COMMUNICATIONS RECEIVERS

A communications receiver is one designed for use in a two-way radio system or to receive transmissions of this nature. These receivers, which may be of either the AM or FM type, operate on the same basic principles as those discussed previously, the only difference being in the technical requirements.

In two-way radiocommunications, fidelity is not nearly as important as selectivity. In fact the audio response of a communications transmitter is generally limited from 300 to 3,000 hertz to keep the bandwidth of emission as narrow as possible. This range contains all the frequencies necessary to convey the human voice intelligibly.

The three major requirements of a communications receiver are selectivity, sensitivity, and stability. Increased selectivity is generally obtained by means of additional tuned circuits. A variable control is often placed on the control panel to select the degree of selectivity (in the case of AM receivers). Also, selectivity can be increased by using one or more additional frequency-conversion stages. A block diagram of a receiver using dual conversion is shown in Fig. 50. In this receiver, the incoming signal is heterodyned twice, creating two intermediate frequencies. One is referred to as the high IF and the other as the low IF. Some receivers even employ triple conversion to obtain the desired results.

Receiver sensitivity is increased by using additional tuned circuits and stages of amplification. One or more controls are generally provided for varying the amount of gain. Some receivers have a potentiometer that varies the RF gain, others have a control that permits adjustment of the IF gain; some have both. Frequency stability in communications receivers is generally maintained by using regulated supply voltages and temperature-compensated components in critical circuits such as the oscillator.

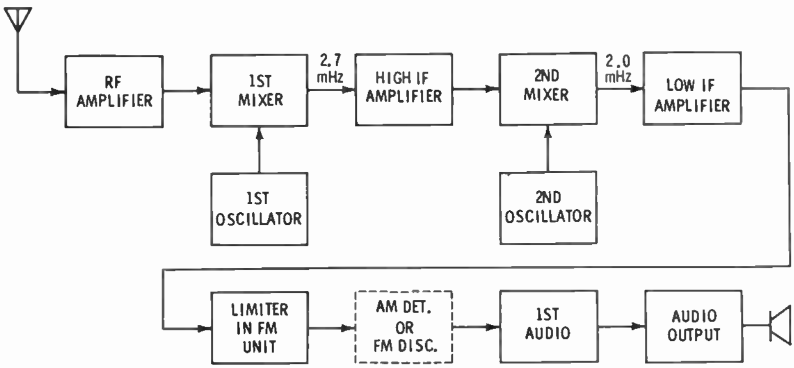


Fig. 50. Block diagram of a dual-conversion superheterodyne receiver.

Squelch Circuits

Some AM and practically all FM communications receivers employ what is known as a squelch circuit. The function of this circuit is to mute the irritating background noise that is normally present when no signals are being received.

Basically there are two types of squelch circuits. One is known as signal operated and the other is noise operated. The former is used primarily with AM receivers, whereas the latter is employed almost exclusively with FM receivers. The squelch circuit produces a DC voltage that is used to bias one of the audio stages to cutoff. Under this condition no sound will be heard from the speaker. When a signal of sufficient strength is received, the bias is automatically reduced, allowing the signal to pass on to the speaker. With the carrier-operated squelch system, it is the presence of the received carrier that causes the cutoff bias on the audio stage to be overcome.

In the noise-operated system, it is the reduction of background noise when a signal is received that "kills" squelch action. Here the normal background noise (with no signals being received) is amplified and then rectified to produce the bias voltage. When a signal is received, the background noise is reduced (the amount depending on the strength of the signal), less bias is produced, and the audio stage is permitted to conduct normally. A squelch control permits the operator to set the average bias level at a point which will determine how strong the incoming signal must be to overcome squelch action. Although the operation of the squelch system is somewhat more complex than described here, the basic action is the same.

AUTOMOBILE RADIO RECEIVERS

Automobile radio receivers usually employ the superheterodyne circuit with automatic volume control and differ from the conventional radio receiver only with respect to the extreme compactness, the tuning controls, and the power supply.

The power supplies for automobile radio receivers are currently going through a transition from the old to new systems. Most of the older auto radios employed a vibrator-type power supply. After 1956, when most American automobiles went to the 12-volt DC

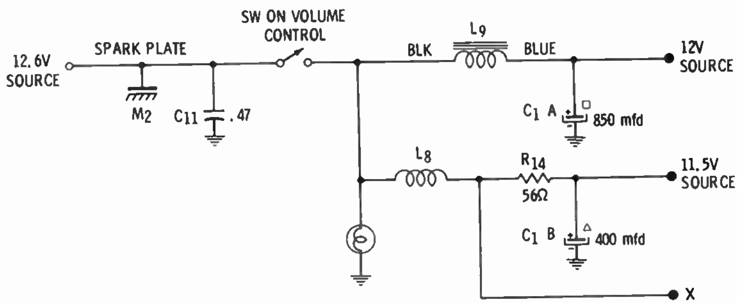


Fig. 51. Power supply for automobile receiver using low-voltage tubes.

electrical systems, many changes began to take place in auto-radio design. Some manufacturers still stood by the conventional vibrator power supply, while others took advantage of new tube designs that required no high voltage. Instead these tubes operate directly from the 12-volt DC battery of the automobile and provide equal if not better performance than the older type tubes.

Fig. 51 shows a power supply designed for a receiver using these low-voltage tubes. As you can see, no vibrator or power transformer is required. The various chokes and capacitors serve to filter out any slight variations or noise that might be present in the DC source voltage.

Shortly after the low-voltage tubes were introduced, auto-radio manufacturers began producing hybrid sets. These consist of both tubes and transistors. At present, nearly all auto receivers use transistors exclusively.

SUMMARY

The function of a radio receiver is to select and amplify the desired radio signals, separate the intelligence transmitted from the unneeded portion of the wave, and convert it into an output that can be heard by the listener. The simplest receiver consists of only a tunable circuit, an antenna, a crystal detector, and headphones. Other, more complicated, receivers include the regenerative and superregenerative, tuned radio frequency (TRF), and the superheterodyne.

The most important receiver characteristics are selectivity, sensitivity, fidelity, and stability. Selectivity is the ability of a receiver to discriminate between signals of different frequencies. Sensitivity is the ability of a receiver to receive weak signals. Fidelity is the faithfulness with which a signal is reproduced. Stability is the ability of a receiver to maintain its selected frequency.

Amplifiers are sometimes used in the RF section of a receiver and nearly always in the audio section. Amplifiers are divided into classes according to the manner in which they are operated. Besides the different classes of amplifiers, various arrangements are used to couple an amplifier to a stage following or to one preceding. The most common of these types are the resistance-coupled, and transformer-coupled amplifiers.

Regenerative receivers work on the principle of feedback of a portion of the signal in such a manner as to bias a tube to the point where it is capable of detecting a signal. Amplification also takes place in the detector in a regenerative circuit.

Detection is the process whereby the modulating frequency is removed from the modulated radio signal. There are many types of detectors, the simplest and most common being the diode detector. Other types include grid-bias, and grid-leak.

A superheterodyne receiver works on the principle of beating (mixing) the incoming signal frequency with a frequency generated within the receiver to produce a third frequency which is then carried through the receiver. This third frequency, called the intermediate frequency (IF), is always constant, regardless of the frequency of the received signal.

Audio amplifiers are used to strengthen the relatively weak detected signal in order to power speakers so that adequate volume of sound is present for listening. This type of amplifier can be one of several different classes and types.

FM receivers detect frequency-modulated signals by changing the variation in frequency to a variation in voltage. Amplification of this variable voltage then is used to power speakers. FM detectors differ from AM detectors. The most common FM detectors are the ratio and discriminator types.

REVIEW QUESTIONS

1. Define selectivity as it relates to receivers.
2. What is fidelity?
3. Define a class-B amplifier?
4. Name two methods used to control regeneration in a regenerative receiver.
5. What is detection?
6. Name two types of AM detectors.
7. Name two types of FM detectors.
8. How is the IF frequency of a receiver produced?
9. What is the purpose of a limiter circuit in an FM receiver?
10. What are AVC and AFC?

CHAPTER 19

Antenna Fundamentals

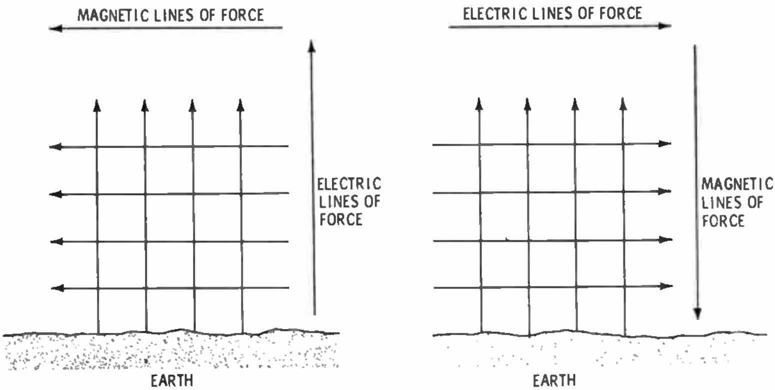
All radio transmitters and receivers require some form of antenna in order to operate properly. The function of the antenna is to transfer RF energy into space when transmitting and to act as a collector of this energy in the receiving mode. An antenna may be quite simple or it can be complex. Also, an antenna that is capable of receiving radio signals is equally capable of transmitting them.

PHYSICAL AND ELECTRICAL CHARACTERISTICS

The design of an antenna has a considerable effect on the manner in which it radiates and/or receives electromagnetic energy. When radio waves strike the receiving antenna they induce a corresponding RF current in the antenna. Just how much current is induced, however, depends on such things as the field strength of the signal, type of antenna, polarization, length and spacing of the antenna elements, etc.

Polarization

As mentioned previously, a radio wave consists of moving fields of electric and magnetic energy. The lines of force within these fields are always at right angles to each other. When the lines of force in the electric field are perpendicular to the earth (Fig. 1A), the wave is said to be *vertically polarized*. Conversely, when the



(A) Vertically polarized wave.

(B) Horizontally polarized wave.

Fig. 1. Relationship between the electric and magnetic fields in a radio wave.

electric lines of force are parallel to the earth as in Fig. 1B, the radio wave is *horizontally polarized*.

Polarization of a radio wave is determined by the position of the electric lines of force with respect to the earth. This in turn is governed by the position of the radiating element of the antenna. The lines of force in the electric field leave the antenna on the same plane as the radiating element (Fig. 2). Thus, a vertical antenna radiates vertically polarized radio waves, and a horizontal antenna radiates horizontally polarized waves. For maximum RF energy to be transferred from the transmitting to the receiving antenna, it is necessary that both antennas be of the same polarization. Signals can be received with an antenna that is cross polarized, but not at optimum efficiency.

Directional Characteristics

All antennas can be classified as either directional or nondirectional in their ability to radiate and receive electromagnetic energy.

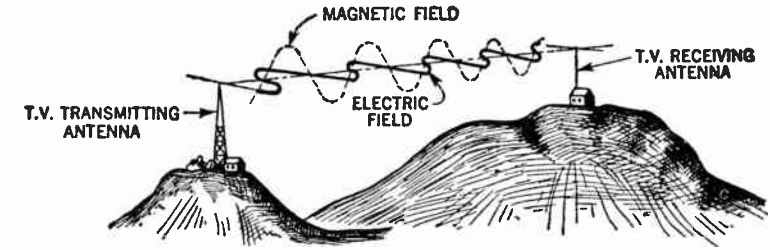


Fig. 2. Electric and magnetic fields of a horizontally polarized wave in relation to transmitting and receiving antennas having the same polarization.

An antenna consisting of a straight vertical rod has what is referred to as an omnidirectional pattern. That is, it responds equally well in all directions. A directional antenna, on the other hand, can respond in one direction or several. A dipole antenna, for example, will radiate or receive radio signals equally well in two directions and is referred to as a bidirectional type. All types of radiation patterns can be obtained through proper antenna design. As a general rule, a horizontal antenna will be directional and a vertical antenna will be nondirectional, although this does not always hold true; some vertical antennas have additional elements that make them more responsive in one direction.

Antenna Gain

Although no antenna is capable of amplifying radio signals, antennas can be designed to concentrate the radiated energy in such a way that it appears to have been produced by a much stronger source. For example, an antenna that concentrates most of the radiated energy in one direction will provide an increase in coverage in that direction over another antenna which is fed the same amount of power, but radiates energy equally well in all directions.

Something cannot be obtained for nothing, however. Therefore, the increase in signal strength in one direction is made possible only by a reduction of field strength elsewhere. This fact is illustrated in Fig. 3. The first figure represents the radiation pattern of a nondirectional antenna as viewed from directly above. As you can see, dimensions A and B are equal. As the radiation pattern becomes

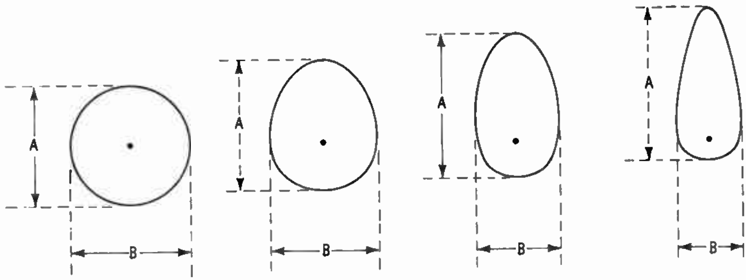


Fig. 3. Radiation patterns showing how increasing the field strength in one direction decreases the strength in other directions.

progressively more directional in the succeeding figures, you can see that an increase in field strength in direction A is made possible at the expense of field strength along dimension B. The same amount of energy as in the first example is being radiated; the only difference is that it is now more concentrated.

It is also possible to obtain omnidirectional gain by lowering the angle of radiation from a vertical antenna. In doing so, that portion of the radiated RF energy that would normally be lost as sky waves is concentrated along the earth's surface as shown in Fig. 4.

Antenna gain is expressed in decibels, which are logarithmic expressions of power ratios. The amount of gain that can be realized from any given antenna is determined by comparing the perform-

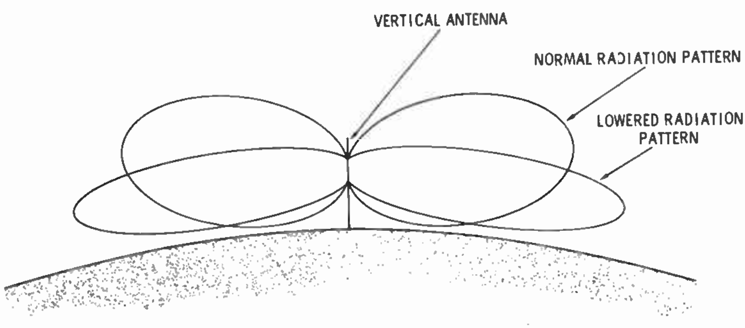


Fig. 4. Omnidirectional gain accomplished by lowering the radiation angle of a vertical antenna.

ance of the antenna in question with that of a standard antenna, and expressing this figure as a ratio of the power levels required to produce equivalent field strengths. The gain, then, in decibels is equal to ten times the logarithm of this power ratio.

Element Length and Spacing

An antenna of a random length will not respond properly to radio signals of a given frequency. A certain mathematical relationship must exist between them. For proper antenna design, it is necessary to know the length of the electromagnetic waves involved. In order to determine wavelengths, however, it is first necessary to know the speed at which electromagnetic waves travel through free space, and the frequency of the waves. In speaking of the frequency of electromagnetic waves, we merely mean the number of waves passing a given point in one second, expressed in megahertz (millions of cycles).

Since electromagnetic waves of all lengths move at the same speed, the number of waves passing a given point in one second will be small if the waves are long, and large if the waves are short. Thus, 500,000 waves of 600 meters in length will pass a given point in one second at a frequency of 500,000 hertz. Similarly, if the waves were only one meter in length, 300,000,000 would pass each second, which is a frequency of 300 mHz. The actual velocity of electromagnetic waves is for all practical purposes 300,000,000 meters or 984,300,000 feet per second.

If the speed at which the waves travel is equal to 3×10^8 meters per second, the distance it will cover in one cycle will be equal to this velocity divided by the frequency in hertz, or:

$$\lambda = \frac{3 \times 10^8}{f}$$

where,

f represents frequency,
λ, the Greek letter *lambda*, stands for wavelength in meters.

Since feet and inches are the measurement used for practical antennas, we obtain:

$$\lambda = \frac{984}{f\ (mHz)} \text{feet (approx)}$$

and

$$\lambda = \frac{11{,}808}{f\ (mHz)} \text{ inches}$$

Because the quarter-wave antenna is most often used, the length of a quarter-wave element in inches is the dimension most frequently required, we obtain:

$$\lambda/4 = \frac{2{,}952}{f\ (mHz)} \text{ inches}$$

Because of certain electrical characteristics of the antenna material, it has been found that, in practice, the antenna elements should be somewhat shorter (about 5 per cent) than the wavelength in the foregoing formula. The formula than becomes:

$$\lambda/4 = \frac{2{,}952 \times 0.95}{f\ (mHz)} = \frac{2{,}804}{f\ (mHz)} \text{ inches}$$

From this latter formula it is comparatively simple to obtain the antenna dimension for each frequency, by substituting the proper value in megahertz (mHz). By using a similar procedure, it is a comparatively simple matter to calculate antenna dimension for any desired frequency.

DIPOLE ANTENNAS

The fundamental form of a dipole antenna consists of two single wires, rods or tubing whose combined lengths are approximately equal to half the transmitting wavelength (see Fig. 5). It is from this basic unit that various forms of antennas are constructed. It is also variously known as a half-wave dipole, half-wave doublet, or Hertz antenna. Dipole antennas are commonly used for FM receivers.

The dipole elements are generally made of aluminum tubing which has been surface treated against corrosion. The receiving dipole is equipped with terminals at its adjacent ends for transmission-line connections and must be properly insulated from the mast or supporting structure (Fig. 6).

FOLDED DIPOLES

The necessity for separating, insulating and fitting the receiving dipole at its center, however, tends to weaken and complicate the antenna assembly. Because of this, a considerable simplification

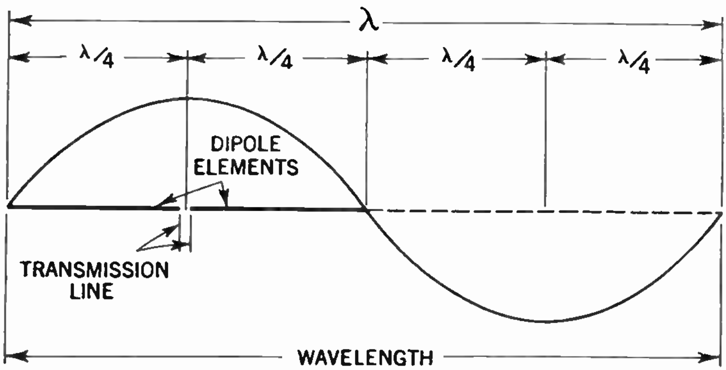


Fig. 5. Relation between wavelength and physical length of dipole elements.

may be obtained by employing an unbroken member bent and clamped to the supporting member as shown in Fig. 7. A television antenna of this type is known as the folded-dipole type and is widely used.

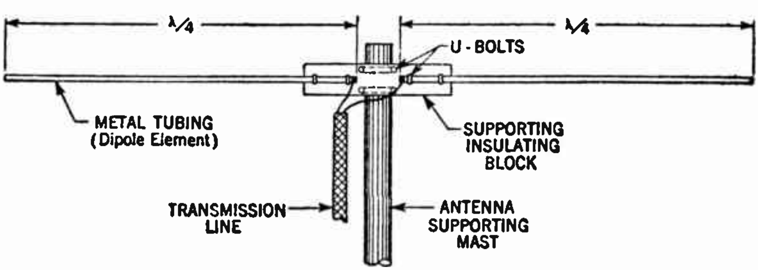


Fig. 6. Basic dipole construction.

The spacing between the folded-dipole elements should vary inversely with the frequency—that is, the higher the frequency, the smaller the spacing.

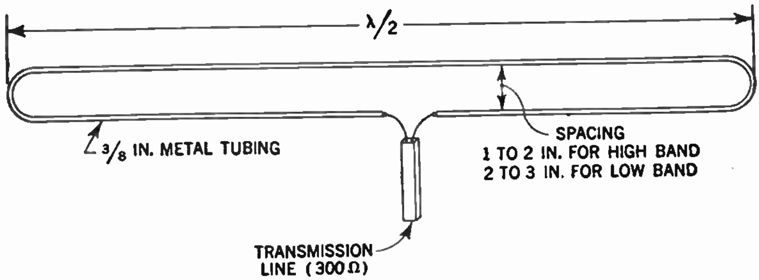


Fig. 7. A folded dipole antenna.

T-MATCHED DIPOLES

A further combination of the common half-wave dipole and the folded dipole has become known as the T-matched dipole type (Fig. 8). This assembly is obtained by cutting the ends of a folded dipole and fitting the remaining stub ends to the bottom element, the T-section having a length of two-thirds the length of the dipole.

There are three principal factors to be considered in the design of a dipole antenna for reception purposes. These are:

1. The length of the dipole must be suitable for the particular wavelength in use.
2. The polarization of the transmitted waves must be that for which the dipole is intended.
3. The directional properties of the dipole must be such as to receive the desired waves effectively, while being unfavorable toward local interference.

PARASITIC ELEMENTS

A parasitic element is basically a dipole slightly too long or too short for exact resonance at the desired frequency. It is mounted at

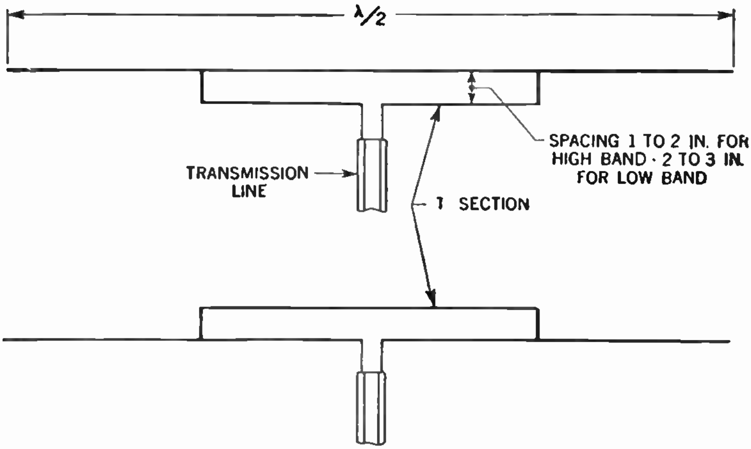


Fig. 8. A T-matched dipole antenna.

some fraction of a wavelength in front of or behind the driven element. Parasitic elements are not cut at the center and are not connected to the transmission line. The center point of a parasitic element is electrically neutral and can be grounded. This is convenient for lightning protection, as it permits making the entire antenna structure of conductive tubing, such as aluminum or stainless steel if desired, and grounding the central supporting mast at the base.

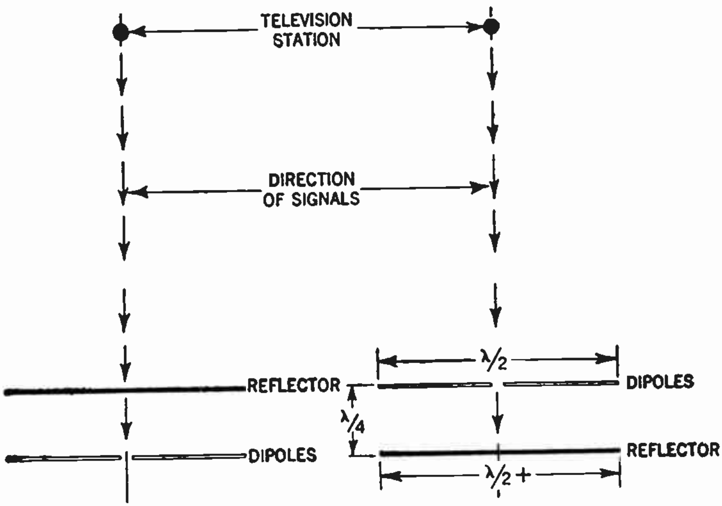
Current induced in a parasitic element by the advancing wave front produces a local field about it which couples it to the driven element by reason of their physical closeness. Spacing and tuning of parasitic elements are adjusted so that the current produced in them by the received signal produces fields around them which add in correct phase to reinforce the field of the received signal itself in the driven element. For signals from the opposite direction, the action in exactly reversed, and the signal is substantially cancelled in the driven element.

Directors and Reflectors

A director element is about 4 per cent shorter than the driven element for average element spacing and is mounted on a horizontal support which holds all the elements in proper relationship. The spacing between director and driven element can vary from about 0.08 to about 0.15 wavelength in practical antennas. Closer spacing will increase the front-to-back ratio, but makes the array tune more sharply. Wider spacing helps broaden the tuning of the array, but lowers the front-to-back ratio. It is possible to use several directors properly tuned and spaced in a line ahead of the driven element.

A reflector element is about five per cent longer than the driven element at usual spacings, and is mounted on the supporting bar behind the driven element, the spacing varying from about 0.10 to 0.25 wavelength. Effects of changing the spacing are quite similar to those produced by similar changes in the director.

The effect of the reflector is critically dependent upon the spacing between reflector and dipole, which, as previously noted, should be one-quarter wavelength, so that radiation from the reflector will exactly reinforce that from the dipole in a forward direction. The effects of the reflector element on the direction of reception are shown in Fig. 9.



(A) Minimum reception. (B) Maximum reception.

Fig. 9. Location of reflector element for maximum reception.

The explanation of this effect is as follows: Radiation from the dipole travels both forward and backward. In the latter direction it reaches the reflector, and induces a current in it. Since the radiation has travelled a quarter wavelength on its way to the reflector, it will reach it 90 degrees lagging in phase relative to that from the dipole where it originated. A current of this phase lag is therefore set up in the reflector, which in turn radiates.

By the time this secondary radiation has returned to the dipole it is a further 90 degrees late in phase, making a total phase lag of 180 degrees, but the oscillations in the dipole will have progressed through a half-cycle during this half-wave time interval, and will be 180 degrees ahead of the initial condition when the radiation left on its way to the reflector. That is to say, the radiation from the dipole will be a half-cycle ahead of the reference point, while that returning from the reflector will be a half-cycle late, bringing the two to the same point in the period of an oscillation.

Being in identical phase, the radiations from the dipole and reflector reinforce each other in the forward direction, while an exten-

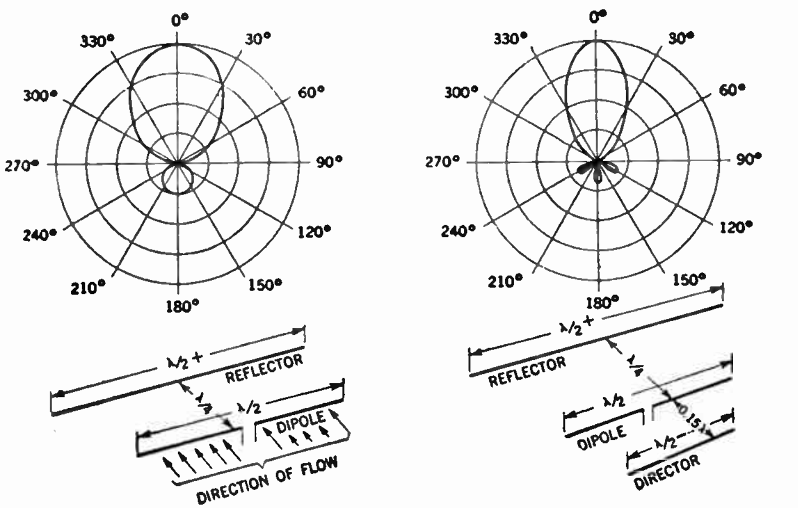


Fig. 10. The effect on the radiation pattern of adding director and reflector elements to a dipole.

sion of the same argument will show that they tend to cancel in the backward direction.

If the current induced into a reflector were as great as that flowing in the dipole, each would produce the same radiated field strength. The forward radiation would therefore be doubled, while that to the rear would be exactly cancelled, giving zero backward radiation.

Since the problems of radiation and absorption by an antenna system are strictly reversible in all ordinary conditions, these directional effects, which are most easily explained when the antenna is regarded as a transmitter, will be exactly similar when it is used for reception, provided, of course, that waves arrive in the plane in which dipole and reflector are situated.

In practice the resistance of a reflector will never be zero, and while the current in it can be made equal to that of the radiator if both are connected to a feeder, the current in a parasitic reflector must always be less than that in the dipole which gave rise to it. The forward radiation is therefore never exactly doubled nor the backward radiation fully prevented. Fig. 10 shows the radiation pattern when a director is added to the dipole and reflector.

ANTENNA DIRECTIVITY PATTERN

The horizontal dipole antenna is inherently directional, being most effective on signals arriving in the broadside direction and least effective on those arriving from a direction parallel to it. This effect is usually represented in the form of a polar diagram, or directivity pattern, in which the radius of the curve from the center of the antenna elements represents the relative response in any given direction.

The function of an antenna pattern is primarily to enable the service man to evaluate the efficiency of an antenna and to properly orientate it on the site of installation.

Antenna receiving patterns are usually made by rotating the antenna about its vertical axis and plotting values of voltage gain radially outward from the center of each change of angle.

The complexity of an antenna has a direct bearing on its efficiency, as well as its directional effects. Roughly, the voltage developed in the antenna is proportional to the combined length of the element multiplied by the field strength of the signal. The field pattern (directional response pattern) of a typical dipole antenna is shown in Fig. 11.

For the sake of simplicity, the directions are given as North, South, East and West, in both the schematic antenna and the polar diagram. From this diagram, it will readily be observed that the maximum single signal strength will be obtained when the antenna is broadside to the transmitter. Similarly, the "signal capture" is not critical over the angle ø, which includes the area over which the antenna can be rotated before losing more than half of its effective-

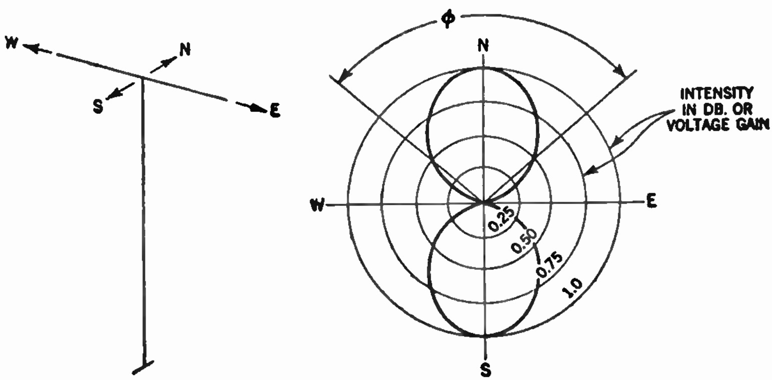


Fig. 11. Directional response pattern of a dipole antenna.

ness. In the diagram the concentric circles represent the voltage gain, where unity, or 1.0, is taken as reference for all comparisons.

ANTENNA IMPEDANCE MATCHING

Impedance matching is a very important factor in antenna installations. When the receiver input matches the impedance of the transmission line, the transmitted signal is completely absorbed and as a result there are no reflections or standing waves on the transmission line. In this connection it should be observed that the antenna impedance is important only from the standpoint of power transfer. It is only when the antenna impedance matches that of the transmission line that maximum power transfer takes place.

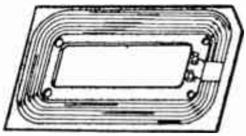


Fig. 12. A typical built-in loop antenna.

ANTENNA TYPES AND APPLICATIONS

Practically all present-day AM radio receivers employ a built-in antenna, although there is often provision for connecting an outside antenna. In the early days of radio it was necessary to string an

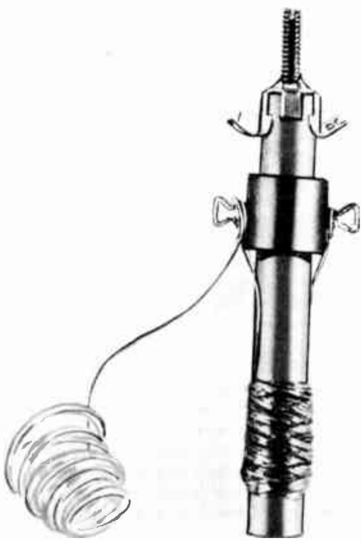


Fig. 13. A ferrite-core antenna.

Courtesy Stancor Electronics, Inc.

outside antenna perhaps 25 feet or more in length and employ a ground rod in order to receive radio signals satisfactorily. With the advanced technology that goes into the design and construction of today's equipment, however, the antenna system appears quite different. Most home-type AM broadcast receivers employ either a loop antenna such as that shown in Fig. 12, or a more efficient and

Fig. 14. A typical beam antenna used for two-way radiocommunications.

compact design known as the loopstick or ferrite-rod antenna (Fig. 13). Of these two the latter is the most popular in household and portable radio receivers.

Some ferrite-rod antennas have very high-Q values. These provide unusually high receiver sensitivity due to the signal-voltage amplification that they produce. On the other hand, they also cause sideband cutting, which causes the sound to be more or less distorted. To reduce the amount of sideband cutting, a resistor of suitable value may be connected across the terminals of the ferrite-rod antenna. In turn, the sensitivity of the antenna is reduced. Thus, the amount of shunt resistance is a compromise between high sensitivity and low distortion.

Most FM broadcast receivers are designed to operate with either a built-in, indoor or outdoor type antenna. Unlike AM receivers, however, many manufacturers of FM units recommend the use of an outside antenna for best reception. This is necessary because of the higher frequencies involved. When outside antennas are employed for FM reception, they are generally of the dipole type shown previously. Some FM receivers use nothing more than a built-in dipole consisting of two wires strung in opposite directions and fastened to the inside of the cabinet, and others use a telescopic dipole similar to the so-called "rabbit ears" employed for television reception.

For communications purposes, where the same antenna is used to transmit and receive radio signals, the antenna is somewhat different. The type employed will depend on the frequencies to be

Courtesy Raytheon Mfg. Co.

Fig. 15. A parabolic antenna used at frequencies above 1,000 mHz.

handled, the coverage desired, and whether communication is to be point-to-point between two or more stations in the same direction or between a base station and several mobile units which will be operating in every direction. A vertical antenna, because of its omnidirectional characteristics, is used almost exclusively for communication between base and mobile units.

For point-to-point communication a directional antenna (usually one providing a certain amount of gain) is generally employed. It may be of the basic dipole design shown previously, or it may consist of a dipole used in conjunction with a number of parasitic elements (reflector and one or more directors). An antenna of the latter design is generally referred to as a *beam antenna* due to its RF energy-concentrating characteristics. Most beams provide a high gain and are highly directional. An example of such an antenna is shown in Fig. 14. As the frequencies become higher, radio waves travel somewhat like a beam of light and can be focused in a given direction. At these frequencies (1,000 mHz or above), you can expect an antenna similar to that shown in Fig. 15.

SUMMARY

The function of an antenna is to transfer RF energy into space when transmitting and to collect RF energy from space when receiving. The amount of energy an antenna receives depends on several factors, chief among them being strength of the signal, type of antenna, polarization, and length and spacing of the antenna elements.

There are many types of antennas. The most common are long wire, dipole, folded dipole, and dipole with parasitic elements. Parasitic elements are added to an antenna to increase its sensitivity and directivity.

Impedance matching of the antenna to the transmission line and the line to the receiver (or transmitter) is very important to obtain maximum transfer of energy. Matching is accomplished by proper selection of transmission line, proper connection to the antenna, and proper design of antenna coils in the receiver or transmitter.

REVIEW QUESTIONS

1. Name three factors affecting the efficiency of an antenna.
2. What is polarization?
3. Is antenna gain an amplification of the received or transmitted signal?
4. Describe a dipole antenna.
5. Is a dipole antenna directional or nondirectional?
6. What is a parasitic element?
7. Is a parasitic element an active or passive component?
8. Is a director element longer or shorter than the driven antenna element?
9. What is a parabolic antenna?
10. Are parabolic antennas practical for AM broadcast frequencies?

CHAPTER 20

Electrical Measuring Instruments

GALVANOMETERS

Instruments designed for measuring small amounts of electricity may be called galvanometers, although a galvanometer is generally employed as an electrodynamic instrument used to indicate current.

There are numerous kinds of galvanometers designed to meet various requirements. Some examples are the astatic, tangent, differential, ballastic and D'Arsonval types, which according to their design may have either a movable magnet and stationary coil or a stationary magnet and movable coil. The only type which is widely used is the D'Arsonval.

D'Arsonval Galvanometer

The principal design of this instrument is shown in Fig. 1. The indicating needle is attached to a coil of wire inside of which is an iron core. The coil is free to turn around the core, which is held in place with a pin, and is suspended between the poles of a horseshoe magnet. When the current to be measured flows through the coil, a magnetic field is set up in and around it, causing the coil to turn. This rotating tendency is prevented by the twisting of the wire which suspends the loop. This galvanometer can be used for determining small amounts of current. It is on this principle that many commercial types of current-measuring devices are based.

The reading of the galvanometer may be facilitated by means of a mirror which is usually attached to the coil in such a way that a beam of light, from a light source directed to the coil by a lens system, will be reflected back to a semicircular graduated scale placed at a suitable distance from the mirror as shown in Fig. 2.

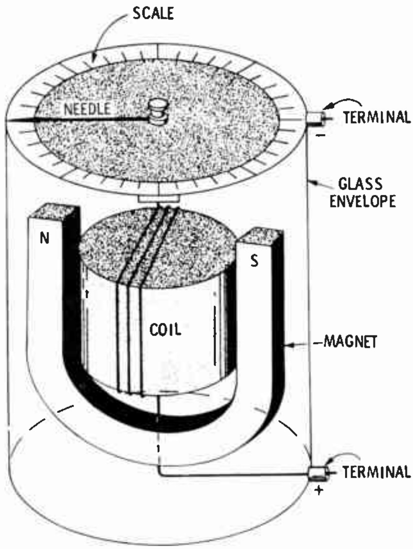


Fig. 1. Essential features of a D'Arsonval galvanometer.

In this way a small deflection of the coil and mirror will produce an enlarged swing of the beam of light on the scale.

DIRECT-CURRENT METERS

Most electrical measuring devices are fundamentally current-measuring devices such as voltmeters, milliammeters or microammeters.

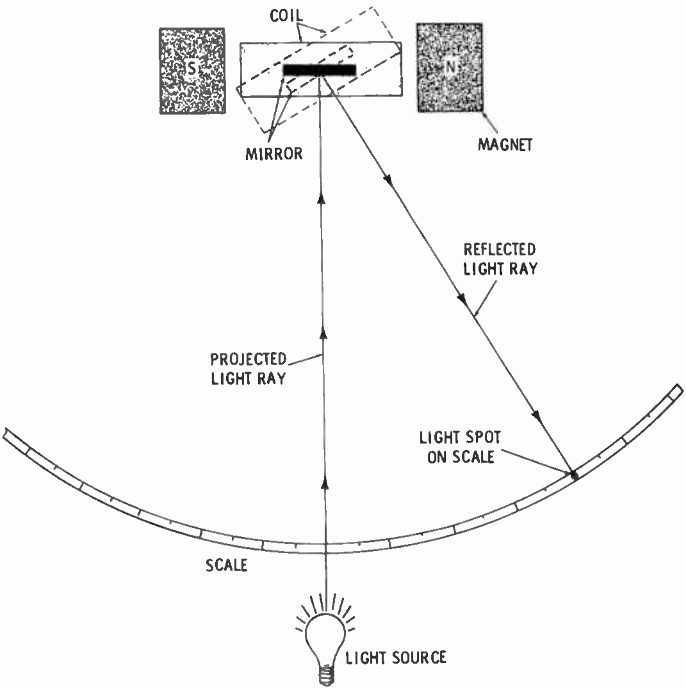


Fig. 2. Method used to obtain an enlarged view of a meter indication.

Construction

An instrument such as this consists primarily of a horseshoe magnet, an armature, and a pointer with a spring arrangement to hold it to its zero position when no current is being passed through the meter coil. Fig. 3 shows the internal construction of a typical direct-current meter. A precision type DC milliammeter is illustrated in Fig. 4.

How Current Is Measured

When current is passed through the armature coil, it becomes an electromagnet with poles of opposite polarity. The reaction between the energized coil and the permanent magnet then causes the coil

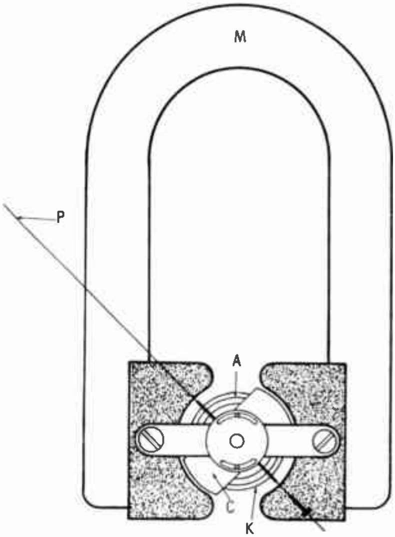
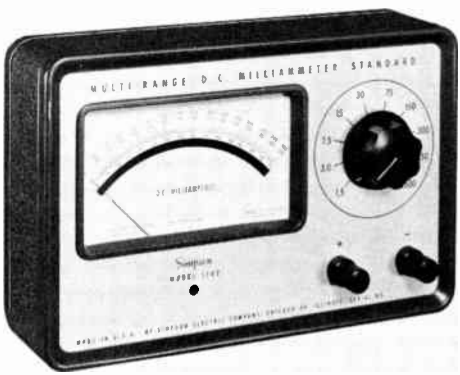


Fig. 3. The essential parts of a DC meter are: A, spiral spring; C, coil; K, soft-iron core; M, permanent magnet; and P, pointer. Current passing through the coil causes the moving system to turn against the restraining force of the spiral spring.

to rotate on its axis due to the attraction of the unlike poles and the repulsion of the like poles of the two magnetic fields. The amount of movement is determined by the balance attained between the resilience of the spring mechanism and the strength of the magnetic



Courtesy Simpson Electric Co.

Fig. 4. A precision type DC milliameter.

field set up around the coil. Since the strength of the magnetic field around the coil is determined by the amount of current flowing through it, the movement may be calibrated in units of current, or in any other unit such as volts, ohms, or microfarads, all of which possess a definite relationship to the unit of current.

Connection of Meters

A meter calibrated for current measurement in terms of amperes or fractions thereof usually has a comparatively low resistance and is connected in series with the circuit in which the current is to be measured. On the other hand, a current-indicating device designed for use as a voltmeter is of comparatively high resistance and is connected across the circuit in which a potential is to be measured.

DC Ammeters

The ammeter, as already described, is an instrument of low resistance, and is always connected in series with the current it is desired to measure.

Ammeters are employed for current measurement in all branches of electrical work and may be designed for measurement of from a few microamperes or milliamperes up to thousands of amperes. A microammeter is an ammeter that measures divisions of currents in 1/1,000,000 of an ampere, and a milliameter is one that is calibrated to indicate in units of 1/1,000 of an ampere.

Using a Milliameter as a Voltmeter

The only difference between a voltmeter and a milliammeter is that a voltmeter has a high resistance connected in series with the moving coil. Hence, by connecting fixed resistors in series with the milliammeter, it is possible to use it as a voltmeter (see Fig. 5).

Of course, it is evident that the accuracy of such a converted meter depends solely upon the accuracy of the milliammeter and the fixed resistance used. A high-accuracy DC voltmeter is illustrated in Fig. 6.

Example: If a 5-milliampere meter is to be employed to read voltages up to 50 volts, what value of series resistance should be used?

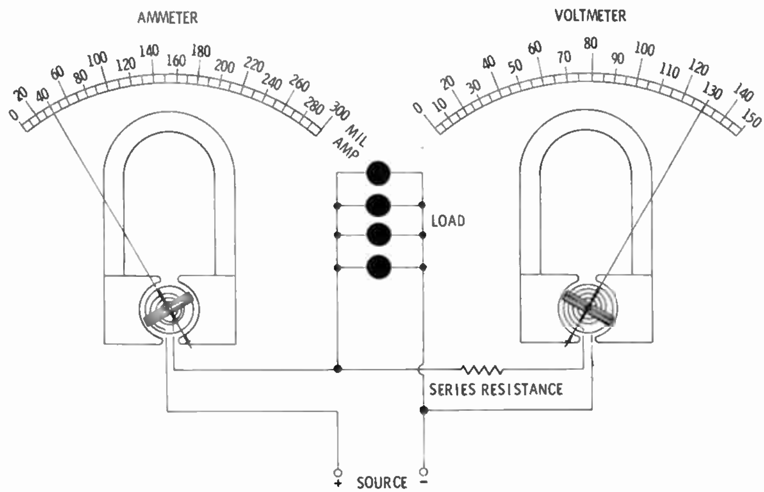


Fig. 5. Methods of connecting meters to indicate current and voltage.

Fig. 6. A high-accuracy DC voltmeter.

Courtesy Simpson Electric Co.

Solution: According to Ohm's law, $E = IR$,

$$\text{or } R = \frac{E}{I} = \frac{50}{0.005}$$

from which $R = 10{,}000$ ohms.

Likewise, if a 1-milliampere meter is to be used to read voltages up to 1,000 volts, then a 1-megohm resistance is placed in series with it.

Assume that the moving-coil milliammeter used in the previous example is to be utilized for a voltage measurement of 110 volts at full-scale deflection. If the allowable current drain is 1 milliampere, what will be the value of the series resistance?

It is evident that the resistance must be of such a value that when the voltage across the meter terminals is 110 volts, exactly 1 milliampere will flow through the resistance and meter coil at full-scale deflection of the needle.

Inasmuch as the moving-coil resistance is very small compared with the series resistance, it may readily be omitted for most practical purposes.

In order to obtain needle deflection in the proper direction the terminals of DC meters are generally marked + (plus) and − (minus). The terminal marked + should always be connected to the positive potential and the terminal marked − connected to the negative potential.

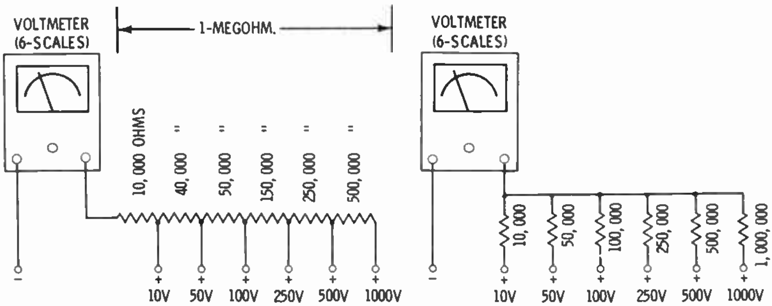
Connections for a Multirange Voltmeter

Resistors for multirange voltmeters may be connected in various ways. Fig. 7 shows two methods. In Fig. 7A, a single tapped resistor is employed, whereas separate resistors are used in the circuit of Fig. 7B. Each resistor will provide a certain definite voltage drop and should be of the precision type, unaffected by nominal temperature variations.

Inspecting the resistance arrangement in Fig. 7B, it will be found that when using the 0-100 volt range, the circuit resistance is 100,000 ohms and when using the 0-250 volt range, the series resistance is 250,000 ohms, and so on for each scale.

A Combination Volt-Ammeter

Since the construction of a voltmeter and that of an ammeter are similar except for the connection of the resistances, it is possible to use a single instrument for measurement of both voltage and current. A typical arrangement of this kind is shown in Fig. 8. When it is desired to employ the meter for current measurement, the current-voltage selector switch is closed toward A, after the proper shunt has been selected. For voltage measurement, the current-voltage selector switch is closed toward V and the meter is connected across the load after selection of the proper resistor.



(A) Tapped resistor. (B) Individual resistors.

Fig. 7. Two methods of connecting multipliers to a voltmeter.

Other meters of this type may also have a resistance, or ohmmeter, scale which makes it convenient to check resistance values. It should be pointed out that an ohmmeter is simply a low-current, DC milliammeter, provided with a source of voltage, usually consisting of dry cells which are connected in series with the unknown resistance.

Before using a multipurpose meter, a precautionary examination should be taken to make sure that the controls are properly adjusted, to prevent the instrument from serious damage. When measuring unknown values of current, it is a good idea to begin with the highest range, then reset the selector to the desired range. When

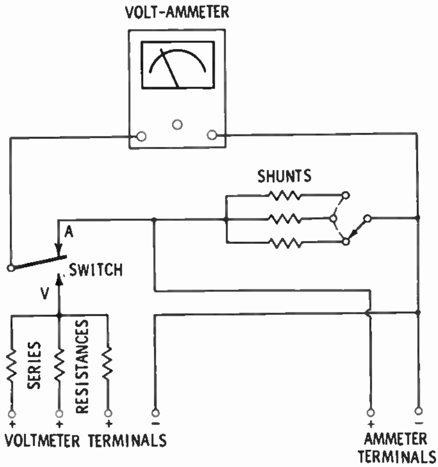


Fig. 8. Switching arrangement used to permit voltage and current measurements with the same meter.

using the instrument as an ohmmeter the leads should never be connected across a circuit in which current is flowing—that is, the receiver power should be turned off when resistance measurements are made.

Shunts and Their Use

All ammeters for use in direct-current measurements may be designed to pass a similar amount of amperes, although the actual amount of current in the circuit may differ greatly.

The main difference between the various ammeters is in the type of shunts employed. The function of a shunt is to bypass a specific amount of the circuit current around the meter. A shunt will carry a certain ratio of the total current, depending on the ratio of its resistance to the resistance of the ammeter coil; this makes it possible to use the same sensitive ammeter for different current-carrying ranges by merely shunting or bypassing a portion of the current.

The resistances of the shunts required are selected from a knowledge of the proportional current to be measured, and of the existing resistance of the ammeter coil.

Example: If a milliammeter giving full-scale deflection on 500 milliamperes $\left(\frac{500}{1{,}000}\text{ of an ampere}\right)$ is required to be changed so as to enable the measurement of currents up to 5 amperes, what size of shunt should be used?

Solution—The increase in current for full-scale deflection is then 5/.5 or 10 times; hence, each scale reading would have to be multiplied by 10 for each actual current indication.

In order to permit 10 times the amount of current to flow, the resistance of the coil and shunt combined would have to be such that the coil would carry 1/10 of the current and the shunt the remaining 9/10 of the total current. By formula: the shunt resistance is equal to the meter resistance divided by the multiplication factor minus one or

$$R = \frac{r}{n - 1}$$

where,

R is the resistance of the shunt,

n is the multiplication factor or the number indicating how many times the meter range is to be extended or multiplied,

r is the internal resistance of the meter.

From the above it follows that the shunt resistance would have to be 1/10 of the coil resistance. If the meter coil has a resistance of 2/10 of an ohm, the shunt resistance would have to be:

$$R = \frac{0.2}{10 - 1} = \frac{2}{90} \text{ or approximately } 0.022 \text{ ohms}$$

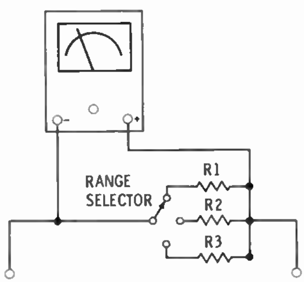


Fig. 9. A multirange current meter.

Hence, a shunt having a resistance of 0.022 ohms must be connected across the meter. This resistance should be of a size sufficient to carry the current without overheating.

Fig. 9 shows an arrangement in which three shunts (R_1, R_2, and R_3) are utilized for different current measurements. In case the meter has only one scale, the current indication on the meter can be multiplied by the value of the multiplication factor given for each shunt.

Hot-Wire Instruments

The operation of this type of meter depends on the heating of a conductor by the current flowing through it. This heating causes an expansion which in turn sets in motion an index needle or pointer, the movement of which correspond to the amount of the actuating current.

One feature of this meter is its ability to measure either direct or alternating current.

The principal disadvantages of this type, however, are:

1. Scale divisions are not uniformly spaced, since the heating effect and movement of the pointer depend on the square of the current (I^2R) flowing through it.
2. The meter indications are somewhat erratic near the zero point.
3. They are sluggish in operation and their readings are affected by changes in room temperature.
4. The actuating wire has a tendency to expand when not in use, hence it is necessary to set the pointer back to zero before making a current measurement.
5. They are inefficient, i.e., the current consumption is considerably in excess of that in other types.

Fig. 10 illustrates the basic construction of the hot-wire instrument. N represents a silk thread connected to spring S, wound around pulley P, and attached to a bead threaded on wire AB. Wire AB, made of platinum alloy, is connected in the circuit whose current is to be measured. This wire lengthens, due to the heating effect

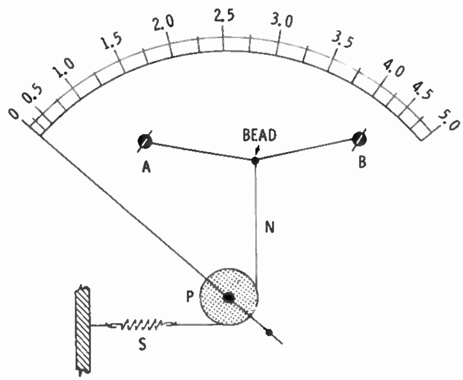


Fig. 10. Simplified diagram showing the construction of a hot-wire instrument.

(I^2R), when a current flows through it. The slack is taken up by spring S, causing P to turn, and the pointer moves over the scale.

Thermocouple Instruments

In thermocouple instruments the direct or alternating current to be measured is passed through heater H (Fig. 11), which heats the junction of two dissimilar metals.

When two dissimilar metals are joined together and their junction is heated, a voltage is generated proportional to the temperature difference between the heated junction and the open end of the thermocouple.

A sensitive milliammeter is connected to the open ends and is generally calibrated to indicate the current through the heater. For measurements of very small values, the heater and the thermocouple are enclosed in an evacuated glass bulb to prevent oxidation.

An instrument of this type, however, has certain disadvantages.

1. The motion of the pointer along the scale will increase approximately in proportion to the square of the current sent through the thermocouple. Hence the instrument scale will not have equal divisions.
2. The thermocouple is sensitive to overloads and may burn out if excessive amounts of current are sent through it, in which

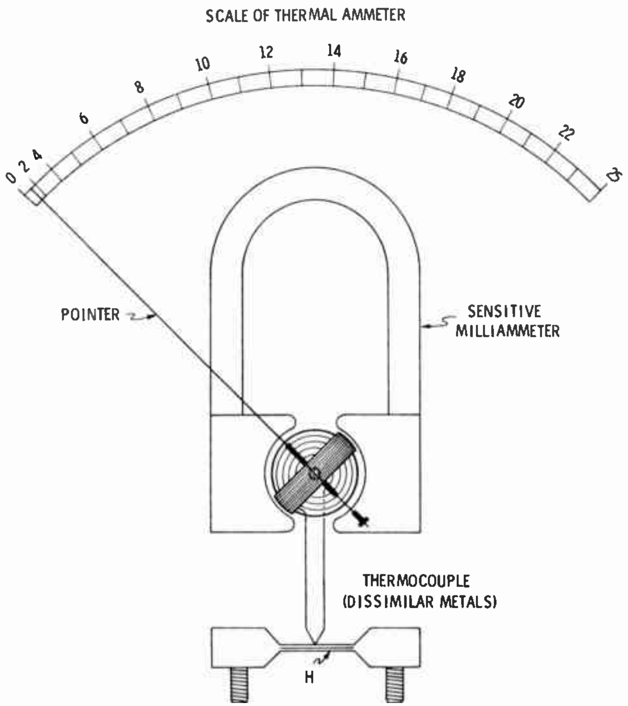


Fig. 11. Thermocouple arrangement and connection to a milliameter.

case the thermocouple will have to be replaced and the instrument recalibrated.

Electrodynamometer Instruments

This type of instrument can be employed to measure either alternating or direct current.

Fig. 12 shows a typical instrument consisting of two stationary coils (A) and (B) and a movable coil (D) to which the indicating pointer is attached. The three coils are connected in series through the two spiral springs, which also hold the movable coil in position.

When current is passed through the coils, coil (D) tends to turn in a clockwise direction because its flux tends to line up with the flux of coils (A) and (B).

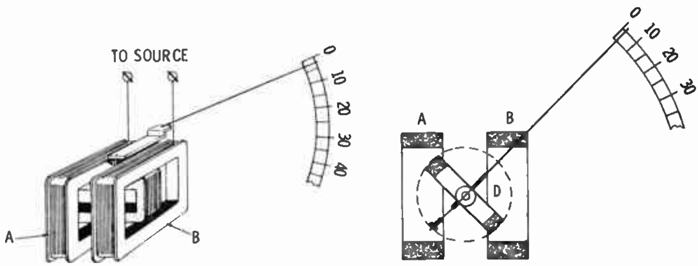


Fig. 12. Construction of an electrodynamic instrument.

If current is sent through the coils in the reverse direction, the amount and direction of torque developed remain the same, hence the instrument can be used on alternating as well as on direct current. However, the scale as shown cannot be graded uniformly as in the moving-coil type, because the torque developed varies as the square of the current (I^2).

One of the detrimental factors in this type of instrument is that the current requirement is approximately 5 times that of a moving-coil instrument. (See Fig. 13.)

Courtesy Sargent-Welch Co.

Fig. 13. An AC voltmeter that has an accuracy of 2 percent.

Wattmeters

In direct-current circuits, the product of voltage and current is a measure of the amount of power dissipated in the circuit in question and is measured in watts.

The number of watts dissipated may be obtained by measuring the voltage across and the current through the circuit. Thus, in a circuit through which a current of 2 amperes flows at a pressure of 110 volts, the power in watts (W) will equal 2 × 110 or 220 watts, or $W = I \times E = 2 \times 110 = 220$ watts.

If the power in an alternating-current circuit is to be measured, this relationship holds true only when the connected load consists of pure ohmic resistance; when the circuit also contains inductive or capacitive reactance, the power in watts will be equal to:

$$E \times I \times \cos\theta, \text{ or } W = E \times I \times \cos\theta$$

where,

W is the power in watts,
E is the pressure in volts,
I is the current in amperes,
θ is the angle of lag or lead between the current and voltage.

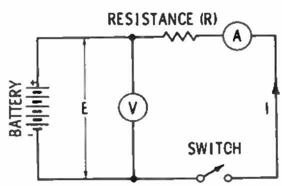
Fig. 14. An AC volt-watt meter.

Courtesy EICO Electronic Instrument Co., Inc.

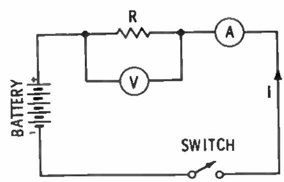
A meter used to measure the power consumption in an electric circuit is called a wattmeter. The wattmeter may be employed to record directly either the AC or DC power at any instant. An AC volt-watt meter is illustrated in Fig. 14.

RESISTANCE MEASUREMENT

The ammeter-voltmeter method is one of the simplest arrangements for measuring resistance and is convenient because the instruments used consist of only an ammeter, voltmeter, battery and switch, connected as shown in Fig. 15A and B. In making the test, the ammeter and voltmeter readings are taken simultaneously by either of the methods illustrated, and the unknown resistance is then calculated from Ohm's law.



(A) Across circuit.



(B) Across resistor.

Fig. 15. Two different connections to obtain resistance values.

Ohmmeter Method

By using an ohmmeter, the value of an unknown resistance may be read directly on the instrument scale without calculation. This type of instrument is shown in Fig. 16.

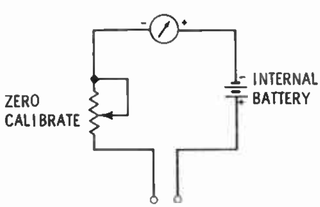


Fig. 16. A basic ohmmeter circuit.

Wheatstone-Bridge Method

The Wheatstone bridge (Fig. 17) consists of several resistances so arranged that an unknown resistance may be calculated in terms of known resistances.

As shown in Fig. 17, the circuit is made to branch at P into two parts, which reunite at Q, so that part of the current flows through point M, the other part through point N. The four conductors, A,B,C,D, are spoken of as the arms of the balance or bridge.

It is by the proportion existing between the resistances of these arms that the resistance of one of them can be calculated when the resistances of the other three are known.

The current in the upper branch generates a voltage drop from P to M, and another from M to Q. There is a voltage drop in the lower branch between P and N, and another between N and Q.

Now if N is the same proportionate distance along the resistance between P and Q as M is along the resistance of the upper line between P and Q, the voltage will have fallen at N to the same value as it has fallen at M. In other words, if the ratio of resistance C to

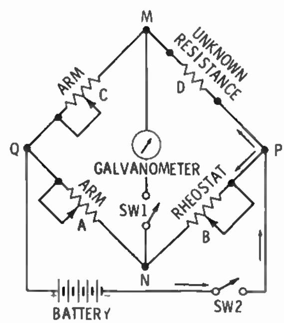


Fig. 17. The basic Wheatstone bridge.

resistance D is equal to the ratio between resistance A and resistance B, then M and N will be at equal voltages. To determine if this condition is obtained, a sensitive galvanometer placed in a branch wire between M and N will show no deflection when M and N are at equal voltages or when the four resistances of the arms "balance" one another by being in proportion, thus:

$$A:C = B:D$$

If, then, the values of A,B, and C are known, D can be calculated. The proportion is reduced to the following equation before substituting.

$$D = \frac{BC}{A}$$

For instance, if A and C in Fig. 13 are 10 ohms and 100 ohms respectively, and B is 15 ohms, D will be:

$$\frac{(15 \times 100)}{10} = 150 \text{ ohms}$$

VOLT-OHM-MILLIAMMETERS

The volt-ohm-milliammeter (VOM), also called a multimeter, is one of the most widely used instruments in a radio shop. A typical VOM is illustrated in Fig. 18. It measures DC voltage, DC current, AC voltage, and resistance. A decibel scale is also provided. The

Fig. 18. A high-quality VOM.

Courtesy Triplett Electrical Instrument Co.

sensitivity rating of the instrument is 20,000 ohms-per-volt on the DC-voltage ranges. This means that the input resistance is 60,000 ohms on the 3-volt range, 240,000 ohms on the 12-volt range, etc. Its sensitivity rating is 5,000 ohms-per-volt on the AC-voltage ranges. Thus, the instrument has an input resistance of 15,000 ohms on the 3-volt range, 60,000 ohms on the 12-volt range, etc. Its center-scale resistance values are 5 ohms on the R $\times$ 1 range, 50 ohms on the R $\times$ 10 range, 5,000 ohms on the R $\times$ 1,000 range, and 500,000 ohms on the R $\times$ 10,000 range.

VACUUM-TUBE VOLT-OHMMETERS

Next to the VOM, the vacuum-tube volt-ohmmeter (VTVM or VTVOM) is the most widely used instrument in radio shops. A VTVM (or VTVOM) is illustrated in Fig. 19. This instrument measures DC voltage, AC voltage, and resistance. A decibel scale is also provided. The chief advantage of a VTVM is that it has a high input resistance on the DC-voltage ranges. For example, the instrument illustrated has an input resistance of 11 megohms on

Fig. 19. A vacuum-tube voltmeter.

Courtesy Heath Co.

all DC-voltage ranges. This high value of input resistance provides more accurate measurements in high-resistance circuits than can be obtained with a VOM. High input resistance results from the use of a vacuum-tube bridge circuit built into the instrument.

Since a VTVM employs vacuum tubes, it must be plugged into a power outlet whenever it is used. A few VTVM's are battery operated and are as portable as a VOM. Another advantage of a VTVM is that it is automatically protected against damage from accidental overloads. That is, the vacuum-tube bridge limits the amount of current that can be applied to the meter. Note that some VOM's are provided with internal overload protection devices; this makes the VOM as immune to accidental damage as a VTVM.

TRANSISTOR VOLT-OHMMETERS

A transistor volt-ohmmeter (TVM or TVOM) is very similar to a VTVM or VTVOM. The only difference in construction is that transistors are used instead of vacuum tubes in the built-in bridge circuit. Most transistor volt-ohmmeters employ FET's because of their high input resistance. In turn, the TVM or TVOM has as high an input resistance on DC-voltage ranges as a VTVM. Since transistors operate at low voltage, most TVM's have built-in battery power supplies which make them as portable as a VOM. The internal bridge circuit of a TVM makes it as immune to damage from accidental overloads as a VTVM.

CAPACITANCE METERS

Most shops have some type of instrument on the bench for measuring capacitance values and capacitor leakage resistance. A typical capacitor tester is illustrated in Fig. 20. This instrument measures capacitance values from 10 mmfd to 10 mfd. It also measures leakage resistance up to 500 megohms. A pulse test voltage from 100 to 900 volts is also provided to check capacitors for possible breakdown at rated working voltage. In addition, a three-lead test can be used to check coupling capacitors for leakage without disconnecting the coupling capacitor from its circuit. This test

Courtesy Simpson Electric Co.

Fig. 20. A capacitance meter and capacitor tester.

does not measure the exact amount of leakage resistance, but does indicate whether leakage is sufficient that capacitor replacement is advisable.

TUBE TESTERS

Tube testers are in very wide use because of the convenience that they provide and because of the extremely large number of tube types that are in use. An in-set test is not always possible, and it is often desired to test a suspected tube when a replacement tube is not immediately available. The simplest type of tube tester is limited to filament or heater continuity checks; Fig. 21 illustrates this type of instrument. The emission-type tester illustrated in Fig. 22 is quite popular; it measures the total cathode emission of a tube.

For a more precise evaluation of tube characteristics, a mutual-conductance (or transconductance) tube tester is employed. Fig. 23 illustrates this type of instrument. It indicates the AC plate

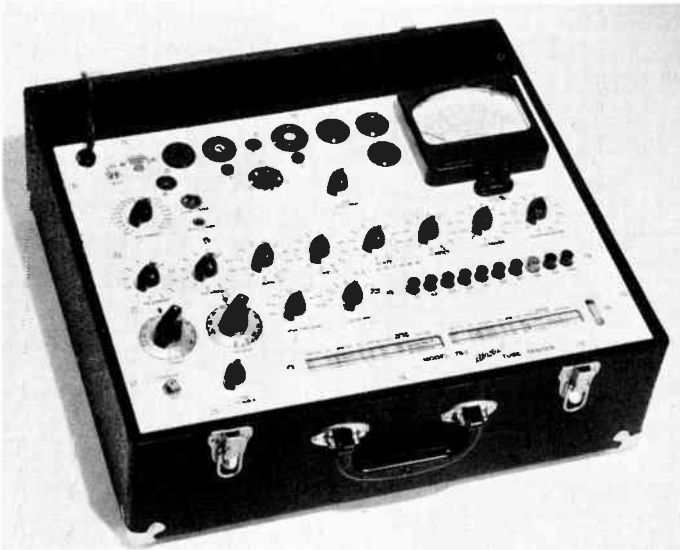
Fig. 21. A filament continuity checker.

Courtesy EICO Electronic Instrument Co., Inc.

current that results from application of a calibrated AC signal to the control grid of the tube under test. Mutual conductance is measured in micromhos. Both mutual-conductance and emission-type testers check a tube for interelectrode leakage. Note that a

Fig. 22. An emission-type tube tester.

Courtesy EICO Electronic Instrument Co., Inc.



Courtesy Hickok Electrical Instrument Co.

Fig. 23. A mutual-conductance tube tester.

tube that has interelectrode leakage (or short-circuits) is useless, even if it has a normal value of emission or of mutual conductance.

TRANSISTOR TESTERS

Various types of transistor testers are used in service shops. Even an ohmmeter can be used for a preliminary test of a transistor. That is, the emitter-base junction normally has a very low resistance in the forward direction, and an extremely high resistance in the reverse direction. Similarly, the collector-base junction normally has a very low forward resistance, and an extremely high reverse resistance. However, a precise test requires the measurement of the current gain of a transistor. As explained previously, the current gain is stated as the ratio of base current to collector current; this is called the *beta* value of the transistor. A beta tester is illustrated in Fig. 24.

Courtesy Triplett Electrical Instrument Co.

Fig. 24. A transistor tester that measures beta.

A transistor tester also measures leakage current. For example, when the collector junction of a transistor is reverse-biased, the leakage current is normally extremely small. One of the most common defects of a transistor that has been in long service is collector-junction leakage. If the leakage is appreciable, the transistor is useless, even if it still has a normal beta value. Junctions can become short-circuited or open-circuited, and a transistor tester indicates these defects. The tester shown in Fig. 24 is an out-of-circuit tester. That is, the transistor must be disconnected from the circuit for test.

In-circuit transistor testers are also used in many practical trouble situations. Although they lack the accuracy of an out-of-circuit tester, a useful indication of transistor condition can be obtained on most transistors while they are connected in the circuit. A typical in-circuit tester shunts low resistances across the transistor electrodes so that the circuit characteristics are "swamped out." An oscillator circuit is built into the tester, and the oscillator coils are also connected to the transistor electrodes. If the transistor oscillates, this fact is indicated by the meter on the instrument. In case a transistor fails to oscillate when tested in this manner, it is probably defective.

SIGNAL TRACERS

A signal tracer, such as illustrated in Fig. 25, is often used by radio technicians to find out where the signal stops in a "dead" receiver. The receiver is tuned to a broadcast station, and the test

Courtesy EICO Electronic Instrument Co., Inc.

Fig. 25. A radio signal tracer.

probe is then applied progressively step-by-step through the signal circuits of the receiver. The program is heard from the built-in speaker until the point is passed in the receiver at which the signal stops. Thereby, considerable time can often be saved in preliminary trouble analysis.

An oscilloscope, such as illustrated in Fig. 26, is a more precise signal tracer because it indicates the voltage of a signal. However, since a scope is a comparatively elaborate instrument, more experience is required to obtain its full capabilities. After a technician learns to use a scope properly, it becomes a valuable troubleshooting tool. In addition to being an AC voltmeter that can be used at high frequencies, the waveforms that it shows can often be analyzed

Courtesy EICO Electronic Instrument Co., Inc.

Fig. 26. A service-type oscilloscope.

to determine what is wrong in circuit operation. Waveform analysis is an extensive subject, and interested readers are referred to specialized books on scope use.

SUMMARY

The most widely used type of galvanometer is the one having a D'Arsonval movement. This type of movement consists of a coil of wire (to which a pointer or needle is attached) free to rotate within the field of a permanent magnet. This type of meter movement is employed in nearly all meters used for radio service work.

Nearly all meters, regardless of their name or function, are actually current-measuring devices. When designed to measure voltage, they have a high resistance placed in series with the moving coil. Ohmmeters are specialized current-measuring instruments, but have a built-in voltage source to produce a flow of current through the resistance being measured. Multirange and multipurpose instruments have means of switching various resistances in series or parallel with the moving coil in order to perform the intended function.

Other types of instruments used in radio service work are hot-wire ammeters, thermocouple instruments, capacitor checkers. tube testers, and oscilloscopes. Many of these are for specialized work.

REVIEW QUESTIONS

1. What is the most common type of meter movement used in radio service work?
2. How is an ammeter connected in a circuit?
3. How can a milliammeter be connected to read voltage?
4. What is the common designation for a meter than can be used to read current, voltage, and resistance?
5. What is a shunt?
6. What is a Wheatstone bridge?
7. What is one advantage of a VTVM over a VOM?
8. What is a disadvantage of a VTVM as compared to a VOM?
9. What type of tube tester gives the most accurate indication of the condition of a vacuum tube?
10. Can an oscilloscope be used to measure voltage?

CHAPTER 21

Radio Testing

It is of the utmost importance that the service technician, in order to intelligently cope with the various troubles that develop in radio receivers, should have the necessary test equipment to make repairs as quickly and easily as possible.

To be of value to a radio service technician, testing equipment must have the following features:

1. It should be fairly compact and portable.
2. It should be ruggedly constructed so that instruments will not be damaged or their calibration changed in transport.
3. The instruments must be designed to withstand considerable overloads without damage, as in service work it is often difficult to estimate beforehand the exact magnitude of the measurements being taken.
4. The equipment should cover the proper operating ranges and be reasonably stable in frequency.

The following basic test instruments are required to properly service radio receivers:

1. A vacuum tube voltmeter (VTVM).

2. A volt-ohm milliammeter (VOM) with a sensitivity of at least 20,000 ohms per volt for measuring voltage, resistance and current.

3. Signal tracer.
4. Some type of output meter (the VOM or VTVM can often be used for this purpose).
5. A signal generator capable of producing all of the required frequencies.
6. A transistor checker (or again the VOM may be employed to make certain tests).
7. Tube tester.

This equipment may be supplemented by a cathode-ray oscilloscope and any number of other instruments that will prove helpful in servicing radios.

The service data and schematic diagram for a receiver are often essential for efficient servicing. This is particularly true of elaborate multiband receivers. Table 1 provides a convenient summary of graphical symbols used in schematic diagrams.

PRELIMINARY POINTERS

Before analyzing a radio for trouble, however, it is a good idea to check all possible causes of trouble (power cord, etc.) before removing a receiver chassis from its cabinet.

If it is evident that the trouble is inside the radio itself, a careful examination of the wiring connections and interior components of the set is next in order. The condition of soldered joints should be examined to be sure that there is good electrical connection. Also look for such things as broken or charred resistors, overheated transformers, capacitors dripping wax, and any other indication that might give a clue as to the trouble. Careful observation can often save considerable time in locating defects.

Also be certain that the insulation of the wiring is not cut or frayed where it passes through metal, around the edges of tube-socket contacts, etc. The tube-socket fingers should be clean and tight. The possibility of shorted tuning capacitor plates should also be checked. A visual inspection of this kind may quickly locate the cause of the trouble. Before making any circuit measurements, be sure to test the tubes either in a tester or by direct substitution.

Tubes can cause just about any trouble symptom and for this reason should be one of the first things checked. A transistor tester is helpful in servicing transistorized receivers. Transistors, however, generally cause less trouble than vacuum tubes. Heat is one of the contributing factors in tube defects.

ELECTRICAL TESTS

One of the first electrical checks on the set should be on the power supply to insure a normal supply of voltage to the various circuits. If the radio is a battery-operated type, check the condition of the batteries. The batteries should give approximately their rated voltage readings with the radio turned on. If the batteries are low they should be replaced. A battery tester is illustrated in Fig. 1.

Having checked the source of power to the radio, the next step is to check the voltage supply to each tube or transistor. A suggested method is to check these components in the order in which the signal passes through them. That is, start with the antenna stage and end with the power amplifier stage. After making preliminary tests and a visual inspection and finding everything in good order, the electrical tests should be made. The logical approach is to first

Fig. 1. A typical battery tester.

Courtesy EICO Electronic Instrument Co., Inc.

Table 1. Electronic Symbols

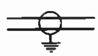
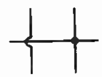
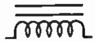
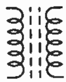
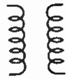
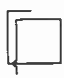
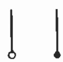
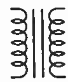
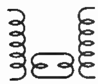
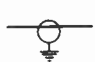
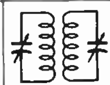
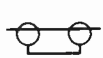
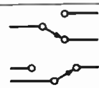
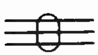
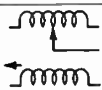
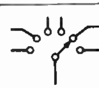
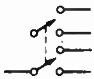
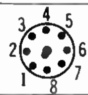
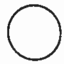
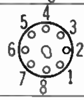
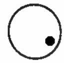
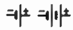
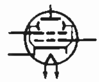
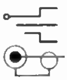
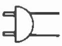
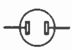
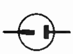
DEVICE	SYMBOL	DEVICE	SYMBOL	DEVICE	SYMBOL
CONDUCTOR OR WIRE		SHIELDED CABLE		TAPPED COIL OR INDUCTOR	
CROSSED WIRES LEFT- NO CONNECTION RIGHT- CONNECTION		FIXED RESISTOR		IRON CORE COIL OR INDUCTOR	
GROUND		VARIABLE RESISTOR		POWDERED IRON CORE COIL OR INDUCTOR	
ANTENNA		FIXED CAPACITOR		POWDERED IRON CORE TRANSFORMER	
COUNTERPOISE		ELECTROLYTIC CAPACITOR		AIR CORE TRANSFORMER	
LOOP ANTENNA		VARIABLE CAPACITOR		VARIABLE COUPLED TRANSFORMER MOVING COIL SHOWN	
TERMINALS		VARIABLE CAPACITOR, MOVING PLATES		IRON CORE TRANSFORMER	
SHIELDING		VARIABLE CAPACITORS, GANGED		LINK COUPLED INDUCTORS	
SHIELDED WIRE		DUAL SECTION CAPACITOR		TUNED AIR CORE TRANSFORMER	
WIRE, TWISTED PAIR		PASS THRU CAPACITOR		KEY	
COAXIAL CABLE		COIL OR INDUCTOR		SINGLE THROW DOUBLE POLE SWITCH	
WIRE IN CABLE		VARIABLE COIL OR INDUCTOR		ROTARY SWITCH	

Table 1. Electronic Symbols —(Cont'd)

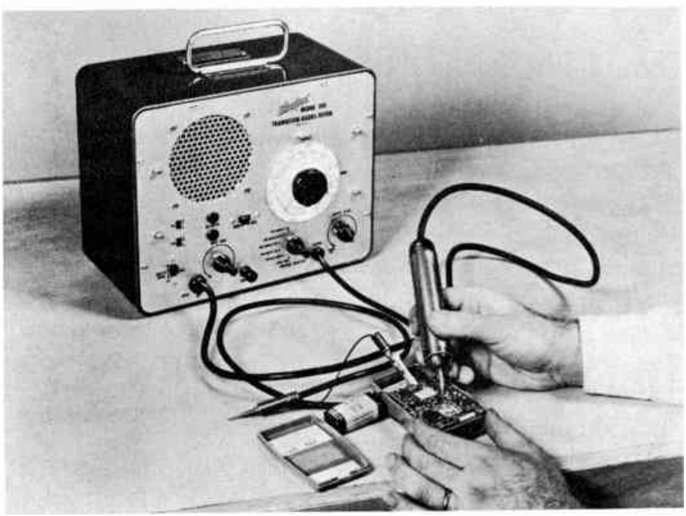
DEVICE	SYMBOL	DEVICE	SYMBOL	DEVICE	SYMBOL
DOUBLE POLE DOUBLE THROW SWITCH		MALE CONNECTOR (TYPICAL)		ENVELOPE OR SHELL	
TYPICAL SELECTOR SWITCH		FEMALE CONNECTOR (TYPICAL)		GAS FILLED ENVELOPE	
POWER SWITCH		DRY CELL OR BATTERY		BEAM TETRODE VACUUM TUBE	
RELAY (TYPICAL CONTACT ARRANGEMENT)		HEADSET		VOLTAGE REGULATOR TUBE	
JACKS		SPEAKER		TRIODE VACUUM TUBE	
PLUGS, MICROPHONE, HEADSET OR SPEAKER		MICROPHONE		PNP TRANSISTOR	
POWER OUTLET PLUG		CATHODE, THERMIONIC		NPN TRANSISTOR	
POWER RECEPTACLE OR OUTLET		CATHODE, COLD DISCHARGE		CRYSTAL	
POLARIZED MALE CONNECTOR		FILAMENT		OXIDE RECTIFIER	
POLARIZED FEMALE CONNECTOR		GRID		FUSE	
TWISTLOCK FEMALE CONNECTOR		PLATE OR ANODE		LAMP OR PILOT LIGHT	
POLARIZED TWO WIRE MALE CONNECTOR		BEAM FOCUSING ELECTRODES		VOLTMETER	

locate the defective section (RF, converter, IF, or audio), then the defective stage in that section, and finally the defective component within the stage.

In general, all electrical tests should be made with the volume control in the maximum volume position, since this position generally gives the optimum distribution of currents and voltages through the various circuits in the radio set. A second set of readings with the volume control in an average operating position is often helpful in locating trouble. The second set of readings gives the current and voltage values in the various circuits under average conditions and should compare favorably with the first set. Radical differences should be checked for a possible source of trouble.

SIGNAL GENERATORS

The fundamental use of a signal generator is to replace the broadcast signal for tests and adjustments of radio circuits. Of special importance to the service technician are the following: align-



Courtesy Hickok Electrical Instrument Co.

Fig. 2. A signal generator built into a signal tracer.

ment of IF, RF and oscillator circuits; determining the gain in any part of radio receivers; testing AVC circuits; checking selectivity; and locating defective stages by using the signal-injection method. A signal generator is illustrated in Fig. 2.

Alignment Procedure

Unless the manufacturer of the receiver instructs otherwise, the following sequence should be followed in the alignment of a radio.

1. The various tuned circuits of the IF amplifier are first aligned properly at the intermediate frequency for which the amplifier was designed.
2. The oscillator tracking capacitor should then be adjusted at about 1,500 kHz so that it tracks properly at the high-frequency end of the dial. Adjust the padding capacitor (if employed) at about 600 kHz so that it tracks at the low-frequency end of the dial.
3. Align the RF stage.

Use of Output Meter

One way to determine the condition of tubes without a tube tester is to feed a signal from a generator into the receiver input. Connect an output meter across the speaker terminals and substitute new tubes or transistors for those in the radio set, one at a time. If the output meter indicates a greater value when each new unit is placed in the set, the original unit should be replaced.

To determine the gain in any part of the receiver, connect an output meter as before and feed a signal to the receiver input. Adjust the signal generator to deliver a high output and move the "hot" lead of the generator to each succeeding RF or IF stage, noting the drop in the output voltage as shown on the output meter. Always use the proper frequency and proper scales for the output meter.

To check if AVC is functioning properly, wide changes in the alignment with a large signal voltage should produce no appreciable change in output.

To check the selectivity, feed a signal of low value to the receiver input, tune the signal generator to perfect resonance, move the generator dial off resonance gradually until signal disappears. Note number of kilocycles between resonance and inaudibility.

CAPACITY MEASUREMENTS

Because capacitors very frequently give rise to trouble in receivers, it is sometimes necessary to measure a capacitor and compare the value to that given in the circuit diagram. Hence, it is important that the service technician should understand the theory of capacity values and how they are derived.

The dials of some AC milliammeters are calibrated to read directly in microfarads. The capacitive reactance of a capacitor in ohms is given by the following formula:

$$X_c = \frac{1{,}000{,}000}{2\pi fC(\text{mfd})}\text{ ohms} \tag{1}$$

When a 60-hertz current is used ($f = 60$) and C is measured in microfarads, this formula then becomes:

$$C(\text{mfd}) = \frac{2{,}650}{X_C} \tag{2}$$

From this last equation it is possible to calibrate an AC milliammeter to read directly in capacity.

If any frequency other than 60 hertz is used, the results obtained in equation (1) or (2) must be multiplied by the fraction $\frac{F}{f}$, where F is 60 hertz and f is the frequency of the current being used. For example, if a 50-hertz current is used, then the values of equation (1) or (2) must be multiplied by $\frac{60}{50}$ or 1.2.

Before using any instruments designed for use on 60 hertz on any other frequency, one must make sure that the equipment will function at the new frequency.

Capacitor Shunted by Noninductive Resistor

It is very frequently desired to obtain the value in microfarads when a capacitor is shunted by a resistor as shown in Fig. 3.

The impedance of the above circuit combination is obtained by the following formula:

$$Z = \sqrt{r^2 + \frac{(R + 2r)\, RX_C{}^2}{R^2 + X_C{}^2}} \qquad (3)$$

where,

r is the resistance of the AC milliammeter in ohms,
R is the resistance of the shunt resistor in ohms,
X_C is the reactance of the capacitor to be measured in ohms,
Z is the impedance of the circuit combination, in ohms.

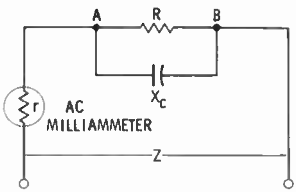


Fig. 3. Connections for measurement of capacity when the capacitor is shunted by a noninductive resistor.

The X_C value used in formula (3) is the effective resistance value of the capacitor given by formula (1).

RC substitution boxes, such as the one shown in Fig. 4, are often useful in troubleshooting procedures.

INDUCTANCE MEASUREMENTS

Inductance values may be obtained in a manner similar to that already described in capacity measurements. It should be remembered, however, that inductive reactance is vectorially positive whereas capacitive reactance is negative, and that the larger the value of the inductive reactance, the lower will be the reading of the AC milliammeter. Also, the larger the capacitive reactance, the higher will be the reading of the AC milliammeter.

The formula for inductive reactance (X_L) in ohms is:

$$X_L = 2\pi fL \text{ ohms} \qquad (4)$$

or if $f = 60$ hertz, then

Courtesy EICO Electronic Instrument Co., Inc.

Fig. 4. A resistance and capacitance substitution box.

$$L = \frac{X_L}{377} \text{ henrys} \tag{5}$$

The formula for current is as follows:

$$I = \frac{E}{\sqrt{R^2 + X_L^2}} \tag{6}$$

where

I is the AC current in amperes
E is the impressed AC voltage
R is the resistance of AC meter in ohms
X_L is the effective resistance of the inductor in ohms.

If 50 hertz is used instead of 60 hertz, the results should be multiplied by $\frac{60}{50}$, or 1.2.

AUTO RADIO TROUBLESHOOTING

Servicing Vibrator Supplies—It is usually not advisable to attempt to service, adjust or repair a vibrator after it has given a normal period of service. Experience indicates that repaired or adjusted vibrators seldom give dependable satisfactory service for any length of time, unless the repair or adjustment is of a minor nature.

Vibrator Inoperative

If there is no humming sound from the vibrator and if the pilot lamp does not light, check for an open fuse or for a poor connection in the fuse holder or at the "A +" connection at the ignition switch. It is also possible that the "on-off" switch is defective.

Vibrator Normal

If the vibrator seems normal but there is no sound from the set, look for a burned-out or defective rectifier or audio tube. Rectifier tubes often give trouble in auto receivers, especially the OZ4 tube used almost universally in the older sets. Check also for a shorted capacitor (usually the plate bypass in the audio-output stage) and check the plate voltages in the audio stages. A common trouble is failure (open condition) of plate resistors due to short leads. When replacing resistors, make all leads long enough to allow for expansion and vibration.

If there is a background hiss from the receiver and if this hiss increases or decreases with the volume-control setting but no stations are received, touch the antenna with a screwdriver. If interfering "pops" are heard, try disconnecting and reconnecting the antenna lead-in. Check also for a defective RF, converter, or IF tube ahead of the second detector. (If the tubes are accessible, feel the envelopes or try removing the last IF tube from its socket and work back toward the RF or converter tube.) Listen for noise when a tube is removed and reinserted. Trouble usually will be found in the stage just ahead of the one in which the noise last appeared.

If stations are received normally but are accompanied by vibrator interference, check for broken or loose ground connections, a loose tube shield, or a loose IF can shield. In some of the older automobiles, this type of interference may require bonding of fenders, instrument panel, etc., or installation of spark plug and distributor suppressors. See that the usual 0.5-mfd capacitors are connected across the low voltage ("A+") side of the generator and from the hot side of the ignition switch to ground.

Vibrator Erratic

If the vibrator acts intermittently and if there is no sound from the set, check for a defective vibrator (sometimes caused by defective buffer capacitors across the secondary of the transformer).

If noise is heard from the speaker but no station is received, check for a defective vibrator, buffer capacitor, or rectifier tube.

If the vibrator sticks and blows fuses, the points of the vibrator are probably badly pitted. Replace the vibrator. (Filing the points is generally only a temporary measure and should be avoided except in emergencies.) Before replacement, check the buffer capacitor. If the set is several years old replace it as a matter of safety.

If a new vibrator does not start properly, or does not start at all, check for low battery voltage, a blown fuse, or oxidized points on the vibrator. Note if the pilot light operates. If the vibrator will start when the auto engine is running, this is an indication that the battery voltage is probably low. If the vibrator points are oxidized replace the vibrator.

In some of the older receivers the current drain on the vibrator is rather heavy and ordinary vibrators will not last too long. In making replacements in such cases, be sure to use a heavy-duty replacement. Also check the buffer capacitor.

Weak Reception

In case of weak reception proceed as follows:

1. Fully extend the antenna and turn on set. Turn volume control to maximum position and tune across the dial.
2. If reception seems slightly weak, tune in a station having good volume and grasp the antenna with your hand. If volume increases adjust the antenna trimmer.
3. Check for weak tubes or transistors by replacing one at a time until the faulty one is located, or test these components with a reliable checker.
4. If the tubes and/or transistors check OK, substitute a test antenna consisting of a piece of wire about ten feet in length and connect it to a standard antenna lead-in cable. Place the test antenna outside and away from the car. If radio operates nearly normal with the substitute antenna, some part of the car antenna or lead-in is at fault. If this does not reveal the source of trouble, the receiver will have to be removed for a thorough test.

Radio Noisy (with Car Standing Still)

The procedure when trouble of this kind occurs is as follows:

1. Start engine, turn on radio and tune to a spot between stations. Engine noise will usually appear as a clicking sound that varies in frequency with the speed of the engine. If noise is present, disconnect the antenna lead-in cable from the receiver.
2. If the engine noise stops when the antenna is disconnected, check all high-tension wires for full seating in the sockets of the coil and distributor cap. Check the distributor rotor (resistance type) by substituting a known good one. If an external suppressor is used, it must be installed at the distributor end of the coil-to-distributor high-tension wire. Do not use a suppressor and a resistance-type distributor together.
3. If the distributor rotor or suppressor does not correct the noise, check the antenna lead-in cable shield for proper ground.
4. If engine noise continues with the antenna disconnected, check the ignition coil and generator capacitors for clean, tight connections. Remove the generator cover band and check for sparking at brushes when the engine is running. If sparking is excessive, check for an open armature coil.
5. If source of noise has not been found, replace ignition coil and generator capacitors with known good ones. Ignition-coil capacitor lead must be attached to battery terminal of coil. Generator-capacitor lead must be connected to "A" terminal of generator. Both capacitors must have good ground connections.
6. If engine noise is present when engine is running at approximately 2,000 rpm and all the foregoing items are satisfactory, the noise is probably due to the generator regulator. Correction may be made by mounting a 0.33-mfd capacitor at one end of the regulator mounting ground screws and attaching the capacitor lead to the battery terminal of regulator.

Set Does Not Light Up

If the set does not light up, check for a blown fuse. If the fuse is not blown, examine the fuse contact ends for corrosion or loose connections, and replace the fuse if necessary. If the fuse-holder connections are poor, stretch the spring in the fuse holder to restore proper contact pressure. Also check the rating of the fuse since it may be the wrong type, in which case the fuse should be replaced with one of the correct type and rating. Also check the on-off switch.

Intermittent Reception

In the case of intermittent reception, wiggle the antenna and lead-in connections and check the antenna for poorly grounded mounting screws. If a push-type antenna plug is used, see that the plug is in the receptacle properly and making good solid contact. Check for the same condition on bayonet or pin-type plugs and see that solder is built up sufficiently to make a positive contact.

If the plug pins or soldered connections appear to be cold soldered, sweat the connection with a hot iron and flow in a small amount of new solder. Try a similar method with the lead-in at the antenna end. Check the tubes by tapping lightly with a pencil. It should be noted that in some instances the set may have to be removed from its mounting to get the cover off.

If a portion of the broadcast band is dead or intermittent, check for a defective oscillator tube or possibly a short between the plates of the tuning capacitor. If a new oscillator tube fails to correct the trouble, check the rectifier tube or measure operating voltages at the oscillator socket. Defective oscillator coupling or padding capacitors are other possibilities.

Set is Noisy

One of the most common sources of trouble in many auto radios is an extremely noisy volume control. If a thorough cleaning proves ineffective in correcting the trouble, replacement with a new control of correct value and taper is usually the only solution.

A microphonic "squeal," usually affected by vibration or high volume, may be due to a noisy tube, generally the oscillator or second detector. A similar effect can also be caused by an intermittently open or loose lead of one of the coupling capacitors.

If the complaint is insufficient volume with distortion during the first half-hour or so of operation but with satisfactory reception thereafter, check for a weak input filter capacitor. A satisfactory test of this condition consists of bridging the faulty capacitor with a good one of the same rating.

Noise Due to Speaker Defects

When the receiver has audio distortion at low levels only and is normal at medium and high volume, check the speaker voice-coil alignment. If it is rubbing against the pole piece, try it realign the cone. If alignment is impossible, the only lasting remedy is to replace the speaker.

Audio distortion at high volume levels indicates a gassy audio-output tube or a leaky coupling capacitor. Also determine that the speaker cone is properly glued and centered and that the audio output is not exceeding the normal rating of the speaker.

Other speaker defects causing noise and unsatisfactory reception may be caused by a loose rim on the speaker cone, a warped cone or a collection of foreign matter or metal filings lodged in the magnet gap.

If the cone is loose reglue it with regular speaker cement, making sure that the cone is properly centered. Use speaker shims.

If the speaker cone is warped, try moistening the cone at a point directly opposite the warp. When dry, the cone often will warp an equal amount in the opposite direction and correct the trouble.

Ignition Noise

This is one of the more frequent complaints when dealing with auto receivers. The usual remedy is the connection of 0.5-mfd capacitors across the ignition switch, generator and other electrical components. Also clean and tighten ground connections. If the foregoing do not correct the trouble, try cleaning the base and insulator of the whip antenna. Corrosion often causes considerable leakage between the antenna and auto body.

If the ignition noise continues to be picked up even with the antenna removed, the trouble may be picked up via the DC source. The most practical solution in this case is to run a separate No. 8 or 10 wire directly from the receiver to the battery, keeping the lead as short as possible and dressing it away from other battery wiring to avoid pickup.

Wheel Static

A high-pitched noise from the receiver, present only when the car is in motion, indicates wheel static. If the noise stops or is reduced when the brakes are applied, install coiled spring suppressors inside the hub caps of the front wheels. These suppressors insure good contact between the wheel and axle.

RECEIVER ALIGNMENT

After all necessary adjustments of the receiver are completed, a complete alignment check should be made. This should include an accurate check of the dial-pointer positions throughout the dial range. In addition a peaking check of the IF, preselector, and RF trimmers should be made. Finally, check the adjustment of the antenna trimmer with the tuning dial set to about 1,400 kHz.

Auto Receiver Alignment

Radio-receiver manufacturers often make general recommendations with regard to the alignment procedure of their products. These recommendations are commonly available and thus well known to service technicians. Circuit alignment should be made only when necessary, and only when all other causes of trouble are removed.

As previously noted, modern auto receivers employ the superheterodyne circuit which uses an intermediate frequency IF amplifier. The characteristics of these amplifiers largely govern the selectivity of the receiver. The IF amplifier characteristics are determined principally by the adjustment and design of the IF transformers. It is, therefore, important that the IF amplifier be correctly adjusted to provide the best selectivity. The adjustments themselves are generally in the form of iron cores placed within the coils.

During alignment it is necessary to adjust only those iron cores specified in the tabulated adjustment procedure to obtain the best operation.

Incorporated in every receiver is a local oscillator, the output of which mixes with the incoming signal from the antenna. The local oscillator does not operate at the same frequency as the incoming signal. The resonant (acceptance) frequency of the IF amplifier establishes the difference in frequency required—260 kHz is generally employed in auto receivers. The local oscillator operates at a frequency higher than the incoming signals; the two predominating resultant frequencies produced are the sum and the difference of the two frequencies. The IF amplifiers are designed to tune to resonance at the difference frequency.

Alignment is generally necessary when replacements have been made in RF and IF circuits. This includes replacement of tubes, bypass capacitors, RF chokes, etc. Before alignment, however, allow the signal generator and receiver about 15 to 20 minutes to warm up for frequency and temperature stabilization. Nonmetallic tools should be used exclusively for alignment.

To perform the alignment correctly, an accurately calibrated signal generator and some type of output measuring device must be used. The output meter may be connected across the secondary of the output transformer. All adjustments should be made with the receiver volume control at maximum and with the signal generator output as low as practical to prevent the AVC action from influencing the reading.

The first step is to align the intermediate-frequency stages. Maximum output of a receiver is obtained only when every tuned section in it is properly aligned. Maximum output from the IF amplifier is obtained when it is adjusted to the frequency for which it is designed and when exactly that frequency is applied to the IF amplifier by the output of the mixer.

To sum up, the best sequence to follow when making these adjustments on standard broadcast-band receivers (unless the manufacturer of the receiver prescribes a different procedure) is:

1. First align the various tuned circuits of the IF amplifier properly at the IF for which the amplifier is designed.
2. The oscillator circuit should then be adjusted at about 1,500 kHz so that it "tracks" properly with the RF circuits at the high-frequency end of the dial.
3. It is preferable to align the tuned circuits of the RF stages at the same time oscillator tracking adjustments are made.

The dummy antenna shown in Fig. 5 will be helpful in providing a good match between the set and signal generator. This gives a much better balance than the makeshift coupling capacitor so often used.

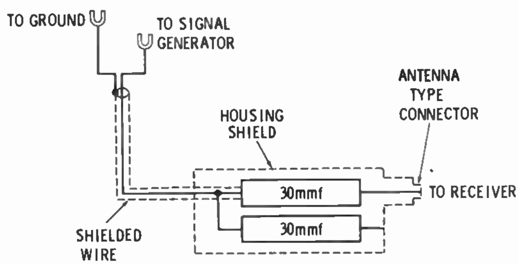


Fig. 5. Dummy antenna for use in alignment of auto radios.

Effects of RF and IF Misalignment

The effects of misaligned RF and IF stages are most commonly observed as a loss of sensitivity either over a portion or over the entire broadcast band; loss of selectivity, often characterized by the selectivity being noticeably unequal on either side of the point of best reception; a change in fidelity; or inaccurate dial indications.

Loss of fidelity will be apparent as a loss of high or low audio frequencies. If the IF amplifier is not tuned to the specific frequency, the oscillator and other tuned circuits will not track. The dial readings will then be incorrect and a portion of the band will have low sensitivity.

Signal-Generator Connection

The chassis, or frame, of the radio receiver is considered as being at ground potential and the "GND" terminal of the signal generator should be connected to the chassis wherever good contact can be established.

The "ANT" or "HIGH" terminal of the signal generator output must be connected to the antenna connection or other points in the radio receiver as specified in the alignment instructions.

The use of a fixed capacitor in series with the signal generator lead is specified in some instances. When this capacitor (sometimes called "dummy antenna") is used, it provides proper input loading to the receiver. It is important that this capacitor (when used) is connected at the point where the signal generator lead joins the radio set, and should not be connected at the generator.

Output-Meter Connection

Any standard type of output meter can be employed during alignment. The meter should be connected across the secondary of the output transformer. It is best to leave the voice coil connected while using the output meter. It is essential that an output meter with sufficient sensitivity be used to avoid the possibility of requiring too much signal generator output to obtain a readable indication on the output meter.

Sometimes it may be desirable to connect the output meter from plate to plate of output tubes. When this connection is employed, a 0.1-mfd capacitor must be connected in series with the meter to afford proper protection from the DC potential.

SUMMARY

It is imperative that a service technician have the necessary tools and test equipment in order to make repairs as quickly and efficiently as possible. Test equipment should be compact and portable, rugged enough to stand normal use and transportation as well as occasional overloads, cover the proper ranges, and be reasonably stable in operation.

A preliminary visual and/or audible check of the defective unit should be made to correct any obvious faults that might render the unit inoperative. This should be followed by regular electrical tests to diagnose the section of the unit that is faulty. Next, the component or components at fault should be determined and repaired or replaced.

A regular and logical sequence of tests should be made with the proper test instruments to arrive quickly and accurately at the receiver fault. Modern test equipment is designed to prevent wasted time if used in the proper manner and in a logical sequence of tests.

REVIEW QUESTIONS

1. List the basic test instruments necessary to properly service radio receivers.
2. What important procedure is a signal generator used for?
3. What is the purpose of an output meter?
4. What is the purpose of the vibrator in older car radios?
5. What should be the first component to check if an auto radio is inoperative?
6. What might cause a radio to play normally at the low end of the dial but go completely dead near the high end?
7. How can you determine if noise in an auto radio is caused by ignition interference?
8. How may static caused by the automobile wheels be reduced or eliminated?
9. List the steps necessary to align a radio receiver.
10. What would cause stations to be received at the proper point in one area on the dial but not in other areas?

CHAPTER 22

Trouble Pointers

Successful radio troubleshooting or servicing requires an intimate knowledge of the component parts.

Years ago, when the best equipment consisted of a dozen or more components, there was generally no difficulty in locating and eliminating the trouble.

However, since then equipment has experienced many revolutionary changes—a glance underneath the chassis of a modern receiver, for example, will illustrate how every fraction of an inch is literally crammed with radio components.

There is a bewildering array of colors stamped onto the radio parts and an equal splash of colors on the connecting wires. In addition, variable capacitors, potentiometers, and other moving parts are built in such a manner that it is sometimes hard to gain access to them. With the increasing refinement and complexity of electronic equipment, the more susceptible it becomes to trouble and the more specialized knowledge will be required to eliminate it. The examples which follow cover some of the more common questions concerning circuit troubles and provide many of the answers to them.

What May Cause a Receiver to Operate Normally for a Period of Perhaps Five to Ten Minutes, Then Suddenly Become Distorted?—There are several possible causes for such trouble—a defective tube; a leaky coupling capacitor; an intermittent open or shorted capacitor, resistor, etc. It is when the receiver reaches a certain temperature while warming up that the trouble becomes evident.

How May Modulation Hum Which Is "Given a Ride" on Any Signal Passing Through the RF and IF Circuits of a Receiver Be Eliminated?—A receiver which emanates hum only when it is tuned to a station gives the best example of trouble of this kind. This trouble is sometimes caused by improper lead dress allowing power leads to run in close proximity to RF and IF circuits, in which case the remedy is obvious.

What May Cause Distorted Sound?—Any number of defects in the audio section may cause distorted sound, such as a bad tube, leaky or shorted capacitors, or a change in resistance values causing improper bias on one or more of the audio amplifiers.

A defect in the speaker may also be the cause of distortion. For example, the voice coil may be off center or warped, causing it to rub the polepieces, or there may be foreign particles between the voice coil and the polepieces. Distortion can also be caused when tuned circuits are not properly aligned.

What May Cause "Fading" in a Radio Receiver?—Trouble of this sort is most likely to be caused by the following: leakage within tubes; defective volume control; defective capacitors, resistors or other parts which change in value with usage; or by extraneous conditions. The source of trouble is usually best found by an evaluation of circuit components. In case replacement is required, care must be observed that correct components are used—otherwise, instead of eliminating the trouble it is likely to be exaggerated.

What Is the Cause of Extensive Squeals and Interference That Change With Tuning?—Known as image-frequency interference—this type of interference is often encountered in inexpensive receivers and usually appears as an annoying whistle on desired stations that changes in pitch as the receiver is tuned. Image interference is due to lack of selectivity in the first-detector circuit. (Constant pitch whistles are another matter and are often experienced even in some of the more expensive receivers.)

If the Rectifier Tube of a Receiver Has Become Defective and Trouble Still Exists After Changing the Tube, What May Be the Cause?—A defective electrolytic capacitor may be the cause. The heat, especially in equipment where space is limited and ventilation is poor, causes the capacitor to dry out, thereby reducing their capacity. Voltage measurement at the output of the rectifier tube may show a decreased output, and hence point to filter-capacitor trouble.

What Is Indicated When the Plates of a Rectifier Tube Glow Bright Red?—This indicates that excessive current is being drawn from the power supply due to a low-resistance path between B+ and ground. The trouble may be in the power-supply circuit itself or in any of the circuits it supplies. To determine which, disconnect all supply leads from the power-supply output. If the rectifier plates appear normal, the trouble lies in one of the circuits being supplied. If the condition still exists, however, the trouble is in the power supply itself. Common causes of this condition are shorted filter or bypass capacitors, bare leads touching each other, etc.

If Tubes Do Not Light in a Series-Wired Receiver, What May Be the Cause?—A burned-out tube or open fusible filament resistor is the most likely cause. In a series circuit an open circuit will affect all tubes. In either case the remedy is obvious—change the faulty component.

What Important Precautions Should Be Observed When Replacing Defective Components in a Radio Receiver?—It is important that exact replacement parts be used wherever possible. If components of different values are inserted, they may upset the circuits or cause trouble in other ways. A list of replacement parts of various receivers is usually available, and it is these parts that should be used for replacement, to prevent continuation and even exaggeration of the trouble.

What Are the Two General Classes of Resistors Used in Radio Receivers, and Where Are They Used?—The two types are classified as the wirewound and the carbon type. Wirewound resistors generally are used where a comparatively large current is required to flow, such as in voltage dividers. Carbon resistors, however, are utilized for smaller currents. The carbon resistor as a rule has a high resistance, and will usually handle power requirements up to 2 watts. The resistance value of a carbon resistor may be identified by means of special color-code markings, and the values of wirewound resistors are usually plainly marked or tagged on the units.

Is It Well To Change or Remove Part of the Wiring To Eliminate Trouble in a Radio Receiver?—Only where substitution of wires is absolutely necessary, but the circuit should not be changed. It is evident that if the circuit was incorrect the receiver would never have functioned in the first place. It may generally be assumed that before a receiver leaves the manufacturer's test room, the circuit as well as its components are correct. Hence, the service technician should not change circuits on the assumption that they are wrong after the set has been operating properly for some time, but should attempt to locate and correct the trouble that has occurred.

When the Plates of an RF Power Amplifier in a Radio Transmitter Glow Red, What Is the Trouble?—The tube is drawing excessive current. This can be caused by several things, including loss of drive, insufficient drive, mistuned plate circuit, or a poor impedance match with the antenna. This condition will also occur if the stage is not terminated with a load. Any of the foregoing can ruin the tube within minutes.

What Meter Reaction Indicates Resonance in a Transmitter RF Power Amplifier Circuit?—When the plate tank circuit of an RF power amplifier is tuned to resonance, the meter will indicate a dip in plate current. At minimum current the stage is delivering maximum RF energy to the antenna. If the stage is tuned off resonance, the plate current can increase to such a degree that it will destroy the tube.

What Are Some of the More Common Causes of Fuses Blowing in Automobile Receivers Using Vibrator Power Supplies?—Automobile receivers have the same potential troubles as household receivers plus several others. The most common causes of fuses blowing in this type of receiver are in the power supply itself. One of the worst offenders is the vibrator, and running a close second is the buffer capacitor. This capacitor is generally connected across the secondary of the vibrator transformer. It is easy to identify because it will have a voltage rating generally between 1,000 and 1,800 volts. Some receivers use two buffer capacitors, in which case both should be checked. Another common cause of trouble is the rectifier tube. These can short, fail to conduct, or conduct intermittently. The most troublesome rectifier is the gaseous type which uses no filament.

What Can Be Done To Compensate for Line-Voltage Fluctuations Which at Times May Amount to 10% or More?—A simple remedy may be afforded by the addition of a booster transformer as shown in Fig. 1. This transformer, which is connected directly to the line circuit, steps up the voltage, thereby compensating for the drop. The transformer should have a rating in watts equal to or higher than that of the radio receiver that it supplies.

The transformer connection is largely self-explanatory. For example, switch No. 2 is the "on-off" control for the booster; when it is thrown to the left it cuts in the booster and when thrown to the right it removes the booster from the line.

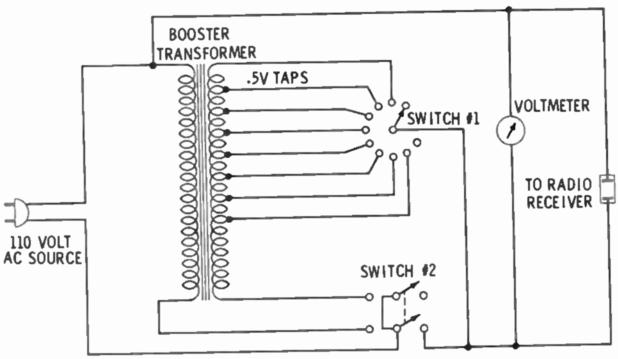


Fig. 1. Schematic diagram of a voltage-compensating circuit.

As a precautionary measure the voltmeter should always be connected in the circuit when the booster is being used. Switch No. 1 controls the actual amount of booster voltage added.

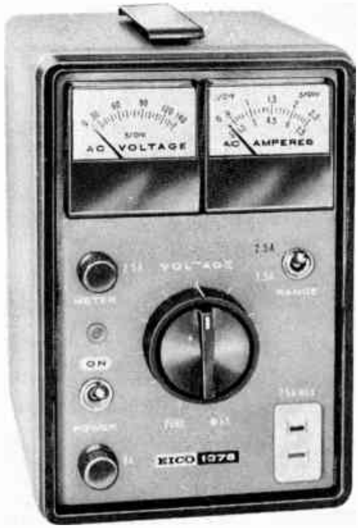


Fig. 2. A metered variable AC bench power supply.

Courtesy EICO Electronic Instrument Co., Inc.

A variable AC bench power supply, such as illustrated in Fig. 2, is a useful servicing aid.

Where Does Radio Interference Originate?—There are four broad classifications into which interference normally falls, namely: 1, that caused by electrical devices; 2, by various radio stations or the neighbor's receiver; 3, originating in the receiver itself; 4, natural atmospheric static.

The first classification is of interest particularly to city dwellers where electrical devices are very numerous and where their usage is intensified. The average city apartment house is a generator of all kinds of so-called man-made radiation interference. The various offending sources, to name just a few, are electric bells and buzzers; elevator motors and contactors; sign flashers; X-ray machines and ultraviolet ray units used by physicians; power lines; etc.

The second classification is also more of a problem to city dwellers than to others. In areas where a number of radios are operated simultaneously, a certain amount of interaction may occur between them. Some sets are capable of regeneration or circuit oscillation which sometimes affects receivers located several blocks away.

The third classification (noise originating in the equipment itself) is a problem for the receiver designer and the service technician. Very often a faulty capacitor or tube, for example, may generate an appalling amount of noise.

The fourth classification deals with natural static, and there is very little anybody can do. It is self-evident that there is no control and nothing that can be done to prevent it. Although the amount of actual disturbance in this case is less noticeable in locations of strong transmitters and where the service areas are well proportioned, at present at least, there is no remedy for natural noise.

How May Radiation Interference Caused by an AC-Operated Vacuum Cleaner Be Eliminated and What Are the Average Capacitor Values To Be Employed?—Capacitors of the values commonly used for interference suppression purposes on fixed electrical machinery are not necessarily suitable for ungrounded appliances such as vacuum cleaners. A breakdown in insulation between the electrical circuits and the metal framework of the cleaner might cause an unpleasant (or even dangerous) shock to the operator.

Fig. 3 illustrates schematically the connections and values of capacitors generally used on vacuum cleaners or similar portable appliances. It is necessary that the capacity values recommended should not be exceeded; also, the voltage rating of the capacitors should be several times that of the voltage employed in operating the appliance in question.

How May the Field Coils of a Small Universal Motor Be Rearranged so as To Cause Less Radiation Interference?—Assuming that the motor is series-wound (i.e. the field coils are in series with the armature), it is probable that a simple alteration will reduce the radiation of interference.

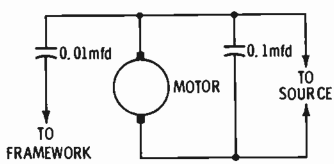
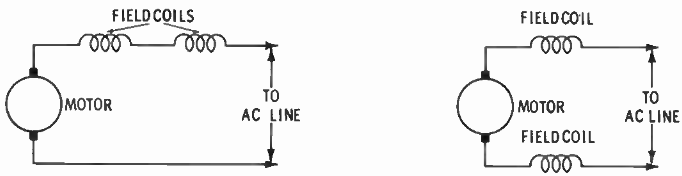


Fig. 3: Schematic diagram showing connection of interference suppressors to a vacuum cleaner.



(A) Before. (B) After.

Fig. 4. Diagram illustrating how the internal connections of a universal motor may be altered to reduce interference.

Normally, the field coils are connected as shown in Fig. 4A. By rearranging them as shown in Fig. 4B, with one coil on each side of the brushes, the bad effects of commutator sparking are reduced due to the fact that the coils now act as radio-frequency chokes and prevent interfering impulses generated by the sparks from feeding out through the wiring. Rearrangement of the coils in the manner described should have no adverse effect on the operation of the motor.

Is There a Possibility That Interference Can Be Caused by a Diesel Engine Located Near the Receiver?—Interference from ordinary internal-combustion engines originates in the electrical ignition system, which is absent in the Diesel engine, and accordingly a compression-ignition engine of this type is totally incapable of causing electrical interference.

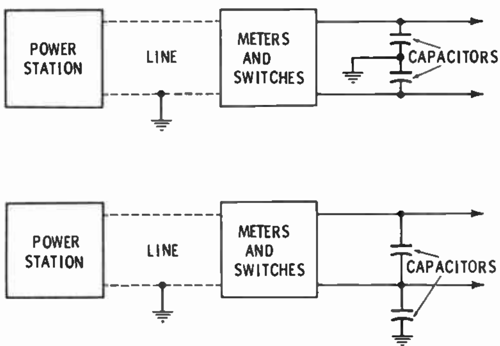


Fig. 5. Method of connecting interference suppressors to prevent noise in an AC wiring system.

How Should Interference Suppressors Be Connected in Order to Reduce Leakage in a Wiring System?—By referring to Fig. 5A it is fairly clear that since one of the main lines is grounded at the power station, full potential is applied between the capacitors and ground. Although the leakage current is relatively small, it is a source of interference. One of several ways of avoiding appreciable leakage is to use capacitors much smaller than the standard value of 2 mfd.

A capacity of 0.01 mfd is generally recommended and in most cases proves to be effective. Another method of reducing leakage to negliglible proportions is to connect the conventional type of suppressor in the manner illustrated in Fig. 5B.

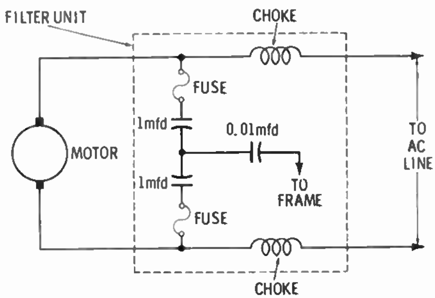


Fig. 6. Interference-suppressor filter added to a washing machine.

It Is Desired To Eliminate Radiation Interference Caused by a Washing Machine. How May This Be Accomplished and What Are the Component Values?—This trouble can usually be eliminated by connecting a filter unit as shown in Fig. 6. Necessary precautions should be observed that the values of the filter do not exceed those given, also that the voltage and frequency of the source are similar to those of the manufacturer's marking on the filter parts.

How Is It Possible To Locate or To Track Down Suspected Sources of Man-Made Static?—This is usually done by a device know as interference locator, usually a portable receiver with a highly directional antenna or radio-frequency pickup system.

How Does Radiation Interference Originate in a Switch and How May It Be Eliminated?—Radiation interference of this sort is often due to defective contacts in the switch, causing a spark which may be of short duration and occuring only when the switch is actuated, in which case a short click will be noticed in the receiver. Ot other times the spark will be observed intermittently, causing a prolonged scraping or howling. Replacing the switch will most likely solve the problem.

However, if the switch is only slightly worn, a thorough cleaning and smoothing of the contact surface will prove to be helpful. A resistance-capacitance filter shown in Fig. 7 is commonly used as a switch interference eliminator. This filter is connected in parallel with the switch. The proper resistor and capacitor values depend on the amount of current drawn by the circuit. In most instances a 500- to 1,000-ohm resistor and a capacitor of 0.1 microfarad will be found satisfactory.

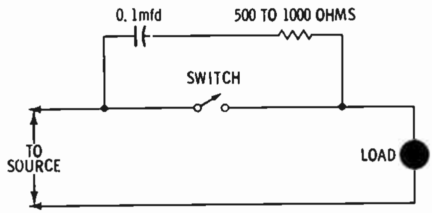


Fig. 7. Switch-filter connection.

What Can Be Done To Eliminate the Interference Caused by a Neon Sign?—Neon signs are notorious as sources of radio interference. In this type of lighting system, interference may be caused by flickering tubing, overloaded transformers, faulty insulation, corona discharges between tubing and ground, loose connections, ungrounded transformer case, etc.

When the sign is found to be the source of interference, each one of the aforementioned trouble sources should be investigated. As a general rule, however, it has been found that the employment of filters across switch contacts, and also across the primary winding of the transformer, will reduce the trouble.

It has also been found effective to include properly insulated chokes between the letters of the sign as shown in Fig. 8. When filters are installed, it should be remembered that the components employed must be able to withstand the potentials and the current (in the case of radio-frequency chokes) which must flow through them.

Where Does Radiation Interference Affecting an Automobile Radio Receiver Usually Originate?—In the electrical system, and particularly so in the ignition system. The interference originating in the ignition system is usually referred to as ignition-noise interference and emanates from the electric sparks in various parts of the system, such as in the spark plugs, distributor cap, loose contacts in the wiring system, etc.

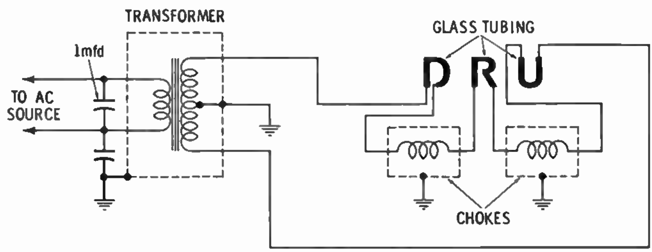


Fig. 8. Interference suppressors added to a neon sign.

What Can Be Done To Eliminate Radio Noise Originating in the Electrical System of the Automobile?—There are a number of suggestions that will be helpful in successfully coping with this problem. They are as follows:

Distributor Suppressor: Remove the high-tension lead to the distributor. Insert a distributor suppressor and connect the wire to the other end of the suppressor.

Generator Capacitor: The generator capacitor should be installed between the armature terminal of the generator and ground (the generator frame).

Withdraw Antenna-Cable Plug: Turn on the receiver and start the engine. If motor noise is heard, proceed as follows:

Bypass Capacitor: Try a .25- or .5-mfd capacitor from the ammeter to ground. Try a capacitor from the ignition switch to ground, electric windshield-wiper connections and various other connections to ground, noting what effect these capacitors have on the noise pickup. Try a .25- or .5-mfd capacitor from the hot side of the coil primary to ground. In some cases this capacitor may not help. It can be tried, however, experimentally.

Spark-Plug Suppressors: If motor noise persists, spark-plug suppressors should be installed. One suppressor is put on each plug. The majority of cars, however, will not require spark-plug suppressors. The newer models employ resistive high-tension cable—also called radio resistance wire. If this type of cable is used, do *not* employ resistor spark plugs, and vice versa. Care should be taken that a good mechanical and electrical connection is made between the spark plugs, suppressors and plug wires.

Then reinsert the antenna-cable plug. If motor noise is still heard when the antenna cable is reconnected, proceed as follows until the noise is satisfactorily reduced:

Dome-Light Lead: To determine the amount of noise due to the dome-light lead, disconnect this lead at its source and coil it up. Then, with the engine running, ground the end of this wire. If this is found to reduce the noise noticeably, interference is being radiated by the dome-light lead.

Reconnect the dome-light lead and try a .25-mfd or .5-mfd capacitor from the connecting point of the lead to ground. If this does not cure the noise, disconnect the lead and encase it in a braided copper shield from the point where it leaves the voltage source to the point of connection. Keep the lead as far as possible from the car ignition wires and ground the shield.

Bonding Cables: Try grounding to the dash all cables and tubing which pass through it, such as oil lines, etc. By means of a file, contact can be established between any of the lines and the dash, in order to determine whether such a ground will reduce the noise.

To bond the cables to the dash, clean the point of contact, wrap a length of braided shielding around the cable and solder the connection. Then solder the end of the shielding to the dash, or ground it under a screw head if one is convenient. Sufficient play should be left in the bonding shielding so that movement of the cables or tubing will not loosen this shielding.

High- and Low-Tension Leads: In some instances, the high- and low-tension leads between the coil and distributor are routed close together. In some cars they are even in the same conduit. If this is the case, remove the low-tension lead from this conduit. In any event, keep the high- and low-tension leads separated as far as possible. Shield and ground the shield of the low-tension lead if separating the two leads is not sufficient.

Grounding Engine and Other Parts: The engine must, every case, be well grounded to the frame of the car. If it is not, use a very heavy braided lead similar to a storage-battery ground lead for this purpose. It may also be necessary to check the grounding of the metal dash, instrument panel, radiator and hood to the frame of the automobile.

Signal Level: Occasional noise may be due to weak signal pickup caused by the automobile being in a "dead spot" or by a faulty antenna system. When signals are weak, the action of the automatic volume control causes the receiver to operate at its maximum sensitivity, thereby increasing the noise level.

Loose Parts in Car: Noisy operation may also be caused in some instances by loose parts in the car body or frame. These loose parts rubbing together affect the grounding and cause noises, due to the rubbing or wiping action. Tightening the frame and body at all points, and in some cases the use of a bonding strap, will eliminate noise of this nature.

Where Does Static Interference in an Automobile Receiver Originate, and What Is Usually Done To Eliminate It?—This kind of interference is most common in older cars and usually originates in wheels and tires and is identified as wheel or tire static. Another source of static interference is badly adjusted brake linings, in which case the remedy is obvious. To eliminate wheel and tire static, it is well to have a clear understanding about the cause, as well as how to identify this particular form of interference.

The sounds developed in a receiver from wheel or tire static may be heard as an intermittent rasping or clicking, with the time intervals varying with the speed of the car, or maybe a steady hissing developed after the car reaches a given speed.

Wheel and tire static occur only while the car is motion and will occur whether the ignition is turned on or off. It will be most pronounced on asphalt or cement pavement, but may be noticed in some cases on brick pavement or on a dry gravel road. Driving off the pavement should stop the noise.

From the above it is clear that it is the friction between the dry pavement and the rubber tires that generates static electricity, which collects on isolated substances in the tires or on the metal wheels, which may be electrically isolated from the body of the car by grease and oil. This electricity then discharges to the car body or road bed, depending upon the potential developed and the distance to either. Generally the distinguishing symptoms between wheel or tire static are that if the noise disappears on application of the brakes, the noise is attributed to wheel static; if not, the trouble is due to tire static.

When the static interference has been identified as wheel static, the most commonly used method of elimination is to make a metallic contact between the movable wheel and the wheel spindle.

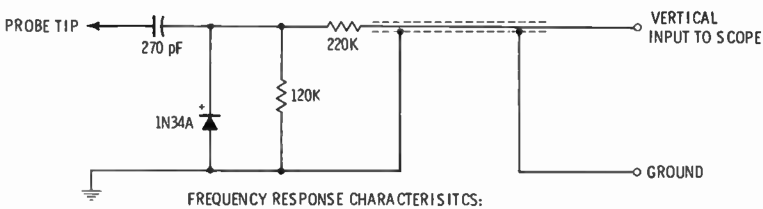
This is accomplished by inserting a large coiled spring inside the hub cap so that one end makes good contact against the spindle and the other against the cap. This type of static eliminator is produced commercially. There is also a powder available that can be blown into the tire to prevent tire static.

It Is Desired To Use a Standard 60-Cycle AC Receiver on an AC System of 25 Hertz. Will This Be Possible and What Changes or Precautions, If Any, Should Be Taken?—This problem may be briefly summed up by the fact that almost any AC receiver may be made to work satisfactorily from a supply source of 25 hertz. Of course a specially designed power transformer must be used. This transformer will be somewhat larger than the one used for a 60-hertz supply, and hence a slight modification of the original chassis layout may become necessary.

It may also be necessary to change the relative positions of the power transformer and any AF transformers in order to minimize hum. There is also the question of smoothing. Theoretically, a more complex filtering system will be required, but in practice the ordinary filter circuit may be quite effective; this is because both the speaker and the human ear are less sensitive to the lower hum frequency of the 25-hertz supply. It is therefore recommended that additional capacitors and possibly an extra choke should not be added until they are found necessary.

How Can the Oscillator Frequency Be Measured?—It is occasionally desired to measure the oscillator frequency. There are several ways to do this, and the method that is chosen will depend on the test equipment which is available.

1. *Signal Generator and Signal Tracer:* Place the signal-tracer probe and the signal-generator output lead near the oscilla-



FREQUENCY RESPONSE CHARACTERISITCS:	
RF CARRIER RANGE	500 kHz to 250 MHz
MODULATED-SIGNAL RANGE	30 to 5000 Hz
INPUT CAPACITANCE (APPROX.)	2.25 pF
EQUIVALENT INPUT RESISTANCE (APPROX.):	
AT 500 kHz	25,000 OHMS
1 MHz	23,000 OHMS
5 MHz	21,000 OHMS
10 MHz	18,000 OHMS
50 MHz	10,000 OHMS
100 MHz	5000 OHMS
150 MHz	4500 OHMS
200 MHz	2500 OHMS
MAXIMUM INPUT:	
AC VOLTAGE	20 RMS VOLTS 28 PEAK VOLTS

Fig. 9 Typical demodulator probe and specifications.

tor coil of the receiver. This arrangement permits the oscillator signal and the generator signal to couple into the signal tracer by means of stray capacitance without loading the oscillator circuit appreciably. Tune the signal generator (with its output control set to maximum) and listen for a beat tone from the signal tracer. Tune to zero beat; the signal-generator dial then indicates the oscillator frequency.

2. *Signal Generator and Oscilloscope:* Connect a demodulator probe (Fig. 9) to the scope, and place the probe near the oscillator coil in the receiver. Also place the output lead from a signal generator near the oscillator coil. Operate the scope at a low-frequency deflection rate, such as 60 Hz. Advance the vertical gain of the scope to maximum and use maximum output from the generator. Tune the signal generator and watch for a sine-wave pattern on the scope screen. Tune for the zero-beat point; this is where the sine wave suddenly collapses to a horizontal trace on the screen. The signal-generator dial then indicates the oscillator frequency.
3. *Grid-Dip Meter and Signal Tracer (or Scope):* Proceed as before, but use the grid-dip meter instead of a signal generator. Hold the coil of the grid-dip meter a couple of inches from the oscillator coil. Tune for zero beat. The dial on the grid-dip meter then indicates the oscillator frequency.
4. *Heterodyne Frequency Meter:* Place the input lead of the heterodyne frequency meter near the oscillator coil in the receiver. Tune the HFM for null indication. The dial of the HFM then indicates the oscillator frequency.

How Can a Receiver Be Operated With a Dead Oscillator?— A radio receiver with a dead oscillator can be operated by injecting a signal of suitable frequency from a signal generator or a grid-dip meter. Proceed as follows:

1. Tune the receiver to some station point on the dial (the station cannot be heard, due to the dead oscillator).

2. Couple the output lead of a signal generator through a small capacitor to the antenna lead. If a loop antenna is used, connect the output lead of the generator to a small coil, and place the coil near the loop.
3. Using high output from the generator, carefully tune the generator to a frequency at which the station is audible from the receiver.
4. If a grid-dip meter is used instead of a signal generator, simply hold the coil of the GDM near the antenna lead, or near the loop antenna of the receiver. Tune the GDM carefully to a frequency at which the station is audible from the receiver.

How Can a Receiver With a Dead Oscillator Be Operated by a Receiver That Is in Normal Working Condition?—This trick of the trade is based on the principle explained above. Simply place the good receiver near the receiver that has the dead oscillator. Tune the receiver with the dead oscillator to some station point on the dial. Then, tune the good receiver carefully to a frequency at which the station is audible from the receiver with the dead local oscillator. In this procedure, the good receiver radiates an oscillator signal which is picked up by the receiver with the dead oscillator. Best results are obtained when the good receiver is placed in a position which couples maximum oscillator signal into the receiver with the dead local oscillator. Note that poor or no response may be obtained if the receivers have well-shielded coils in the RF section.

SUMMARY

Successful servicing depends on the technician being thoroughly familiar with all the component parts in the faulty equipment. Advances in the design and manufacture of electronic components have produced thousands of parts that would be unfamiliar to anyone not keeping abreast of recent developments.

REVIEW QUESTIONS

1. Name two faults that can cause distortion in a radio receiver.
2. If the plates of a rectifier tube get red hot, what component is likely defective?
3. What might cause the plate of an RF power amplifier to glow red hot?
4. Is ignition interference from a diesel truck possible?
5. How can a hum, present only when a receiver is tuned to a station, be eliminated?
6. How can a burned-out tube in an AC/DC receiver be found?
7. What is the most likely fault in a receiver when stations do not come in at the proper point on the dial?
8. Name two steps that can be taken to reduce interference in an auto radio.
9. What check can be made to determine if the local oscillator of a receiver is operating?
10. Is the AVC voltage of a receiver positive or negative?

APPENDIX I

Radio Data

The purpose of symbols and abbreviations is to make it possible to illustrate and describe more briefly and clearly.

A drawing in which every part or piece of apparatus would be repeatedly described would obviously be impractical. Therefore, symbols have been devised which represent every part and piece of apparatus and which take up little space. Similarly, where long words or terms are to be used, abbreviations that have been adopted as standard are substituted.

On the following pages are given the most important symbols and abbreviations currently employed.

PREFIXES

Kilo	Denotes a quantity one thousand times as great as a unit.
Milli	Denotes a quantity equal to one-thousandth part of a unit.
Micro	Denotes a quantity equal to one-millionth part of a unit.
Meg	Denotes a quantity one million times as great; for example, 1,000,000 hertz = 1 megahertz and 1,000,000 ohms = 1 megohm.

SYMBOLS

μ = permeability (B/H)
π = 3.1416
ρ = volume resistivity
τ = thickness
λ = wavelength in meters
θ = phase angle (degree or radian)
ϕ = angle
ψ = difference in phase
$\omega = 2\pi f$ (angular velocity in radians per second)
Φ = magnetic flux
Ψ = electrostatic flux
Ω = ohm

AF = audio frequency
RF = radio frequency
emf = electromotive force
mmf = magnetomotive force
AC = alternating current
DC = direct current
MFD = microfarad
MMF = micromicrofarad
h = henry
mh = millihenry
μh = microhenry
f = frequency
rms = root-mean-square
rpm = revolutions per minute
rps = revolutions per second
pf = power factor

GREEK ALPHABET

Letters	Names	Letters	Names	Letters	Names
Α α	Alpha	Ι ι	Iota	Ρ ρ	Rho
Β β	Beta	Κ κ	Kappa	Σ σς	Sigma
Γ γ	Gamma	Λ λ	Lambda	Τ τ	Tau
Δ δ	Delta	Μ μ	Mu	Υ υ	Upsilon
Ε ε	Epsilon	Ν ν	Nu	Φ φ	Phi
Ζ ζ	Zeta	Ξ ξ	Xi	Χ χ	Chi
Η η	Eta	Ο ο	Omicron	Ψ ψ	Psi
Θ θ	Theta	Π π	Pi	Ω ω	Omega

MORSE CODE CHARACTERS

E — dit
I — di-dit
S — di-di-dit
H — di-di-di-dit
5 — di-di-di-di-dit

2 — di-di-dah-dah-dah
V — di-di-di-dah
3 — di-di-di-dah-dah
4 — di-di-di-di-dah
A — di-dah

MORSE CODE CHARACTERS (Cont'd)

error — di-di-di-di-di-di-di-dit (The sender has made a mistake.)
U — di-di-dah
F — di-di-dah-dit
? — di-di-dah-dah-di-dit (Also a request for repetition of transmission not understood.)

R — di-dah-dit (Also means message received o.k.)
L — di-dah-di-dit
wait — di-dah-di-di-dit
W — di-dah-dah
P — di-dah-dah-dit
J — di-dah-dah-dah
1 — di-dah-dah-dah-dah

end — di-dah-di-dah-dit
period — di-dah-di-dah-di-dah
quotation marks — "di-dah-di-di-dah-dit"
T — dah
N — dah-dit
D — dah-di-dit
B — dah-di-di-dit
6 — dah-di-di-di-dit
hyphen (-) — dah-di-di-di-di-dah
K — dah-di-dah
Y — dah-di-dah-dah
parenthesis ( ) — dah-di-dah-dah-di-dah
C — dah-di-dah-dit
semicolon (;) — dah-di-dah-di-dah-dit
X — dah-di-di-dah
fraction bar (/) — dah-di-di-dah-dit
break (--) — dah-di-di-di-dah
M — dah-dah
G — dah-dah-dit
Z — dah-dah-di-dit
7 — dah-dah-di-di-dit
O — dah-dah-dah
0 — (zero) — dah-dah-dah-dah-dah
9 — dah-dah-dah-dah-dit
8 — dah-dah-dah-di-dit

MORSE CODE CHARACTERS (Cont'd)

colon (:) — dah-dah-dah-di-di-dit
Q — dah-dah-di-dah
comma (,) — dah-dah-di-di-dah-dah

ABBREVIATIONS

C capacity (electrostatic capacity)
E effective electromotive force
I effective current
K dielectric constant
L inductance
M mutual inductance
N number of conductors or turns
Q quantity of electricity
R resistance
T period, or one complete cycle
W watts
X reactance
Z impedance

d diameter; distance
f frequency; hertz
g conductance
h height
i instantaneous current
k coefficient of coupling
l length
r distance from a point (radius)
t time
v velocity

VACUUM-TUBE NOTATION

Grid potential . . . . E_g, e_g
Grid current . . . . I_g, i_g
Grid conductance . . . . g_g
Grid resistance . . . . r_g
Grid bias voltage . . . . E_g
Plate potential . . . . E_p, e_p
Plate current . . . . I_b, I_p, i_p
Plate conductance . . . . g_p
Plate resistance . . . . r_p
Plate supply voltage . . . . E_b

VACUUM-TUBE NOTATION (Cont'd)

Mutual conductance	g_m
Amplification factor	μ
Filament terminal voltage	E_f
Filament current	I_f
Grid-plate capacity	C_{gp}
Grid-cathode capacity	C_{gk}
Plate-cathode capacity	C_{pk}
Grid capacity (input)	C_g
Plate capacity (output)	C_p

SIGNS

$\propto$	proportional to; varies as	$\angle$	angle
$=$	equal to	$<$	is less than
$\times$	multiplied by	$\ll$	much less than
$+$	plus; addition	$>$	is greater than
$-$	minus; subtraction	$\gg$	much greater than
$\div$	divided by	$\sim$	cycle
$\odot$	circle		

ELECTRICAL UNITS

Electrical units are based on the metric system, which is the name applied to the system of units employed in continental Europe.

The fundamental units in the metric system are the meter, the gram, and the second. The *unit meter* is the length of a certain standard metal bar which is preserved at the International Bureau near Paris.

From this unit of length, the units of *volume* (liter) and of *mass* (gram) are derived. The three units—*meter, liter and gram*—are simply related, thus one cubic decimeter equals one liter and one liter of water weighs one kilogram.

The above units are comparatively familiar to the radio technician as the meter is universally used for the expression of the length of radio waves. The meter is 39.37 inches or 3.281 feet.

Without giving any historical information as to the development of electric and magnetic units, it may be said that those now used are the so-called international electric units. The international units are based on four fundamental units—the *ohm*, *ampere*, *centimeter* and *second*. The first of these is the unit of *resistance*, and is defined in terms of the resistance of a very pure conductor of specified dimensions. The *ampere* is the unit of current and is defined in terms of a chemical effect of electric current, the amount of silver deposited from a certain solution by a current flow for a definite time. The other electric units follow from these in accordance with the principles of electrical science. Some of the units thus defined are given in the following definitions, which are those adopted by international congresses of science and universally used in electrical work.

One *ohm* = the resistance of a column of mercury (at the temperature of melting ice) of a uniform cross section of one square millimeter and a length of 106.30 centimeters.

One *ampere* = the current which, when passed through a solution of silver nitrate in water in accordance with certain specifications, deposits silver at the rate of 0.001118 gram per second.

One *volt* = the electromotive force which produces a current of one ampere when steadily applied to a conductor having a resistance of one ohm.

One *coulomb* = the quantity of electricity transferred by a current of one ampere in one second.

One *farad* = the capacitance of a capacitor in which a potential difference of one volt will store a charge of one coulomb of electricity.

One *henry* = the inductance in a circuit in which the electromotive force induced is one volt when the inducing current varies at the rate of one ampere per second.

One *watt* = the power expanded by a current of one ampere through a resistance of one ohm.

Horsepower is sometimes used as a unit of power in rating electric machinery. The horsepower is equal to 746 watts.

One *joule* = the energy expended in one second by a flow of one ampere through a resistance of one ohm.

The *gram-calorie* or simply "calorie" is the energy required to raise one gram of water one degree centigrade in temperature. One gram-calorie is, very nearly, equal to 4.18 joules.

Another unit of quantity of electricity, in addition to the coulomb, is the *ampere-hour* which is the quantity of electricity transferred by a current of one ampere in one hour, and is, therefore, equal to 3,600 coulombs.

Since the farad is found to be too large a unit, the units of capacity actually used in radio work are the *microfarad* $= 10^{-6}$ farads (a millionth of a farad) and the *micromicrofarad* $= 10^{-12}$ farads (a millionth of a microfarad). Another unit sometimes used is the cgs electrostatic unit of capacity, often called the centimeter of capacity, which is approximately equal to 1.11 microfarads.

The units of inductance commonly used in radio work are the *millihenry* $= 10^{-3}$ henry (a thousandth of a henry) and the *microhenry* $= 10^{-6}$ henry (a millionth of a henry). Another unit sometimes used is the *centimeter of inductance*, which is one one-thousandth of a microhenry.

PRACTICAL FORMULAS

Ohm's Law for Direct Current

$$I = \frac{E}{R}, \; R = \frac{E}{I}, \; E = I \times R$$

where,

I = amperes,
E = volts,
R = resistance.

Resistances in Series

$$R_{(\text{Total})} = R_1 + R_2 + R_3 + \text{etc.}$$

Resistances in Parallel

$$R_{(\text{Total})} = \frac{1}{\frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} \text{ etc.}}$$

Fundamental Frequency

$$f = \frac{1}{2\pi \sqrt{LC}}$$

where,

f = frequency in hertz,
L = inductance of the circuit in henrys,
C = capacitance of the circuit in farads.

Inductive Reactance

$$X_L = 2\pi fL$$

where,

X_L = inductive reactance,
L = Inductance in henrys.

Capacitive Reactance

$$X_C = \; = \frac{1}{2\pi fC}$$

where,

X_C = capacitive reactance,
C = capacity in farads.

Ohm's Law for Alternating Current

$$I = \frac{E}{Z} \text{ or } I = \frac{E}{\sqrt{R^2 + \left[\left(2\pi fL\right) - \left(\frac{1}{2\pi fC}\right)\right]^2}}$$

where,

I = current,
E = voltage,
Z = impedance (total of all oppositions).

Capacitors in Parallel

$$C_{(Total)} = C_1 + C_2 + C_3 \text{ etc.}$$

Capacitors in Series

$$C_{(Total)} = \frac{1}{\frac{1}{C_1} + \frac{1}{C_2} + \frac{1}{C_3} \text{ etc.}}$$

Resonance

$$2\pi \, fL = \frac{1}{2\pi fC}$$

where,

$2\pi fL$ = inductive reactance,
$2\pi fC$ = capacitive reactance.

Wavelength

$$(\lambda) \text{ wavelength} = 1885 \sqrt{LC}$$

where,

L = inductance in microhenrys,
C = capacity in microfarads.

Antenna Radiation

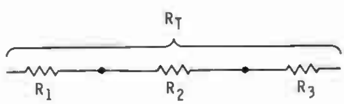
$$W = 1578 \times \frac{h^2}{\lambda^2} \times I^2$$

in which,

W = the energy radiated in watts, effective,
h = the effective height of the antenna in meters,
λ = the wavelength of the antenna in meters,
I = the current in amperes at the base of the antenna or point of maximum current.

Resistances in Series

A series resistance circuit may be defined as one in which the resistances are connected in a continuous run (i.e., connected end to end) as shown.

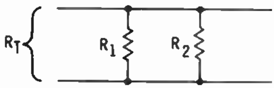


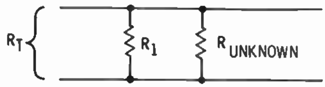
$$R_t = R_1 + R_2 + R_3 + \text{etc.}$$

where,

R_t is the total resistance
R_1, R_2, R_3, etc., are the individual resistances.
All resistances must be expressed in the *same unit* (*ohms*, *megohms*, etc.)

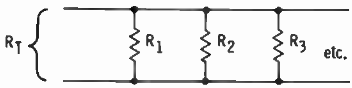
Resistances in Parallel (Two Only)





$$R_t = \frac{R_1 \times R_2}{R_1 + R_2} \qquad R_{(unknown)} = \frac{R_t \times R_1}{R_1 - R_t}$$

Resistances in Parallel (Many)



$$\frac{1}{R_t} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} + etc.$$

$$\text{or, } R_t = \frac{1}{\frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} + etc.}$$

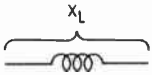
All resistances must be expressed in the *same unit* (*ohms*, *megohms*, etc.)

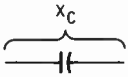
Ohm's Law for DC Circuits

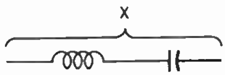
Ohm's law can be expressed in several different forms, all of which are conveniently tabulated below.

I (amperes) =			$\frac{E}{R}$	$\sqrt{\frac{W}{R}}$	$\frac{W}{E}$		
R (ohms) =	$\frac{E}{I}$				$\frac{E^2}{W}$	$\frac{W}{I^2}$	
E (volts) =		IR		$\sqrt{WR}$		$\frac{W}{I}$	
W (watts) =	EI	I^2R	$\frac{E^2}{R}$				

AC Circuit Relations



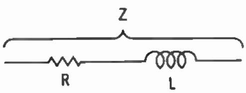


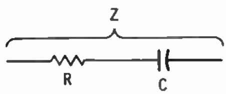


$$X_L = 2\pi fL \qquad X_C = \frac{1}{2\pi fC} \qquad X = 2\pi fL - \frac{1}{2\pi fC}$$

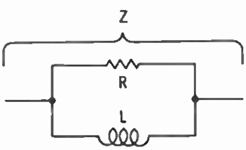
where,

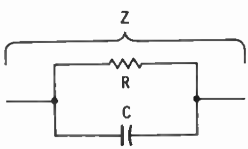
X_L is the inductive reactance in *ohms*,
X_C is the capacitive reactance in *ohms*,
X is the net reactance in *ohms*,
2π is a "constant" equal to *6.28*,
f is the frequency in *hertz*,
L is the inductance in *henrys*,
C is the capacitance in *farads*.





$$Z = \sqrt{R^2 + (2\pi fL)^2} \qquad Z = \sqrt{R^2 + \frac{1}{(2\pi fC)^2}}$$





$$Z = \frac{2\pi fLR}{\sqrt{R^2 + (2\pi fL)^2}} \qquad Z = \frac{R}{\sqrt{4\pi^2 f^2 R^2 C^2 + 1}}$$

where,

Z is the impedance of the circuit in *ohms* and all other quantities have the same meaning as explained previously.

Impedance of Resistance, Capacitance, and Inductance in Series

$$Z = \sqrt{R^2 + \left(2\pi fL - \frac{1}{2\pi fC}\right)^2}$$

Impedance of Resistance, Capacitance, and Inductance in Parallel

$$Z = \frac{RX_LX_C}{\sqrt{X_L^2X_C^2 + R^2(X_L - X_C)^2}} \text{ ohms}$$

Ohm's Law for AC Circuits

$$I = \frac{E}{Z}, \qquad E = I \times Z, \qquad Z = \frac{E}{I}$$

where,

I = current in *amperes*,
E = emf in *volts*,
Z = the impedance in *ohms*.

Sine-Wave Voltage Relations

For a sine-wave voltage:

(1) *Maximum* voltage = 1.414 × effective voltage
(2) *Effective* voltage = 0.707 × maximum voltage
(3) *Average* voltage = 0.636 × maximum voltage

Power in AC Circuits

$$W = E \times I \times \frac{R}{Z}, \text{ or } E \times I \times \textit{cosine } \phi$$

where,

W = power in *watts*

and $\frac{R}{Z}$ is called the *Power Factor.*

$$PF = \frac{\textit{true power}}{\textit{apparent power}} = \frac{I \times R}{E}$$

Resonance

$$f = \frac{1}{2\pi\sqrt{LC}}, \text{ or } L = \frac{1}{(2\pi f)^2C}, \text{ or } C = \frac{1}{(2\pi f)^2L}$$

where,

f = resonance frequency in *hertz,*
L = inductance in *henrys,*
C = capacitance in *farads.*

When f, L and C are expressed in the units indicated below, the formulas become:

$$f_{(kHz)} = \frac{159.2}{\sqrt{L\ (microhenrys) \times C\ (mfd)}}$$

or,

$$f_{(kHz)} = \frac{159{,}200}{\sqrt{L\ (microhenrys) \times C\ (mmf)}}$$

$$L_{(microhenrys)} = \frac{(159.2)^2}{f^2_{(kHz)} C_{(mfd)}}$$

$$C_{(mfd)} = \frac{(159.2)^2}{f^2_{(kHz)} L_{(microhenrys)}}$$

Resonant Wavelength

$$wavelength\ (meters) = 1885 \sqrt{L\ (microhenrys) \times C\ (mfd)}$$

or,

$$wavelength\ (meters) = 1.885 \sqrt{L\ (microhenrys) \times C\ (mmf)}$$

Frequency and Wavelength Relations

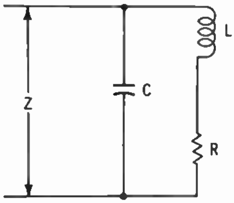
$$wavelength\ (meters) = \frac{300{,}000{,}000}{frequency\ (hertz)}$$

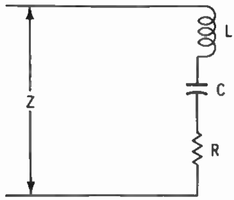
$$wavelength\ (meters) = \frac{300{,}000}{frequency\ (kHz)}$$

$$frequency\ (hertz) = \frac{300{,}000{,}000}{wavelength\ (meters)}$$

$$frequency\ (kHz) = \frac{300{,}000}{wavelength\ (meters)}$$

Impedance Relations in Series and Parallel Resonant Circuits





$$Z = \frac{2\pi fL}{4\pi^2 f^2 LC - 1}$$

At resonance:

$$Z = Q\, 2\pi fL$$

$$Z = \sqrt{\left(2\pi fL - \frac{1}{2\pi fC}\right)^2 + R^2}$$

At resonance:

$$Z = R$$

where Q is the "factor of merit" of the coil $= \dfrac{2\pi fL}{R}$

Coil Calculations

The formula for the inductance of a single-layer coil is

$$L = \frac{0.2 \times A^2 \times N^2}{3A + 9B + 10C}$$

where,

L is inductance in microhenrys,
N is the total number of turns,
A is the inside diameter of coil in inches,
B is the length of winding in inches,
C is the radial depth of coil in inches (omitted for single-layer coils).

Example—Assume that a coil is to be wound on a coil form of one-inch diameter with a required inductance of 240 microhenrys. The coil is to wound with No. 32 enamel wire close-wound. The wire table gives the number of turns per inch as 120. Find the total number of turns (N).

$$A = 1 \text{ inch}$$

$$B = \frac{\text{no of turns}}{\text{turns per inch}} = \frac{N}{120}$$

$$L = 240$$

Applying the known factors to the equation we have

$$240 = \frac{0.2 \times N^2}{3 + \frac{9N}{120}} = \frac{24N^2}{360 + 9N}$$

This becomes

$$N^2 - 90N - 3600 = 0$$

or

$$N = 45 \pm \sqrt{45^2 + 3600} = 45 \pm 75$$

from which the positive root equals 120 turns.

Voltage Across Series Capacitors

When an AC voltage is applied across a number of capacitors connected in series, the voltage drop across the combination is, of course, equal to the applied voltage. The drop across each individual capacitor is inversely proportional to its capacitance. The voltage drop across any capacitor in a group of series capacitors is calculated by the formula

$$E_C = \frac{E_A \times C_T}{C}$$

where,

E_C is the voltage across the selected capacitor,
E_A is the applied voltage,

Table 1. Copper Wire Table.

Gauge No. B. & S.	Diam. in Mils[1]	Circular Mil Area	Turns per Linear Inch[2]				Turns per Square Inch[2]			Feet per Lb.		Ohms per 1000 ft. 25° C.	Current Carrying Capacity at 1500 C.M. per Amp.[3]
			Enamel	S.C.C.	D.S.C. or S.C.C.	D.C.C.	S.C.C.	Enamel S.C.C.	D.C.C.	Bare	D.C.C.		
1	289.3	83690	—	—	—	—	—	—	—	3.947	—	.1264	55.7
2	257.6	66370	—	—	—	—	—	—	—	4.977	—	.1593	44.1
3	229.4	52640	—	—	—	—	—	—	—	6.276	—	.2009	35.0
4	204.3	41740	—	—	—	—	—	—	—	7.914	—	.2533	27.7
5	181.9	33100	—	—	—	—	—	—	—	9.980	—	.3195	22.0
6	162.0	26250	—	—	—	—	—	—	—	12.58	—	.4028	17.5
7	144.3	20820	—	—	—	—	—	—	—	15.87	—	.5080	13.8
8	128.5	16510	7.6	—	7.4	7.1	—	—	—	20.01	19.6	.6405	11.0
9	114.4	13090	8.6	—	8.2	7.8	—	—	—	25.23	24.6	.8077	8.7
10	101.9	10380	9.6	—	9.3	8.9	87.5	84.8	80.0	31.82	30.9	1.018	6.9
11	90.74	8234	10.7	—	10.3	9.8	110	105	97.5	40.12	38.8	1.284	5.5
12	80.81	6530	12.0	—	11.5	10.9	136	131	121	50.59	48.9	1.619	4.4
13	71.96	5178	13.5	—	12.8	12.0	170	162	150	63.80	61.5	2.042	3.5
14	64.08	4107	15.0	—	14.2	13.8	211	198	183	80.44	77.3	2.575	2.7
15	57.07	3257	16.8	—	15.8	14.7	262	250	223	101.4	97.3	3.247	2.2
16	50.82	2583	18.9	18.9	17.9	16.4	321	306	271	127.9	119	4.094	1.7
17	45.26	2048	21.2	21.2	19.9	18.1	397	372	329	161.3	150	5.163	1.3
18	40.30	1624	23.6	23.6	22.0	19.8	493	454	399	203.4	188	6.510	1.1
19	35.89	1288	26.4	26.4	24.4	21.8	592	553	479	256.5	237	8.210	.86
20	31.96	1022	29.4	29.4	27.0	23.8	775	725	625	323.4	298	10.35	.68
21	28.46	810.1	33.1	32.7	29.8	26.0	940	895	754	407.8	370	13.05	.54
22	25.35	642.4	37.0	36.5	34.1	30.0	1150	1070	910	514.2	461	16.46	.43
23	22.57	509.5	41.3	40.6	37.6	31.6	1400	1300	1080	648.4	584	20.76	.34
24	20.10	404.0	46.3	35.3	41.5	35.6	1700	1570	1260	817.7	745	26.17	.27
25	17.90	320.4	51.7	50.4	45.6	38.6	2060	1910	1510	1031	903	33.00	.21
26	15.94	254.1	58.0	55.6	50.2	41.8	2500	2300	1750	1300	1118	41.62	.17
27	14.20	201.5	64.9	61.5	55.0	45.0	3030	2780	2020	1639	1422	52.48	.13
28	12.64	159.8	72.7	68.6	60.2	48.5	3670	3350	2310	2067	1759	66.17	.11
29	11.26	126.7	81.6	74.8	65.4	51.8	4300	3900	2700	2607	2207	83.44	.084
30	10.03	100.5	90.5	83.3	71.5	55.5	5040	4660	3020	3287	2534	105.2	.067
31	8.928	79.70	101.	92.0	77.5	59.2	5920	5280	—	4145	2768	132.7	.053
32	7.950	63.21	113.	101.	83.6	62.6	7060	6250	—	5227	3137	167.3	.042
33	7.080	50.13	127.	110.	90.3	66.3	8120	7360	—	6591	4697	211.0	.033
34	6.305	39.75	143.	120.	97.0	70.0	9600	8310	—	8310	6168	266.0	.026
35	5.615	31.52	158.	132.	104.	73.5	10900	8700	—	10480	6737	335.0	.021
36	5.000	25.00	175.	143.	111.	77.0	12200	10700	—	13210	7877	423.0	.017
37	4.453	19.83	198.	154.	118.	80.3	—	—	—	16660	9309	533.4	.013
38	3.965	15.72	224.	166.	126.	83.6	—	—	—	21010	10666	672.6	.010
39	3.531	12.47	248.	181.	133.	86.6	—	—	—	26500	11907	848.1	.008
40	3.145	9.88	282.	194.	140.	89.7	—	—	—	33410	14222	1069	.006

[1] A mil is 1/1000 (one thousandth) of an inch.
[2] The figures given are approximate only, since the thickness of the insulation varies with different manufacturers.
[3] The current-carrying capacity at 1000 C.M. per ampere is equal to the circular-mil area (Column 3) divided by 1000.

C_T is the total capacitance of the series combination,
C is the capacitance of the selected capacitor.

Conductance

Conductance is the measure of the ability of a component to conduct electricity. Conductance for DC circuits is expressed as the reciprocal of resistance; therefore

$$G = \frac{1}{R}$$

where,

G is the conductance in mhos,
R is the resistance in ohms.

Ohm's law formulas when conductance is considered are

$$I = EG$$

$$R = \frac{1}{G}$$

$$E = \frac{I}{G}$$

where,

I is the current in amperes,
E is the voltage in volts,
G is the conductance in mhos,
R is the resistance in ohms.

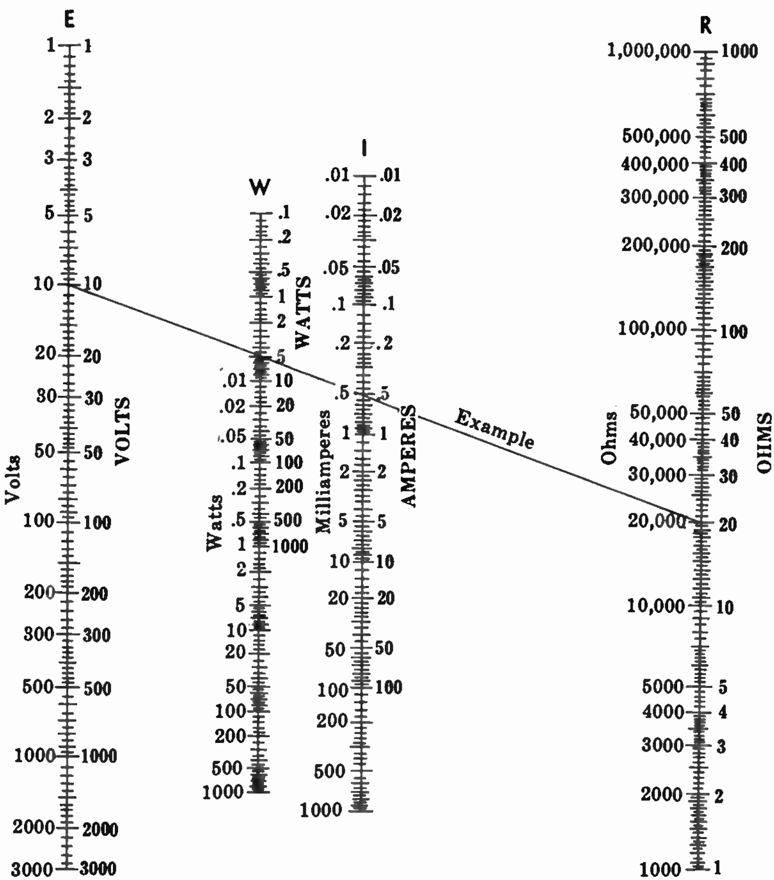
Average, RMS, Peak, and Peak-To-Peak Values

Given Value	Multiplying Factor to Get			
	Average	Rms	Peak	Peak-to-Peak
Average	—	1.11	1.57	3.14
RMS	0.9	—	1.414	2.828
Peak	0.637	0.707	—	2.0
Peak -to-Peak	0.32	0.3535	0.5	—

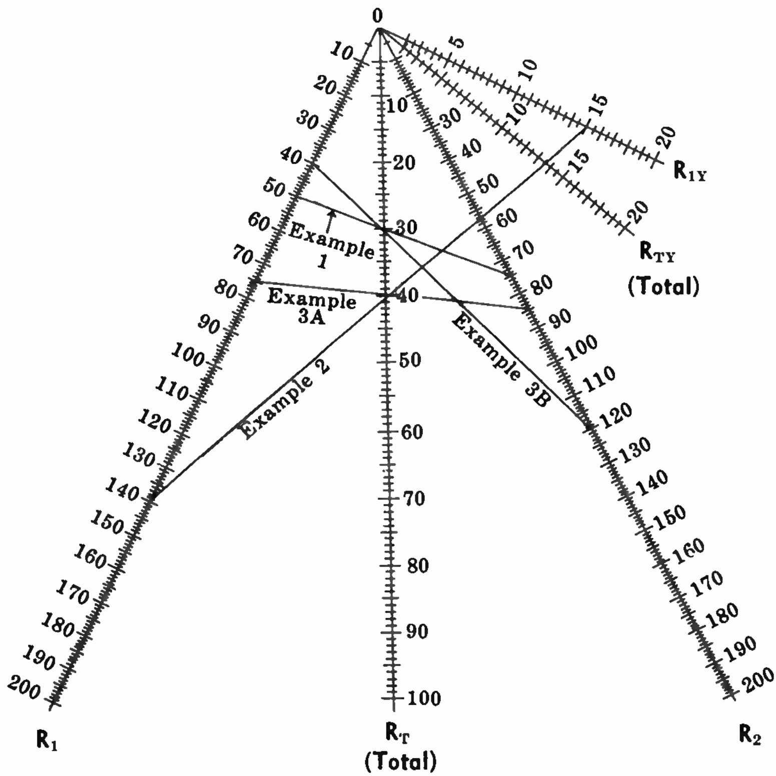
Nomographs

A nomograph is simply a chart which enables one to solve numerical formulas and equations by using only a straightedge.

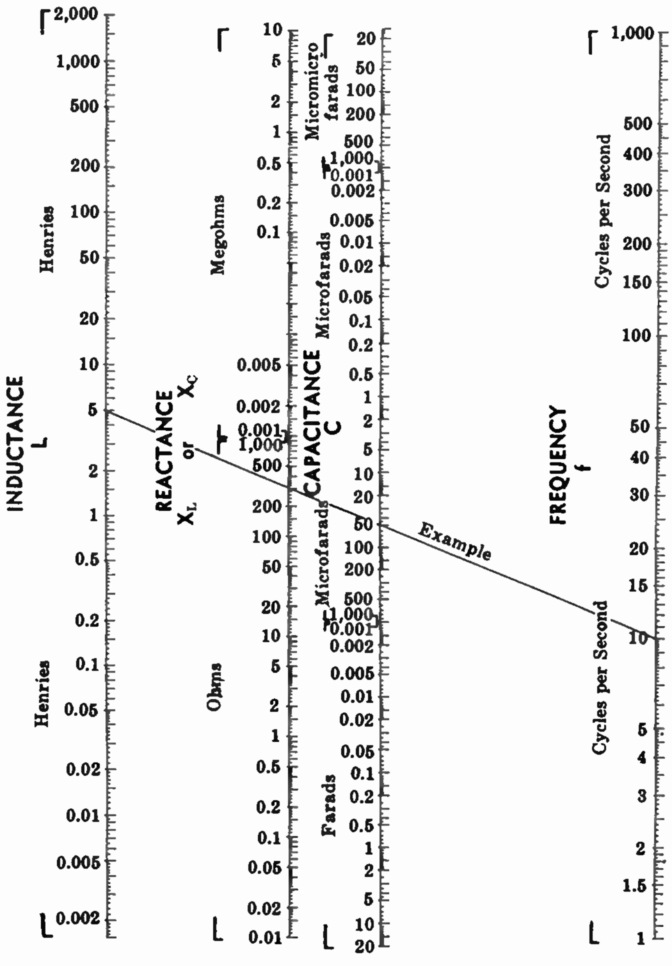
Ohm's-Law Nomograph



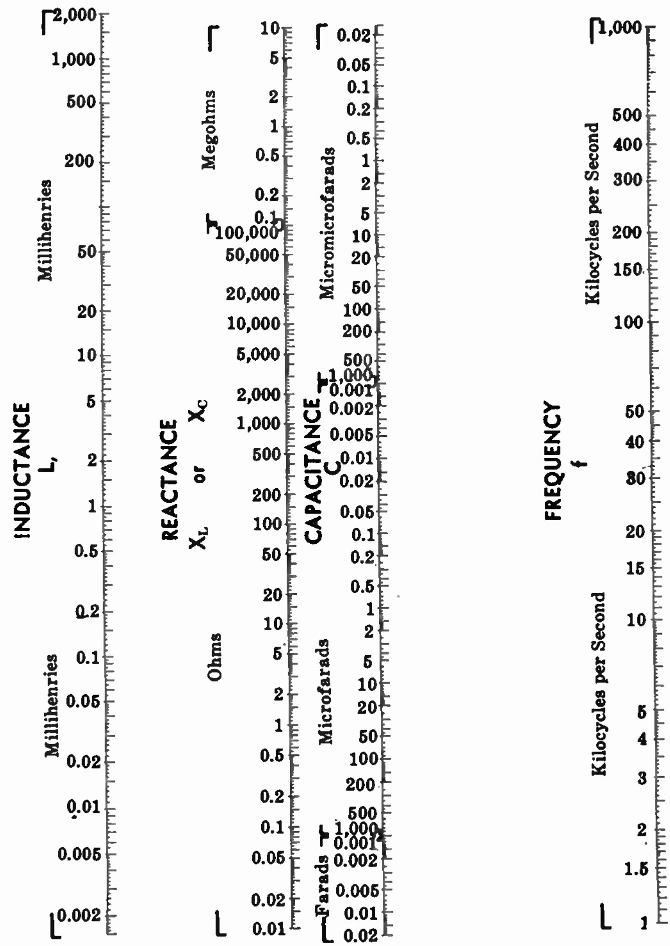
Parallel-Resistance Nomograph



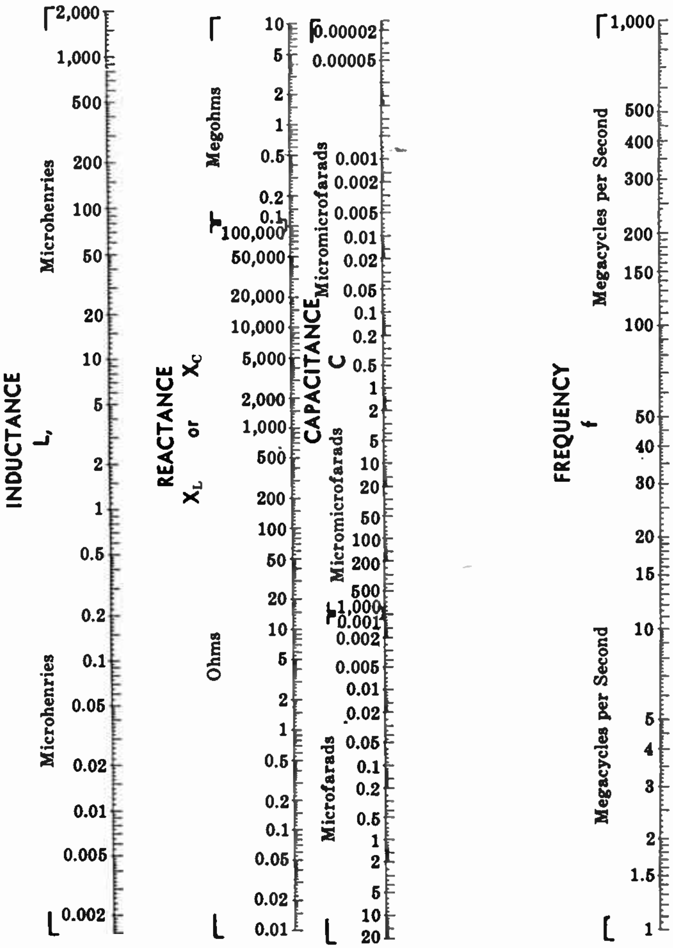
Reactance Chart—1 hertz to 1 kHz



Reactance Chart— 1kHz to 1mHz



Reactance Chart—1 mHz to 1,000 mHz



APPENDIX II

Radio-Circuit Calculations

A coil has a DC resistance of 10 ohms and an inductance of 0.1 henry. If the frequency of the source is 60 hertz, what is the voltage necessary to cause a current of 2 amperes to flow through the circuit?

$$E_R = IR = 2 \times 10 = 20 \text{ volts}$$
$$X_L = 2\pi fL = 2\pi 60 \times 0.1 = 37.7 \text{ ohms}$$
$$E_L = IX_L = 2 \times 37.7 = 75.4 \text{ volts}$$

The applied voltage must therefore be

$$E = \sqrt{E_R^2 + E_L^2} = \sqrt{20^2 + 75.4^2} = 78 \text{ volts}$$

A coil that has a negligible resistance takes 3 amperes when connected to a 180-volt, 60-hertz supply. What is the inductance of the coil?

$$X_L = \frac{E}{I} = \frac{180}{3} = 60 \text{ ohms}$$

and

$$X_L = 2\pi fL$$

from which

$$L = \frac{60}{2\pi \times 60} = 0.159 \text{ henry}$$

The ratio of the primary to secondary turns in a certain transformer is 8/20, and a load of 4,000 ohms is connected to the secondary winding. What is the primary impedance of this transformer?

The formula for the impedance relations in a transformer is

$$Z_p = Z_s N^2$$

where,

Z_p is impedance of primary as viewed from source of power,
Z_s is impedance of load connected to secondary,
N is turns ratio, primary to secondary.

In this particular problem the turns ratio equals $8/20 = 0.4$. A substitution of values in the formula gives,

$$Z_p = 4{,}000 \times 0.4^2 = 640 \text{ ohms}$$

A power-supply circuit and associated voltage divider contains 5 resistors. With the current drains and voltage drops indicated in the figure, calculate:

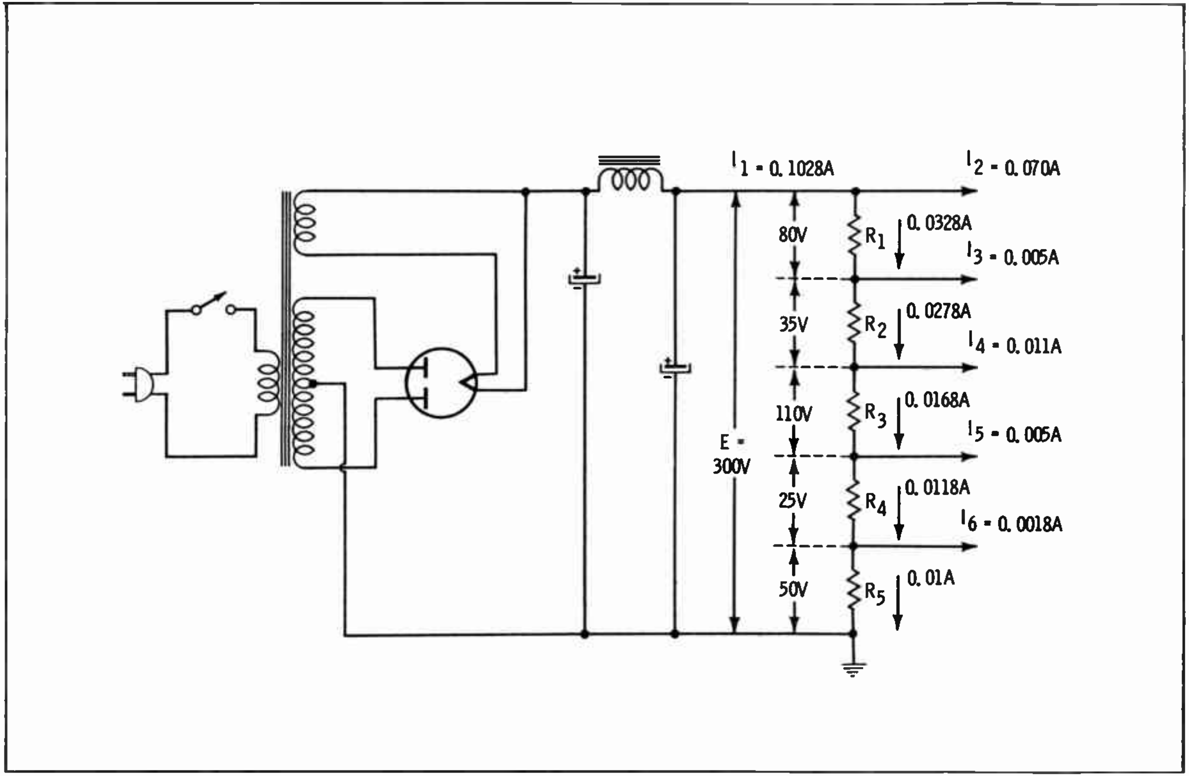
(a) Individual resistance values.

(b) Power dissipation in each resistance.

In the present example the total current drain obviously is the sum of the currents required by the individual tube circuits. To this must be added a bleeder current of approximately 10% of the total current requirements. The current rating of the power supply is:

$$\begin{aligned}
I_2 &= 0.0700 \text{ Amp.}\\
I_3 &= 0.0050 \text{ Amp.}\\
I_4 &= 0.0110 \text{ Amp.}\\
I_5 &= 0.0050 \text{ Amp.}\\
I_6 &= \underline{0.0018} \text{ Amp.}\\
\text{Total drain} &= 0.0928 \text{ Amp.}
\end{aligned}$$

Assuming a bleeder current of 0.01 or 10 milliamperes, the total drain to be delivered by the supply as indicated will be $0.0928 + 0.010 = 0.1028$ or 102.8 milliamperes. From this value a current of 0.07 amperes will be required by circuit I_2. The re-


I1 = 0.1028A
I2 = 0.070A
80V
R1
0.0328A
I3 = 0.005A
35V
R2
0.0278A
I4 = 0.011A
110V
R3
0.0168A
I5 = 0.005A
E = 300V
25V
R4
0.0118A
I6 = 0.0018A
50V
R5
0.01A

mainder or 0.1028 − 0.07 = 0.0328 amperes must pass through resistance R_1. The value of resistance R_1 may now be calculated by applying Ohm's law to this part of the circuit. We have:

$$R_1 = \frac{E}{I} = \frac{80}{0.0328} = 2{,}439 \text{ ohms}$$

The current taken by I_3 equals 0.005 ampere. Therefore, the current flow in resistance R_2 is 0.328 − 0.005 = 0.0278 ampere. Its resistance value is therefore,

$$R_2 = \frac{E}{I} = \frac{35}{0.0278} = 1{,}259 \text{ ohms}$$

The current flowing through R_3 is 0.0278 − 0.0011 = 0.0168 ampere, since 0.011 ampere is required in circuit I_4. Resistance R_3 can now be calculated. As previously, we have

$$R_3 = \frac{110}{0.0168} = 6{,}548 \text{ ohms}$$

Similarly, the current flowing in R_4 must be 0.0168 − 0.005 = 0.0118 ampere. Hence,

$$R_4 = \frac{E}{I} = \frac{25}{0.0118} = 2{,}119 \text{ ohms}$$

Now, since the last circuit (I_6) will require a current drain of 0.0018 ampere, the value of R_5 may readily be calculated.
The current through R_5 equals 0.0118 − 0.0018 = 0.01 ampere. The value of resistance R_5 is finally

$$R_5 = \frac{E}{I} = \frac{50}{0.01} = 5{,}000 \text{ ohms}$$

The power dissipation for each resistance may be calculated as follows:

$$W_1 = I^2R_1 = 0.0328^2 \times 2{,}439 = 2.62 \text{ watts}$$

$$W_2 = I^2R_2 = 0.0278^2 \times 1{,}259 = 1.00 \text{ watt}$$

$$W_3 = I^2R_3 = 0.0168^2 + 6{,}548 = 1.85 \text{ watts}$$

$$W_4 = I^2R_4 = 0.0118^2 \times 2{,}119 = 0.30 \text{ watt}$$

$$W_5 = I^2R_5 = 0.01^2 \times 5{,}000 = 0.50 \text{ watt}$$

The total power consumption in the foregoing power supply equals the sum of the power dissipated in the individual resistances. That is

$$W_1 + W_2 + W_3 + W_4 + W_5 = 6.27 \text{ watts}$$

The wattage rating of the various resistance units may also be obtained by using the formula, watts $= E \times I$, that is, the current flowing through each resistance should be multiplied by the voltage drop across it.

A series-connected circuit consists of a coil of 4 microhenrys and a capacitor of 12 micromicrofarads. Calculate the wavelength in meters to which the combination will resonate.

If it is remembered that the wavelength in meters equals $3 = 10^8$ divided by the frequency in hertz, we may write:

$$\lambda = \frac{3 \times 10^8}{f} \text{ or } f = \frac{3 + 10^8}{\lambda}$$

Substituting f in the equation for resonance, we obtain:

$$f = \frac{3 \times 10^8}{\lambda} = \frac{1}{2\pi\sqrt{LC}}; \text{ or } \lambda = 10^8 \times 6\pi\sqrt{LC}$$

Substituting numerical values in the foregoing equation we have,

$$\lambda = 10^8 \times 6\pi\sqrt{4 \times 10^{-6} \times 12 \times 10^{-12}} = 13.058 \text{ or}$$
$$13.06 \text{ meters}$$

A constant AC potential of 100 volts is impressed on a series circuit, having a resistance of 25 ohms, an inductance of 0.08 henry and a capacitance of 3.2 microfarads. If the frequency is variable, at what frequencies will the power taken by the entire circuit be 150 watts? What frequency

will produce the maximum voltage across the inductance and what will this maximum voltage be?

From the data supplied, the following equation applies:

$$P = I^2R = 150 \text{ watts}$$

$$I = \sqrt{\frac{P}{R}} = \sqrt{\frac{150}{25}} = \sqrt{6} \text{ amperes}$$

$$\text{and } I = \frac{E}{Z} = \frac{100}{\sqrt{R^2 + \left(2\pi fL - \frac{1}{2\pi fC}\right)^2}} = \sqrt{6}$$

Squaring both sides of the foregoing equation, we have

$$\frac{10{,}000}{R^2 + \left(2\pi fL - \frac{1}{2\pi fC}\right)^2} = 6$$

substituting values for R, L and C, then:

$$10{,}000 = 6\left[625 + \left(0.503\ f - \frac{10^6}{20.1\ f}\right)^2\right]$$

and

$$1{,}041 = \left(\frac{10.1\ f^2 - 10^6}{20.1\ f}\right)^2$$

If the foregoing equation is solved with respect to frequencies or (f) we obtain

$$f_1 = 284$$
$$f_2 = 348$$

Maximum voltage across inductance (L) occurs at resonance

$$\text{Resonance frequency, } f = \frac{1}{2\pi\sqrt{LC}}$$

A substitution of values gives

$$f = \frac{1}{2\pi\sqrt{0.08 \times 3.2 \times 10^{-6}}} = \frac{10^3}{2\pi \times 0.506} = 314 \text{ hertz}$$

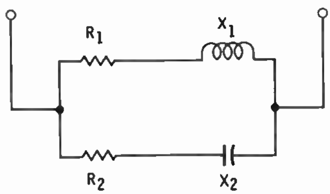
At resonance Z = R; that is, $I = \frac{100}{25} = 4$ amperes

We also have $X_L = 2\pi fL = 2\pi \times 314 \times 0.08 = 158$ ohms.

The maximum voltage across the inductance (X_L) is finally

$$E_L = I \times X_L = 4 \times 158 = 632 \text{ volts.}$$

What is the resonant frequency of the circuit below if resonance is defined as current being in phase with the applied voltage, i.e., unity power factor?



Since the condition for resonant frequency is one in which the current is in phase with the applied voltage, we may write:

$$X_1X_2 (X_1 + X_2) + R_1^2X_2 + R_2^2X_1 = 0$$

In this particular case $X_1 = \omega L$ and $X_2 = \frac{1}{\omega C}$

Where, $\omega = 2\pi f$.

Therefore we obtain

$$-\frac{L}{C}\left(\omega L - \frac{1}{\omega C}\right) - \frac{R_1^2}{\omega C} + R_2^2\,\omega L = 0$$

Multiplying both sides of our equation with (ω) we have

$$\frac{-\omega^2L^2}{C} + \frac{L}{C^2} - \frac{R_1^2}{C} + R_2^2\,\omega^2L = 0; \text{ or}$$

$$\omega^2\left(R_2{}^2 L - \frac{L^2}{C}\right) = \frac{R_1{}^2}{C} - \frac{L}{C^2}; \text{ that is}$$

$$\omega^2 = \frac{\dfrac{R_1{}^2}{C} - \dfrac{L}{C^2}}{R_2{}^2 L - \dfrac{L^2}{C}}\ ; \text{ but since } \omega = 2\pi f,$$

we may write

$$f = \frac{1}{2\pi\sqrt{LC}}\sqrt{\frac{L - R_1{}^2\,C}{L - R_2{}^2\,C}}$$

At what frequency will 50 microhenrys and 0.000030 microfarad resonate?

$$f = \frac{1}{2\pi\sqrt{LC}} = \frac{1}{2\pi\sqrt{50 \times 10^{-6} \times 30 \times 10^{-12}}}$$

$$= \frac{1 \times 10^9}{2\pi \times 38.73} = 4.10 \text{ mHz}$$

To what frequency will 4 microhenrys inductance and 12 micromicrofarads capacitance resonate?

$$f = \frac{1}{2\pi\sqrt{4 \times 10^{-6} \times 12 \times 10^{-12}}} = \frac{1 \times 10^9}{2\pi \times 6.93}$$

$$= \frac{1 \times 10^9}{43.54} = 22.97 \text{ mHz}$$

What inductance will resonate at 5.0 megahertz with a capacitance of 300 micromicrofarads?

Solving the resonance formula with respect to inductance in henrys we obtain:

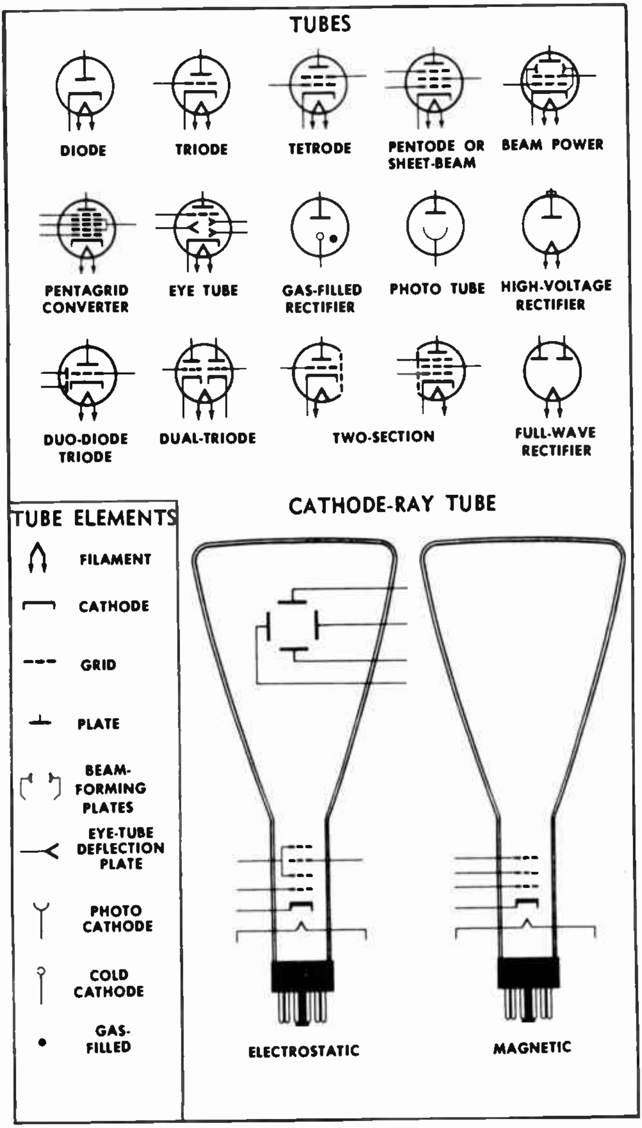
$$L = \frac{1}{4\pi^2 f^2 C}$$

A substitution of numerical values in the equation gives

$$L = \frac{1}{4 \times 9.87 \times 25 \times 10^{12} \times 300 \times 10^{-12}} = 0.0000034 \text{ or}$$

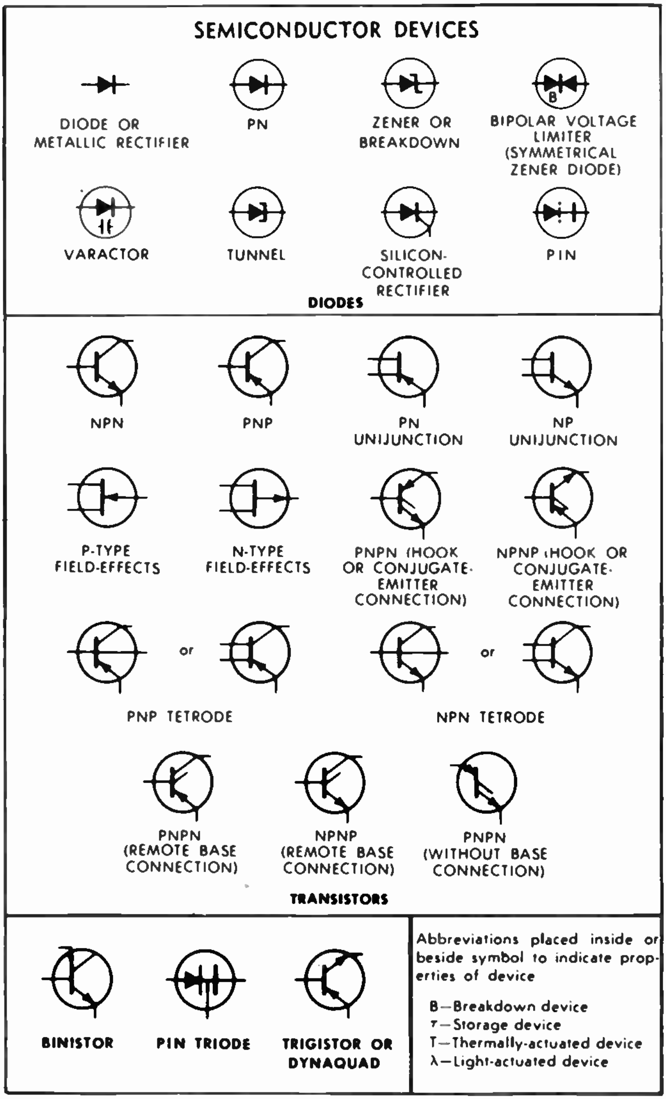
3.4 microhenrys.

Electronic Schematic Symbols

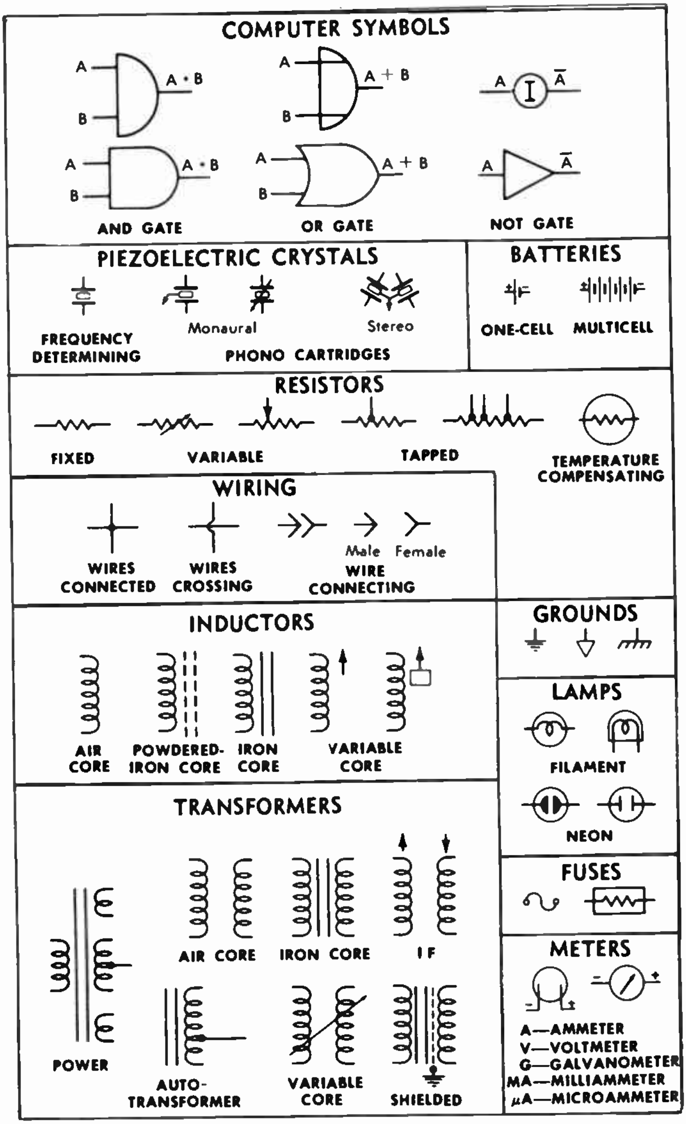


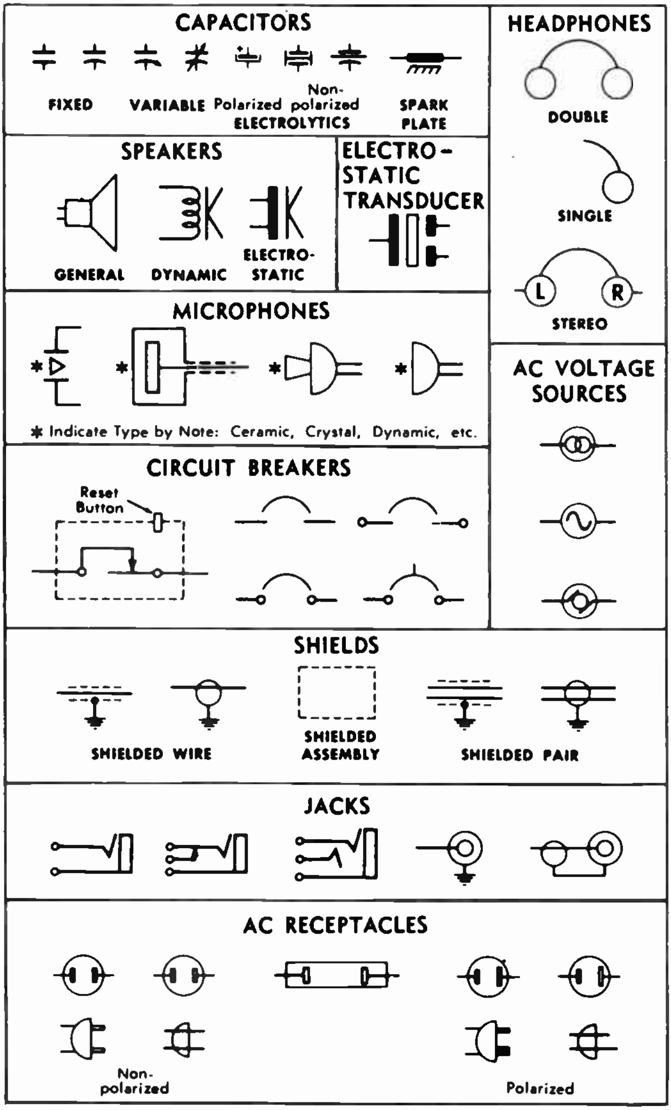
APPENDIX II

Electronic Schematic Symbols



Electronic Schematic Symbols




CAPACITORS
FIXED
VARIABLE
Polarized
Non-polarized
ELECTROLYTICS
SPARK PLATE
HEADPHONES
DOUBLE
SINGLE
L
R
STEREO
SPEAKERS
GENERAL
DYNAMIC
ELECTRO-STATIC
ELECTRO-STATIC TRANSDUCER
MICROPHONES
*
* Indicate Type by Note: Ceramic, Crystal, Dynamic, etc.
AC VOLTAGE SOURCES
CIRCUIT BREAKERS
Reset Button
SHIELDS
SHIELDED WIRE
SHIELDED ASSEMBLY
SHIELDED PAIR
JACKS
AC RECEPTACLES
Non-polarized
Polarized

Index

W

Z

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