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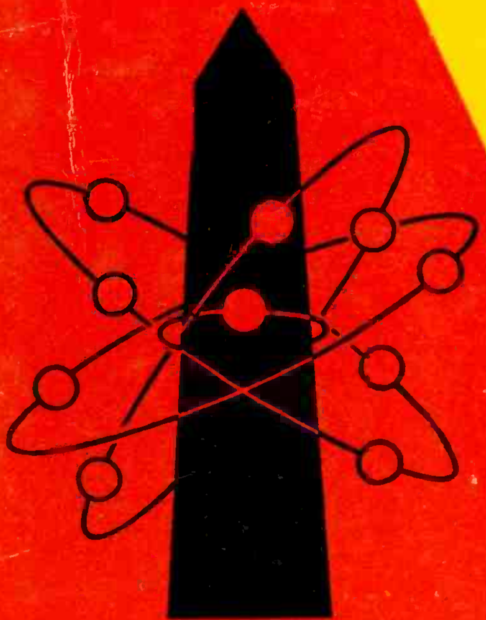
basic electricity

by VAN VALKENBURGH, NOOGER & NEVILLE, INC.



VOL. 3

ALTERNATING CURRENT

RESISTANCE, INDUCTANCE, CAPACITANCE IN AC

REACTANCE

AC METERS

A. STICH

RIDER

basic electricity

by VAN VALKENBURGH,
NOOGER & NEVILLE, INC.

VOL. 3

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PREFACE

The texts of the entire Basic Electricity and Basic Electronics courses, as currently taught at Navy specialty schools, have now been released by the Navy for civilian use. This educational program has been an unqualified success. Since April, 1953, when it was first installed, over 25,000 Navy trainees have benefited by this instruction and the results have been outstanding.

The unique simplification of an ordinarily complex subject, the exceptional clarity of illustrations and text, and the plan of presenting one basic concept at a time, without involving complicated mathematics, all combine in making this course a better and quicker way to teach and learn basic electricity and electronics. The Basic Electronics portion of this course will be available as a separate series of volumes.

In releasing this material to the general public, the Navy hopes to provide the means for creating a nation-wide pool of pre-trained technicians, upon whom the Armed Forces could call in time of national emergency, without the need for precious weeks and months of schooling.

Perhaps of greater importance is the Navy's hope that through the release of this course, a direct contribution will be made toward increasing the technical knowledge of men and women throughout the country, as a step in making and keeping America strong.

Van Valkenburgh, Nooger and Neville, Inc.

New York, N. Y.
October, 1954

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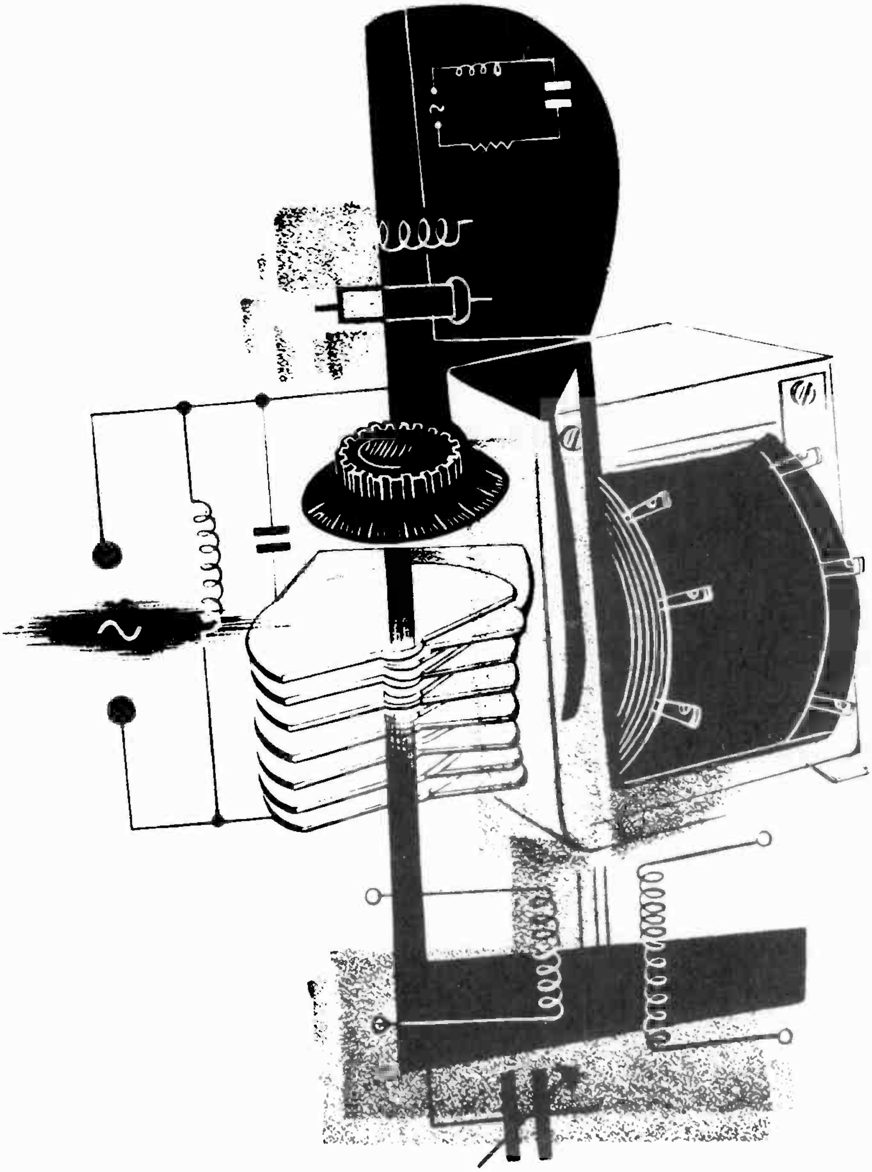


Alternating current circuits

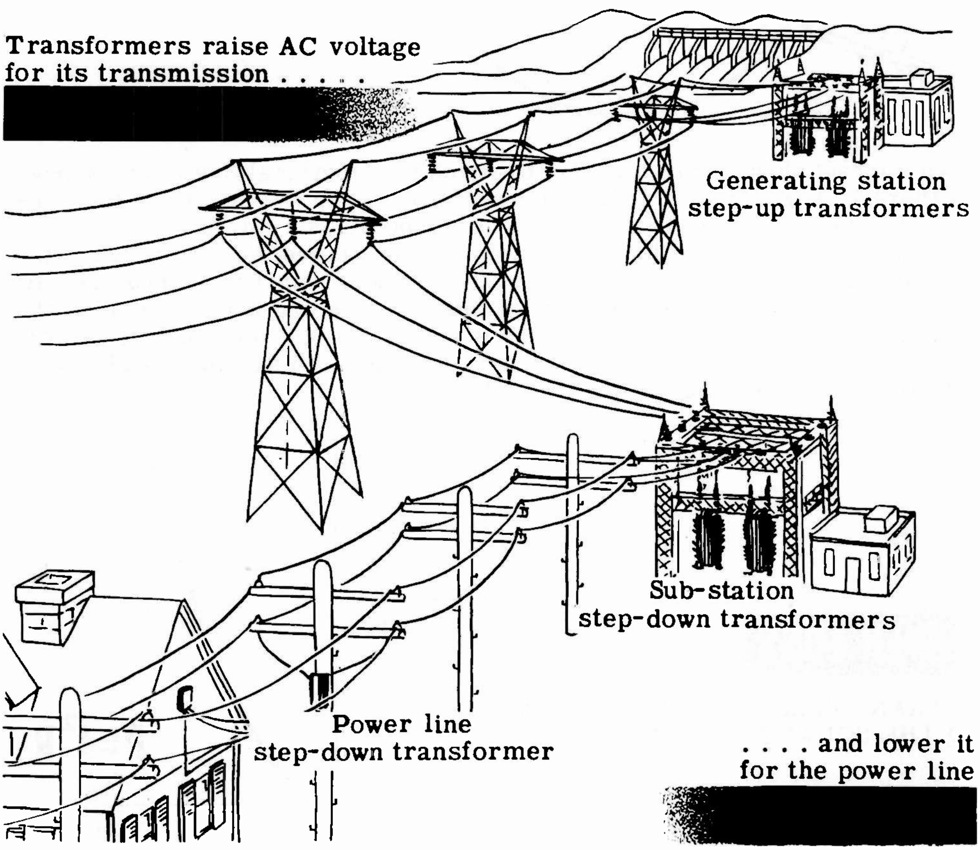
WHAT ALTERNATING CURRENT IS

Alternating Current Power Transmission

As you probably know, most electric power lines carry alternating current. Very little direct current is used for electric lighting and power.

There are many good reasons for this choice of AC over DC for electric power transmission. Alternating current voltage can be increased or decreased easily and without appreciable power loss, through the use of a transformer, while direct current voltages cannot be changed without a considerable power loss. This is a very important factor in the transmission of electric power, since large amounts of power must be transmitted at very high voltages. At the power station the voltage is "stepped up" by transformers to very high voltages and sent over the transmission line; then at the other end of the line, other transformers "step down" the voltage to values which can be used for lighting and power.

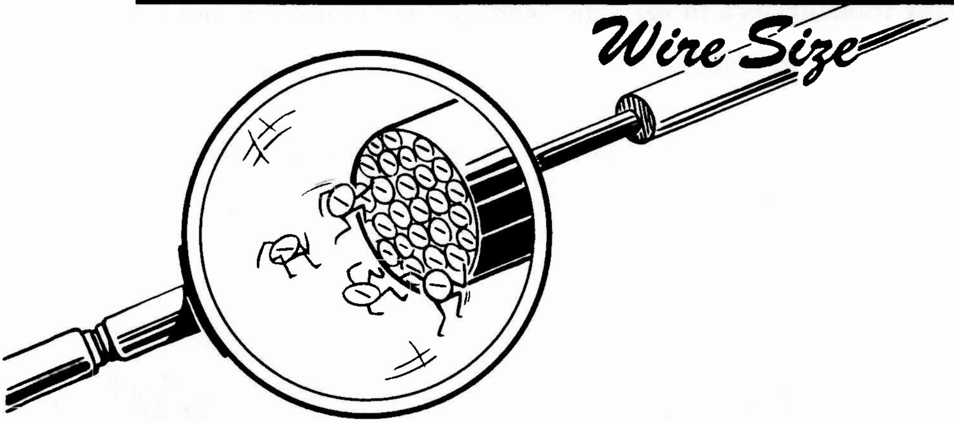
Various kinds of electrical equipment require different voltages for proper operation, and these voltages can easily be obtained by using a transformer and an AC power line. To obtain such voltages from a DC power line requires both a complicated and inefficient circuit.



Alternating Current Power Transmission (continued)

Since the power transmitted equals the voltage multiplied by the current ($P = EI$), and the size of the wire limits the maximum current which can be used, the voltage must be increased if more power is to be transmitted over the same size wires. Also, excessive current flow causes overheating of the wires, resulting in large power loss, so that the maximum current is kept as low as possible. The voltage, however, is limited only by the insulation of the transmission line. Since the insulation can be easily strengthened, the voltage can be increased considerably, permitting the transfer of large amounts of power with smaller wires and much less power load.

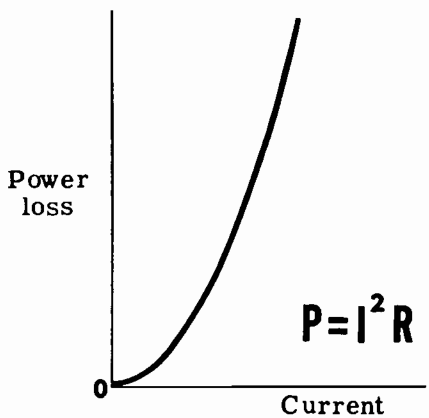
IN POWER TRANSMISSION THE CURRENT IS LIMITED BY



When current flows through a wire to reach the electrical device using power, there is a power loss in the wire proportional to the square of the current ($P = I^2R$). Any reduction in the amount of current flow required to transmit power results in a reduction in the amount of power lost in the transmission line. By using high voltage, lower current is required to transmit a given amount of power. Transformers are needed to raise the voltage for power transmission and lower it for use on electric power lines and, since transformers can only be used with AC, nearly all electric power lines are AC rather than DC.

POWER LOSS

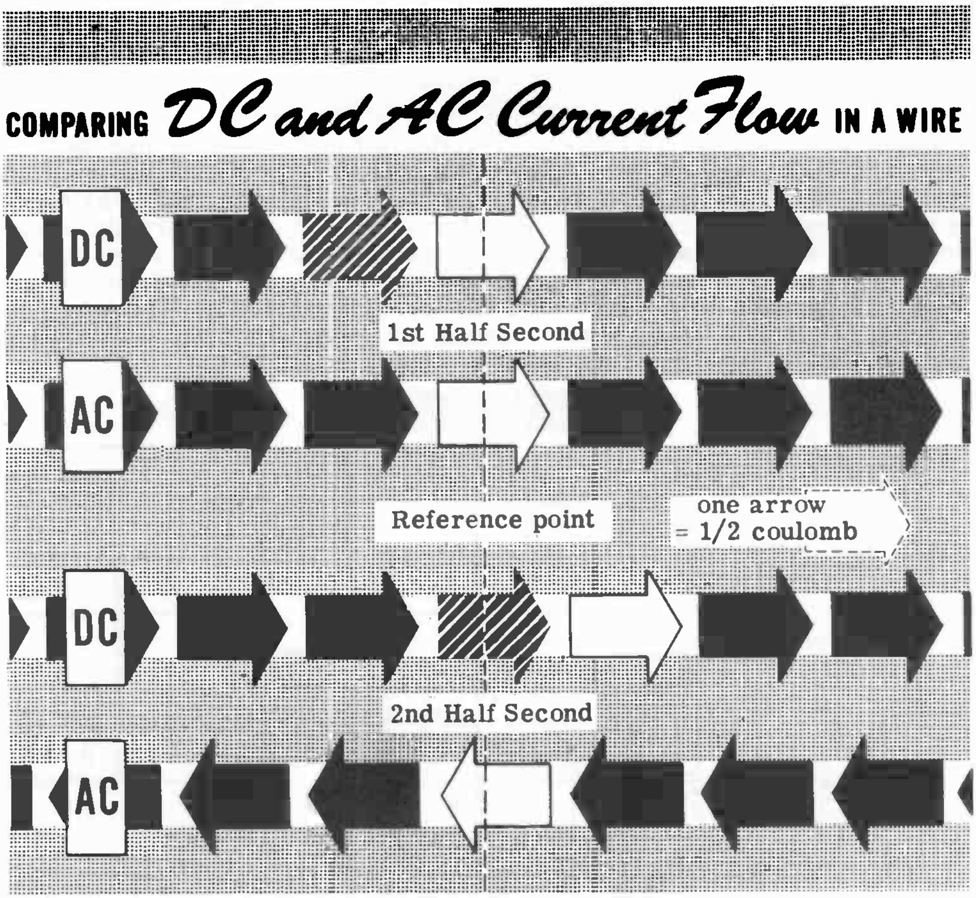
IN TRANSMISSION IS PROPORTIONAL TO THE SQUARE OF THE CURRENT



DC and AC Current Flow

Alternating current—AC—flows back and forth in a wire at regular intervals, going first in one direction and then the other. You know that direct current flows only in one direction, and that current is measured by counting the number of electrons flowing past a point in a circuit in one second.

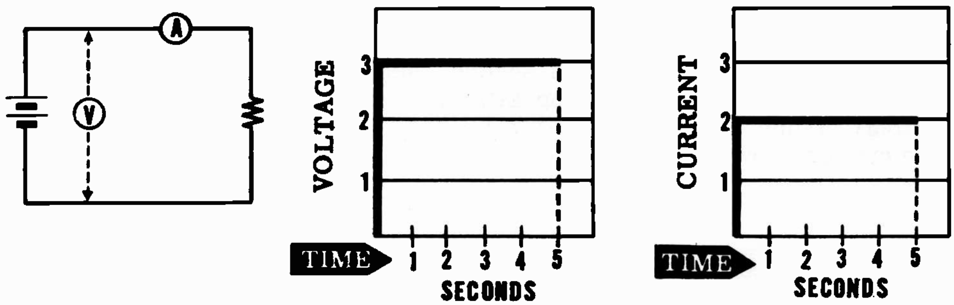
Suppose a coulomb of electrons moves past a point in a wire in one second with all of the electrons moving in the same direction; the current flow then is one ampere DC. If a half coulomb of electrons moves in one direction past a point in a half second, then reverses direction and moves past the same point in the opposite direction during the next half second, a total of one coulomb of electrons passes the point in one second—and the current flow is one ampere AC.



Waveforms

Waveforms are graphical pictures showing how voltages and currents vary over a period of time. The waveforms for direct current are straight lines, since neither the voltage nor current vary for a given circuit. If you connect a resistor across a battery and take measurements of voltage across, and current through, the resistor at regular intervals of time, you find no change in their values. Plotting the values of E and I, each against time, you obtain straight lines—the waveforms of the circuit voltage and current.

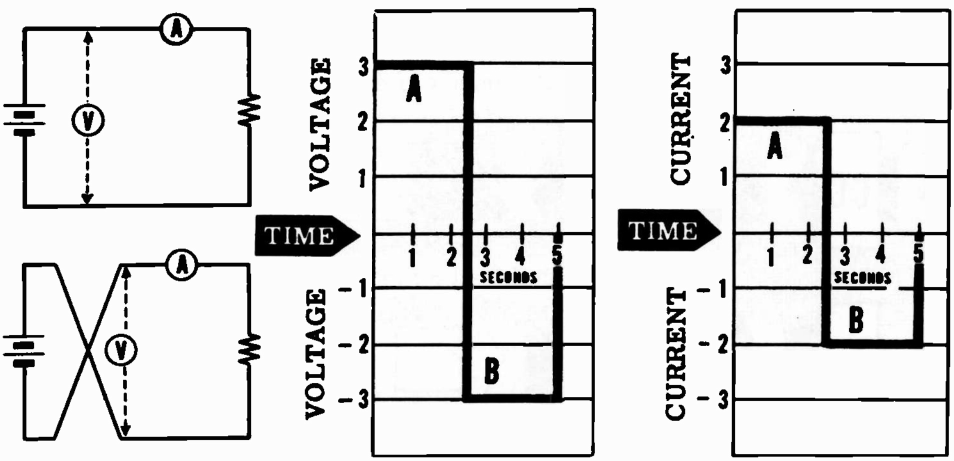
WAVEFORMS ARE PICTURES OF VOLTAGE OR CURRENT VARIATIONS



DC WAVEFORMS

Imagine that you have a zero-center voltmeter and ammeter, and can take readings above and below zero when the polarity of the measured voltage and current is reversed. If you reverse the battery leads while taking the measurements, you find that the waveforms consist of two straight lines—one above and one below zero. By connecting the ends of these lines to form a continuous line, you can obtain the waveforms of voltage and current. These waveforms show that the current and voltage are AC rather than DC, since they indicate the changing direction of the current flow and the reversal in polarity of the voltage.

AC WAVEFORMS

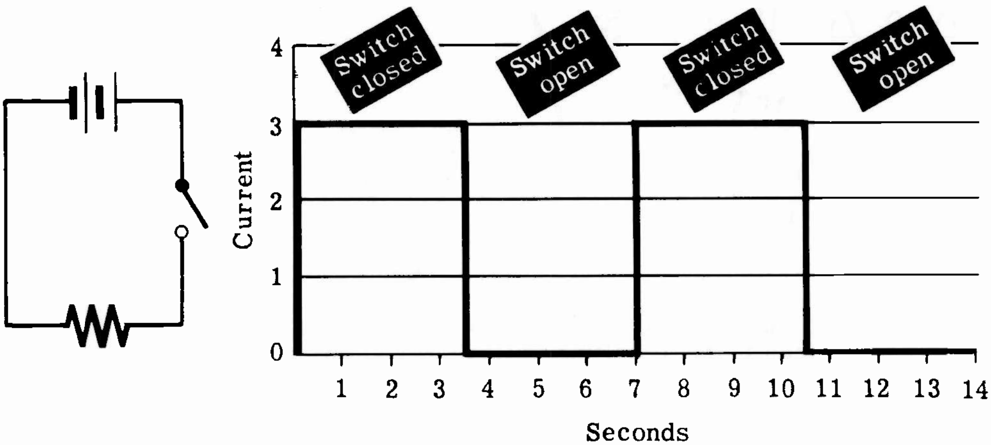


Waveforms (continued)

Another type of waveform is pulsating direct current, which represents variations in voltage and current flow without a change in the direction of current flow. This waveform is common to the DC generator, since the generator output contains a ripple or variation due to commutator action. Battery waveforms do not vary unless the circuit itself changes, such as reversing the battery terminals to obtain an AC waveform.

If, in a circuit consisting of a resistor and a switch connected across a battery, you open and close the switch, causing the current to stop and start but not to reverse direction, the circuit current is pulsating direct current. The waveforms for this pulsating current resemble AC waveforms, but do not go below zero since the current does not change its direction.

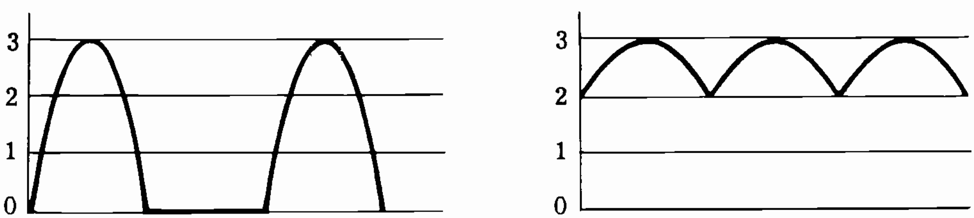
PULSATING DC



Waveforms of voltage and current are not always made of straight lines connecting points. In most cases waveforms are curved, representing gradual changes in voltage and current. This is particularly true of pulsating DC waveforms.

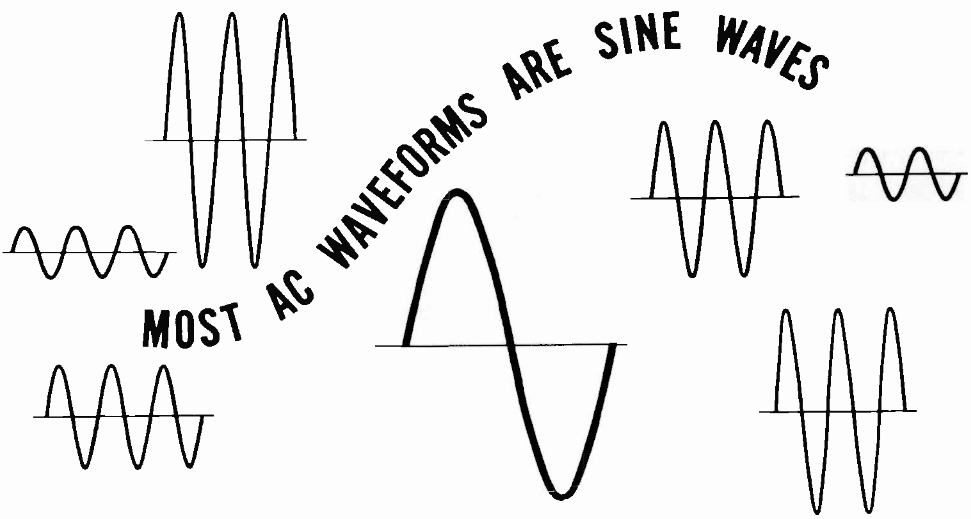
Also, pulsating direct current does not always vary between zero and a maximum value, but may vary over any range between these values. The waveform of a DC generator is pulsating DC and does not fall to zero but, instead, varies only slightly below the maximum value.

OTHER WAVEFORMS OF PULSATING DC.....



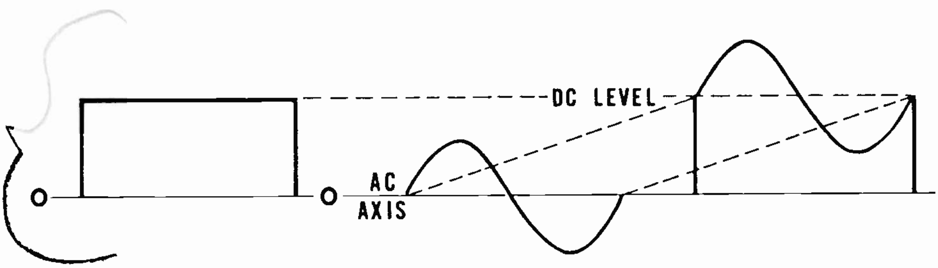
Waveforms (continued)

The waveforms of most alternating currents are curved to represent gradual changes in voltage and current, first increasing then decreasing in value for each direction of current flow. Most of the alternating current which you will use has a waveform represented by a sine curve, which you will find out about a little later. While alternating currents and voltages do not always have waveforms which are exact sine curves, they are normally assumed to have a sine waveform unless otherwise stated.



When direct current and alternating current voltages are both present in the same circuit, the resulting voltage waveform is a combination of the two voltages. The AC wave is added to the DC wave, with the value of the DC voltage becoming the axis from which the AC wave moves in each direction. Thus the maximum point of DC voltage replaces the zero value as the AC waveform axis. The resulting waveform is neither DC nor AC and is called "super-imposed AC," meaning that the AC wave is added to or placed over the DC wave.

When AC and DC are added together, the AC axis shifts, resulting in "Superimposed AC"



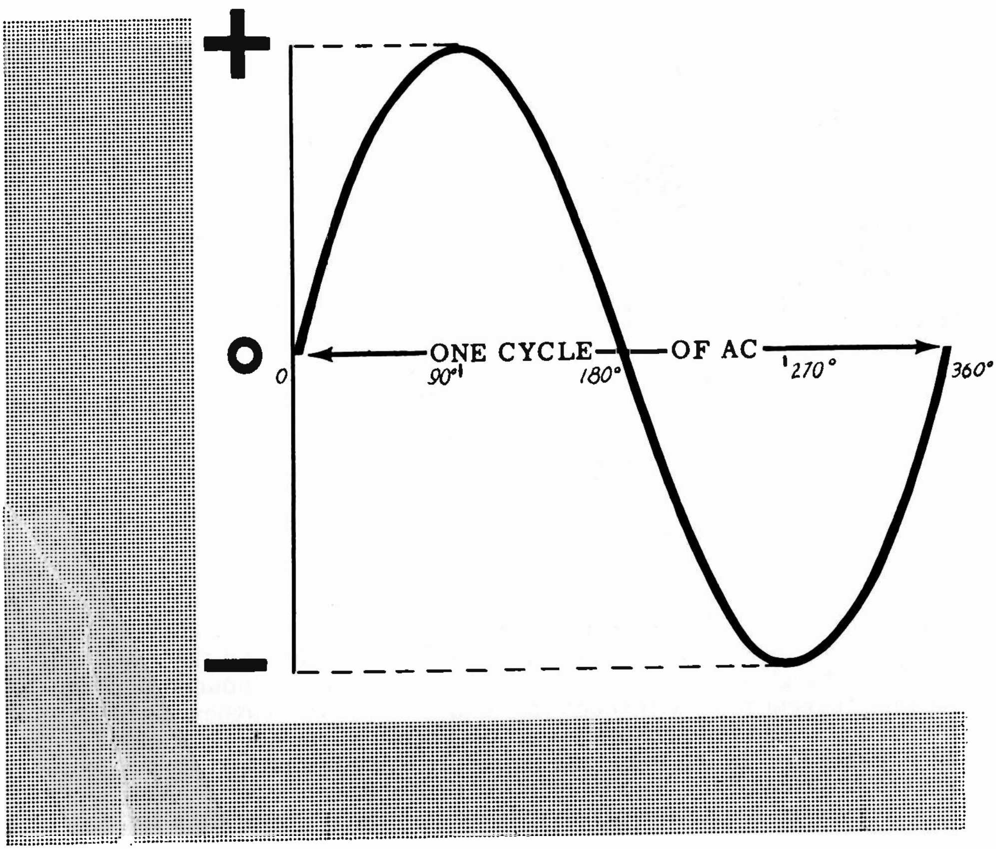
DC waveform + AC waveform = Superimposed AC waveform

Alternating Current Cycles

When the waveform of an AC voltage or current passes through a complete set of positive and negative values, it completes a cycle. AC current first rises to a maximum and falls to zero in one direction, then rises to maximum and falls to zero in the opposite direction. This completes a cycle of AC current and the cycle repeats as long as the current flows. Similarly, AC voltage first rises to a maximum and falls to zero in one polarity, then rises to maximum and falls to zero in the opposite polarity to complete a cycle. Each complete set of both positive and negative values of either voltage or current is a cycle.

On the next sheet you will see that an AC generator consists of a coil of wire rotating in a magnetic field between two opposite magnetic poles, and that each time a side of the coil passes from one pole to the other the current flow generated in the coil reverses its direction. In passing two opposite poles, the current flows first in one direction and then the other, completing a cycle of current flow.

A CYCLE IS A COMPLETE SET OF POSITIVE AND NEGATIVE VALUES

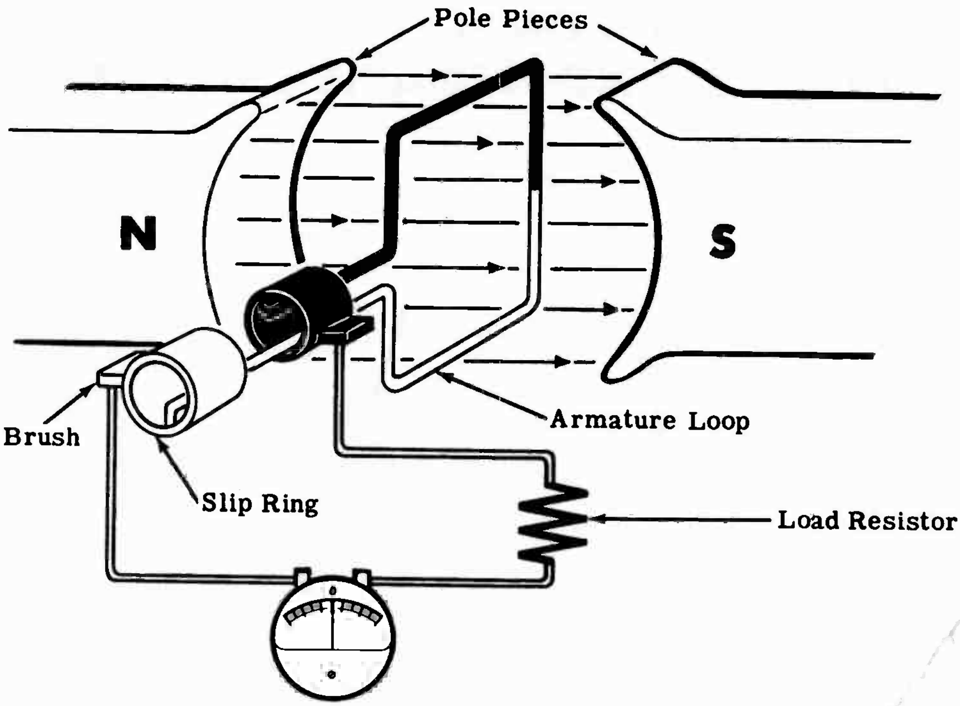


Elementary Generator Construction

An elementary generator consists of a loop of wire placed so that it can be rotated in a stationary magnetic field to cause an induced current in the loop. Sliding contacts are used to connect the loop to an external circuit in order to use the induced current.

The pole pieces are the north and south poles of the magnet which supplies the magnetic field. The loop of wire which rotates through the field is called the "armature." The ends of the armature loop are connected to rings called "slip rings," which rotate with the armature. Brushes ride up against the slip rings to pick up the electricity generated in the armature and carry it to the external circuit.

THE ELEMENTARY GENERATOR



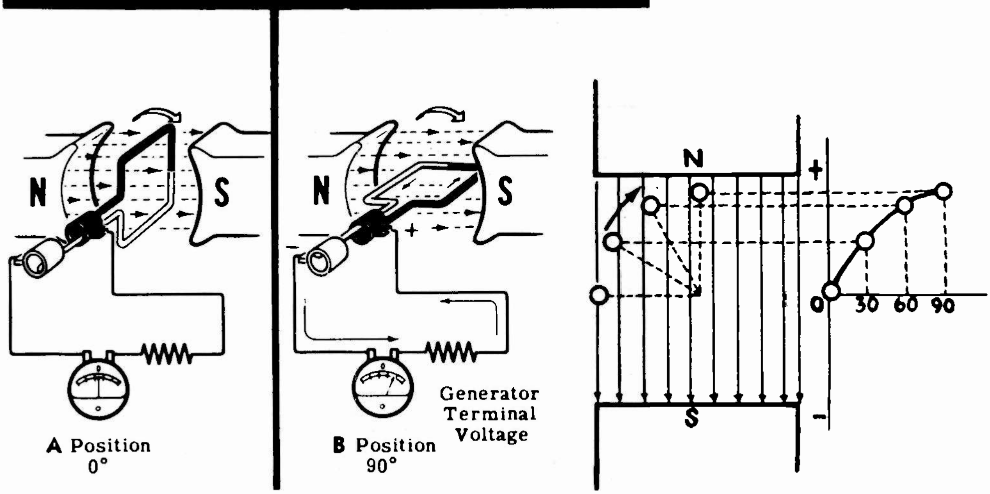
In the description of the generator action as outlined on the following sheets, visualize the loop rotating through the magnetic field. As the sides of the loop cut through the magnetic field, they generate an induced emf which causes a current to flow through the loop, slip rings, brushes, zero-center current meter and load resistor—all connected in series. The induced emf that is generated in the loop, and therefore the current that flows, depends upon the position of the loop in relation to the magnetic field. Now you are going to analyze the action of the loop as it rotates through the field.

Elementary Generator Operation

Here is the way the elementary generator works. Assume that the armature loop is rotating in a clockwise direction, and that its initial position is at A (zero degrees). In position A, the loop is perpendicular to the magnetic field and the black and white conductors of the loop are moving parallel to the magnetic field. If a conductor is moving parallel to a magnetic field, it does not cut through any lines of force and no emf can be generated in the conductor. This applies to the conductors of the loop at the instant they go through position A—no emf is induced in them and, therefore, no current flows through the circuit. The current meter registers zero.

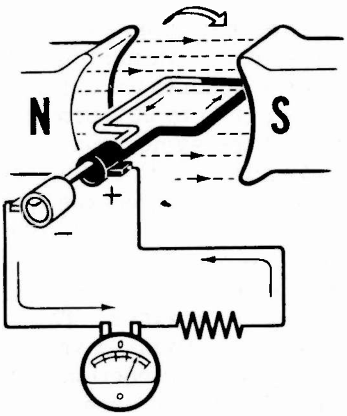
As the loop rotates from position A to position B, the conductors are cutting through more and more lines of force until at 90 degrees (position B) they are cutting through a maximum number of lines of force. In other words, between zero and 90 degrees, the induced emf in the conductors builds up from zero to a maximum value. Observe that from zero to 90 degrees the black conductor cuts down through the field while at the same time the white conductor cuts up through the field. The induced emfs in both conductors are therefore in series-adding, and the resultant voltage across the brushes (the terminal voltage) is the sum of the two induced emfs, or double that of one conductor since the induced voltages are equal to each other. The current through the circuit will vary just as the induced emf varies—being zero at zero degrees and rising up to a maximum at 90 degrees. The current meter deflects increasingly to the right between positions A and B, indicating that the current through the load is flowing in the direction shown. The direction of current flow and polarity of the induced emf depend on the direction of the magnetic field and the direction of rotation of the armature loop. The waveform shows how the terminal voltage of the elementary generator varies from position A to position B. The simple generator drawing on the right is shown shifted in position to illustrate the relationship between the loop position and the generated waveform.

HOW THE ELEMENTARY GENERATOR WORKS

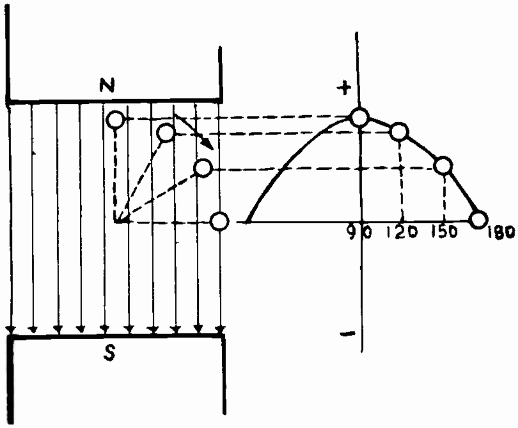


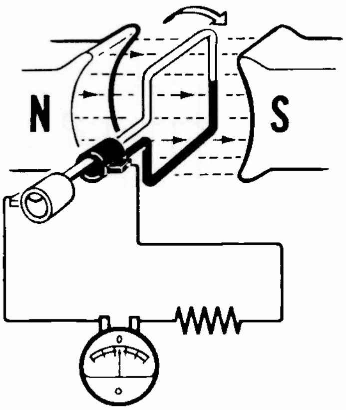
Elementary Generator Operation (continued)

As the loop continues rotating from position B (90 degrees) to position C (180 degrees), the conductors which are cutting through a maximum number of lines of force at position B cut through fewer lines, until at position C they are moving parallel to the magnetic field and no longer cut through any lines of force. The induced emf therefore will decrease from 90 to 180 degrees in the same manner as it increased from zero to 90 degrees. The current flow will similarly follow the voltage variations. The generator action at positions B and C is illustrated.



B Position
90°

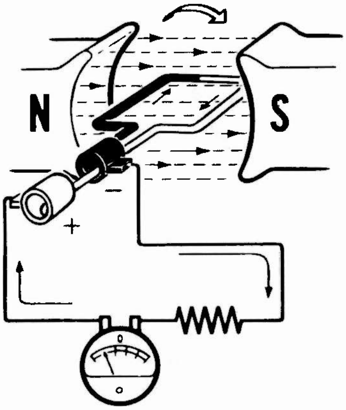




C Position
180°

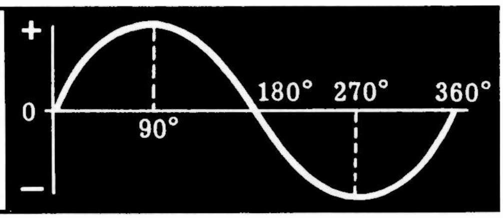
Elementary Generator Operation (continued)

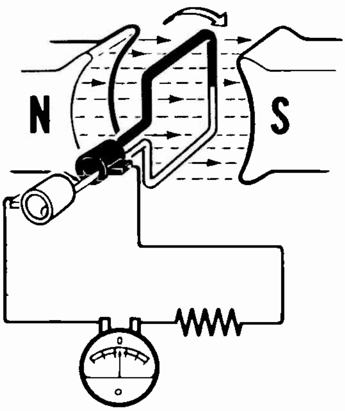
From zero to 180 degrees the conductors of the loop have been moving in the same direction through the magnetic field and, therefore, the polarity of the induced emf has remained the same. As the loop starts rotating beyond 180 degrees back to position A, the direction of the cutting action of the conductors through the magnetic field reverses. Now the black conductor cuts up through the field, and the white conductor cuts down through the field. As a result, the polarity of the induced emf and the current flow will reverse. From positions C through D back to position A, the current flow will be in the opposite direction than from positions A through C. The generator terminal voltage will be the same as it was from A to C except for its reversed polarity. The voltage output waveform for the complete revolution of the loop is as shown.



D Position
270°

Generator Terminal Voltage

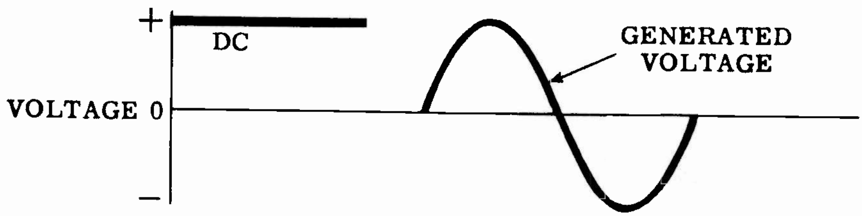




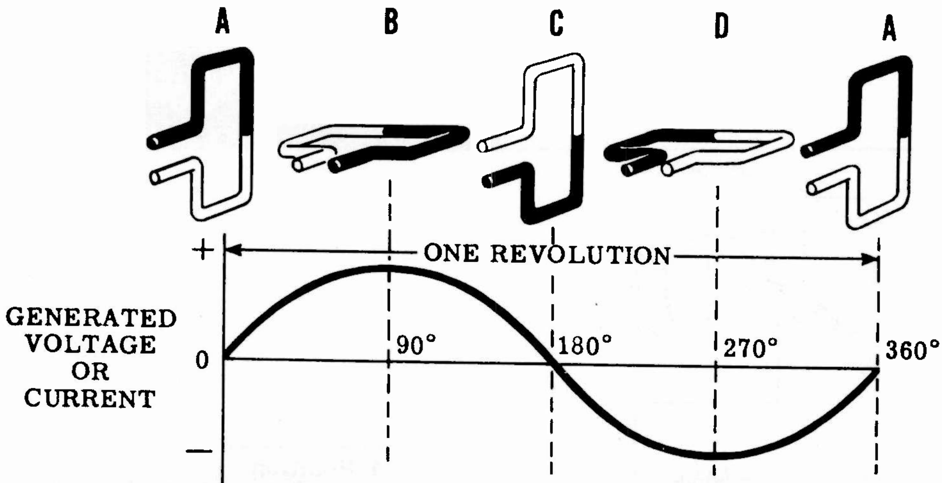
A Position
360°

Elementary Generator Output

Suppose you take a closer look at the output waveform of the elementary generator and study it for a moment. How does it compare to the voltages with which you have been dealing up to this time? The only voltages you have used so far are DC voltages like those obtained from a battery. A DC voltage can be represented as a straight line whose distance above the zero reference line depends upon its value. The diagram shows the DC voltage next to the voltage waveform put out by the elementary AC generator. You see the generated waveform does not remain constant in value and direction, as does the DC curve. In fact, the generated curve varies continuously in value and is as much negative as it is positive.



The generated voltage is therefore not DC voltage, since a DC voltage is defined as a voltage which maintains the same polarity output at all times. The generated voltage is called an "alternating voltage," since it alternates periodically from plus to minus. It is commonly referred to as an AC voltage—the same type of voltage that you get from the AC wall socket. The current that flows, since it varies as the voltage varies, must also be alternating. The current is also referred to as AC current. AC current is always associated with AC voltage—an AC voltage will always cause an AC current to flow.



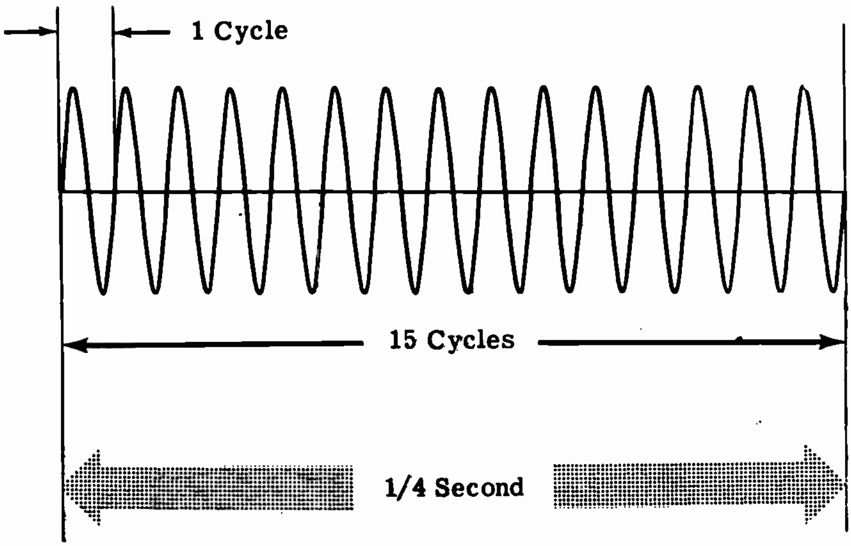
the AC waveform

Alternating Current Frequency

When the armature of an AC generator is rotating, the faster the armature coil turns past the magnetic poles the more often the current reverses each second. Therefore it completes more cycles per second, since each current reversal ends a half cycle of current flow. The number of cycles per second is "frequency."

Alternating current frequency is important to understand, since most AC electrical equipment requires a specific frequency as well as a specific voltage and current for proper operation. The standard commercial frequency used in this country is 60 cycles per second. Lower frequencies cause flicker when used for lighting, since each time the current changes direction it falls to zero—turning an electric lamp off momentarily. With 60 cycles, the lamp turns on and off 120 times each second; however, no flicker is noticeable since the eye cannot react fast enough to see the light turn off.

FREQUENCY IS THE NUMBER OF CYCLES PER SECOND

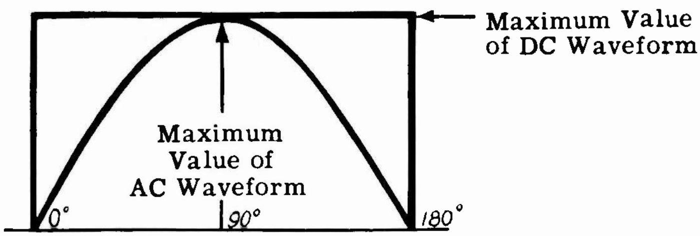


If 15 cycles are completed in 1/4 second, the frequency is 60 cycles per second.

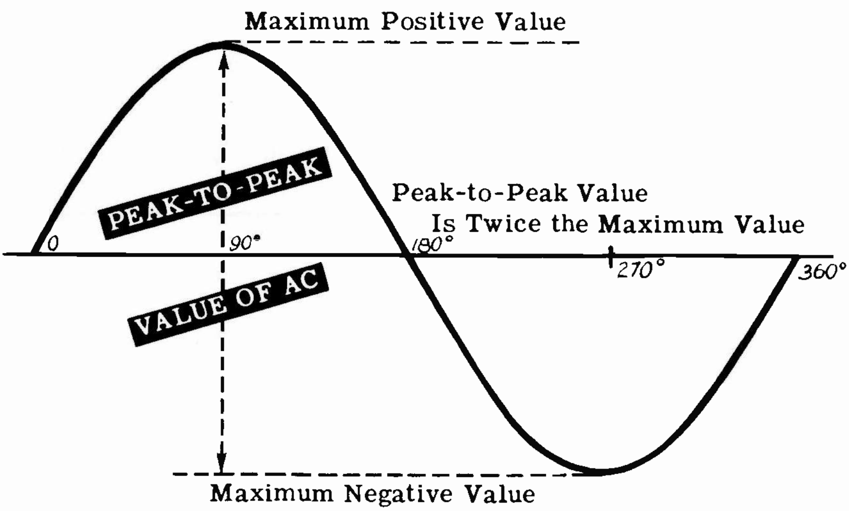
Maximum and Peak-to-Peak Values of a Sine Wave

Suppose you compare a half cycle of an AC sine wave to a DC waveform for the same length of time. If the DC starts and stops at the same moment as the half-cycle sine wave and each rises to the same maximum value, the DC values are greater than the corresponding AC values at all points except the pointat which the AC sine wave passes through its maximum value. At this point the DC and AC values are equal. This point on the sine wave is the maximum or peak value.

COMPARISON of DC and AC WAVEFORMS



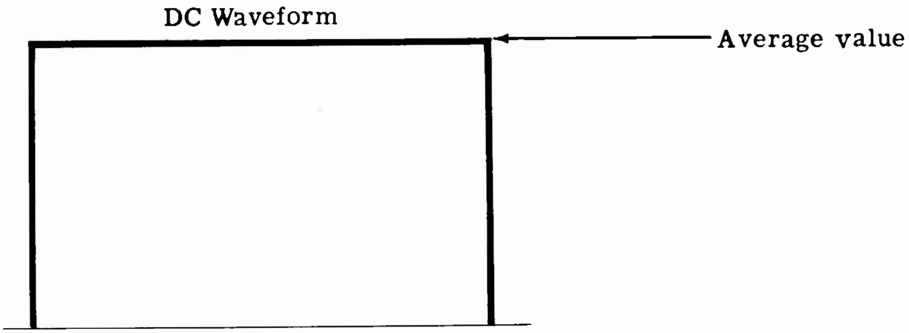
For each complete cycle of AC there are two maximum or peak values, one for the positive half cycle and the other for the negative half cycle. The difference between the peak positive value and the peak negative value is called the peak-to-peak value of a sine wave. This value is twice the maximum or peak value of the sine wave and is sometimes used for measurement of AC voltages. An oscilloscope and certain types of AC voltmeters measure peak-to-peak values of AC voltages at the input and output of radio amplifiers, phonograph amplifiers, etc.; but usually AC voltages and currents are expressed in effective values (a term you will find out about later), rather than peak-to-peak values.



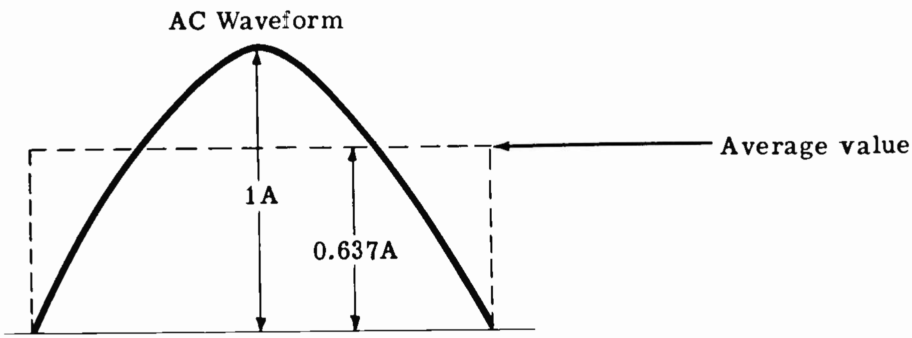
Average Value of a Sine Wave

In comparing a half-cycle AC sine wave to a DC waveform you found that the AC instantaneous values are all less than the DC value except at the peak value of the sine wave. Since all points of the DC waveform are equal to the maximum value, this value is also the average value of the DC wave. The average value of a half cycle of the AC sine wave is less than the peak value, since all but one point on the waveform are lower in value. For all sine waves, the average value of a half cycle is 0.637 of the maximum or peak value. This value is obtained by averaging all the instantaneous values of the sine wave (for a half cycle). Since the shape of the sine wave does not change, even though its maximum value changes, the average value of any sine wave is always 0.637 of the peak value.

AVERAGE VALUES OF WAVEFORMS



DC average value equals maximum value



AC average value equals 0.637 maximum value

While an AC sine wave with a maximum value of 1 ampere has an average value of 0.637 ampere for each half cycle, the power effect of a 1-ampere AC current is not the same as that of a 0.637-ampere DC current. For this reason, average values of AC current and voltage waves are not often used.

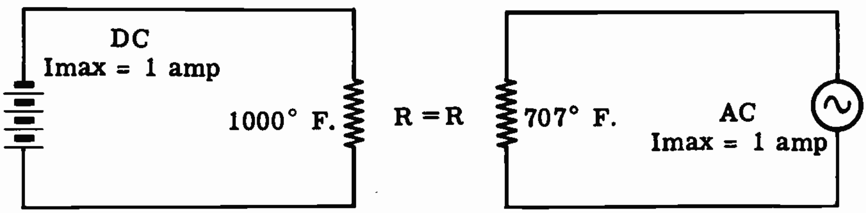
Effective Value of a Sine Wave

If a direct current flows through a resistance, the resulting energy converted into heat equals I^2R, or E^2/R in watts. An alternating current with a maximum value of 1 ampere, for instance, is not expected to produce as much heat as a direct current of 1 ampere, as alternating current does not maintain a constant value.

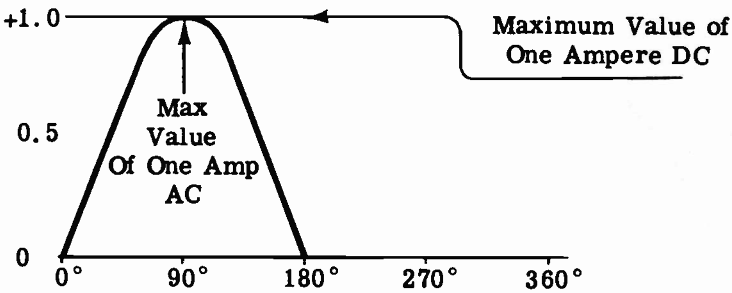
The rate at which heat is produced in a resistance forms a convenient basis for establishing an effective value of alternating current, and is known as the "heating effect" method.

An alternating current is said to have an effective value of one ampere when it will produce heat in a given resistance at the same rate as does one ampere of direct current.

HEATING EFFECT OF ONE AMPERE OF DC AND AC



DC AND AC MAXIMUM WAVEFORM



$$\text{AC } I_{EFF} = \frac{\text{The Heating Effect Of 1 Maximum AC Ampere}}{\text{The Heating Effect Of 1 Maximum DC Ampere}}$$

$$\text{AC } I_{EFF} = \frac{707^\circ \text{ F}}{1000^\circ \text{ F}} \qquad \text{AC } I_{EFF} = .707$$

RMS

WHAT ALTERNATING CURRENT IS

Root mea

Effective Value of a Sine Wave (continued)

The effective value of a sine wave of current may be computed to a fair degree of accuracy by taking equally spaced instantaneous values and extracting the square root of their average, squared values.

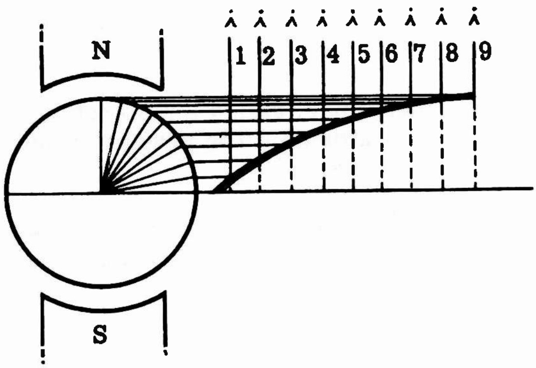
For this reason, the effective value is often called the "root-mean-square" (rms) value.

By this method or by means of higher mathematics it may be shown that the effective value (I) of any sine-wave current is always 0.707 times the maximum value (Imax).

Since alternating currents are caused to flow by alternating emf's, the ratio between effective and maximum values of emf's is the same as for currents. The effective, or rms, value (E) of a sine-wave emf is 0.707 times the maximum value (Emax).

When an alternating current or voltage is specified, it is always the effective value that is meant unless there is a definite statement to the contrary. It should be noted that all meters, unless marked to the contrary, read effective values of current and voltage.

EFFECTIVE VALUE OF A SINE WAVE



EFFective Value (RMS)

$$I_{EFF} = \sqrt{\text{Average of the Sum of the Squares of } I_{ins}}$$

$I_{EFF} = 0.707 \times I_{max}$ $\qquad$ $I_{max} = 1.414 \times I_{EFF}$

Transformers

Electrical energy requires a convenient means for conversion, and for transfer from circuit to circuit. A device called a transformer is ideally suited for these purposes. Transformers change voltages from one level to another as needed, and transfer energy from one circuit to another with great efficiency.

Transformers are generally composed of two coils placed close to each other but not connected together. The coil which receives energy from the line voltage source, etc., is called the "primary" and the coil which delivers energy to a load is called the "secondary." Even though the coils are not physically connected together they manage to convert and transfer energy as required. This action is complex and is explained in detail later.

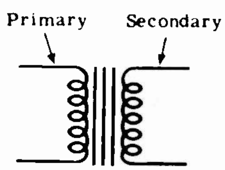
Some transformers take a high input voltage at the primary and deliver a low output voltage at the secondary. These are called "step-down" transformers. On the other hand, "step-up" transformers take a low input voltage at the primary and deliver a high output voltage at the secondary. The transformer used in the demonstration on the following sheets is of the step-down variety because it takes 117-volts, AC, at the primary and delivers 6.3-volts, AC, from the secondary as shown below.

One variation in the transformer family is found in a device called the autotransformer. This device uses only one coil to do all the work. There are two input ("primary") leads and at least two output ("secondary") leads. The primary and secondary leads are attached to, or tapped off, the same coil; the extent to which the input voltage is changed is determined by the points at which the secondary leads are attached. These devices deliver step-up and step-down voltage—just as transformers do.

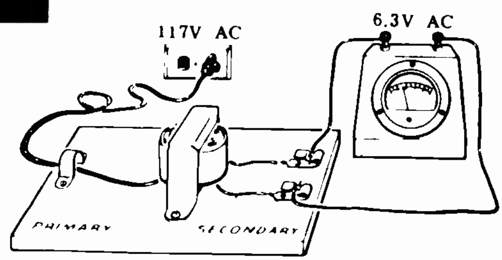
One type of variable transformer, called a powerstat, is sometimes used as a voltage source in laboratories. The powerstat permits the instructor to make voltage settings as desired

In some schools you may not use the transformer shown below at all but will use a powerstat instead for all demonstrations described in this section.

MEASURING THE TRANSFORMER'S SECONDARY VOLTAGE



Transformer Symbol

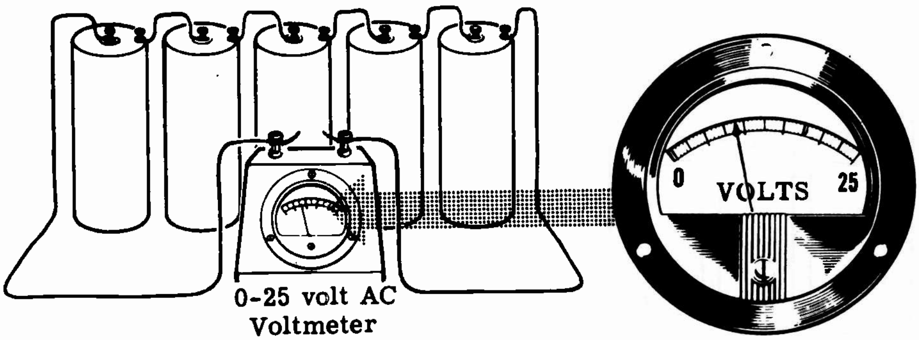


Demonstration—AC Voltmeter

Although calibrated to read the effective value of AC voltages, AC voltmeters can also be used to measure the approximate value of a DC voltage. To show how the effective value of an AC voltage compares to a DC voltage, the instructor uses an AC voltmeter to measure both the DC voltage of a 7.5-volt battery and the effective AC voltage output of a 6.3-volt transformer.

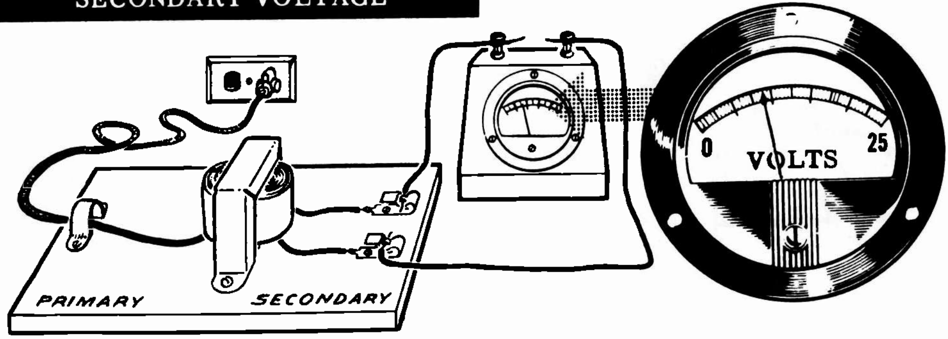
Five dry cells are connected to form a 7.5-volt battery, and the 0-25 volt AC voltmeter is used to measure the voltage across the battery terminals. You see that the meter reading is approximately 7.5 volts, but the reading is not as accurate as it would be if a DC voltmeter were used.

MEASURING A BATTERY VOLTAGE WITH AN AC VOLTMETER



Next, the instructor connects the 117-volt primary lead of the transformer across the AC power line. The voltage across the secondary leads is then measured with the AC voltmeter, and you see that it is approximately 7.5 volts. Although the transformer is rated at 6.3 volts AC, the secondary voltage will always be higher than its rated value when the transformer is not furnishing power. The size of the load determines the exact value of the secondary voltage. In comparing the measured voltages —7.5 volts DC and 7.5 volts AC—you find that the two meter readings are nearly the same. Some difference in the readings should be expected, as the AC voltage is approximately 7.5 volts effective while the DC voltage is exactly 7.5 volts.

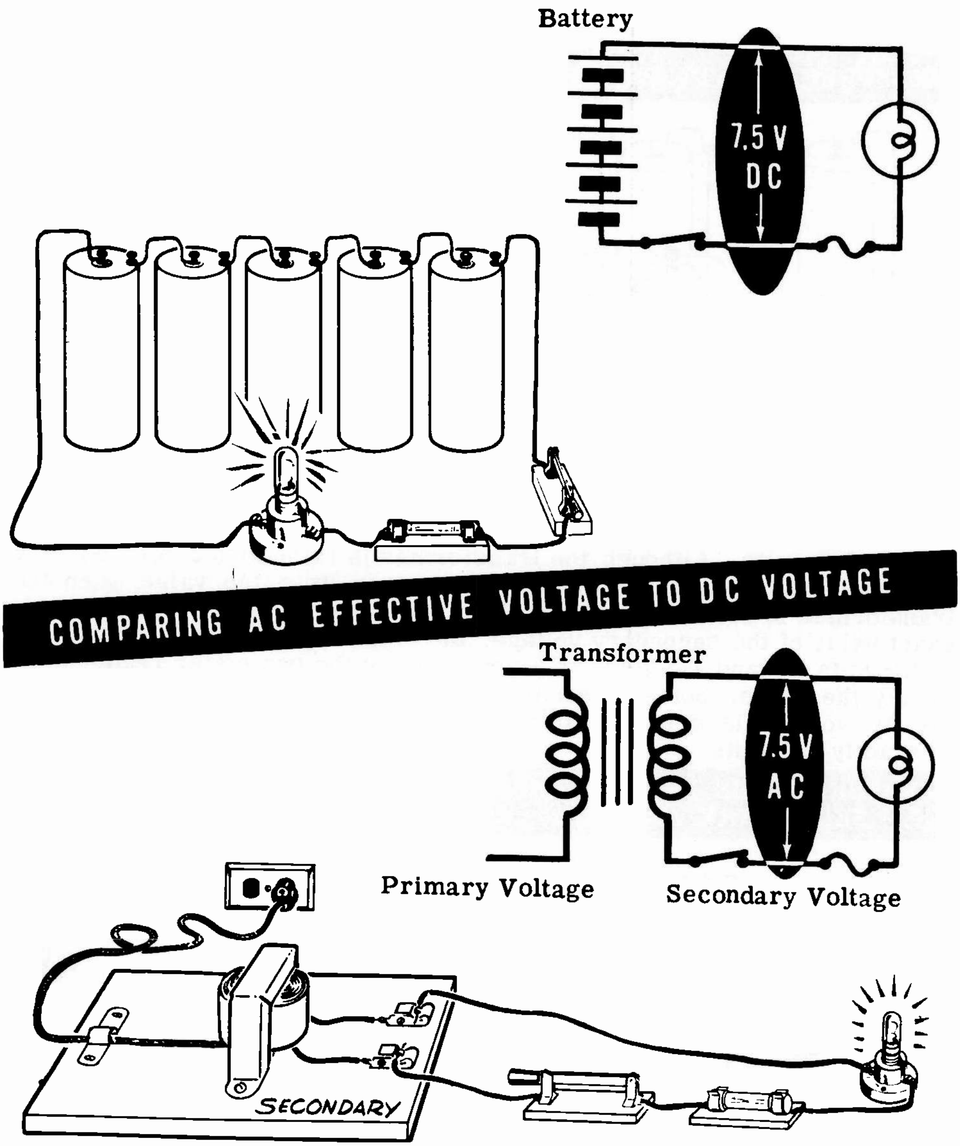
MEASURING THE TRANSFORMER'S SECONDARY VOLTAGE



Demonstration—Effective Value of AC Voltage

To show that the 7.5 volts effective AC has the same effect as 7.5 volts DC, the 7.5-volt battery and the 6.3-volt transformer are each used to light the same type of lamp. Although the transformer is furnishing power, the load is light enough so that for all practical purposes the effective AC voltage can be assumed to be 7.5 volts.

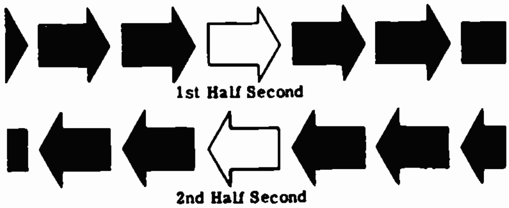
One lamp socket is connected across the battery and another is connected across the secondary leads of the transformer. The instructor then inserts identical lamps in each socket, and you see that the brightness of the two lamps is the same. This shows that the power effect of the two voltages is the same.



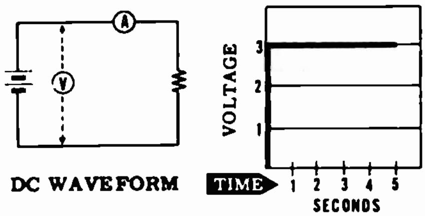
Review of Alternating Current

Alternating current differs from direct current not only in its waveform and electron movement but also in the way it reacts in electrical circuits. Before finding out how it reacts in circuits you should review what you have already found out about AC and the sine wave.

ALTERNATING CURRENT — Current flow which is constantly changing in amplitude, and reverses its direction at regular intervals.

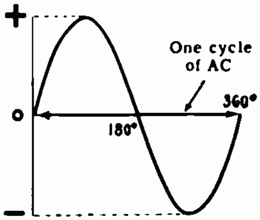


WAVEFORM — A graphical picture of voltage or current variations over a period of time.

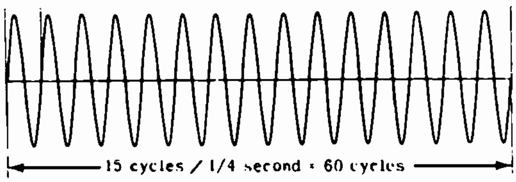


SINE WAVE — A continuous curve of all the instantaneous values of an AC current or voltage.

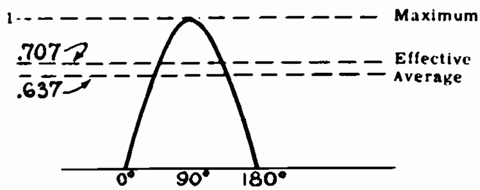
CYCLE — A complete set of positive and negative values of an AC current or voltage wave.



FREQUENCY — The number of cycles per second.



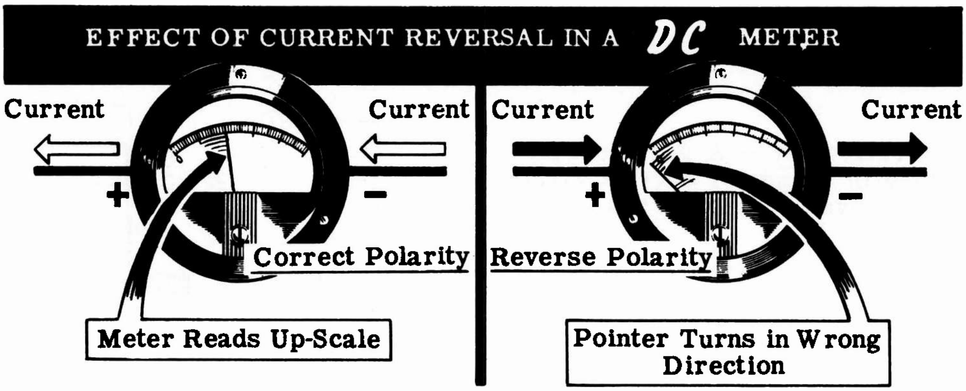
MAXIMUM, EFFECTIVE, AND AVERAGE VALUES of a sine wave.



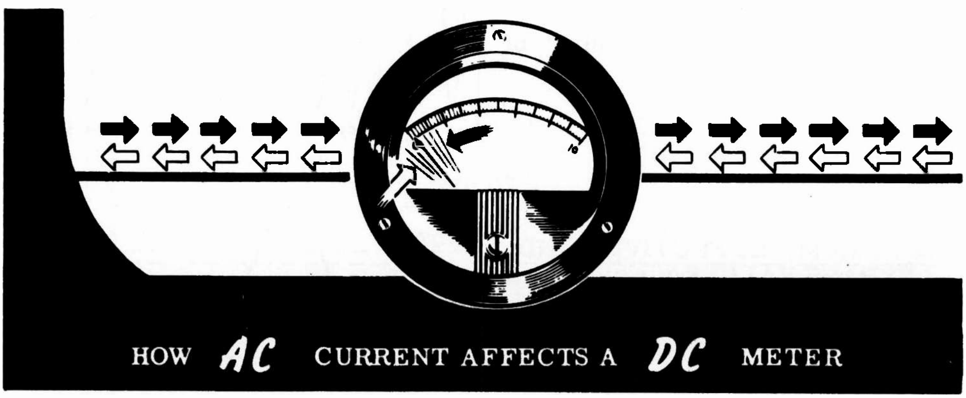
Why DC Meters Cannot Measure AC

There are noticeable differences, particularly in the scales, between DC and AC voltmeters. There is also a basic difference in the meter movements themselves.

DC meters use a basic moving-coil meter movement in which the moving coil is suspended in the magnetic field between the poles of a permanent magnet. Current flow through the coil in the correct direction (polarity) causes the coil to turn, moving the meter pointer up-scale. However, you will recall that a reversal of polarity causes the moving coil to turn in the opposite direction, moving the meter pointer down below zero.

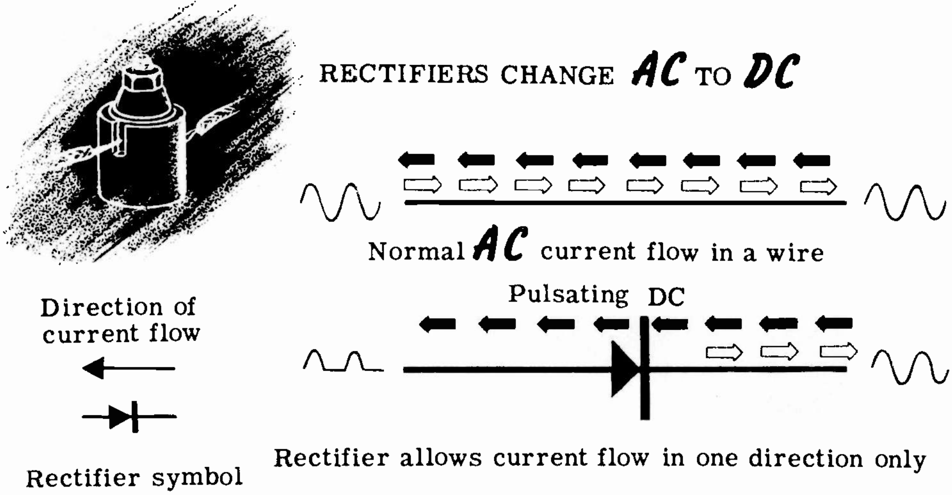


If an AC current were passed through a basic DC meter movement, the moving coil would turn in one direction for a half cycle, then—as the current reversed direction—the moving coil would turn in the opposite direction. For ordinary 60 cycles the pointer would be unable to follow the reversal in current fast enough, and the pointer would vibrate back and forth at zero, the average position of the AC wave. The greater the current flow the further the pointer would attempt to swing back and forth and, in a short time, the excess vibration would break the needle. Even if the pointer could move back and forth fast enough, the speed of movement would be so great that you could not obtain a meter reading.

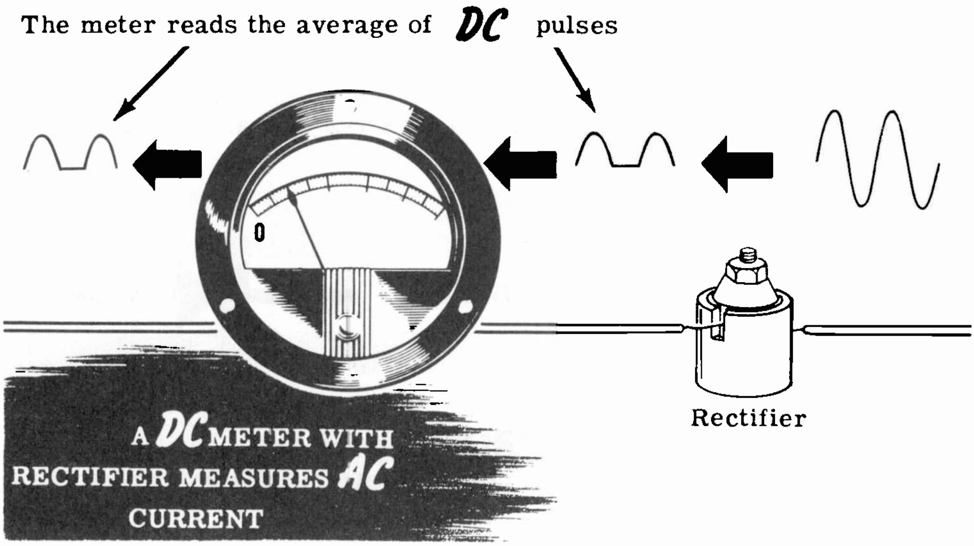


Rectifier Type AC Voltmeters

A basic DC meter movement may be used to measure AC through the use of a rectifier—a device which changes AC to DC. The rectifier permits current flow in only one direction so that, when AC tries to flow through it, current only flows for a half of each complete cycle. The effect of such a rectifier on AC current flow is illustrated below.

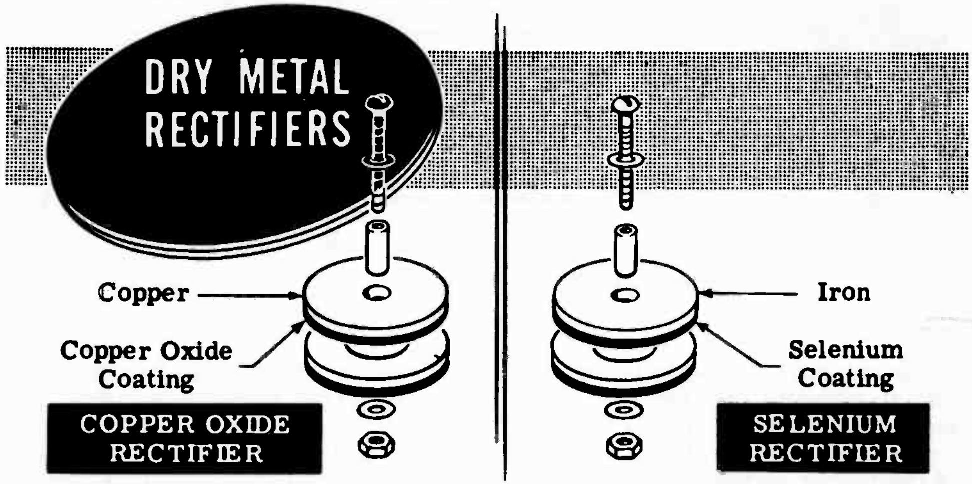


If the rectifier is connected in series with a basic DC meter movement so that it permits current flow only in the direction necessary for correct meter polarity, the meter current flows in pulses. Since these pulses of current are all in the same direction, each causes an up-scale deflection of the meter pointer. The pointer cannot move rapidly enough to return to zero between pulses, so that it continuously indicates the average value of the current pulses.

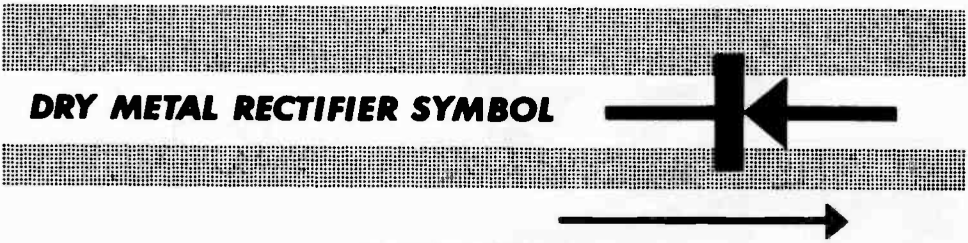


Rectifier Type AC Voltmeters (continued)

When certain metallic materials are pressed together to form a junction, the combination acts as a rectifier having a low resistance to current flow in one direction and a very high resistance to current flow in the opposite direction. This action is due to the chemical properties of the combined materials. The combinations usually used as rectifiers are copper and copper oxide, or iron and selenium. Dry metal rectifiers are constructed of disks ranging in size from less than a half inch to more than six inches in diameter. Copper-oxide rectifiers consist of disks of copper coated on one side with a layer of copper oxide while selenium rectifiers are constructed of iron disks coated on one side with selenium.



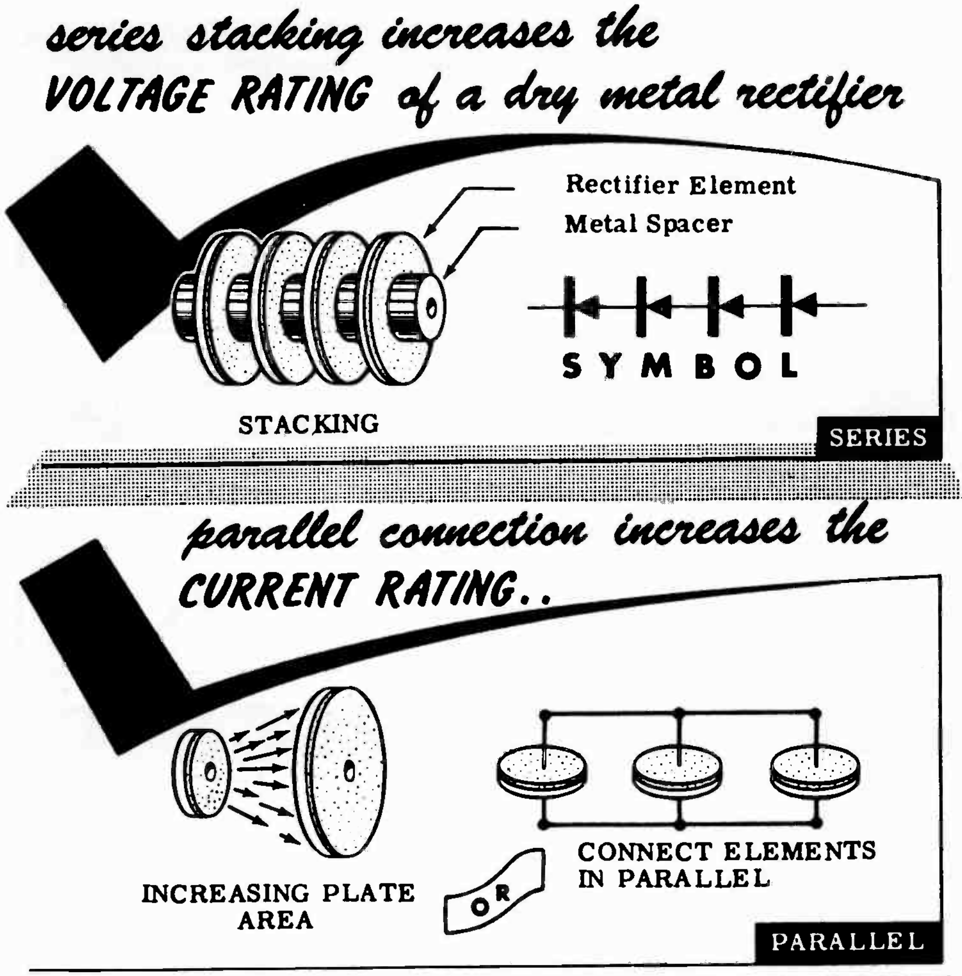
Dry metal rectifier elements (an element is a single disk) are generally made in the form of washers which are assembled on a mounting bolt,in any desired series or parallel combination,to form a rectifier unit. The symbol shown below is used to represent a dry metal rectifier of any type. Since these rectifiers were made before the electron theory was used to determine the direction of current flow, the arrow points in the direction of conventional current flow but in the direction opposite to the electron flow. Thus the arrow points in opposite direction to that of the current flow as used in electronics.



ELECTRON current flow
opposite direction from symbol arrow

Rectifier Type AC Voltmeters (continued)

Each dry metal rectifier element will stand only a few volts across its terminals but by stacking several elements in series the voltage rating is increased. Similarly each element can pass only a limited amount of current. When greater current is desired several series stacks are connected in parallel to provide the desired amount of current.



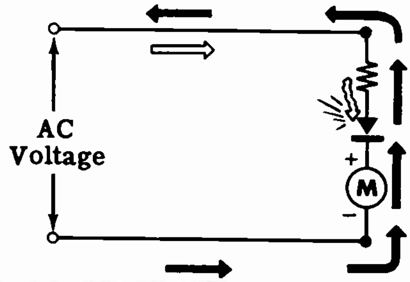
Dry metal rectifiers are very rugged and have an almost unlimited life if not abused. Because of the low voltage rating of individual units they are normally used for low voltages (130 volts or less) since it becomes impractical to connect too many elements in series. By paralleling stacks or increasing the diameter of the disks, the current rating can be increased to several amperes so that they are often used for low-voltage-high-current applications. Very small units are used to measure AC voltage on a DC voltmeter. Larger units are used in battery chargers and various types of power supplies for electronic equipment.

Rectifier Type AC Voltmeters (continued)

Rectifier type AC meters are only used as voltmeters and the meter range is determined and changed in the same manner as that of a DC voltmeter. They cannot be used for current measurement, since ammeters are connected in series with the line current and a rectifier type meter so connected would change the AC circuit current to DC, which is not desirable. Various AC rectifier type meter circuits are illustrated below:

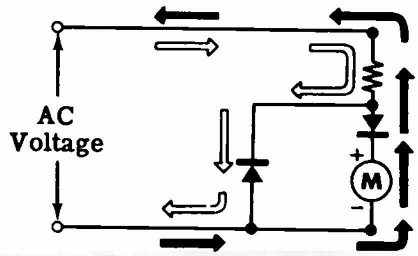
SIMPLE METER RECTIFIER CIRCUIT ....

1. A simple meter rectifier circuit consists of a multiplier, rectifier and basic meter movement connected in series. For one half cycle, current flows through the meter circuit. During the next half cycle, no current flows, although a voltage exists across the circuit including the rectifier.



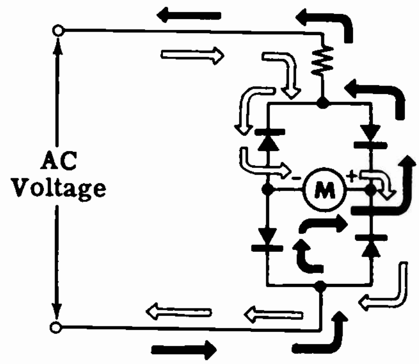
ADDING A RECTIFIER TO THE SIMPLE METER CIRCUIT

2. To provide a return path for the AC current half-cycle pulses not used to operate the meter movement, an additional rectifier is connected across the meter rectifier and meter movement. The unused pulses flow through this branch—not through the meter.



BRIDGE RECTIFIER CIRCUIT ....

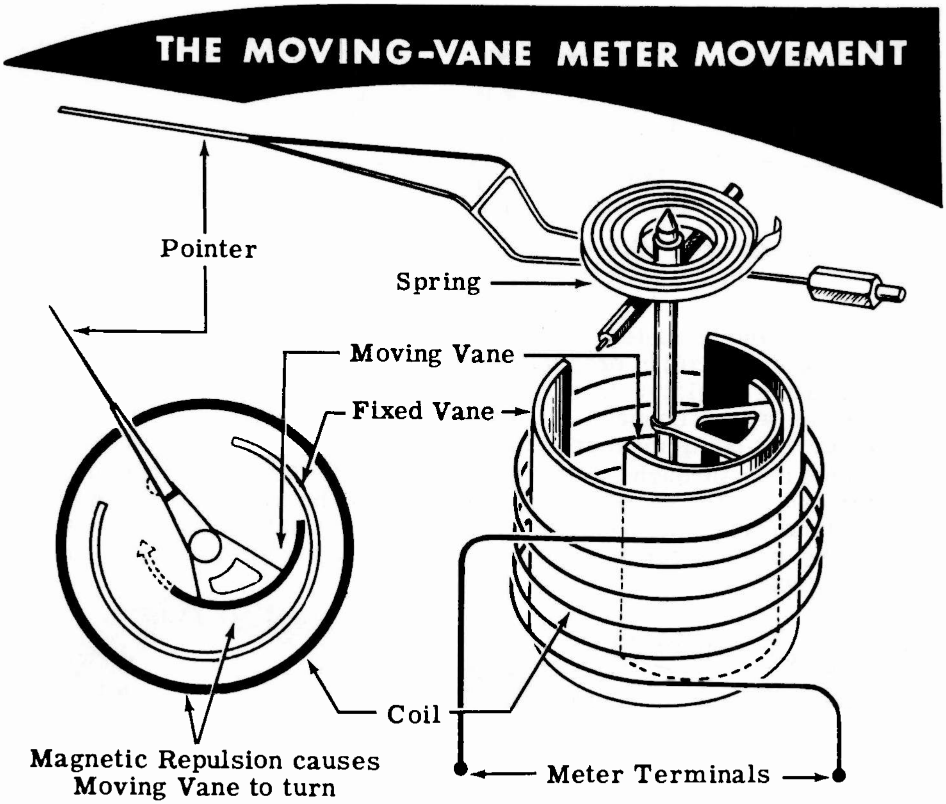
3. A bridge circuit using four rectifiers is sometimes used. It is so connected that both halves of the AC current wave must follow paths that lead through the meter in the same direction. Thus, the number of current pulses flowing through the meter movement is doubled.



Because the meter reading is the average of the half-cycle current pulses, the scale is not the same as that used for DC. Although the amount of deflection is a result of average current flow through the meter movement, the scale is calibrated to read effective values of voltage.

Moving-Vane Meter Movements

A meter which you can use to measure both AC current and voltage is the moving-vane meter movement. The moving-vane meter operates on the principle of magnetic repulsion between like poles. The current to be measured flows through a field coil producing a magnetic field proportional to the strength of the current. Suspended in this field are two iron vanes—one fixed in position, the other movable and attached to the meter pointer. The magnetic field magnetizes these iron vanes with the same polarity regardless of the direction of current flow in the coil. Since like poles repel, the movable vane pulls away from the fixed vane moving the meter pointer. This motion exerts a turning force against a spring. The distance the vane will move against the force of the spring depends on the strength of the magnetic field, which in turn depends on the coil current.

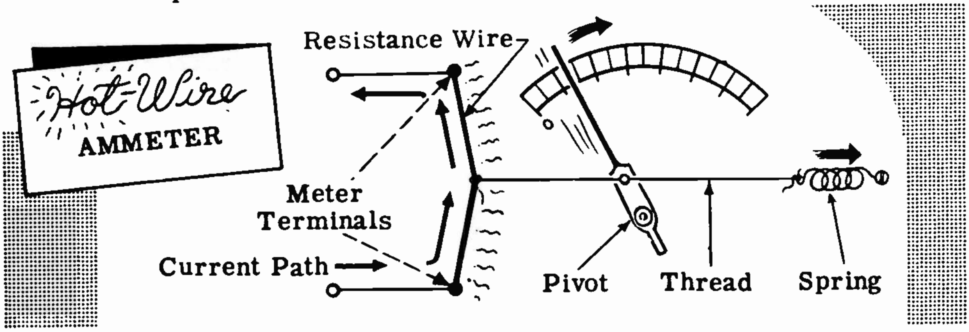


Moving-vane meters may be used for voltmeters, in which case the field coil consists of many turns of fine wire which generate a strong field with only a small current flow. Ammeters of this type use fewer turns of a heavier wire, and depend on the larger current flow to obtain a strong field. These meters are generally calibrated at 60 cycles AC, but may be used at other AC frequencies. By changing the meter scale calibration, moving-vane meters will measure DC current and voltage.

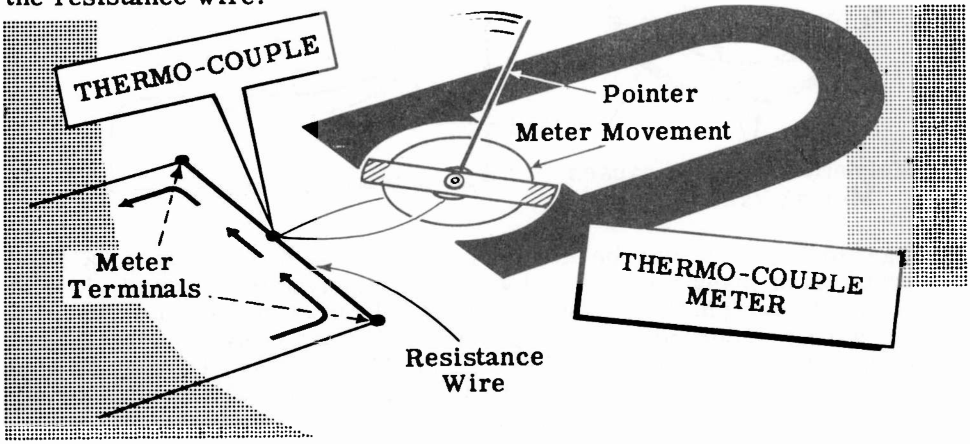
Hot-Wire and Thermocouple Meters

Hot-wire and thermocouple meters both utilize the heating effect of current flowing through a resistance to cause meter deflection, but each uses this effect in a different manner. Since their operation depends only on the heating effect of current flow, they may be used to measure direct current and alternating current of any frequency.

The hot-wire ammeter deflection depends on the expansion of a high resistance wire caused by the heating effect of the wire itself as current flows through it. A resistance wire is stretched taut between the two meter terminals with a thread attached at a right angle to the center of the wire. A spring connected to the opposite end of the thread exerts a constant tension on the resistance wire. Current flow heats the wire, causing it to expand. This motion is transferred to the meter pointer through the thread and a pivot.

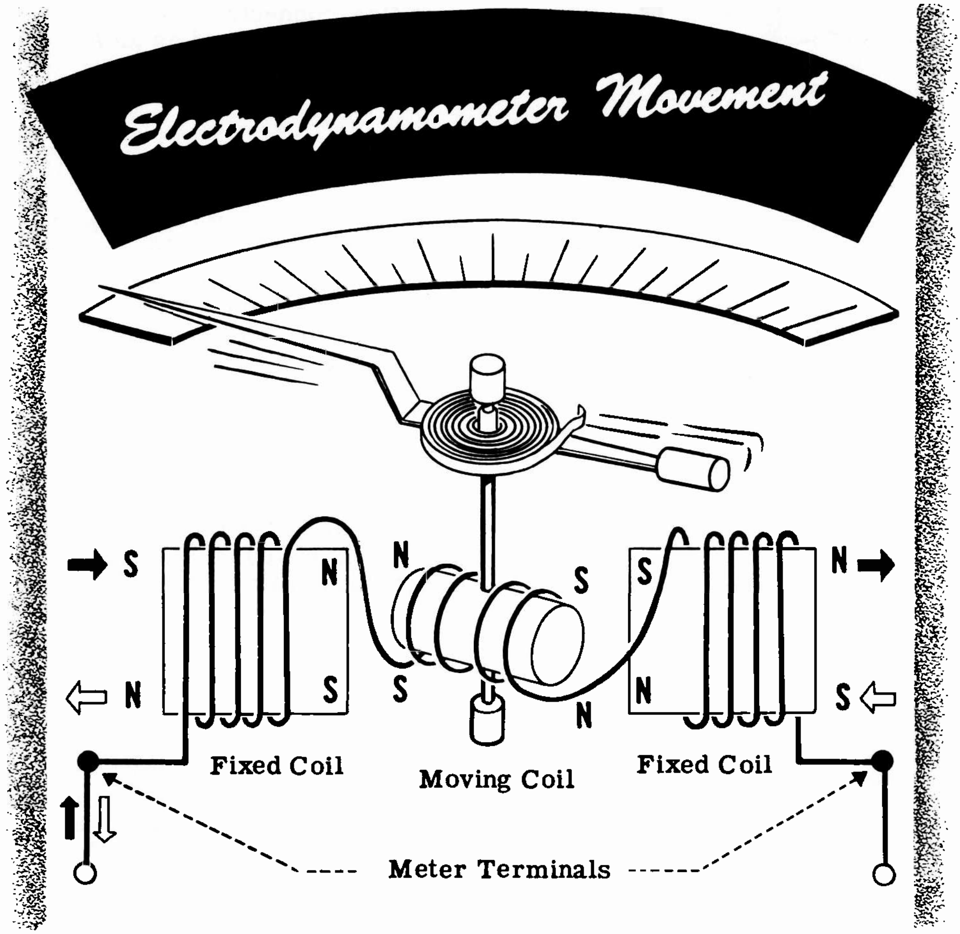


The thermo-couple meter consists of a resistance wire across the meter terminals which heats in proportion to the amount of current flow. Attached to this heating resistor is a small thermo-couple junction of two unlike metal wires which connect across a very sensitive DC meter movement. As the current being measured heats the heating resistor, a small current (which flows only through the thermo-couple wires and the meter movement) is generated by the thermo-couple junction. The current being measured flows only through the resistance wire, not through the meter movement itself. The pointer turns in proportion to the amount of heat generated by the resistance wire.



Electrodynamometer Movements

An electrodynamometer movement utilizes the same basic operating principle as the basic moving-coil DC meter movement, except that the permanent magnet is replaced by fixed coils. A moving coil to which the meter pointer is attached is suspended between two field coils and connected in series with these coils. The three coils (two field coils and the moving coil) are connected in series across the meter terminals so that the same current flows through each.

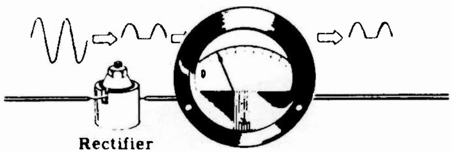


Current flow in either direction through the three coils causes a magnetic field to exist between the field coils. The current in the moving coil causes it to act as a magnet and exert a turning force against a spring. If the current is reversed, the field polarity and the polarity of the moving coil reverse simultaneously, and the turning force continues in the original direction. Since reversing the current direction does not reverse the turning force, this type of meter can be used to measure both AC and DC current. While some voltmeters and ammeters use the dynamometer principle of operation, its most important application is in the wattmeter about which you will find out a little later.

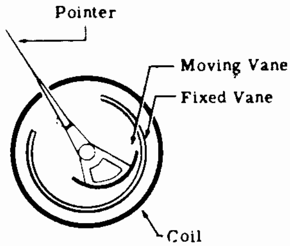
AC METERS

Review of AC Meters

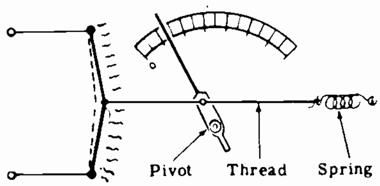
To review the principles and construction of AC meters, suppose you compare the various meter movements and their uses. Although there are other types of meters used for AC, you have found out about those which are most commonly used.



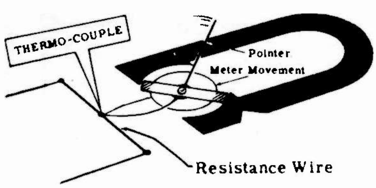
RECTIFIER TYPE AC METER — A basic DC meter movement with a rectifier connected to change AC to DC. Commonly used as an AC voltmeter.



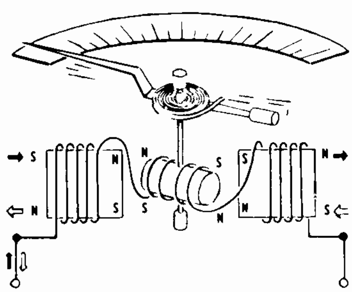
MOVING-VANE METER — Meter which operates on magnetic repulsion principle, using one movable and one fixed vane. Can be used on AC or DC to measure either voltage or current.



HOT-WIRE AMMETER — Meter movement based on the expansion of a wire heated by current flow through it. Used only to measure current.



THERMO-COUPLE AMMETER — Meter movement utilizing the heat of a resistor through which current flows to develop a measurable current in a thermo-couple.

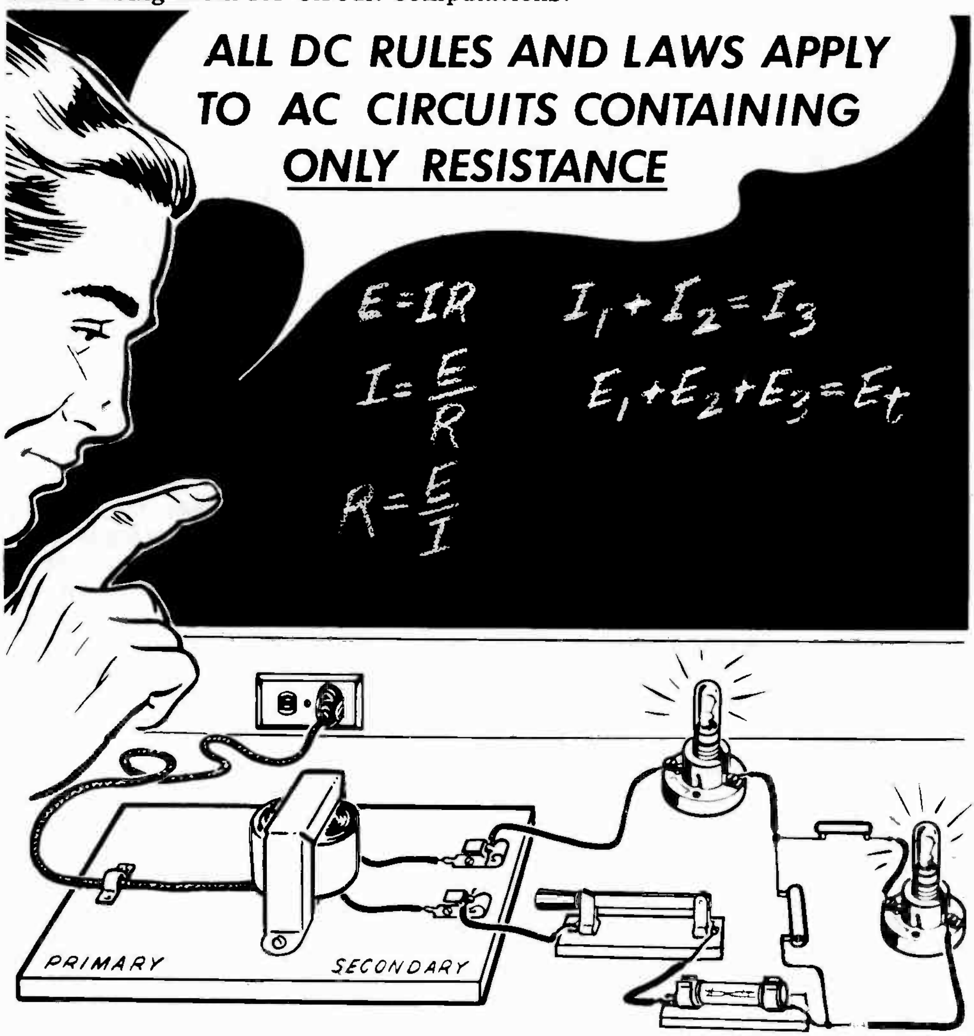


ELECTRODYNAMOMETERS — Commonly used in wattmeters rather than voltmeters and ammeters. Basic principle is identical to that of a D'Arsonval movement except that field coils are used instead of a permanent magnet.

AC Circuits Containing Resistance Only

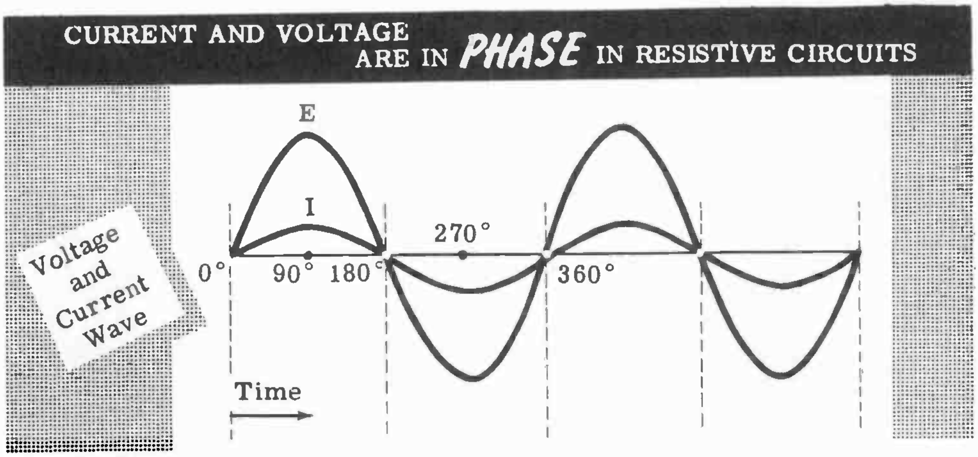
Many AC circuits consist of pure resistance, and for such circuits the same rules and laws apply as for DC circuits. Pure resistance circuits are made up of electrical devices which contain no inductance or capacitance (you will find out about inductance and capacitance a little later). Devices such as resistors, lamps and heating elements have negligible inductance or capacitance and for practical purposes are considered to be made up of pure resistance. When only such devices are used in an AC circuit, Ohm's Law, Kirchhoff's Laws and the circuit rules for voltage, current and power can be used exactly as in DC circuits.

In using the circuit laws and rules you must use effective values of AC voltage and current. Unless otherwise stated, all AC voltage and current values are given as effective values. Other values such as peak-to-peak voltages measured on the oscilloscope must be changed to effective values before using them for circuit computations.

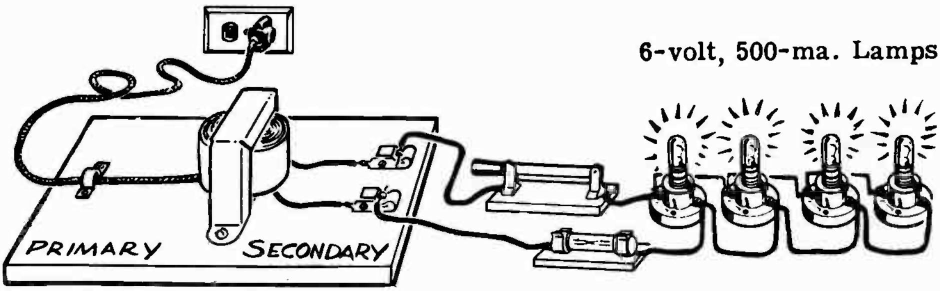


Current and Voltage in Resistive Circuits

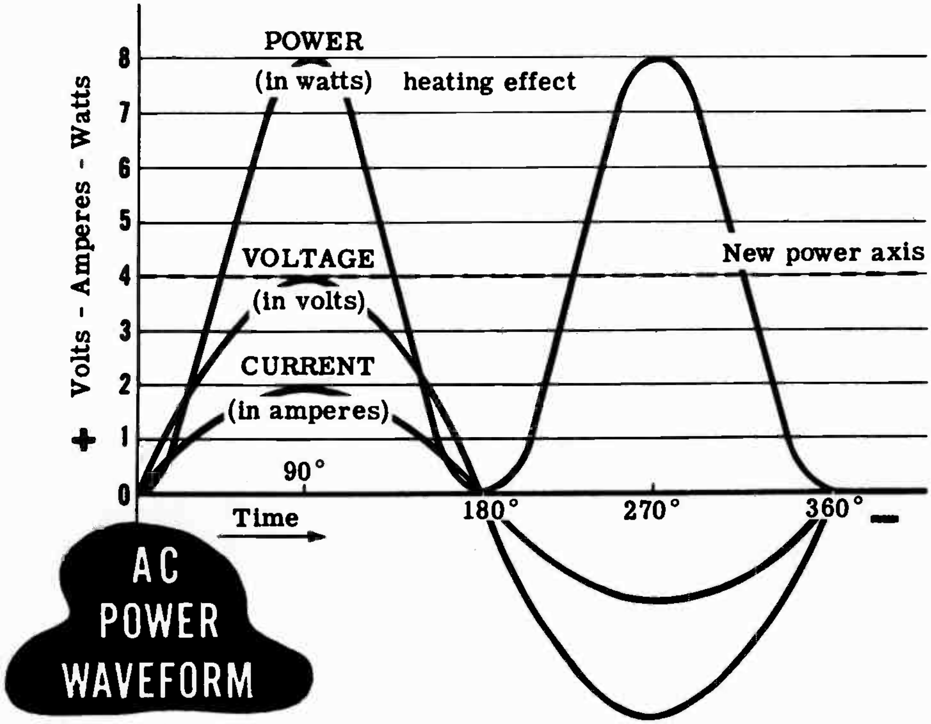
When an AC voltage is applied across a resistor the voltage increases to a maximum with one polarity, decreases to zero, increases to a maximum with the opposite polarity and again decreases to zero, to complete a cycle of voltage. The current flow follows the voltage exactly: as the voltage increases the current increases; when the voltage decreases the current decreases; and at the moment the voltage changes polarity the current flow reverses its direction. Because of this, the voltage and current waves are said to be "in phase."



Sine waves of voltages or currents are "in phase" whenever they are of the same frequency and pass through zero simultaneously, both going in the same direction. The amplitude of two voltage waves or two current waves which are "in phase" are not necessarily equal, however. In the case of "in phase" current and voltage waves, they are seldom equal since they are measured in different units. In the circuit shown below the effective voltage is 6.3 volts, resulting in an effective current of 2 amperes, and the voltage and current waves are "in phase."



Power in AC Circuits



The power used in an AC circuit is the average of all the instantaneous values of power or heating effect for a complete cycle. To find the power, all of the corresponding instantaneous values of voltage and current are multiplied together to find the instantaneous values of power, which are then plotted for the corresponding time to form a power curve. The average of this power curve is the actual power used in the circuit.

For "in phase" voltage and current waves, all of the instantaneous powers are above the zero axis and the entire power curve is above the zero axis. This is due to the fact that whenever two positive values are multiplied together the result is positive, and whenever two negative values are multiplied together the result is also positive. Thus, during the first half cycle of E and I, the power curve increases in a positive direction from zero to a maximum and then decreases to zero just as the E and I waves do. During the second half cycle, the power curve again increases in a positive direction from zero to maximum and then decreases to zero while E and I both increase and decrease in the negative direction. Notice that if a new axis is drawn through the power wave, halfway between its maximum and minimum values, the power wave frequency is twice that of the voltage and current waves.

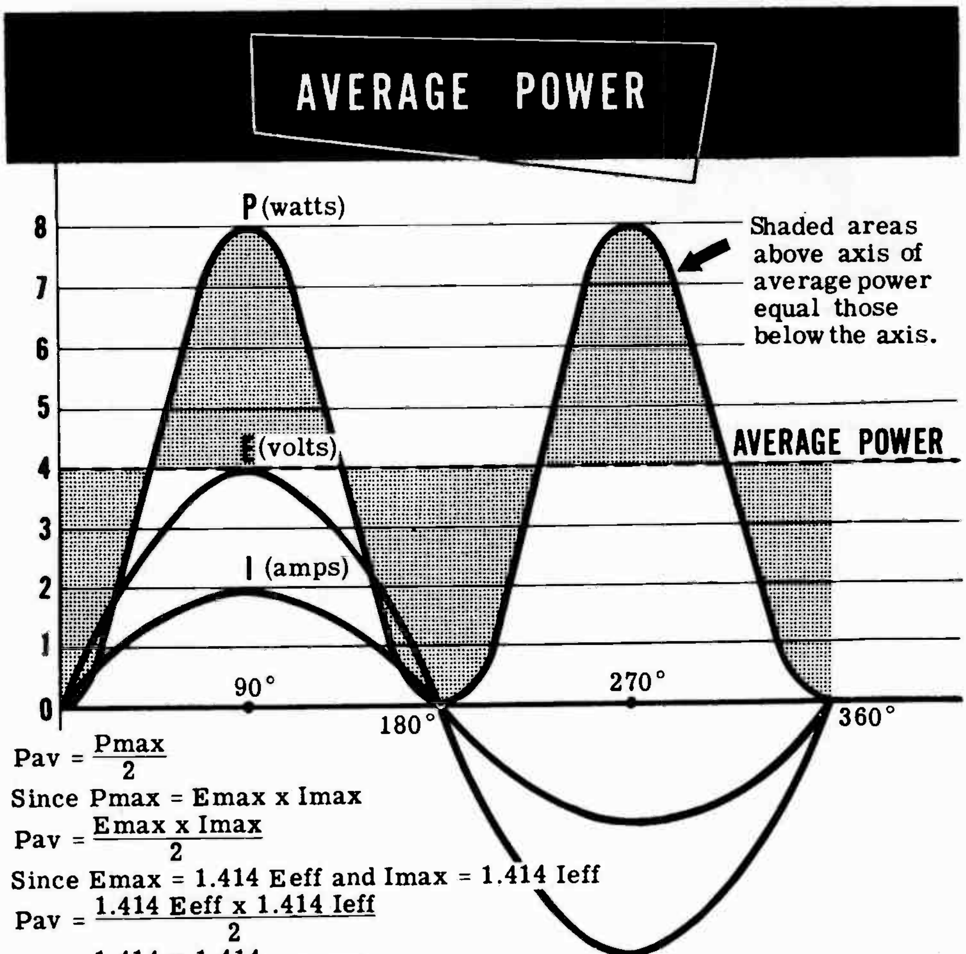
When two numbers—each being less than 1—are multiplied together, the result is a smaller number than either of the original numbers—for example, 0.5V x 0.5A = 0.25W. For that reason, some or all of the instantaneous values of a power wave may be less than those for the circuit current and voltage waves.

Power in Resistive Circuits

A line drawn through the power wave exactly halfway between its maximum and minimum values is the axis of the power wave. This axis represents the average value of power in a resistive circuit, since the shaded areas above the axis are exactly equal in area to those below the axis. Average power is the actual power used in any AC circuit.

Since all the values of power are positive for AC circuits consisting only of resistance, the power wave axis and the average power for such circuits is equal to exactly one-half the maximum, positive, instantaneous power value. This value can also be found by multiplying the effective values of E and I together. This applies to AC circuits containing resistance only, since AC circuits containing inductance or capacitance may have negative instantaneous power values.

IN AC CIRCUITS WITH RESISTANCE ONLY



$$Pav = \frac{Pmax}{2}$$

Since Pmax = Emax x Imax

$$Pav = \frac{Emax \times Imax}{2}$$

Since Emax = 1.414 Eeff and Imax = 1.414 Ieff

$$Pav = \frac{1.414\ Eeff \times 1.414\ Ieff}{2}$$

$$Pav = \frac{1.414 \times 1.414}{2} \times Eeff\ Ieff$$

Since 1.414 x 1.414 = 2, Pav = Eeff x Ieff or P = EI

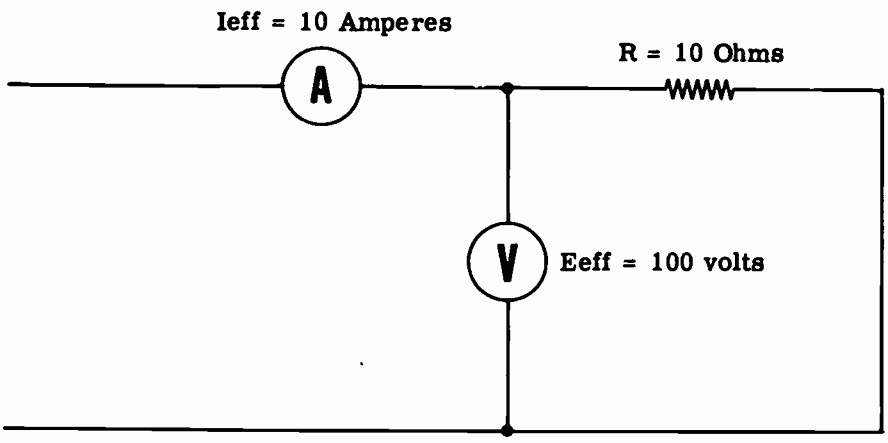
Power Factor

When Ieff and Eeff are in phase, the product is power in watts the same as in DC circuits. As you will find out later, the product of Ieff and Eeff is not always power in watts, but is called "volt-amperes". The power in watts becomes I^2R or E^2/R or Power used in the resistive part of the circuit.

While a source may produce volts and amperes the power in watts may be small or zero. The ratio between the power in watts of a circuit and the volt-amperes of a circuit is called "power factor." In a pure resistive circuit power in watts is equal to Ieff x Eeff so "power factor" in a pure resistive circuit is equal to power in watts divided by volt-amperes which equals 1 (one).

Power factor is expressed in percent or as a decimal.

POWER FACTOR IN RESISTIVE CIRCUITS



I^2R or E^2/R = Eeff x Ieff

I^2R or E^2/R = Watts

$$\text{Power Factor} = \frac{I^2R}{\text{Ieff x Eeff}} \text{ or } \frac{E^2/R}{\text{Ieff x Eeff}} = \frac{1000}{1000} = 1. \text{ or } 100\%$$

$$\text{Power Factor} = \frac{\text{Watts}}{\text{Volt-Amperes}}$$

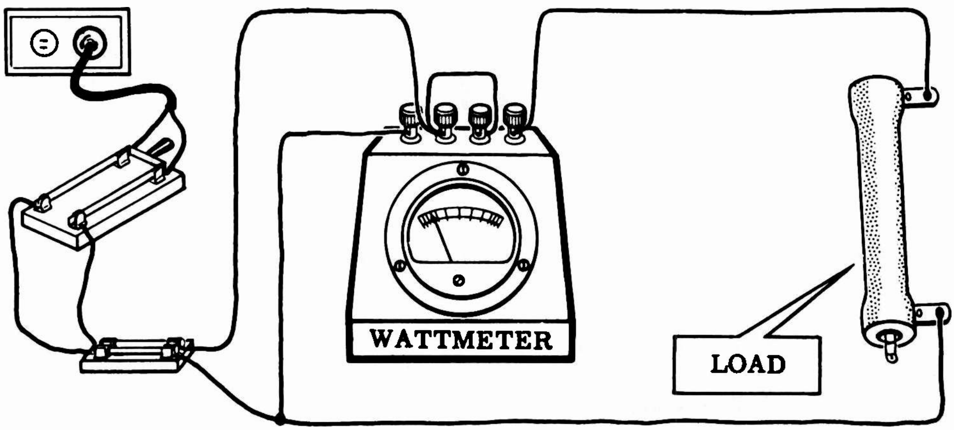
Power Factor = 1.0 or 100% in a pure resistive circuit

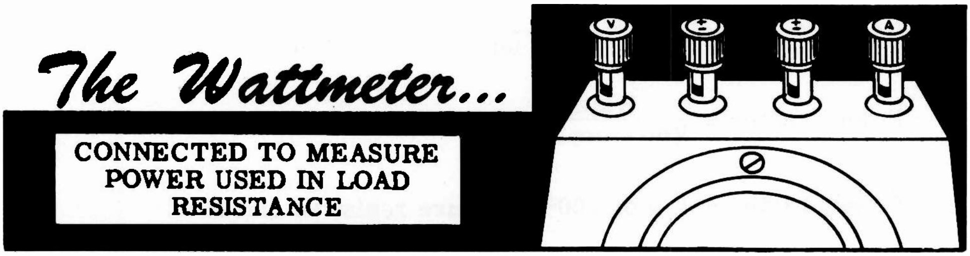
Wattmeters

While power may be computed from the measured effective values of E and I in AC circuits containing only resistance, it can be measured directly with a wattmeter. Wattmeters are not used as commonly as the meters with which you are familiar—voltmeters, ammeters and ohmmeters—but in order to find out about AC circuits you will need to use them. Since wattmeters work differently than the meters you have used and are easily damaged if connected incorrectly, you must find out how to operate them properly.

You see the wattmeter looks very much like any other type of meter, except that the scale is calibrated in watts and it has four terminals, instead of the usual two. Two of these terminals are called the "voltage terminals" and the other two are called the "current terminals." The voltage terminals are connected across the circuit exactly as a voltmeter is connected, while the current terminals are connected in series with the circuit current in the same manner as an ammeter is connected.

Two terminals—one voltage terminal and one current terminal—are marked ±. In using the wattmeter, these two terminals must always be connected to the same point in the circuit. This is usually done by connecting them together directly at the meter terminals. For measuring either AC or DC power, the common (±) junction is connected to either side of the power line. The voltage terminal (V) is connected to the opposite side of the power line. The current terminal (A) is connected to the power-consuming load resistance.



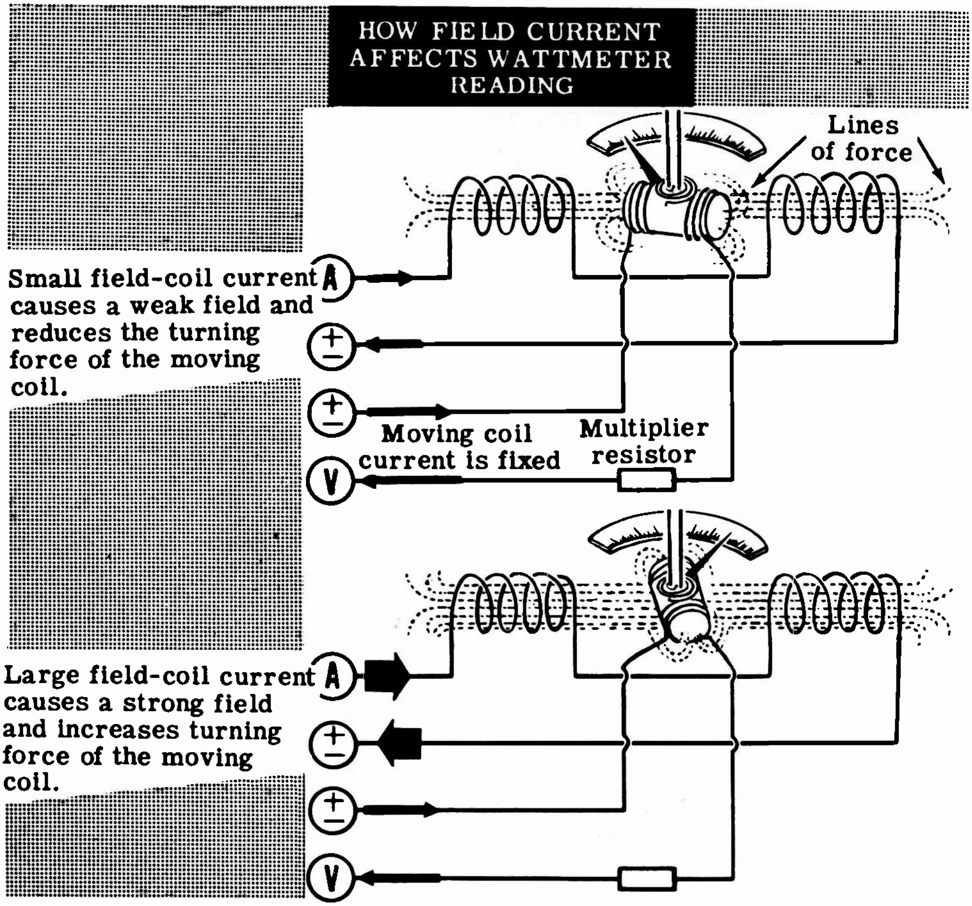


Wattmeters (continued)

Wattmeters are not constructed with a D'Arsonval or Weston basic meter movement. Instead, they use a dynamometer type movement, which differs from the other types in that it has no permanent magnet to furnish the magnetic field. This field is obtained from the field coils, two coils of wire placed opposite each other just as the poles of the permanent magnets are placed in other types of meters.

These field coils are connected in series across the wattmeter current terminals, so that the circuit current flows through the coils when measurements are being made. A large circuit current makes the field coils act as strong magnets, while a small circuit current makes them act as weak magnets. Since the strength of the meter's magnetic field depends on the value of the circuit current, the wattmeter reading varies as the circuit current varies.

Since the current in the moving coil—the voltage coil—is dependent on the circuit voltage and this turning force is dependent on both the moving coil current and the field coil current, for a fixed current in the moving coil the turning force and meter reading depend only on the circuit current.



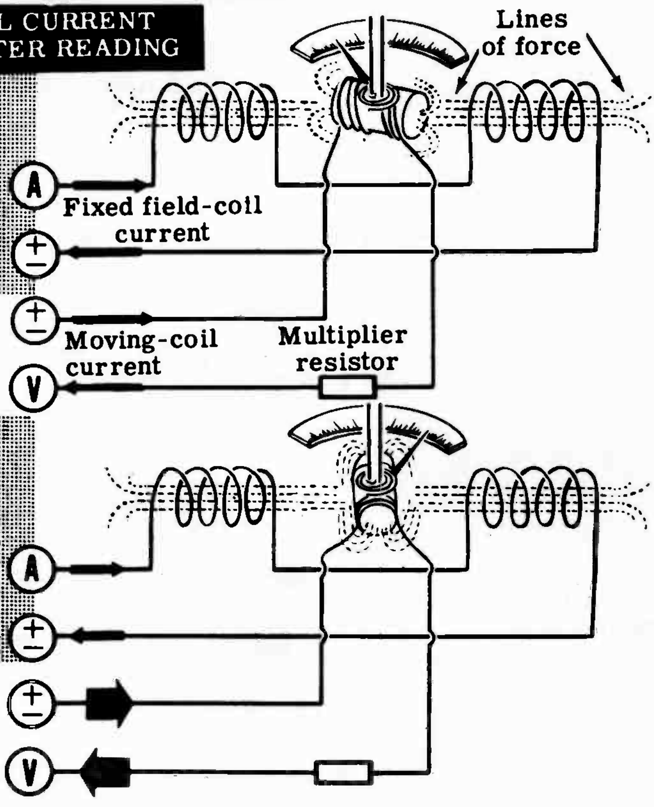
Wattmeters (continued)

The moving coil of a wattmeter is like those used in the basic meter movement and is connected in series with an internal multiplier resistor to the voltage terminals of the wattmeter. The voltage terminals are connected across the circuit voltage in the same manner as a voltmeter, and the multiplier resistor limits the current flow through the moving coil. Since the resistance of the multiplier is fixed, the amount of current flow through it and the moving coil varies with the circuit voltage. A high voltage causes more current to flow through the multiplier and moving coil than a low voltage.

For a given magnetic field, determined by the amount of circuit current (that which flows through the load), the turning force of the moving coil depends on the amount of current flowing through the moving coil. Since this current depends on the circuit voltage, the meter reading will vary as the circuit voltage varies. Thus, the meter reading depends on both the circuit current and the circuit voltage and will vary if either changes. Since power depends on both voltage and current, the meter measures power.

Wattmeters may be used on DC, or on AC up to 133 cycles, but they must always be connected properly to prevent damage. When used on AC, the currents in the field coils and in the moving coil reverse simultaneously, so the meter turning force is always in the same direction.

HOW MOVING-COIL CURRENT AFFECTS WATTMETER READING



Small moving-coil current in fixed field produces small turning force.

Large moving-coil current in fixed field produces large turning force.

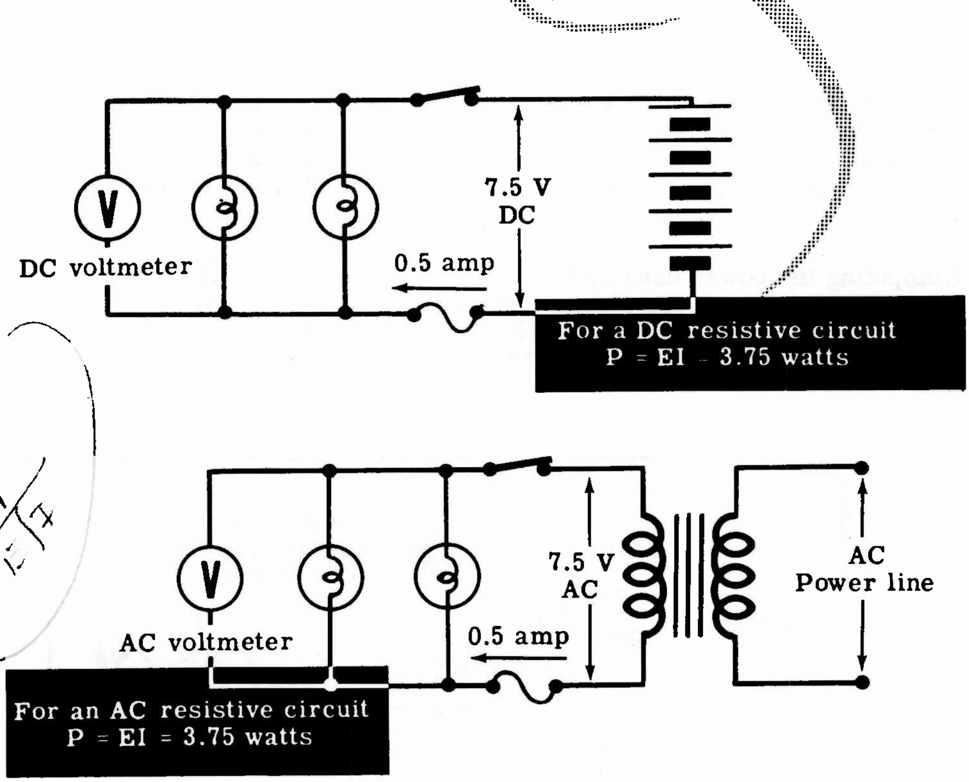
RESISTANCE IN AC CIRCUITS

Demonstration—Power in Resistive AC Circuits

To show that effective values of AC voltage and current can be used to determine the power used in resistance circuits in the same manner as DC values, the instructor connects two lamp sockets in parallel across a 7.5-volt battery—five dry cells in series. Next the 0-10 volt DC voltmeter is connected across the lamp terminals to measure the circuit voltage.

Six-volt lamps, each rated at 250 ma., are inserted in the sockets and you see that each lamp lights with equal brilliance. Together they allow 0.5 amperes to flow through the circuit, while the voltage is about 7.5 volts. Using the power formula (P = EI), the power then is 7.5 x 0.5, or 3.75 watts.

COMPARING POWER USED BY RESISTIVE CIRCUITS



Next the battery is disconnected and the DC voltmeter is replaced with an AC meter of the same range. The 6.3-volt transformer is used as an AC voltage source, and you see that the lamps light as brightly as they did in the DC circuit. Notice that the voltmeter reading is almost the same as that obtained using DC, about 7.5 volts.

Applying the power formula, the effective AC power is 7.5 x 0.5, or 3.75 watts, equal to the DC power and causing the same amount of light.

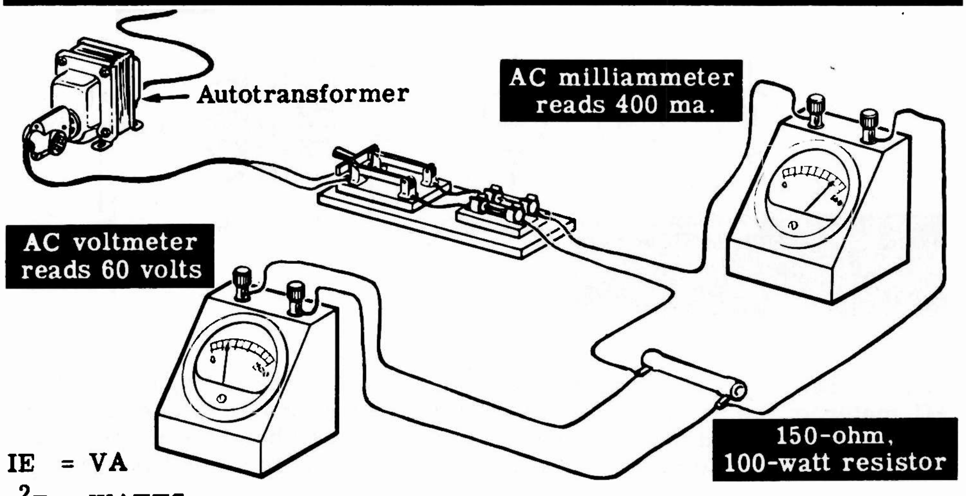
Demonstration—Power in Resistive AC Circuits (continued)

Wattmeters with a range of less than 75 watts are not generally available and, since it would be difficult to read 3 or 4 watts on a standard 0-75 watt meter scale, a larger amount of power is used to demonstrate power measurement with a wattmeter. To obtain a larger amount of power, the instructor uses the 117-volt AC power line as a power source through a step-down autotransformer, which provides a voltage of about 60 volts AC. He will measure the power used by a resistor, first using a voltmeter and milliammeter and then a wattmeter.

The instructor connects the DPST knife switch and the DP fuse holder in the line cord, as shown below, and inserts 1-amp fuses in the fuse holder. With a 0-500 ma. range AC milliammeter connected in series with one of its leads, the line cord is connected across a 150-ohm, 100-watt resistor. Then a 0-250 volt range AC voltmeter is connected directly across the terminals of the resistor to measure resistor voltage. The line cord plug is inserted in the transformer outlet, and with the switch closed, the line voltage indicated on the voltmeter is about 60 volts, and the 150-ohm resistor allows a current flow of about 0.40 ampere as measured by the milliammeter. The resistor becomes hot due to the power being used, so the switch is opened as soon as the readings have been taken. The current reading may vary slightly as the heated resistor changes in resistance value, so an average current reading is used.

Computing the power used by the resistor you see that it is approximately 24 watts. Assuming that the voltage is 60 volts and the current is exactly 0.40 ampere, the power is then 60 x 0.40, or 24 watts. The actual results may be slightly different, depending on the exact voltage and current readings which are obtained.

COMPUTING AC POWER USED BY A RESISTOR



$IE = VA$

$I^2R = \text{WATTS}$

$PF = \dfrac{I^2R}{VA}$

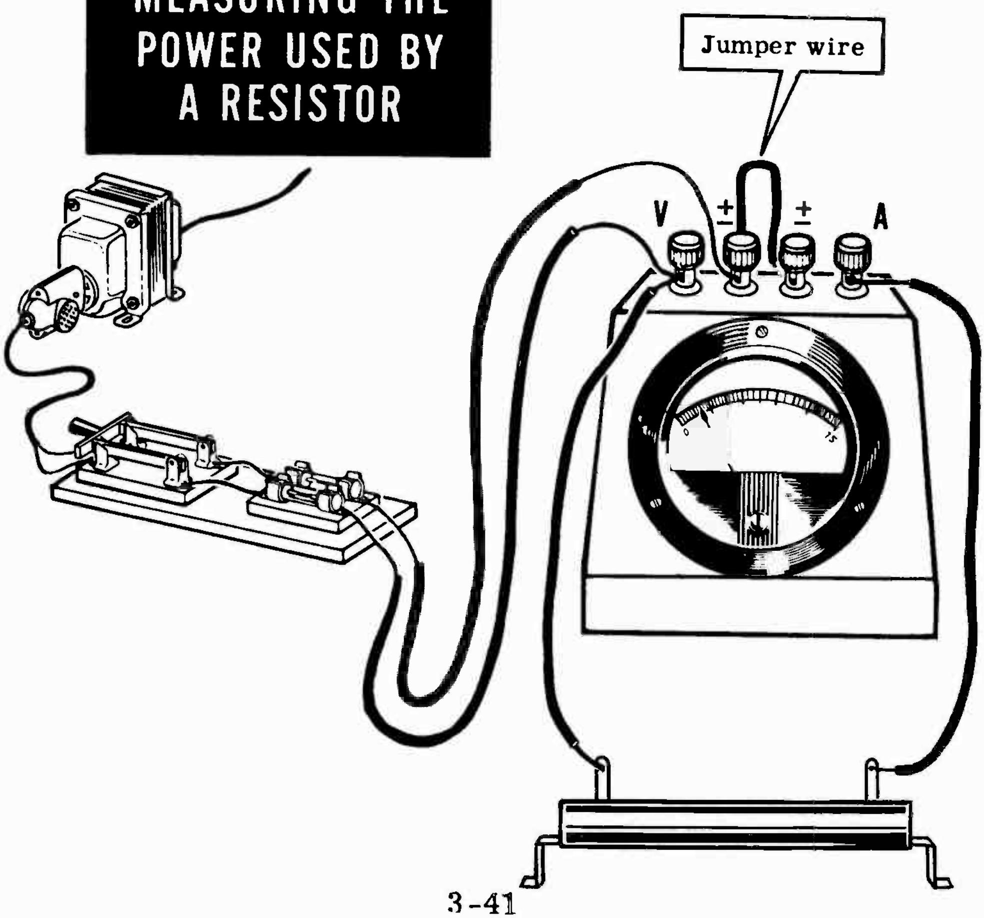
For a Resistive Circuit P = EI
Approximate Power Used is 24 Watts.

Demonstration—Power in Resistive AC Circuits (continued)

Now the milliammeter and voltmeter are removed from the circuit and the wattmeter is connected to measure directly the power used by the resistor. The current and voltage $\pm$ terminals are connected together with a short jumper wire to form a common $\pm$ terminal. One lead from the fuse block is then connected to this common $\pm$ terminal, and the other fuse block lead is connected to the remaining voltage terminal marked V. Wires are connected to each end of the resistor and these are in turn connected to the wattmeter—one to the voltage terminal V and the other to the current terminal A.

When the connections are completed, the autotransformer is connected to the AC power outlet and the switch is closed. You see that the wattmeter indicates that about 24 watts of power is being used. The wattage reading will vary slightly as the resistor heats and changes value, but will become steady when the resistor temperature reaches a maximum. Observe that the measured power is very nearly the same as that obtained using a voltmeter and a milliammeter; and the two results can be considered to be equal for all practical purposes.

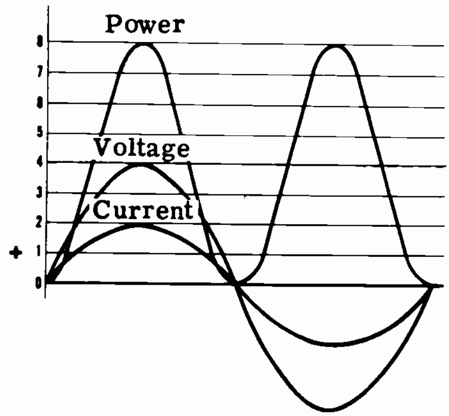
MEASURING THE POWER USED BY A RESISTOR



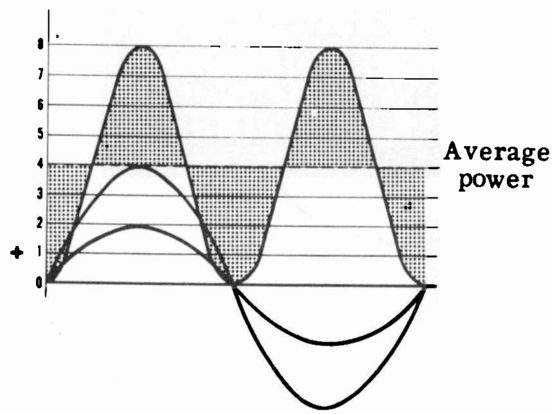
Review of Resistance in AC Circuits

Suppose you review some of the facts concerning AC power, power waves and power in resistive circuits. These facts you have already learned will help you to understand other AC circuits, which are not made up of only pure resistance.

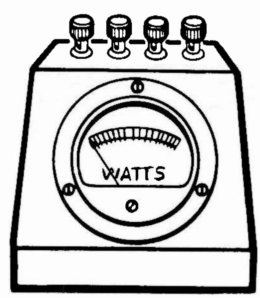
AC POWER WAVE — Pictorial graph of all the values of instantaneous power.



AVERAGE POWER — A value equal to the axis of symmetry drawn through a power wave.



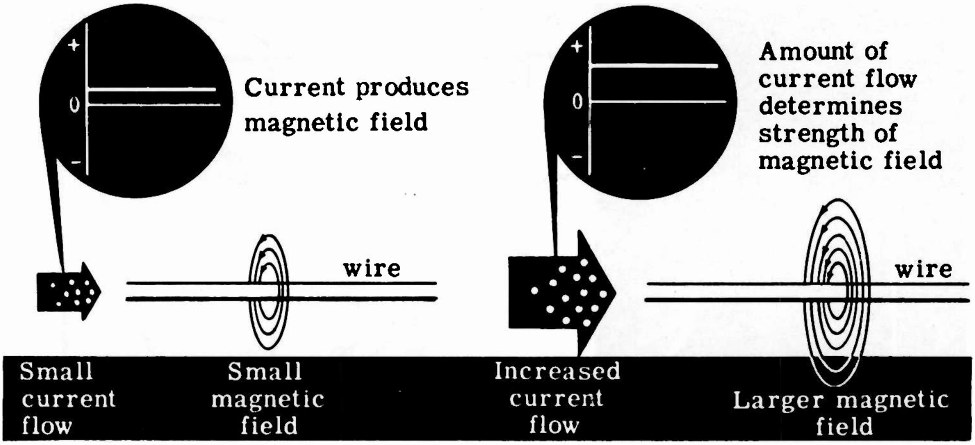
WATTMETER — Meter used to measure power directly when connected in a circuit.



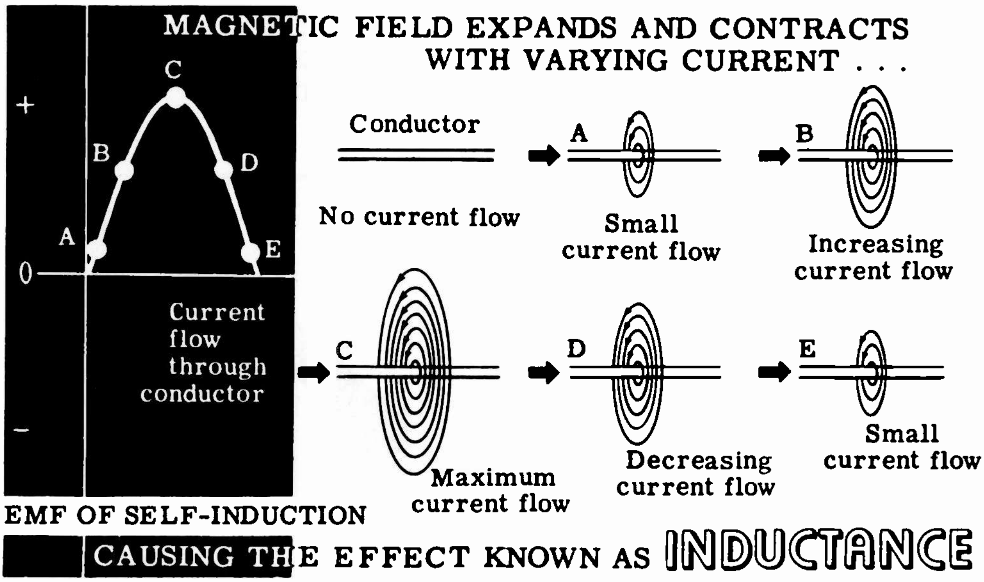
Remember that the power formula (P = EI) can be used to find the power used in a resistive AC circuit, provided effective values of E and I are used.

Emf of Self-Induction

Inductance exists in a circuit because an electric current always produces a magnetic field. The lines of force in this field always encircle the conductor which carries the current, forming concentric circles around the conductor. The strength of the magnetic field depends on the amount of current flow, with a large current producing many lines of force and a small current producing only a few lines of force.

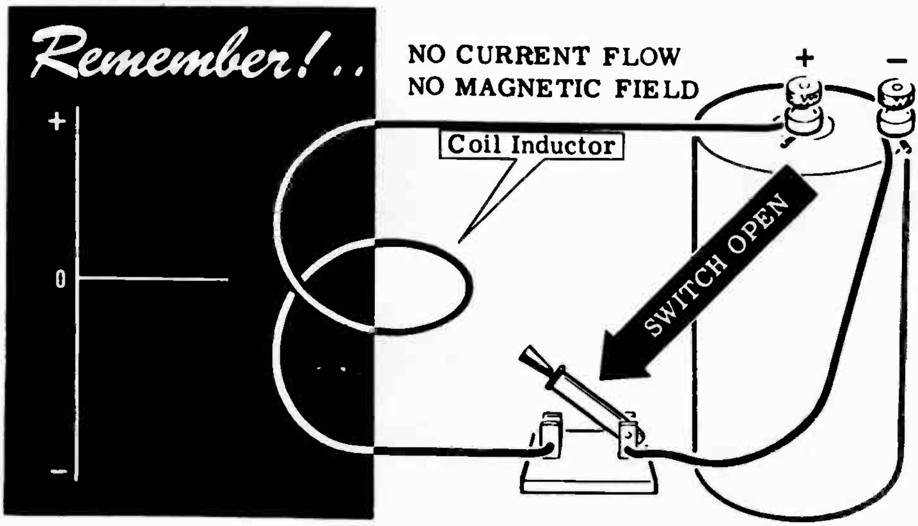


When the circuit current increases or decreases, the magnetic field strength increases and decreases in the same direction. As the field strength increases, the lines of force increase in number and expand outward from the center of the conductor. Similarly, when the field strength decreases, the lines of force contract toward the center of the conductor. It is actually this expansion and contraction of the magnetic field as the current varies which causes an emf of self-induction, and the effect is known as "inductance."

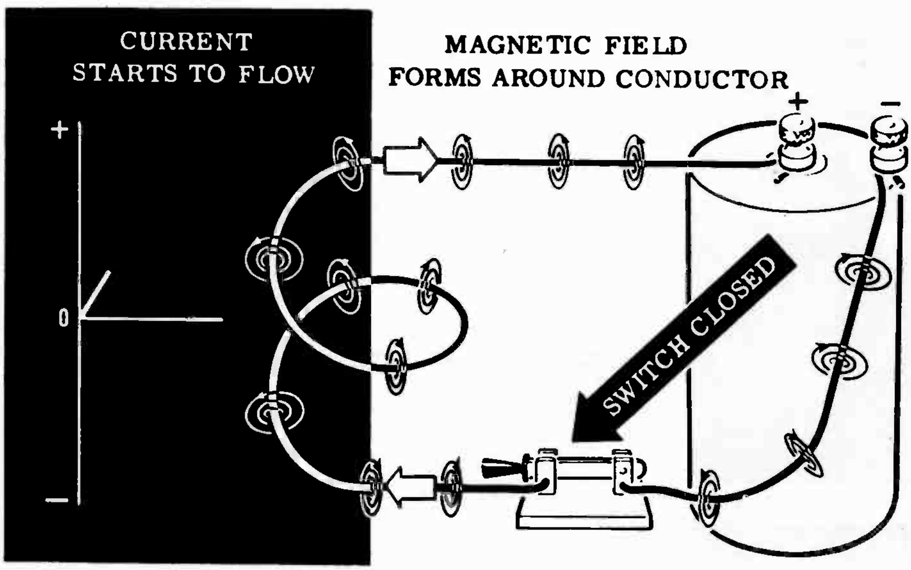


Inductance in a DC Circuit

To see how inductance is caused, suppose your circuit contains a coil like the one shown below. As long as the circuit switch is open, there is no current flow and no field exists around the circuit conductors.

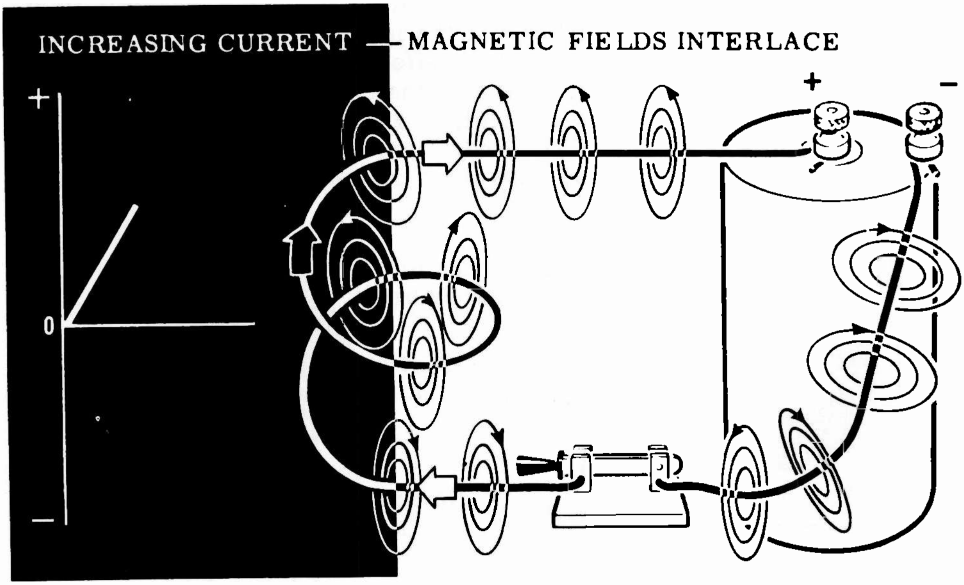


When the switch is closed, current flows through the circuit and lines of force expand outward around the circuit conductors including the turns of the coil. At the instant the switch is closed, the current flow starts rising from zero toward its maximum value. Although this rise in current flow is very rapid, it cannot be instantaneous. Imagine that you actually are able to see the lines of force in the circuit at the instant the current starts to flow. You see that they form a field around the circuit conductors.

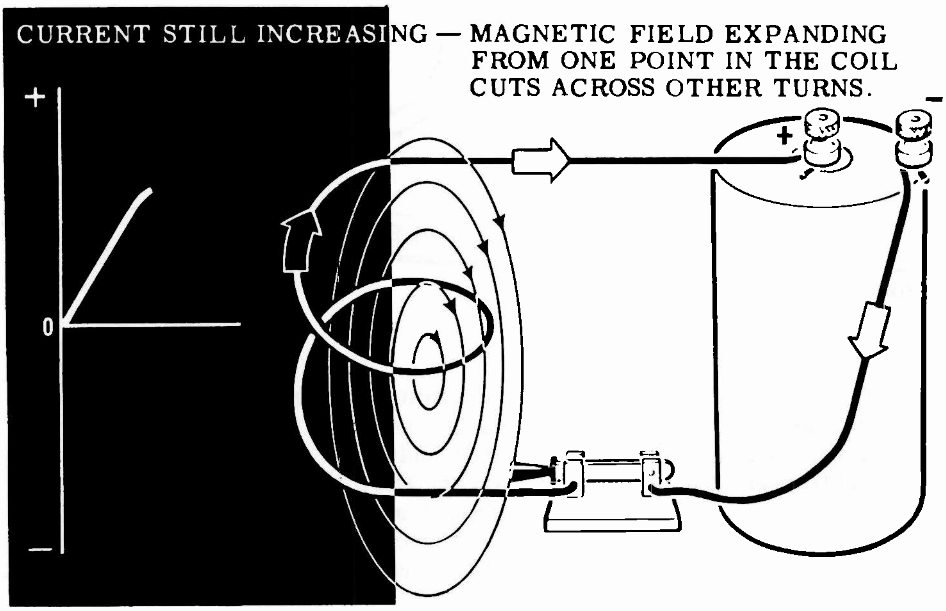


Inductance in a DC Circuit (continued)

As the current continues to increase, the lines of force continue to expand. The fields of adjacent turns of wire interlace.

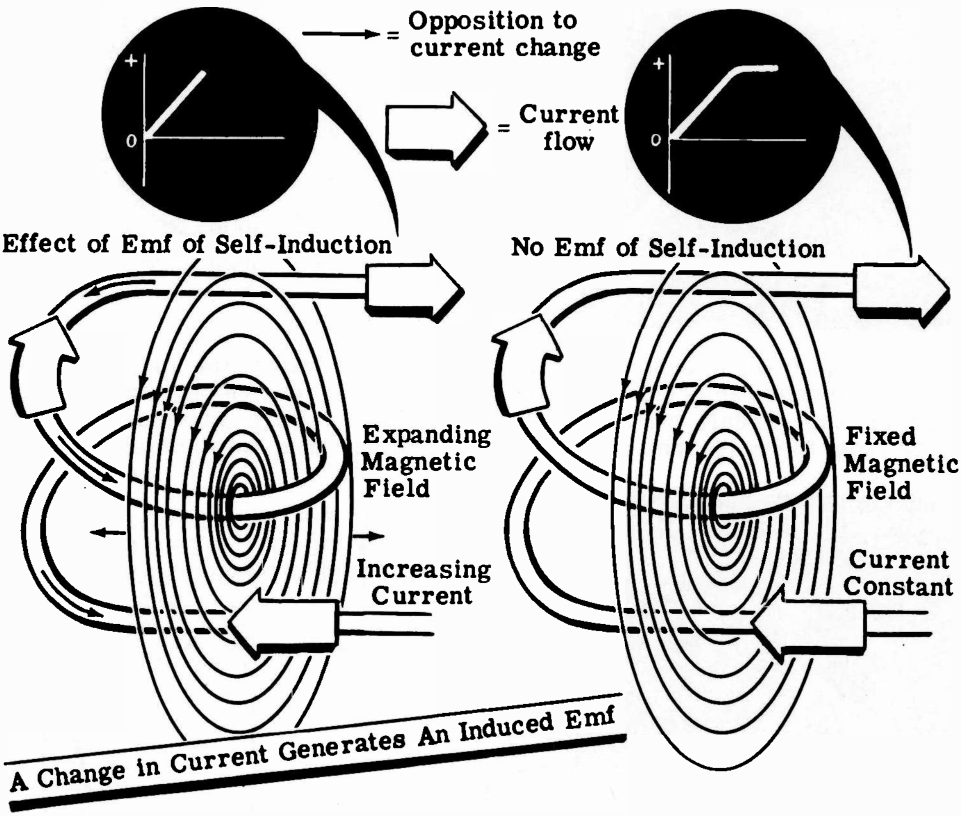


The lines of force around each turn continue their expansion and, in so doing, cut across adjacent turns of the coil. This expansion continues as long as the circuit current is increasing, with more and more lines of force from the coil turns cutting across adjacent turns of the coil.



Inductance in a DC Circuit (continued)

Whenever a magnetic field moves across a wire, it induces an emf in the wire. Whenever a current flows through a coil, it induces a magnetic field that cuts adjacent coil turns. Whenever the initial current changes in direction, the induced field changes and the effect of this changing field in cutting the adjacent coil turns is to oppose the change in current. The initial current change is caused by the emf, or voltage, across the coil and this opposing force is an emf of self-induction. Inductance is the property of generating an emf of self-induction which opposes changes in the coil.



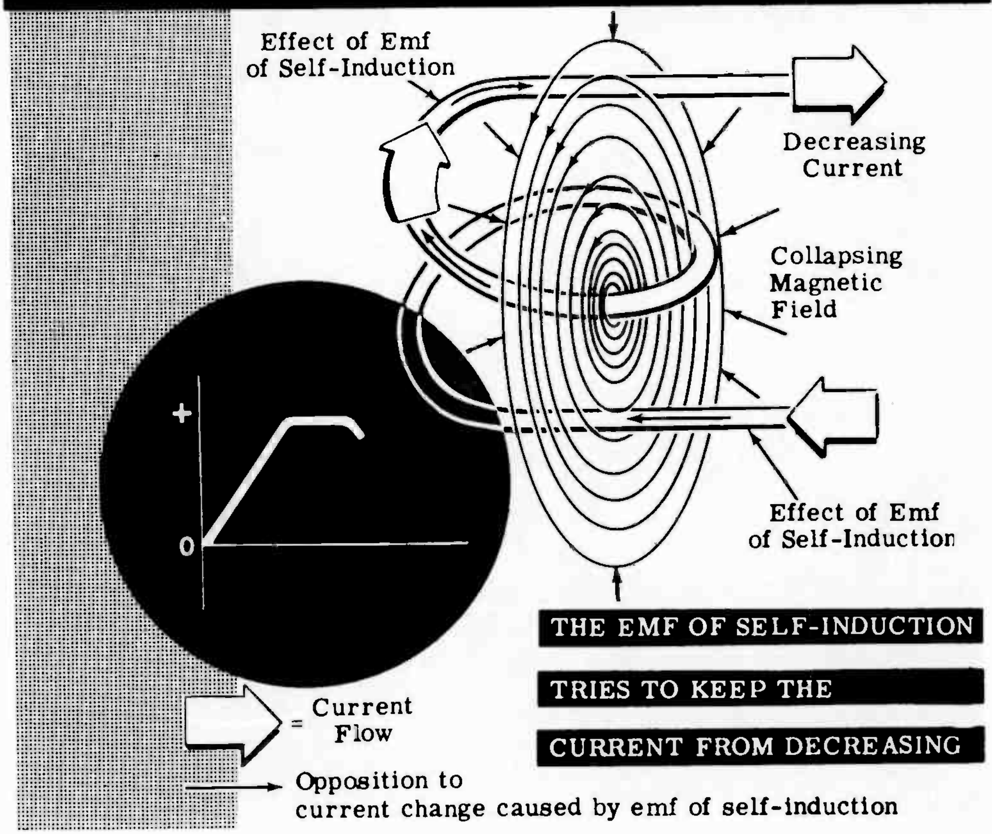
When the circuit current reaches its maximum value, determined by the circuit voltage and resistance, it no longer changes in value and the field no longer expands, so that no emf of self-induction is generated. The field remains stationary but, should the current attempt to rise or fall, the field will either expand or contract and generate an emf of self-induction opposing the change in current flow. For direct current, inductance affects the current flow only when the power is turned on and off, since only at those times does the current change in value.

Inductance in a DC Circuit (continued)

With the current and magnetic field at maximum, no emf of self-induction is generated but if you lowered the source voltage or increased the circuit resistance, the current would decrease. Suppose the source voltage decreases. The current drops toward its new Ohm's law value, determined by E and R. As the current decreases the field also diminishes, with each line of force contracting inward toward the conductor. This contracting or collapsing field cuts across the coil turns in a direction opposite to that caused by the rise in circuit current.

Since the direction of change is reversed, the collapsing field generates an emf of self-induction opposite to that caused by the expanding field, thus having the same polarity as the source voltage. This emf of self-induction then increases the source voltage, trying to prevent the fall in current. However, it cannot keep the current from falling indefinitely since the emf of self-induction ceases to exist whenever the current stops changing. Thus inductance—the effect of emf of self-induction—opposes any change in current flow, whether it be an increase or decrease, slowing down the rate at which the change occurs.

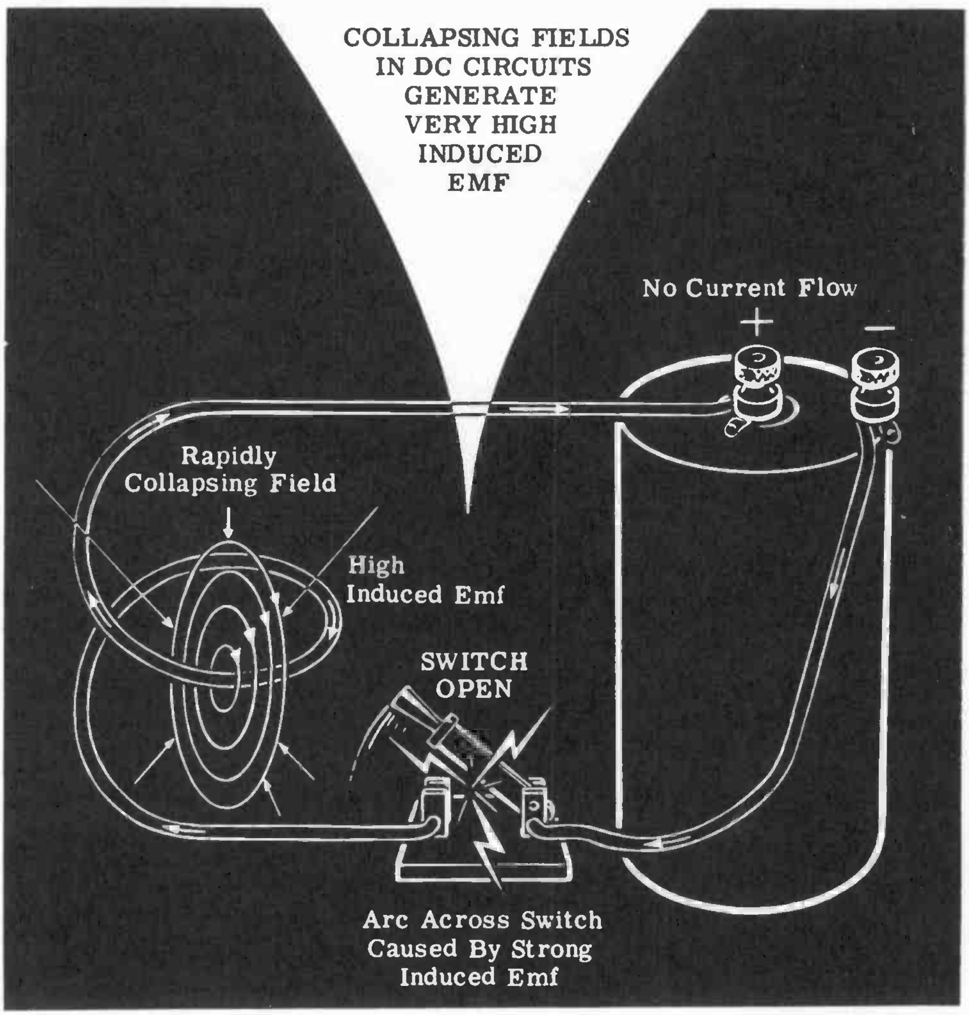
A COLLAPSING FIELD ALSO GENERATES AN EMF OF SELF-INDUCTION



Inductance in a DC Circuit (continued)

As long as the circuit is closed, the current remains at its Ohm's law value and no induced emf is generated. Now suppose you open the switch to stop the current flow. The current should fall to zero and stop flowing immediately but, instead, there is a slight delay and a spark jumps across the switch contacts.

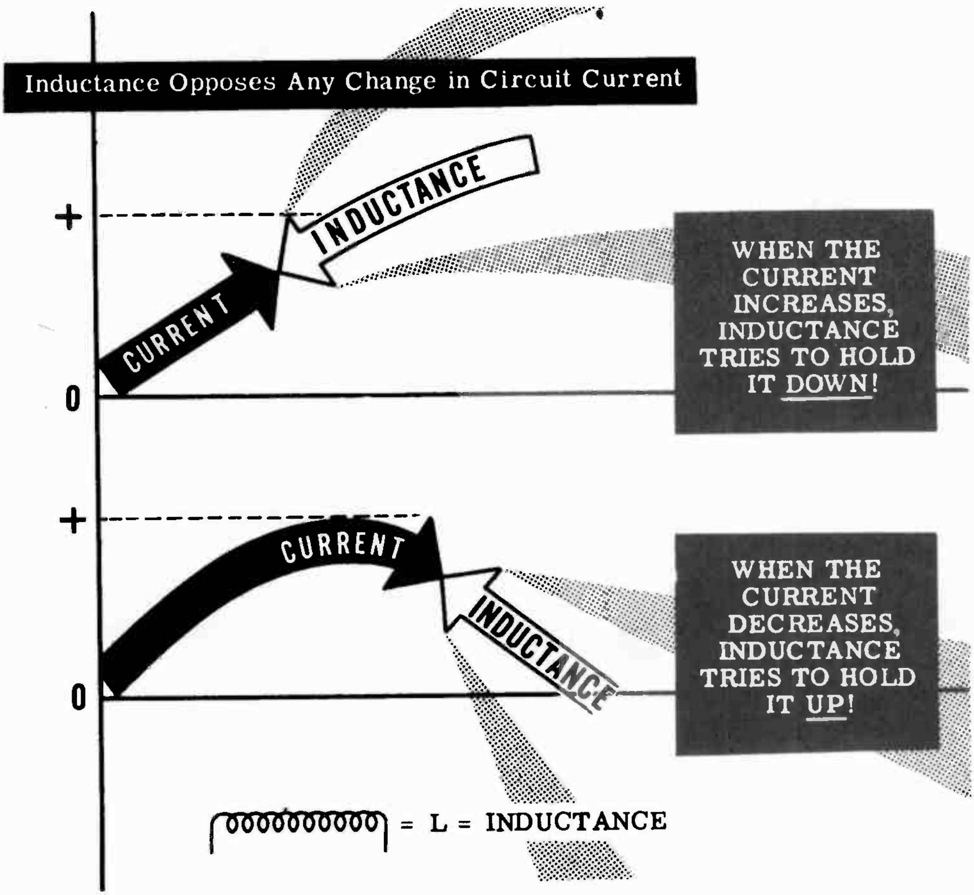
When the switch is opened, the current drops rapidly toward zero and the field also collapses at a very rapid rate. The rapidly collapsing field generates a very high induced emf, which not only opposes the change in current but also causes an arc across the switch to maintain the current flow. Although only momentary, the induced emf caused by this rapid field collapse is very high, sometimes many times that of the original source voltage. This action is often used to advantage in special types of equipment to obtain very high voltages.



Inductance Symbols

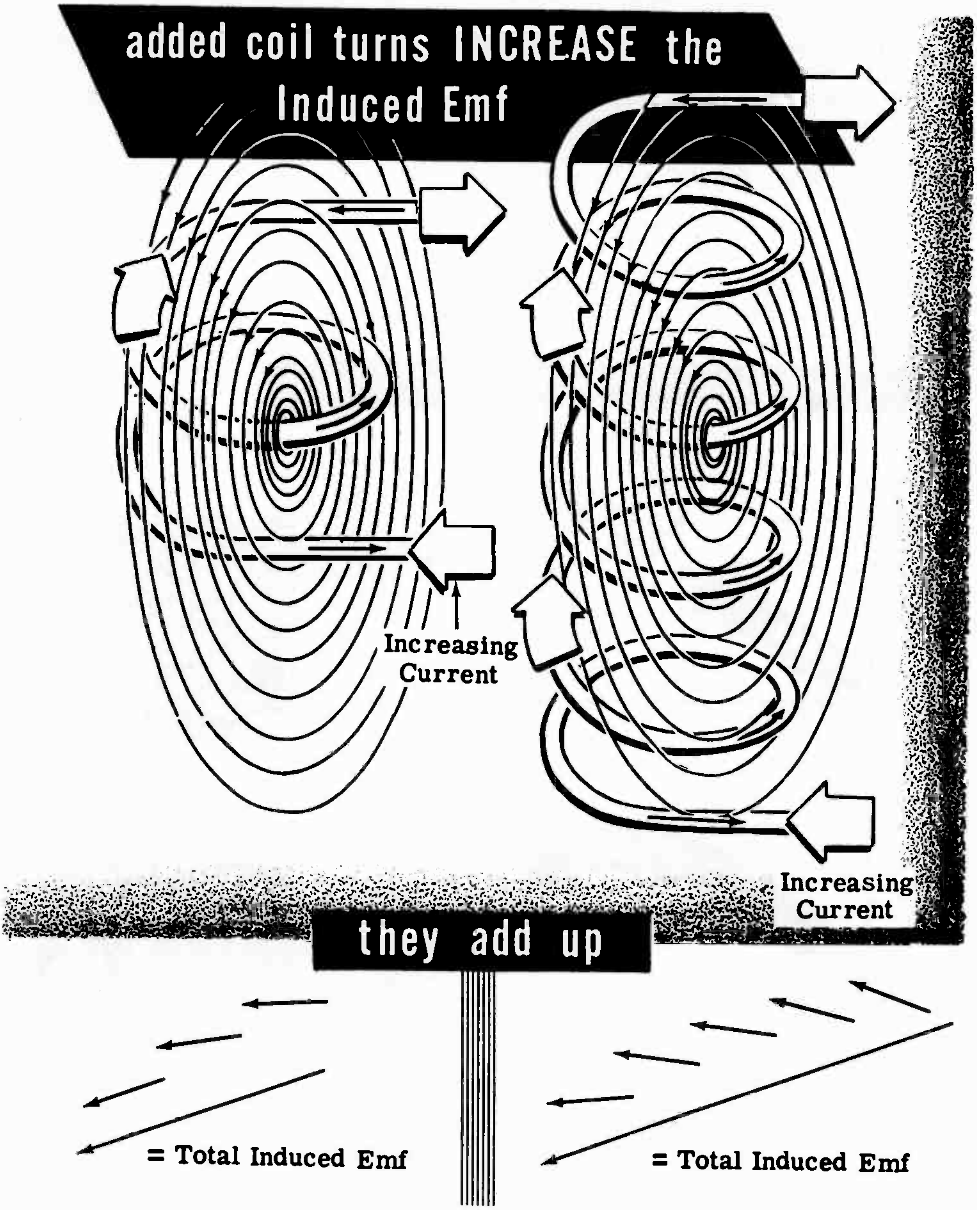
While you cannot see inductance, it is present in every electrical circuit and has an effect on the circuit whenever the circuit current changes. In electrical formulas the letter L is used as a symbol to designate inductance. Because a coil of wire has more inductance than a straight length of the same wire, the coil is called an "inductor." Both the letter and the symbol are illustrated below.

Since direct current is normally constant in value except when the circuit power is turned on and off to start and stop the current flow, inductance affects DC current flow only at these times and usually has very little effect on the operation of the circuit. Alternating current, however, is continuously changing so that the circuit inductance affects AC current flow at all times. Although every circuit has some inductance, the value depends upon the physical construction of the circuit, and the electrical devices used in it. In some circuits the inductance is so small its effect is negligible, even for AC current flow.



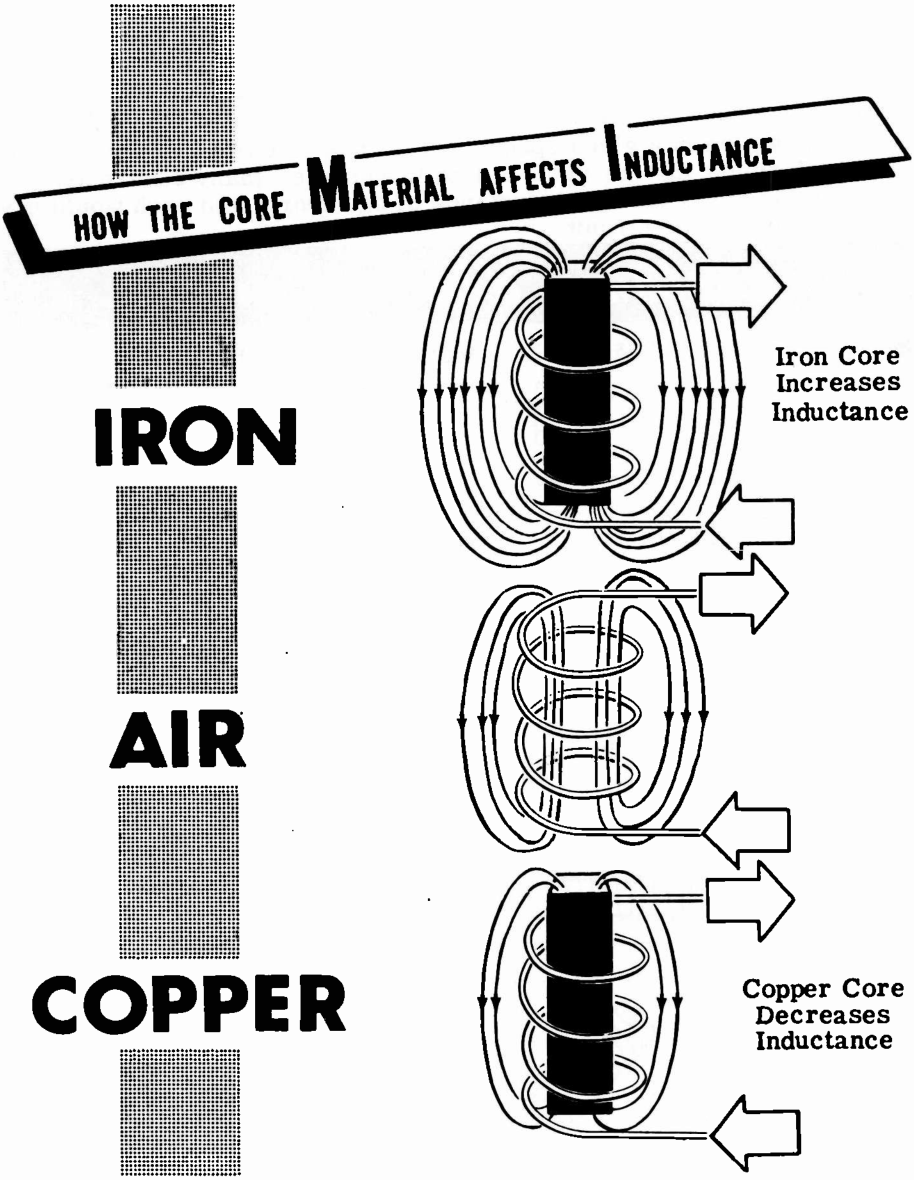
Factors Which Affect Inductance

Every complete electric circuit has some inductance since the simplest circuit forms a complete loop or single-turn coil. An induced emf is generated even in a straight piece of wire, by the action of the magnetic field expanding outward from the center of the wire or collapsing inward to the wire center. The greater the number of adjacent turns of wire cut across by the expanding field, the greater the induced emf generated—so that a coil of wire having many turns has a high inductance.



Factors Which Affect Inductance (continued)

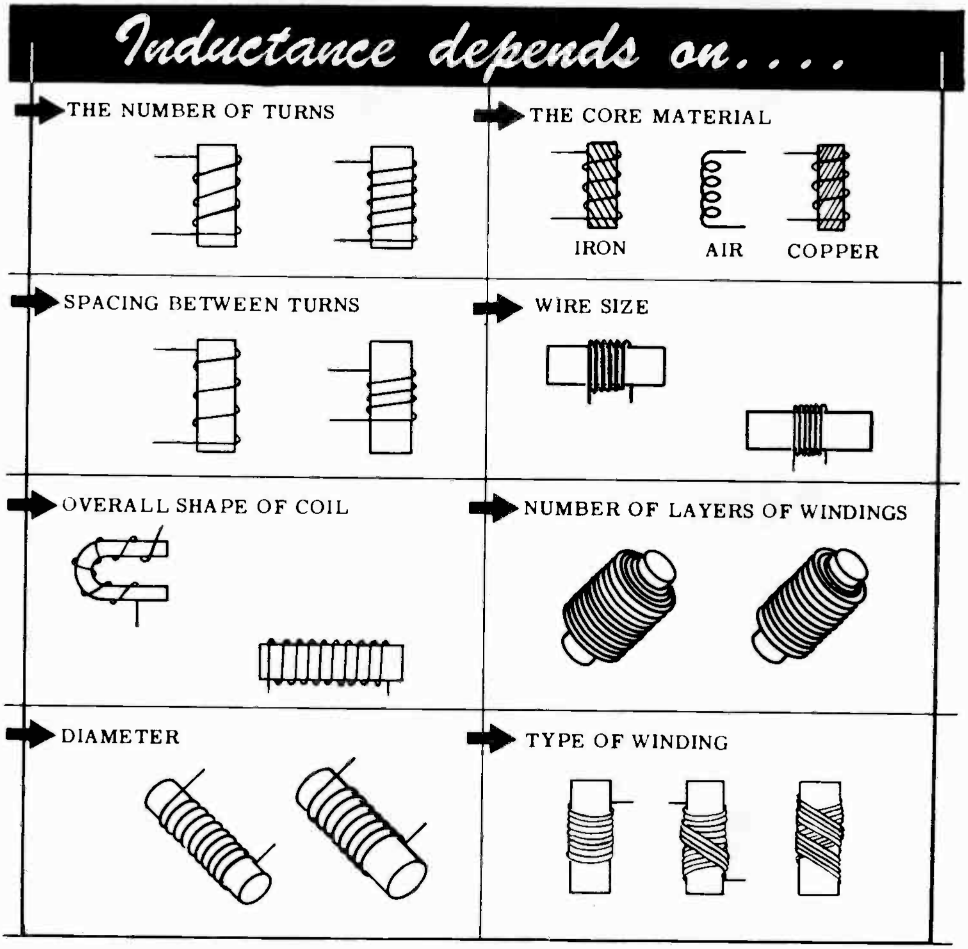
Any factors which tend to affect the strength of the magnetic field also affect the inductance of a circuit. For example, an iron core inserted in a coil increases the inductance because it provides a better path for magnetic lines of force than air. Therefore, more lines of force are present that can expand and contract when there is a change in current. A copper core piece has exactly the opposite effect. Since copper opposes lines of force more than air, inserting a copper core piece results in less field change when the current changes, thereby reducing the inductance.



Units of Inductance

In electrical formulas the letter L is used as a symbol to designate inductance. The basic unit of measure for inductance is the henry. For quantities of inductance smaller than one henry, the millihenry and microhenry are used. A unit larger than the henry is not used since inductance normally is of a value which can be expressed in henries or part of a henry.

Inductance can only be measured with special laboratory instruments and depends entirely on the physical construction of the circuit. Some of the factors most important in determining the amount of inductance of a coil are: the number of turns, the spacing between turns, coil diameter, kind of material around and inside the coil, the wire size, number of layers of wire, type of coil winding and the overall shape of the coil. Wire size does not affect the inductance directly, but it does determine the number of turns that can be wound in a given space. All of these factors are variable, and no single formula can be used to find inductance. Many differently constructed coils could have an inductance of one henry, and each would have the same effect in the circuit.



Mutual Induction

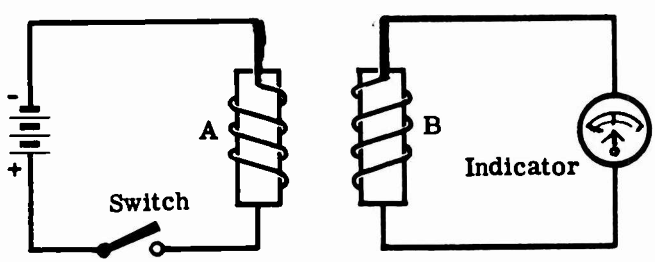
The term "mutual induction" refers to the condition in which two circuits are sharing the energy of one of the circuits. It means that energy is being transferred from one circuit to another.

Consider the diagram below. Coil A is the primary circuit which obtains energy from the battery. When the switch is closed, the current starts to flow and a magnetic field expands out of coil A. Coil A then changes electrical energy of the battery into the magnetic energy of a magnetic field. When the field of coil A is expanding, it cuts across coil B, the secondary circuit, inducing an emf in coil B. The indicator (a galvanometer) in the secondary circuit is deflected, and shows that a current, developed by the induced emf, is flowing in the circuit.

The induced emf may be generated by moving coil B through the flux of coil A. However, this voltage is induced without moving coil B. When the switch in the primary circuit is open, coil A has no current and no field. As soon as the switch is closed, current passes through the coil and the magnetic field is generated. This expanding field moves or "cuts" across the wires of coil B, thus inducing an emf without the movement of coil B.

The magnetic field expands to its maximum strength and remains constant as long as full current flows. Flux lines stop their cutting action across the turns of coil B because expansion of the field has ceased. At this point the indicator needle reads zero because no induced emf exists anymore. If the switch is opened, the field collapses back to the wires of coil A. As it does so, the changing flux cuts across the wires of coil B, but in the opposite direction. The current present in the coil causes the indicator needle to deflect, showing this new direction. The indicator, then, shows current flow only when the field is changing, either building up or collapsing. In effect, the changing field produces an induced emf exactly as does a magnetic field moving across a conductor. This principle of inducing voltage by holding the coils steady and forcing the field to change is used in innumerable applications. The transformer, as shown in the diagram below, is particularly suitable for operation by mutual induction.

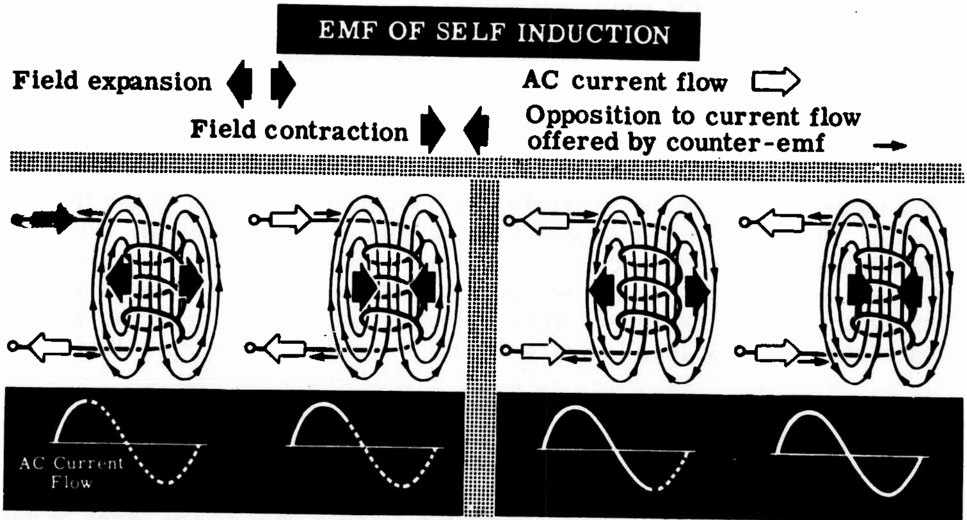
For purposes of explanation a battery is used in the above example. The transformer is, however, a perfect component for transferring and changing AC voltages as needed.



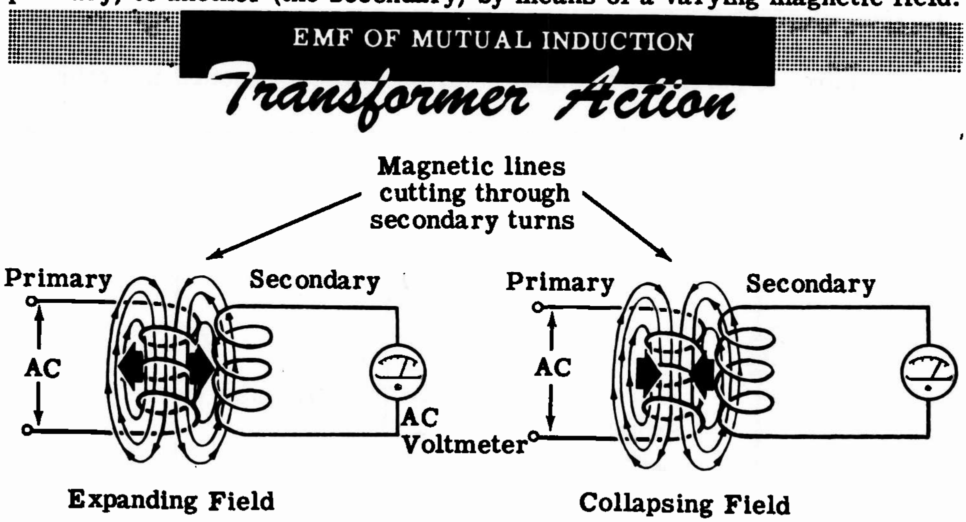
Mutual Induction Circuits

How a Transformer Works

When AC flows through a coil, an alternating magnetic field is generated around the coil. This alternating magnetic field expands outward from the center of the coil and collapses into the coil as the AC through the coil varies from zero to a maximum and back to zero again. Since the alternating magnetic field must cut through the turns of the coil an emf of self induction is induced in the coil which opposes the change in current flow.



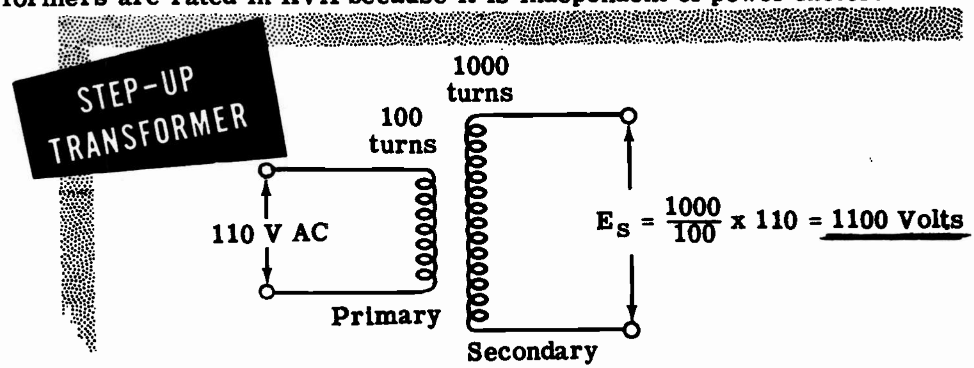
If the alternating magnetic field generated by one coil cuts through the turns of a second coil, an emf will be generated in this second coil just as an emf is induced in a coil which is cut by its own magnetic field. The emf generated in the second coil is called the "emf of mutual induction," and the action of generating this voltage is called "transformer action." In transformer action, electrical energy is transferred from one coil (the primary) to another (the secondary) by means of a varying magnetic field.

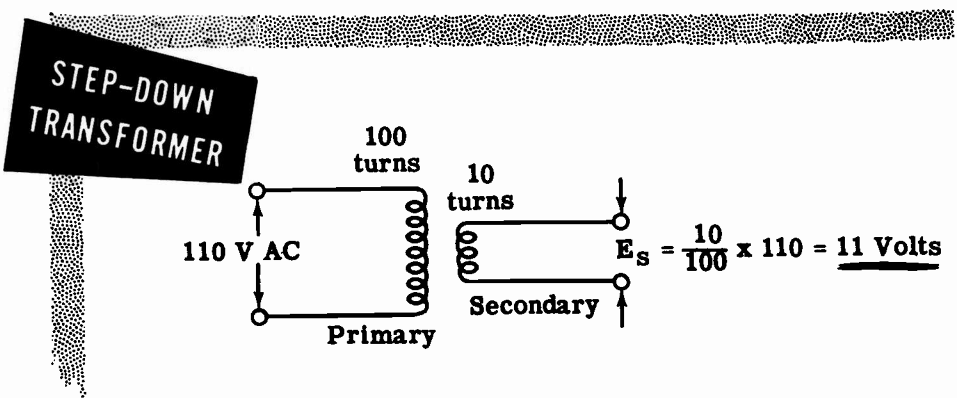


How a Transformer Works (continued)

A simple transformer consists of two coils very close together, electrically insulated from each other. The coil to which the AC is applied is called the "primary." It generates a magnetic field which cuts through the turns of the other coil, called the "secondary," and generates a voltage in it. The coils are not physically connected to each other. They are, however, magnetically coupled to each other. Thus, a transformer transfers electrical power from one coil to another by means of an alternating magnetic field.

Assuming that all the magnetic lines of force from the primary cut through all the turns of the secondary, the voltage induced in the secondary will depend on the ratio of the number of turns in the secondary to the number of turns in the primary. For example, if there are 1000 turns in the secondary and only 100 turns in the primary, the voltage induced in the secondary will be 10 times the voltage applied to the primary ($\frac{1000}{100} = 10$). Since there are more turns in the secondary than there are in the primary, the transformer is called a "step-up transformer." If, on the other hand, the secondary has 10 turns and the primary has 100 turns, the voltage induced in the secondary will be one-tenth of the voltage applied to the primary ($\frac{10}{100} = \frac{1}{10}$). Since there are less turns in the secondary than there are in the primary, the transformer is called a "step-down transformer." Transformers are rated in KVA because it is independent of power factor.





How a Transformer Works (continued)

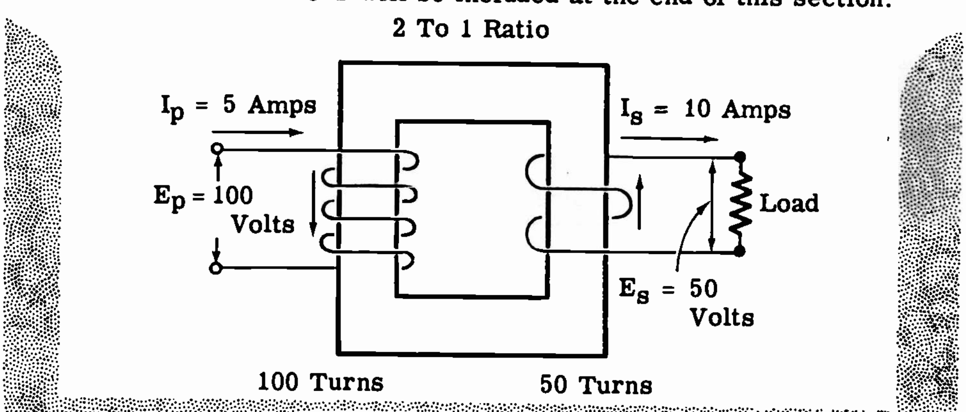
The current in the primary of a transformer flows in a direction opposite to that which flows in the secondary because of the emf of mutual-induction. An emf of self-induction is also set up in the primary which is in opposition to the applied emf.

When no load is present at the output of the secondary, the primary current is very small because the emf of self-induction is almost as large as the applied emf. If no load is present at the secondary there is no current flow. Thus, the magnetic field of self-induction, which usually bucks the magnetic field of the primary, cannot be developed in the secondary. The magnetic field of the primary may then develop to its maximum strength without opposition from the field which is usually developed by current flow in the secondary. When the primary field is developing to its maximum strength it produces the strongest possible emf of self-induction and this opposes the applied voltage. This is the point, mentioned above, at which the emf of self-induction almost equals the applied emf. Any difference between the emf of self-induction and the applied emf causes a small current to flow in the primary and this is the exciting or magnetizing current.

The current which flows in the secondary is opposite to the current in the primary. As a load is applied to the secondary it causes the momentary collapse of flux lines which produces a demagnetizing effect on the flux linking the primary. The reduction in flux lines reduces the emf of self-induction and permits more current to flow in the primary.

In all cases of electromagnetic induction the direction of the induced emf is such that the magnetic field set up by the resulting current opposes the motion which is producing the emf. This is a statement of Lenz's law which you will learn about in the next section.

In order to find the unknowns in a transformer use the formula $\frac{E_p}{E_s} = \frac{I_s}{I_p} = \frac{T_p}{T_s}$ and cross-multiply to find the required information. Further details about transformers will be included at the end of this section.



Example of a Step-Down Transformer

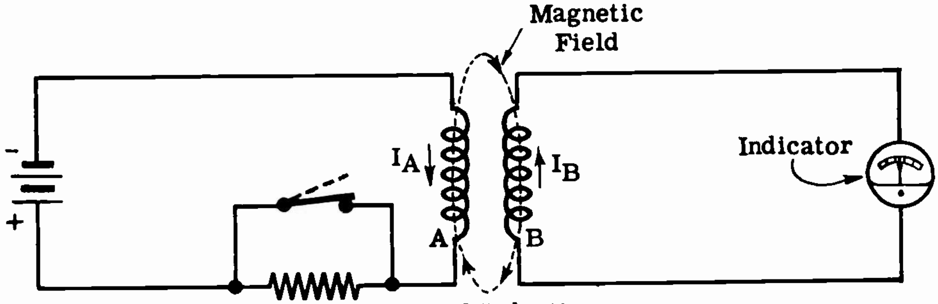
Faraday's Law

Michael Faraday was an English scientist who did a great deal of important work in the field of electromagnetism. He is of interest to you at this time because his work in mutual induction eventually led to the development of the transformer.

Faraday is responsible for the law which is used in developing the principles of mutual induction. He found that if the total flux linking a circuit changes with time, an emf is induced in the circuit. Faraday also found that if the rate of flux-change is increased, the magnitude of the induced emf is increased as well. Stated in other terms, Faraday found that the character of an emf induced in a circuit depends upon the amount of flux and also the rate of change of flux which links a circuit.

You have all seen demonstrations of the principle just stated. You have been shown that if a conductor is made to move with respect to a magnetic field an emf is induced in the conductor which is directly proportional to the velocity of the conductor with respect to the field. The other point concerning Faraday's Law which has been demonstrated is the fact that the voltage induced in a coil is proportional to the number of turns of the coil, the magnitude of the inducing flux and the rate of change of this flux.

An example of mutual induction (inducing an emf in a neighboring conductor) is now described. Consider the two coils in the figure below. Electrons are moving as a current in the directions indicated. This current produces a flux of magnetic field and if the current remains constant the number of flux lines produced is fixed. If, however, the current is changed by opening the shorting switch, the number of flux lines in coil A is decreased, and consequently the flux linking coil B is decreased also. This changing flux induces an emf in coil B, as evidenced by the movement of the indicator pointer. Thus, it is seen that energy can be transferred from one circuit to another by the principle of electromagnetic induction.



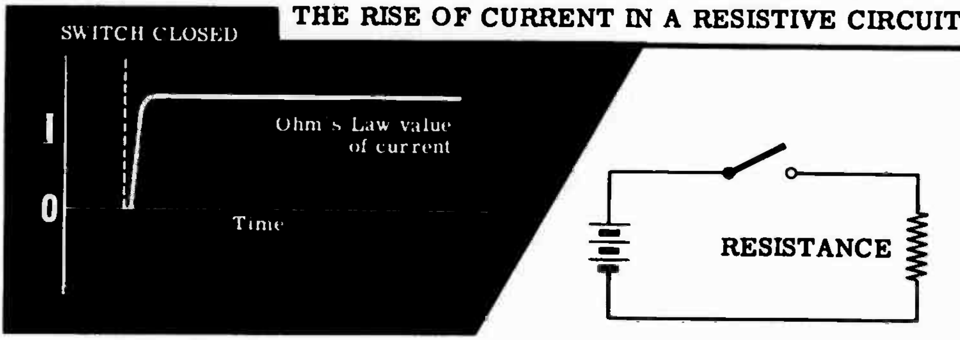
Mutual Induction

A battery is used in the above diagram as a source of emf. The only way current variations can be developed, then, is by the opening or closing of the switch. If an AC voltage source with an extremely low frequency (one cycle per second) is used to replace the battery, the indicator shows continuous variations in current. The indicator needle moves to the left (or right) first, and then reverses its position, to show the reversal in AC flow.

Inductive Time Constant in a DC Circuit

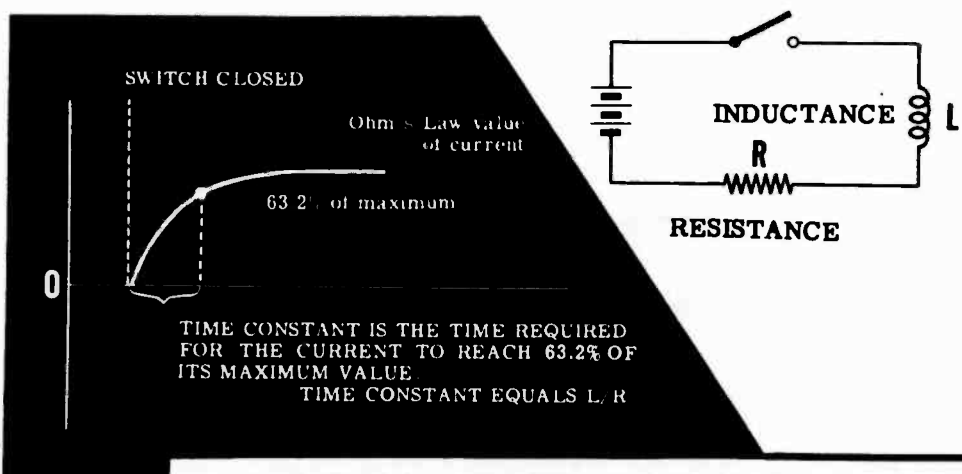
In a circuit consisting of a battery, switch and a resistor in series, the current rises to its maximum value at once whenever the switch is closed. Actually it cannot change from zero to its maximum value instantaneously, but the time is so short that it can be considered to be instantaneous.

THE RISE OF CURRENT IN A RESISTIVE CIRCUIT



If a coil of wire is used in series with the resistor, the current does not rise instantaneously—it rises rapidly at first, then more slowly as the maximum value is approached. For all inductive circuits the shape of this curve is basically the same, although the total time required to reach the maximum current value varies. The time required for the current to rise to its maximum value is determined by the ratio of the circuit inductance to its resistance in ohms. This ratio L/R—inductance divided by the resistance—is called the "time constant" of the inductive circuit and gives the time in seconds required for the circuit current to rise to 63.2 percent of its maximum value.

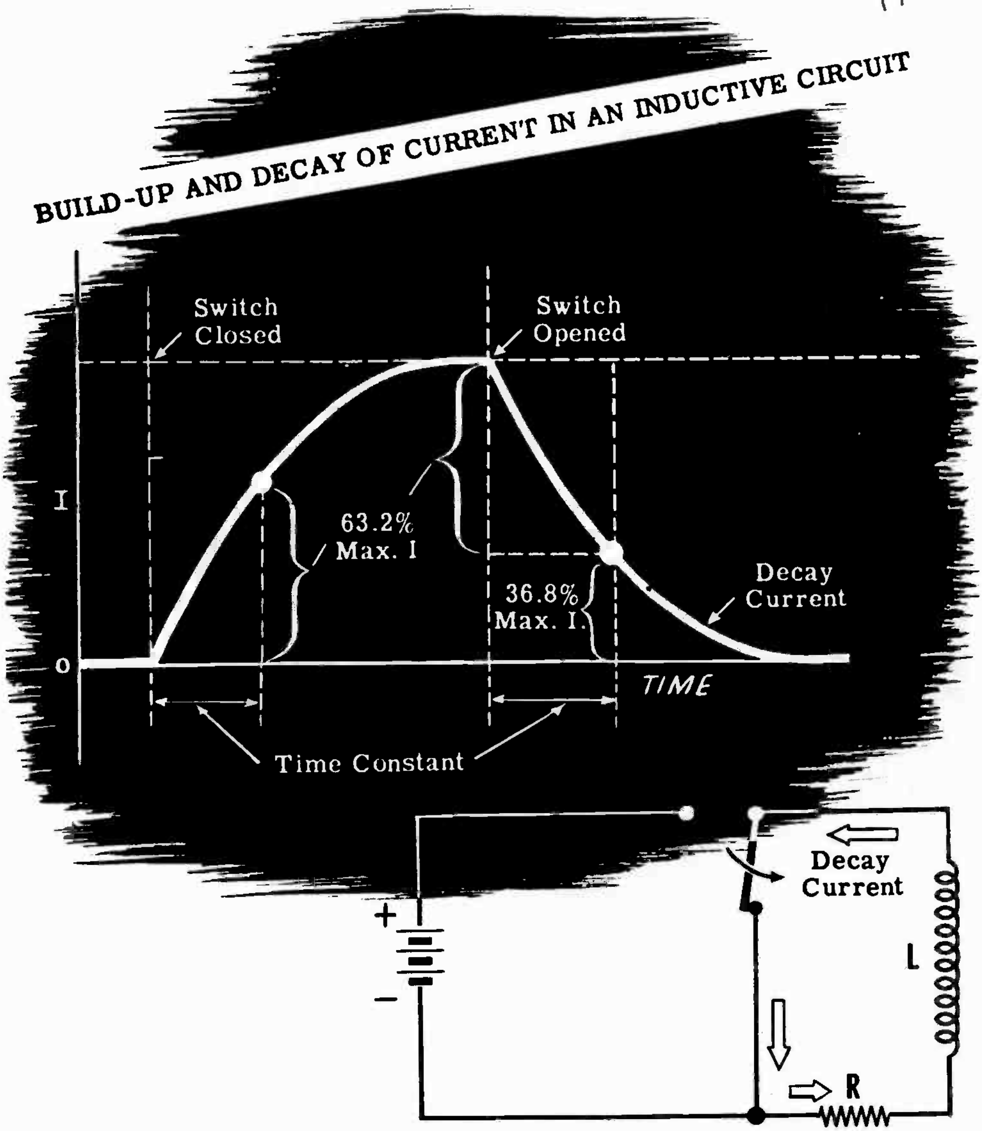
This delayed rise in the current of a circuit is called "self-inductance," and is used in many practical circuits such as time-delay relay and starting circuits.



DELAYED RISE OF CURRENT IN AN INDUCTIVE CIRCUIT

5 Time constants in the maximum

Inductive Time Constant in a DC Circuit (continued)



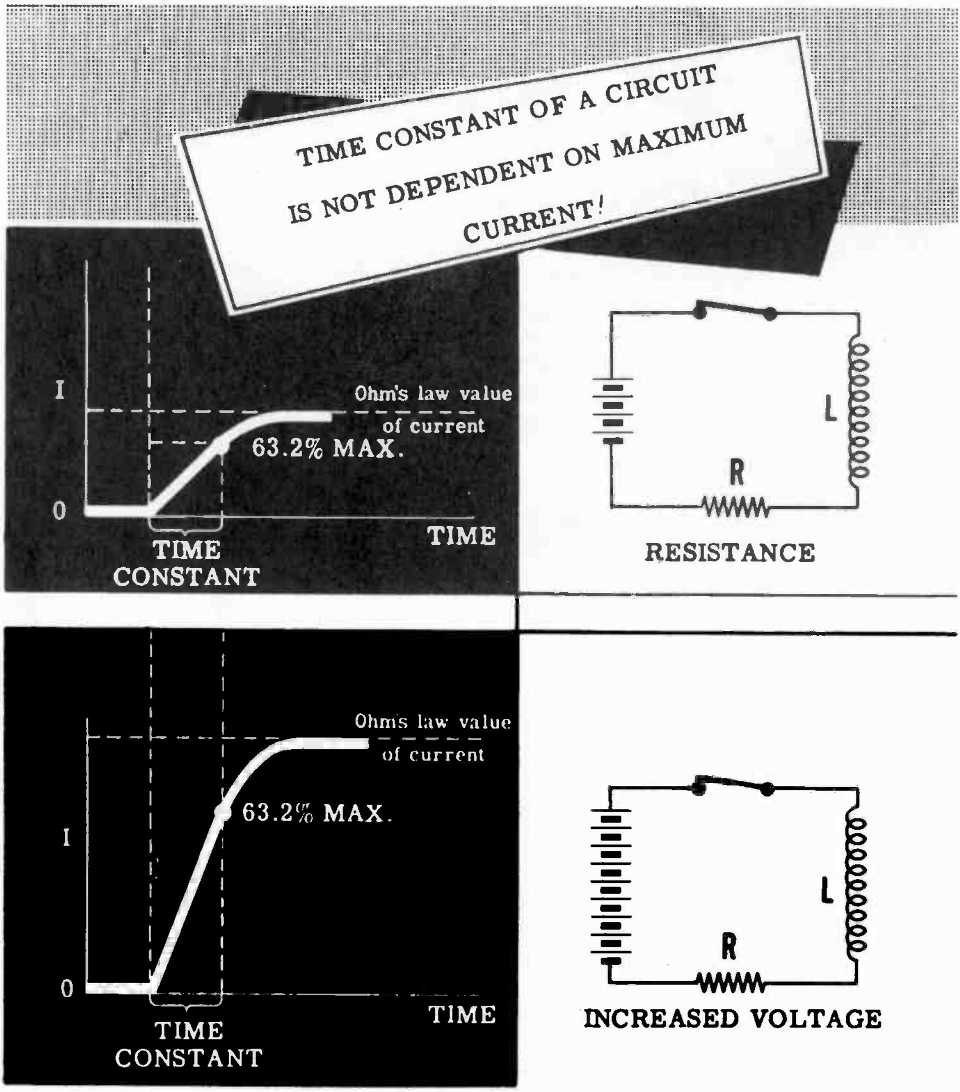
If the coil terminals are shorted together at the same moment that the battery switch is opened, the coil current continues to flow due to the action of the collapsing field. The current falls in the same manner as the original rise in current, except that the curve is in the opposite direction.

Again the "time constant" can be used to determine when the current has decreased by 63.2 percent, or has reached 36.8 percent of its original maximum value. For inductive circuits the lower the circuit resistance, the longer the time constant for the same value of inductance.

Inductive Time Constant in a DC Circuit (continued)

The time constant of a given inductive circuit is always the same for both the build-up and decay of the current. If the maximum current value differs, the curve may rise at a different rate but will reach its maximum in the same amount of time; and the general shape of the curve is the same. Thus, if a greater voltage is used, the maximum current will increase but the time required to reach the maximum is unchanged.

Every inductive circuit has resistance, since the wire used in a coil always has resistance. Thus a perfect inductance—an inductor with no resistance—is not possible.

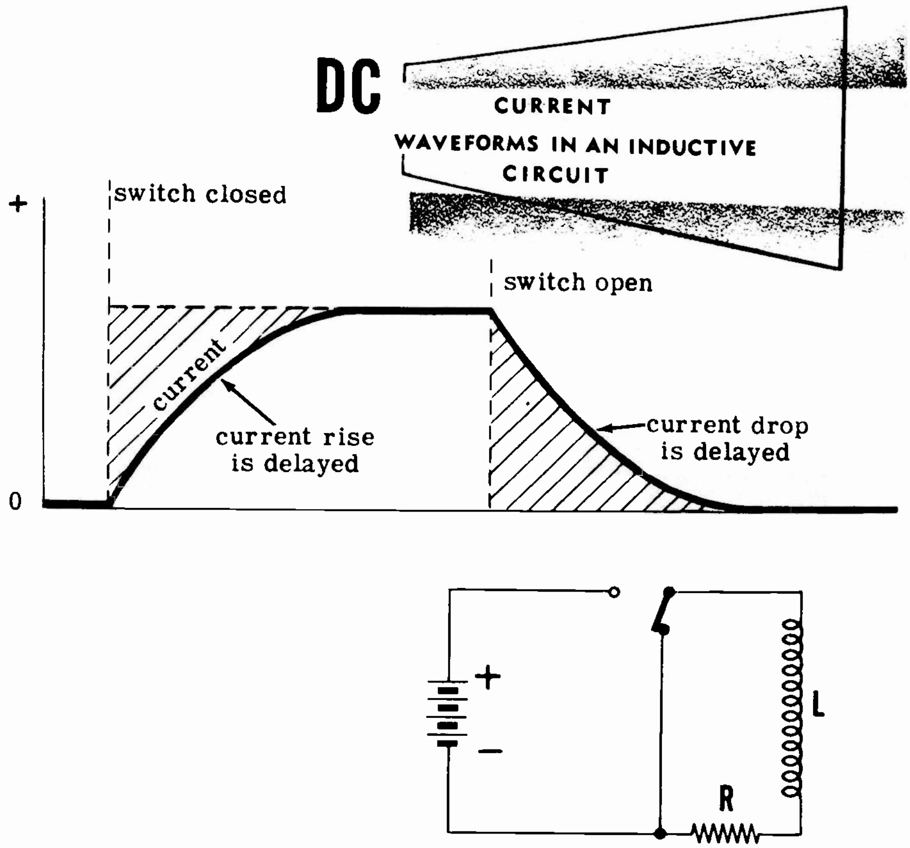


Inductive Reactance

Inductive reactance is the opposition to current flow offered by the inductance of a circuit. As you know, inductance only affects current flow while the current is changing, since the current change generates an induced emf. For direct current the effect of inductance is noticeable only when the current is turned on and off but, since alternating current is continuously changing, a continuous induced emf is generated.

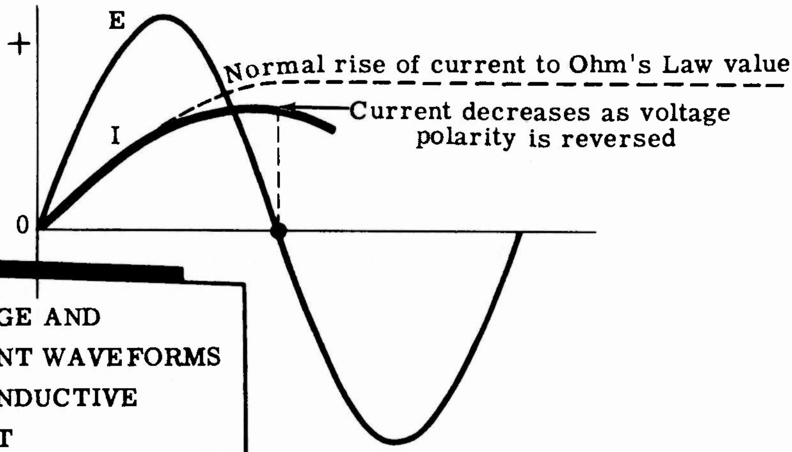
Suppose you consider the effect of a given inductive circuit on DC and AC waveforms. The time constant of the circuit is always the same, determined only by the resistance and inductance of the circuit.

For DC the current waveforms would be as shown below. At the beginning of the current waveform, there is a shaded area between the maximum current value and the actual current flow which shows that inductance is opposing the change in current as the magnetic field builds up. Also, at the end of the current waveform, a similar area exists showing that current flow continues after the voltage drops to zero because of the field collapse. These shaded areas are equal, indicating that the energy used to build up the magnetic field is given back to the circuit when the field collapses.



Inductive Reactance (continued)

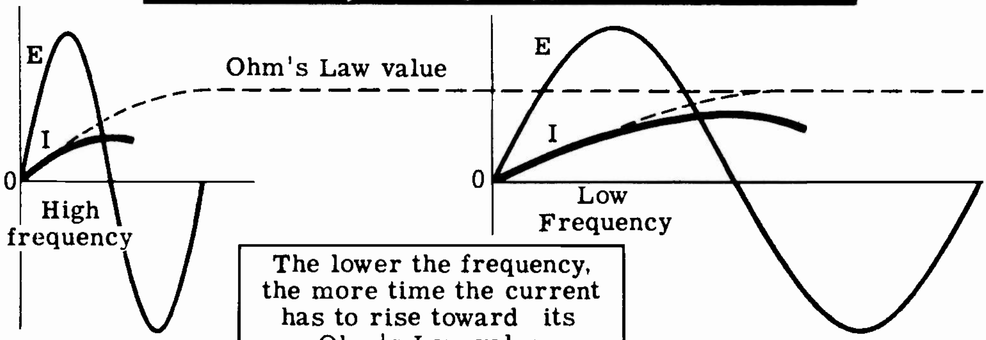
The same inductive circuit would affect AC voltage and current waveforms as shown below. The current rises as the voltage rises, but the delay due to inductance prevents the current from ever reaching its maximum DC value before the voltage reverses polarity and changes the direction of current flow. Thus, in a circuit containing inductance, the maximum current will be much greater for DC than for AC.



AC VOLTAGE AND CURRENT WAVEFORMS IN AN INDUCTIVE CIRCUIT

If the frequency of the AC wave is low, the current will have time to reach a higher value before the polarity is reversed than if the frequency is high. Thus the higher the frequency, the lower the circuit current through an inductive circuit. Frequency, then, affects the opposition to current flow as does circuit inductance. For that reason, inductive reactance—opposition to current flow offered by an inductance—depends on frequency and inductance. The formula used to obtain inductive reactance is $X_L = 2\pi fL$. In this formula X_L is inductive reactance, f is frequency in cycles per second, L is the inductance in henries, and 2π is a constant number (6.28) representing one complete cycle. Since X_L represents opposition to current flow, it is expressed in ohms.

How Frequency Affects Current

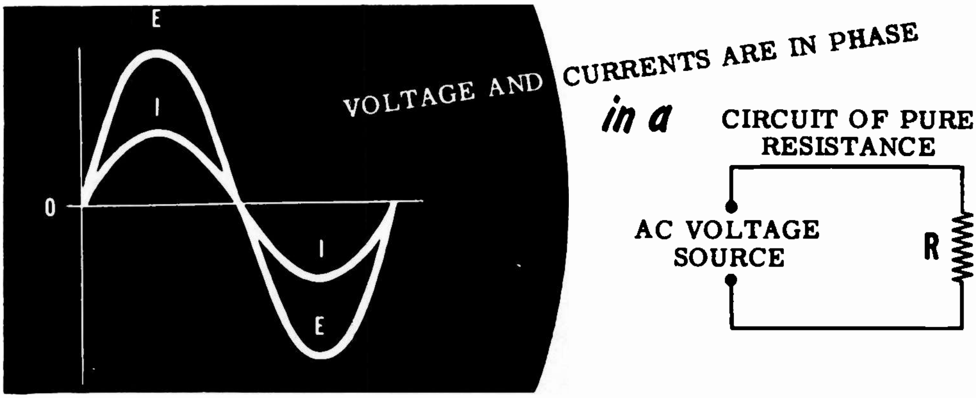


The lower the frequency, the more time the current has to rise toward its Ohm's Law value

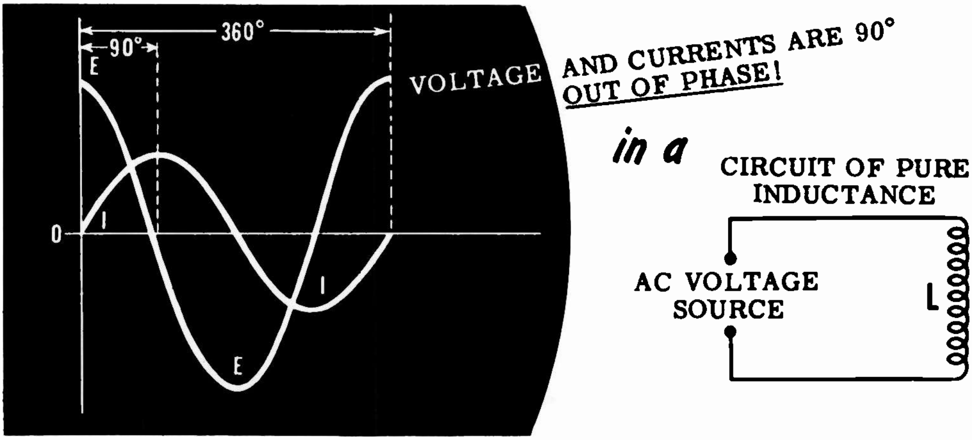
Inductive Reactance (continued)

Actually the circuit current does not begin to rise at the same time the voltage begins to rise. The current is delayed to an extent depending on the amount of inductance in the circuit as compared to the resistance.

If an AC circuit has only pure resistance, the current rises and falls at exactly the same time as the voltage and the two waves are said to be in phase with each other.



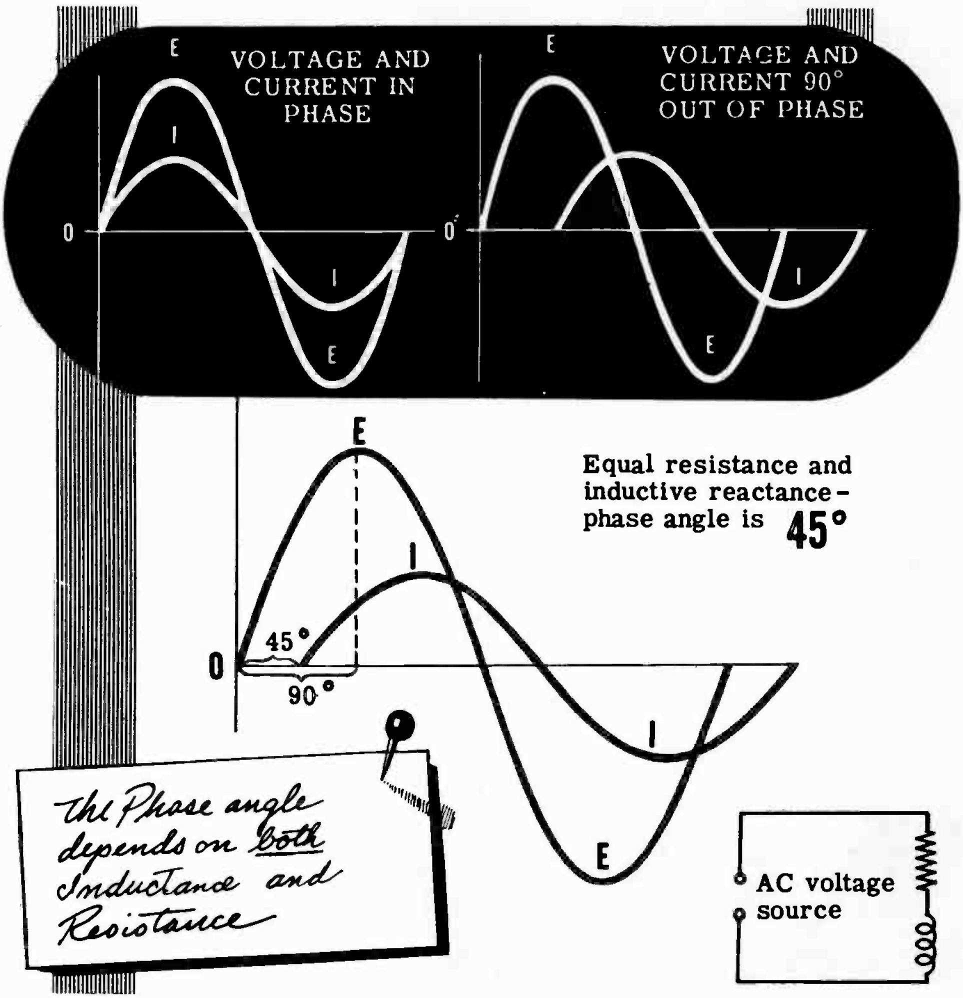
With a theoretical circuit of pure inductance and no resistance, the current will not begin to flow until the voltage has reached its maximum value, and the current wave then rises while the voltage falls to zero. At the moment the voltage reaches zero the current starts to drop towards zero, but the collapsing field delays the current drop until the voltage reaches its maximum value in the opposite polarity. This continues as long as voltage is applied to the circuit, with the voltage wave reaching its maximum value a quarter cycle before the current wave on each half cycle. A complete cycle of an AC wave is considered to be 360 degrees, represented by the emf generated in a wire rotated once around in a complete circle between two opposite magnetic poles. A quarter cycle then is 90 degrees; and in a purely inductive circuit the voltage wave leads the current by 90 degrees or, in opposite terms, the current wave lags the voltage by 90 degrees.



Inductive Reactance (continued)

In a circuit containing both inductive reactance and resistance, the AC current wave will lag the voltage wave by an amount between zero degrees and 90 degrees; or, stated otherwise, it will lag somewhere between "in phase" and "90 degrees out of phase." The exact amount of lag depends on the ratio of circuit resistance to inductance—the greater the resistance compared to the inductance, the nearer the two waves are to being "in phase"; and the lower the resistance compared to the inductance, the nearer the waves are to being a full quarter cycle (90 degrees) "out of phase."

When stated in degrees the current lag is called the "phase angle." If the phase angle between the voltage and the current is 45 degrees lagging, it means that the current wave is lagging the voltage wave by 45 degrees. Since this is halfway between zero degrees—the phase angle for a pure resistive circuit—and 90 degrees—the phase angle for a pure inductive circuit—the resistance and the inductance reactance must be equal, with each having an equal effect on the current flow.



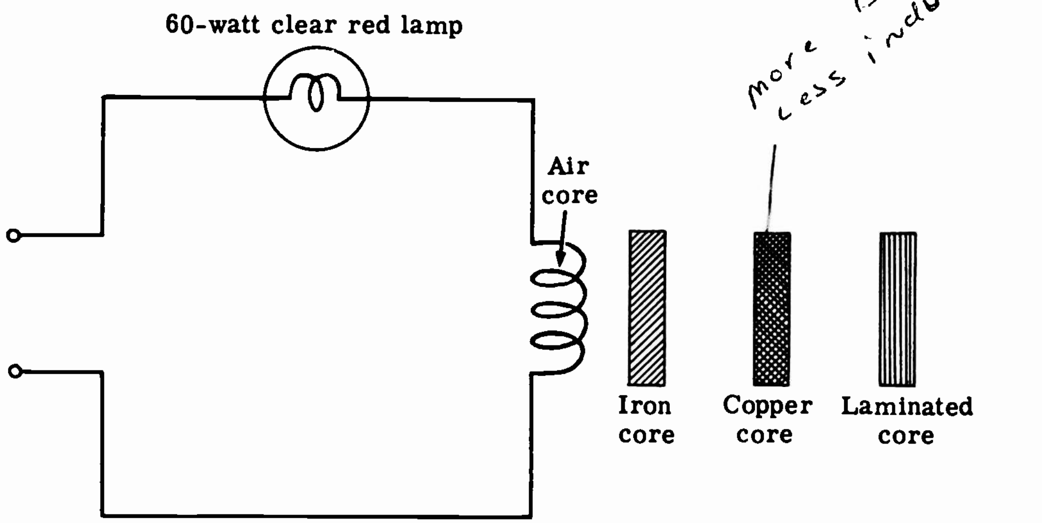
Demonstration—Effect of Core Material on Inductance

The instructor wires a series circuit of the flat air-core coil and the 60-watt lamp. When the circuit is energized from the 115-volt AC line, the lamp brilliance is noted.

With the circuit energized, the instructor carefully inserts the iron core into the coil. Note the decrease in lamp brilliance resulting from the increased inductance of the coil. A larger percentage of the 115-volt source voltage is now dropped across the coil.

Next he removes the iron core and inserts a copper core. Note the increase in lamp brilliance resulting from the decreased inductance of the coil. The large eddy current losses in the copper weaken the coil magnetic field, thus decreasing its inductance. A larger percentage of the source voltage is now dropped across the lamp and it, therefore, gets brighter.

He next removes the copper core and inserts the laminated core. Note that the lamp brilliance has dropped greatly. The laminated iron core has increased the coil inductance an even greater amount than the solid iron core because the laminations have greatly reduced the hysteresis losses. Most of the source voltage is now dropped across the coil and as a result the lamp barely lights.



HOW INDUCTANCE VARIES WITH CORE MATERIAL

Demonstration—Generation of Induced EMF

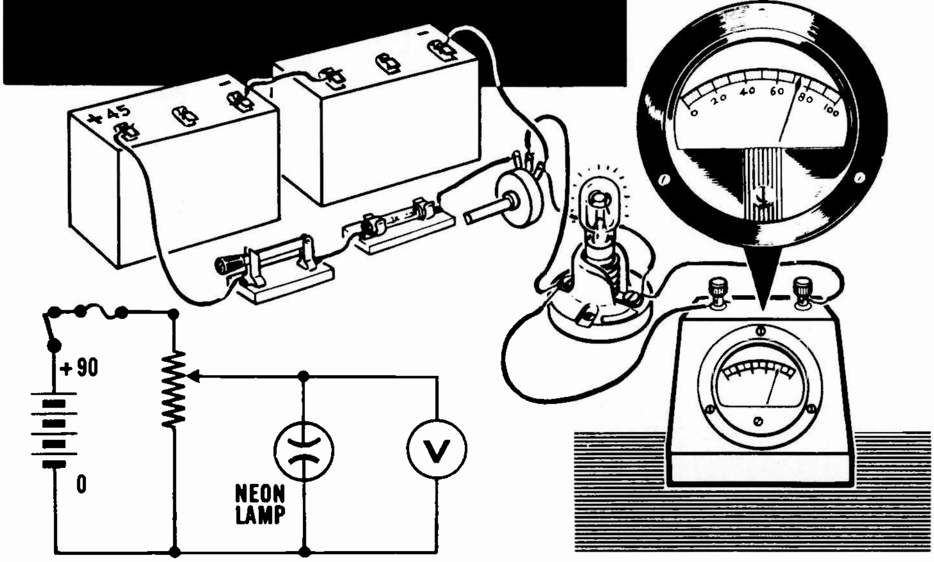
When the current flow in a DC circuit containing inductance is stopped abruptly, by opening a switch, for example, the magnetic field of the inductance tries to collapse instantaneously. The rapid collapse of the field momentarily generates a very high voltage, and this induced emf may cause an arc at the switch. While the field collapse is too rapid to allow measurement of this voltage with a voltmeter, a neon lamp can be used to show that the voltage is much higher than the original battery voltage.

Neon lamps differ from ordinary lamps in that they require a certain voltage before they begin to light. This voltage, called the "starting voltage," varies for different neon lamps. Its value can be determined by increasing the voltage applied across the lamp until it lights. The voltage applied at the time the lamp first lights is the starting voltage.

To find the starting voltage required for the neon lamp, the instructor first connects two 45-volt batteries in series to form a 90-volt battery. Across the 90-volt battery he connects a variable resistor as a potentiometer, with the outside or end terminals of the variable resistor connected to the battery terminals. A lamp socket is connected between the center terminal of the variable resistor and one of the outside terminals, and a 0-100 volt range DC voltmeter is connected across the lamp socket terminals.

With the neon lamp inserted, the instructor varies the voltage applied to the lamp by varying the setting of the variable resistor. The correct starting voltage is found by lowering the voltage to a value which does not light the lamp, and then slowly increasing it until the lamp first lights. You see that the starting voltage required to light the lamp is approximately 70 volts.

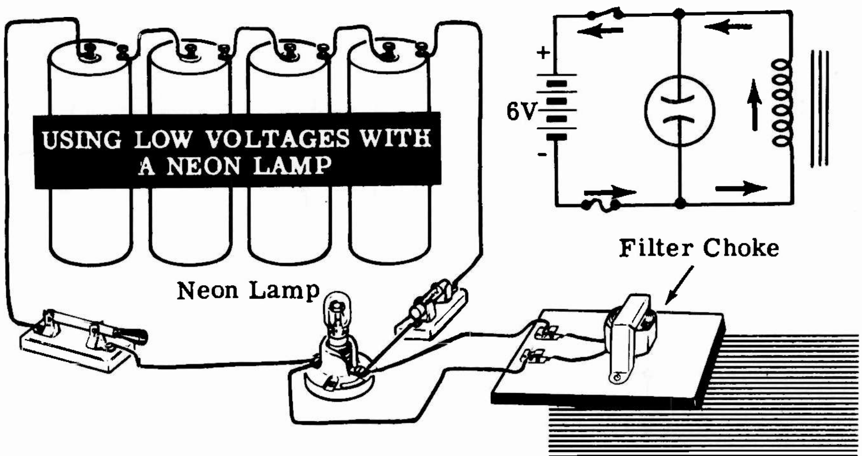
DETERMINING THE STARTING VOLTAGE OF A NEON LAMP



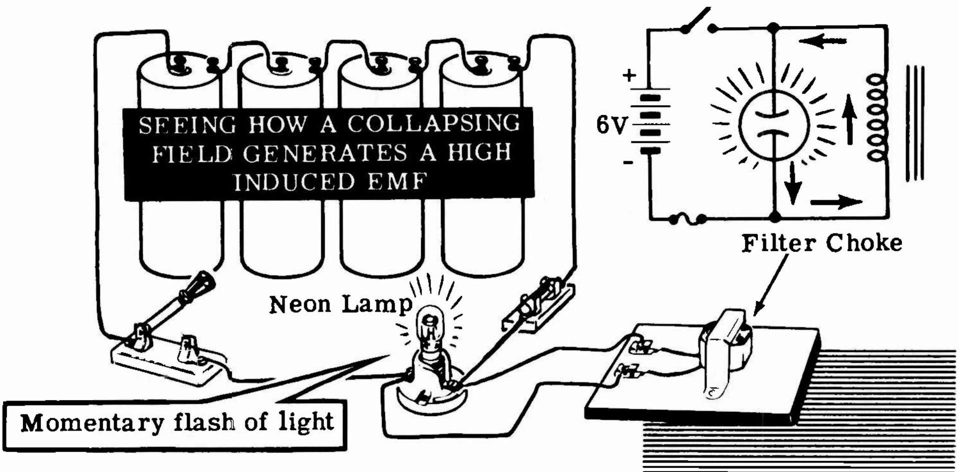
Demonstration—Generation of Induced Emf (continued)

Next, four dry cells are connected in series to form a 6-volt battery, with the lamp socket connected across its terminals through a fuse and switch. A neon lamp is inserted in the socket, and the choke coil is connected across the lamp terminals.

When the instructor closes the switch, you see that the lamp does not light and the battery voltage measured with an 0-10 volt DC voltmeter is 6 volts. Since six volts is less than the starting voltage of the lamp, some means of obtaining a higher voltage is required in order to cause the lamp to light.



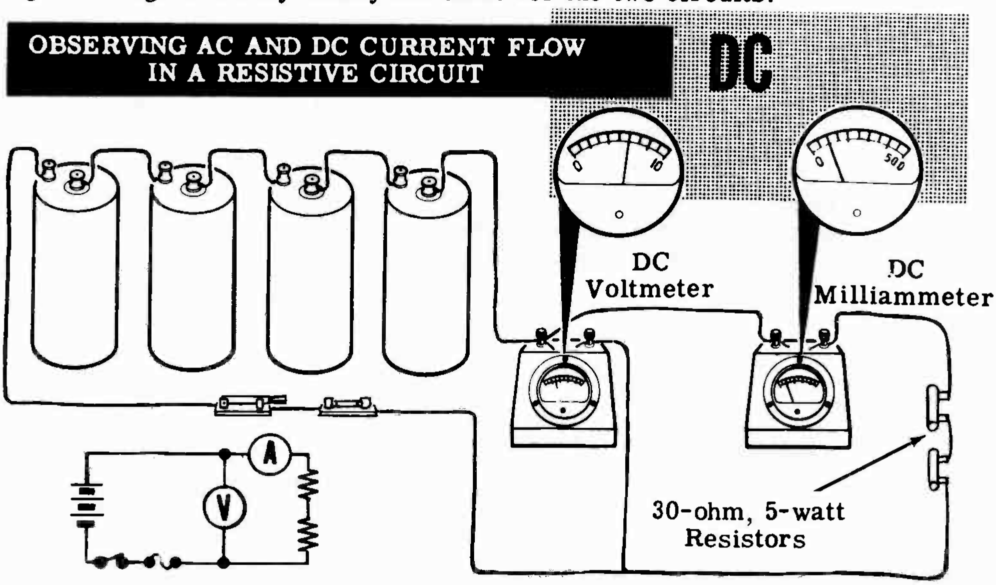
As the switch is opened you see that the lamp flashes, indicating that the voltage across the lamp and coil in parallel is higher than the starting voltage required for the lamp. This voltage is the induced emf generated by the collapsing field of the choke, and is a visible effect of inductance.



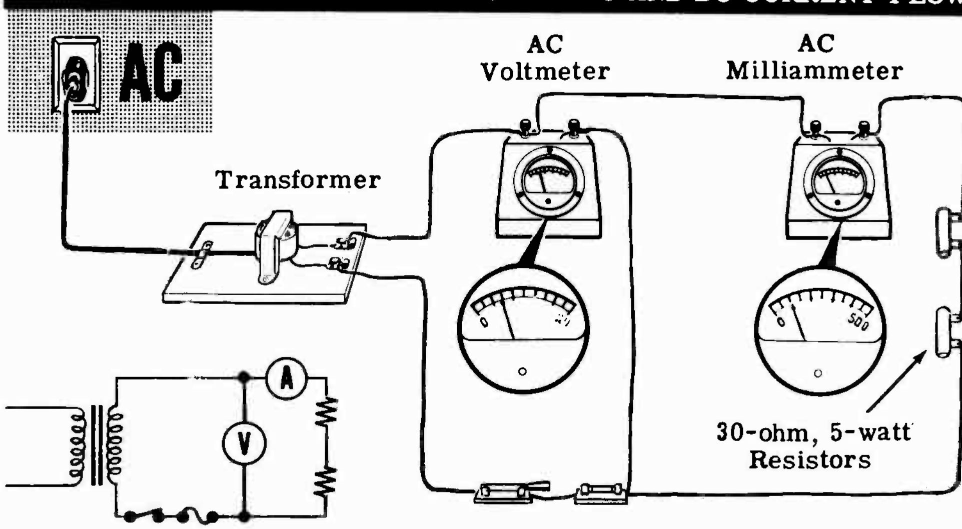
Demonstration—Current Flow in Inductive Circuits

To compare the effect of circuit inductance on the amount of current flow in AC and DC circuits, the instructor connects two identical circuits—one using the six-volt battery as a DC voltage source and the other using the 6.3-volt transformer as an AC voltage source, with the correct type of meters (AC or DC) being used in each circuit. At first the two circuits will be compared when 60 ohms of resistance is the only load, with 0-500 ma. range milliammeters, 0-10 volt DC and 0-25 volt AC voltmeters connected to measure the voltage and current. Two 30-ohm resistors in series are used to obtain each resistance. Observe that the current and voltage readings are very nearly the same for the two circuits.

OBSERVING AC AND DC CURRENT FLOW IN A RESISTIVE CIRCUIT

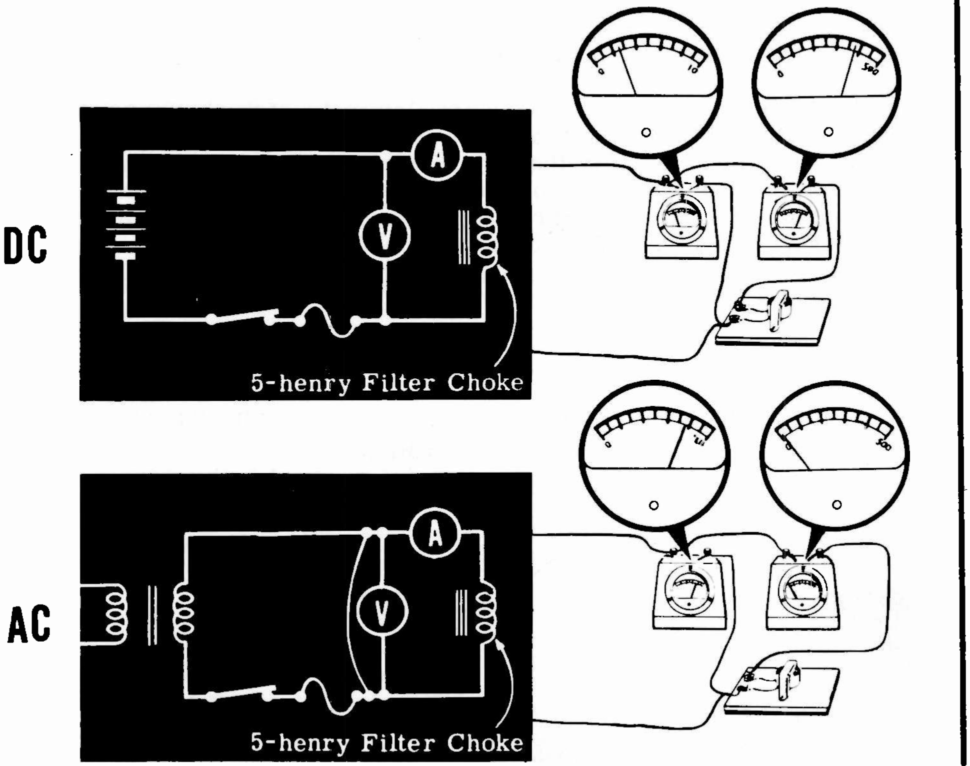


RESISTANCE HAS THE SAME EFFECT ON AC AND DC CURRENT FLOW



Demonstration—Current Flow in Inductive Circuits (continued)

OBSERVING AC AND DC CURRENT FLOW IN AN INDUCTIVE CIRCUIT



Inductance holds back AC current more than DC current

Next, the resistors are removed from the circuits and replaced by 5-henry, 60-ohm filter chokes. With power applied, you see that the current flow in the DC circuit is approximately the same as when the resistors were in the circuit, but the current in the AC circuit is much less and cannot be read on the 0-500 ma. range AC milliammeter, because the deflection is too small to be observed.

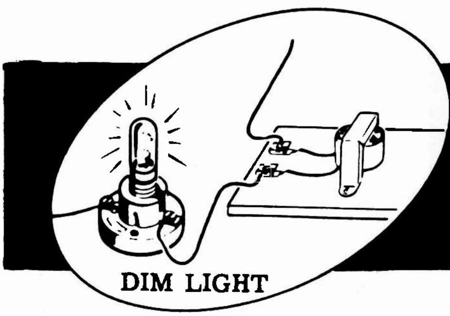
Although the filter choke is rated at 2 henries, it only operates at this value when the current is 200 ma. DC. Its inductance is greater for the smaller current values which you commonly use, and its effect can be calculated by assuming an inductance of 5 henries. For DC, the inductance has no effect, and the choke merely acts as a 60-ohm resistor. For AC, since the voltage and current are changing constantly, inductance is an important factor. The effect which inductive reactance has on AC can be calculated by using the formula $X_L = 2\pi fL$ ($2\pi = 6.28$, $f = 60$ cycles which is the power line frequency and $L = 5$ henries). You can find the inductive reactance, X_L, by substituting these values for the formula symbols and multiplying them together ($X_L = 6.28 \times 60 \times 5 = 1884\ \Omega$). Inductive reactance is expressed in ohms, since it opposes or "resists" AC current flow.

Demonstration—Current Flow in Inductive Circuits (continued)

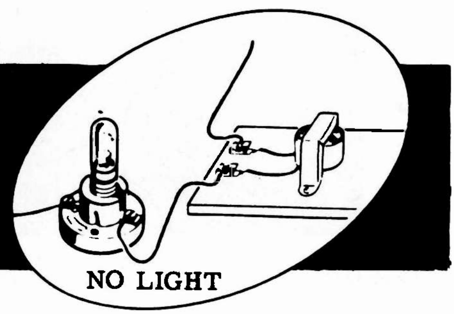
To further demonstrate that it is the inductive reactance which is reducing the current flow in the AC circuit, the instructor connects a lamp socket in series with the choke in each circuit. With the power applied to each circuit you see that the lamp lights dimly in the DC circuit, but the current in the AC circuit is insufficient to light the lamp.

Using short pieces of wire as jumpers, the instructor shorts across the terminals of the chokes in each circuit. In the DC circuit the lamp brightness increases, showing that the circuit resistance has been reduced. In the AC circuit the lamp lights to a brightness equal to that of the lamp in the DC circuit. Since the lamp brightness is changed from no light to maximum brightness in the AC circuit, you see that the choke or inductance has a great effect on the current in the AC circuit, while in the DC circuit it merely acts as a resistance.

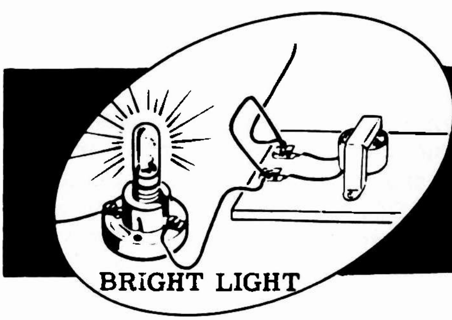
HOW INDUCTIVE REACTANCE AFFECTS THE TOTAL CIRCUIT CURRENT



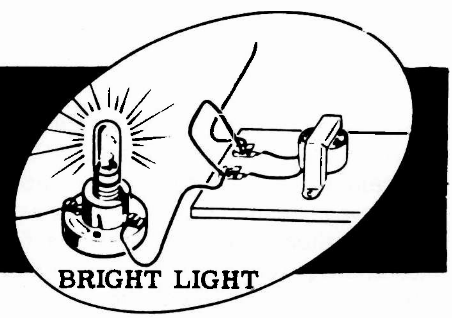
DC ___no jumper



AC ___no jumper



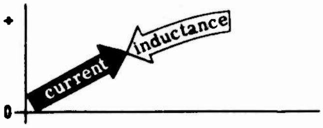
DC ___with a jumper



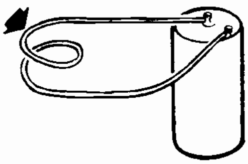
AC ___with a jumper

Review of Inductance in AC Circuits

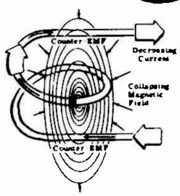
To review inductance, what it is and how it affects current flow, consider facts concerning inductance and inductive reactance.



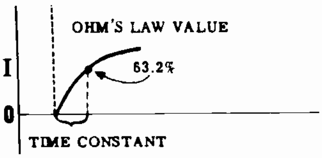
INDUCTANCE — The property of a circuit which opposes any change in the current flow; measured in henries and symbolized by letter L.



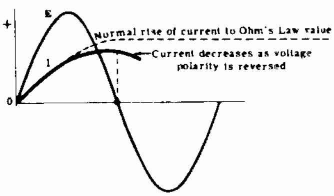
INDUCTOR — A coil of wire used to supply inductance in a circuit.



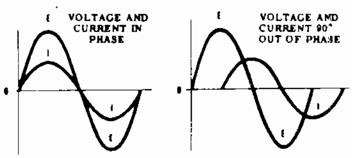
INDUCED EMF — A voltage which is generated within a circuit by the movement of the magnetic field whenever the circuit current changes, and which opposes the current change.



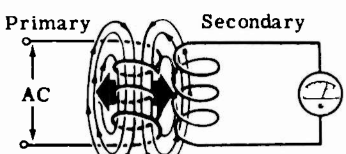
INDUCTIVE TIME CONSTANT — The ratio of L to R which gives the time in seconds required for the circuit current to rise to 63.2 percent of its maximum value.



INDUCTIVE REACTANCE — The action of inductance in opposing the flow of AC current and in causing the current to lag the voltage; measured in ohms and symbolized by letter X_L.



PHASE ANGLE — The amount in degrees by which the current wave lags the voltage wave.



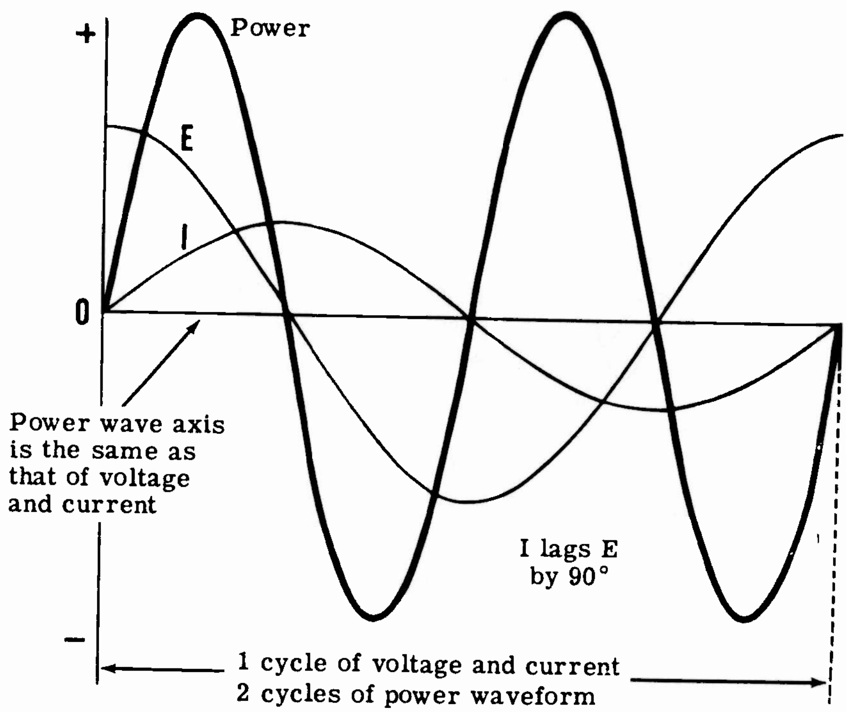
TRANSFORMER ACTION — The method of transferring electrical energy from one coil to another by means of an alternating magnetic field. The coil which generates the magnetic field is called the primary, and the coil in which the voltage is induced is called the secondary. The voltage induced in the secondary depends upon the turns ratio between the secondary and primary.

The Effect of Phase Difference on the Power Wave

In a theoretical circuit containing only pure inductance the current lags the voltage by 90 degrees. To determine the power wave for such a circuit, all of the corresponding instantaneous values of voltage and current are multiplied together to find the instantaneous values of power, which are then plotted to form the power curve.

As you already know the power curve for "in phase" voltages and currents is entirely above the zero axis, since the result is positive when either two positive numbers are multiplied together or two negative numbers are multiplied together. When a negative number is multiplied by a positive number however, the result is a negative number. Thus, in computing instantaneous values of power when the current and voltage are not in phase, some of the values are negative. If the phase difference is 90 degrees, as in the case of a theoretical circuit containing only pure inductance, half the instantaneous values of power are positive and half are negative as shown below. For such a circuit the voltage and current axis is also the power wave axis, and the frequency of the power wave is twice that of the current and voltage waves.

POWER IN A CIRCUIT CONTAINING *Inductance Only*

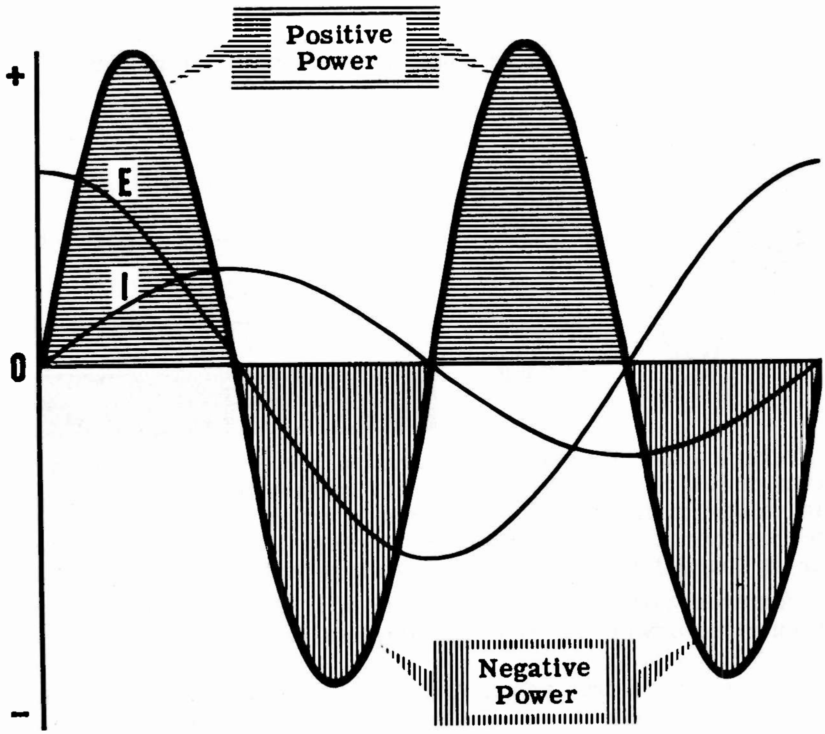


Positive and Negative Power

That portion of a power wave which is above the zero axis is called "positive power" and that which is below the axis is called "negative power." Positive power represents power furnished to the circuit by the power source, while negative power represents power the circuit returns to the power source.

In the case of a pure inductive circuit the positive power furnished to the circuit causes a field to build up. When this field collapses, it returns an equal amount of power to the power source. Since no power is used for heat or light in a circuit containing only pure inductance (if it were possible to have such a circuit), no actual power would be used even though the current flow were large. The actual power used in any circuit is found by subtracting the negative power from the positive power.

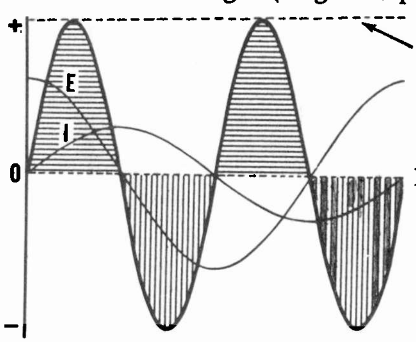
POSITIVE AND NEGATIVE POWER



Apparent and True Power

Any practical inductive circuit contains some resistance, and since the phase angle depends on the ratio between the inductive reactance and the resistance, it is always less than 90 degrees. For phase angles of less than 90 degrees the amount of positive power always exceeds the negative power, with the difference between the two representing the actual power used in overcoming the circuit resistance. For example, if your circuit contains equal amounts of inductive reactance and resistance, the phase angle is 45 degrees and the positive power exceeds the negative power, as shown below.

90° Phase Angle (Negative power equals the positive power)



Apparent power E x I = V. A.

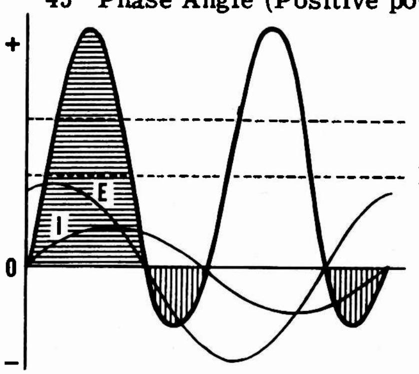
Power wave axis—True power is zero

Power Factor

$$\text{P. F.} = \frac{I^2R \text{ or } \frac{E^2}{R}}{\text{V. A.}} = 0\% \text{ at } 90°$$

Volts Amps

45° Phase Angle (Positive power exceeds negative power)



Apparent power ExI = V. A.

Power wave axis—True power used (I^2R)

$$\text{P. F.} = \frac{I^2R}{\text{V. A.}} = 70\% \text{ at } 45°$$

DECREASING THE PHASE ANGLE INCREASES THE TRUE POWER

The average value of actual power, called "true power," is represented by an axis drawn through the power wave halfway between the opposite maximum values of the wave. As the phase angle increases, this axis moves nearer to the axis for voltage and current. In AC circuits the apparent power is found by multiplying the voltage and current just as in DC circuits (Apparent power = Voltage x Current). When apparent power is divided into true power, the resultant decimal is the power factor.

Apparent power and true power for AC circuits are equal only when the circuit consists entirely of pure resistance. The difference between apparent and true power is sometimes called "wattless power" since it does not produce heat or light but does require current flow in a circuit.

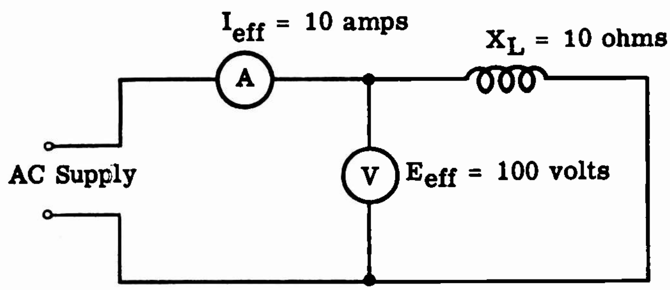
POWER IN INDUCTIVE CIRCUITS

Power Factor

You have already learned that in a pure resistive circuit I^2R or E^2/R (power in watts) is equal to Ieff Eeff (apparent power), and that the power factor is equal to 100%. Power factor is the ratio of true power to apparent power.

In an inductive circuit a phase angle exists and power in watts does not equal apparent power, and as a result power factor will be between zero and 100%.

POWER FACTOR IN A PURE INDUCTIVE CIRCUIT



$I_{eff} \times E_{eff}$ = Apparent Power (VA) = 1000

I^2R or E^2/R = True Power (Watts) = 0

$$\text{P. F.} = \frac{\text{True Power}}{\text{Apparent Power}} = \frac{\text{Watts}}{\text{Volt Amps}} = \frac{0}{1000} = 0 \text{ or } 0\%$$

Power Factor is a method of determining what percentage of the supplied power is used in watts, and what percentage is returned to the source as wattless power.

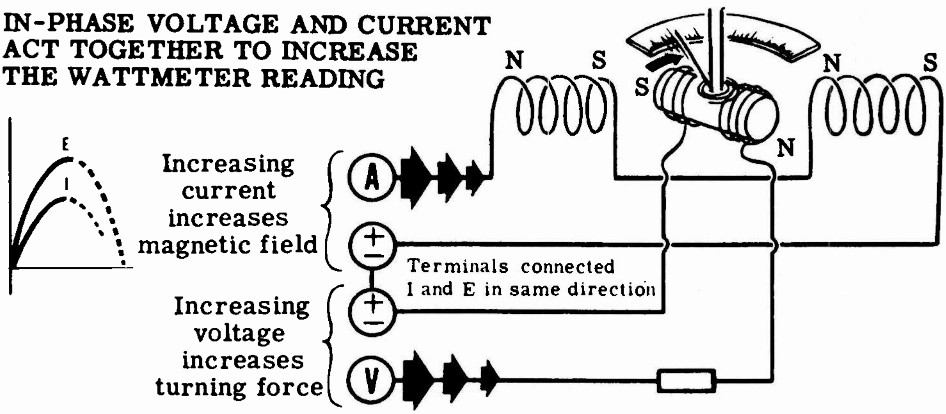
Power Factor in a pure inductive circuit is equal to zero percent. The phase angle is 90°.

Measurement of True Power

Since the product of the circuit current and voltage is the apparent power and not the true power, a wattmeter is used to measure the true power used in an AC circuit. Voltmeter and ammeter readings are not affected by the phase difference between circuit current and voltage, since the voltmeter reading is affected only by voltage and the ammeter reading is affected only by current. The wattmeter reading is affected by both the circuit current and voltage and the phase difference between them, as shown below.

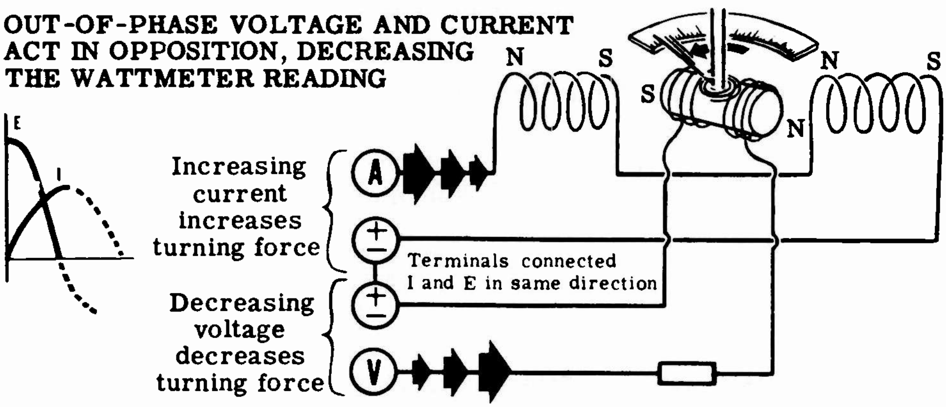
When the voltage and current are in phase, the current increases at the same time as the voltage. The circuit current increases the meter field simultaneously with the increase in current through the moving coil which is caused by the voltage. The voltage and current thus act together to increase the turning force on the meter pointer.

IN-PHASE VOLTAGE AND CURRENT ACT TOGETHER TO INCREASE THE WATTMETER READING



If the current lags the voltage, the meter field does not increase at the same time as the moving coil current. This results in less turning force on the wattmeter pointer. The power indicated then is less than with in-phase voltage and current of the same magnitude.

OUT-OF-PHASE VOLTAGE AND CURRENT ACT IN OPPOSITION, DECREASING THE WATTMETER READING



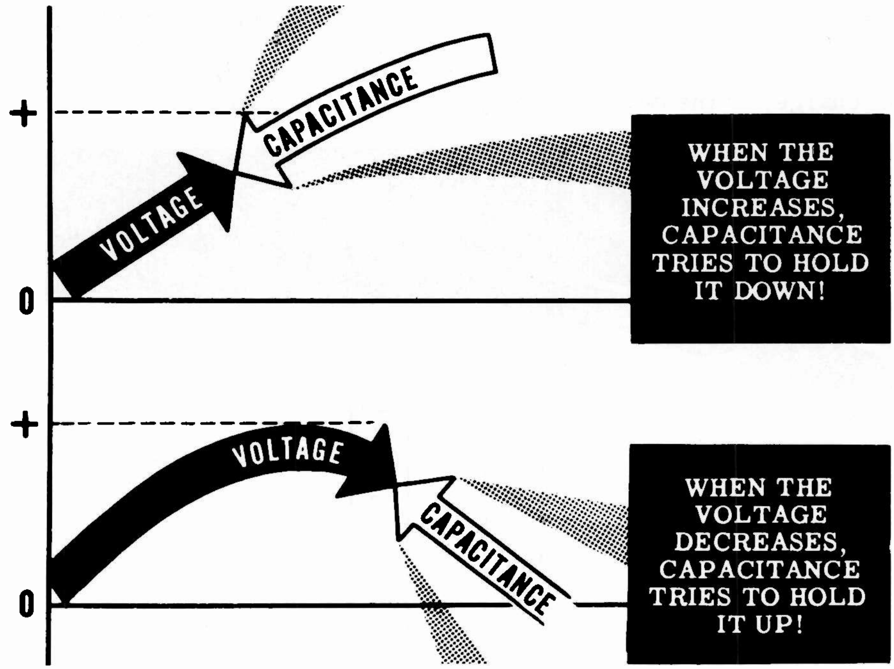
Similarly, if the current leads the voltage, the meter field strength and the moving coil current will not increase at the same time. This results in a lower wattmeter reading, the actual power used by the circuit again being less than the apparent power.

CAPACITANCE IN AC CIRCUITS

Capacitance

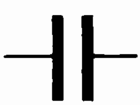
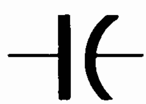
When the voltage across an electric circuit changes, the circuit opposes this change. This opposition is called "capacitance." Like inductance, capacitance cannot be seen, but its effect is present in every electrical circuit whenever the circuit voltage changes.

Capacitance Opposes Any Change in Circuit Voltage



Because DC voltage usually varies only when it is turned on and off, capacitance affects DC circuits only at these times. In AC circuits, however, the voltage is continuously changing, so that the effect of capacitance is continuous. The amount of capacitance present in a circuit depends on the physical construction of the circuit and the electrical devices used. The capacitance may be so small that its effect on circuit voltage is neglibible.

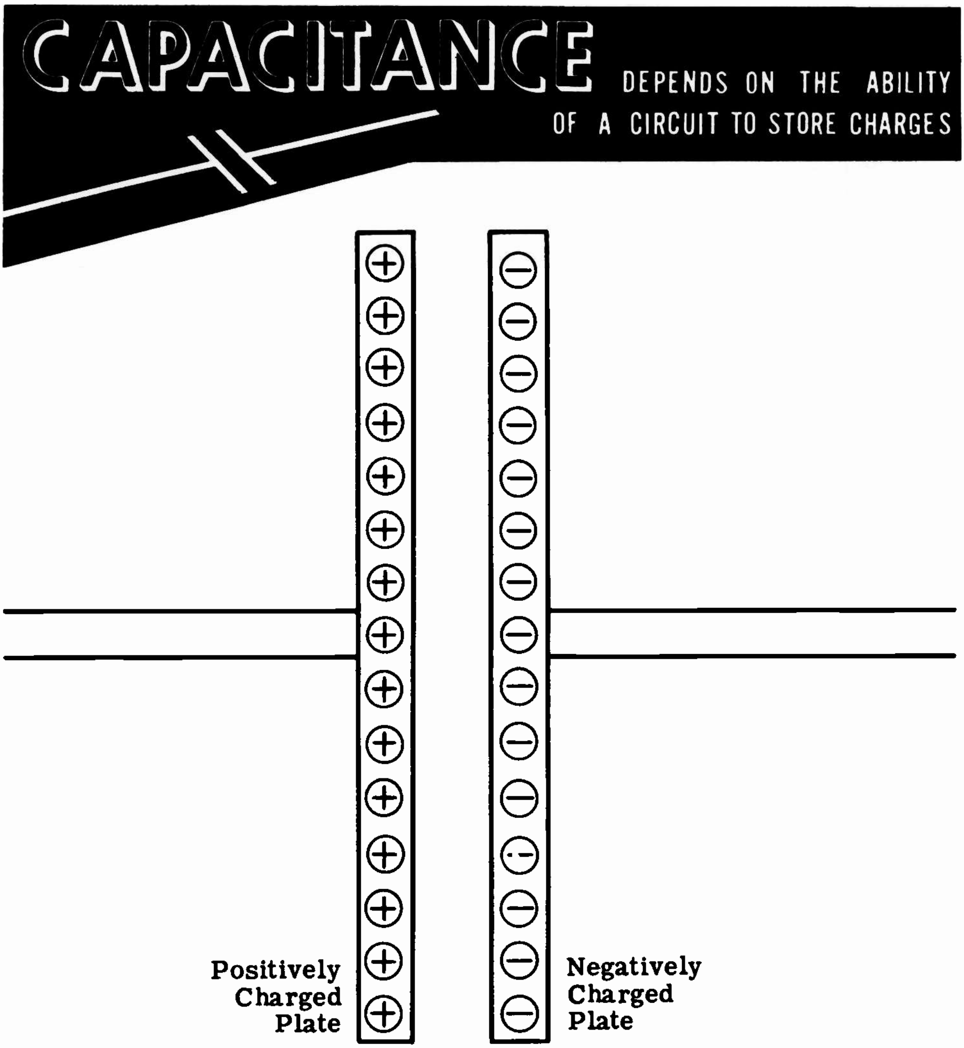
Electrical devices which are used to add capacitance to a circuit are called "capacitors," and the circuit symbol used to indicate a capacitor is shown below. Another term frequently used instead of capacitor is "condenser." You will often find the words "capacitor" and "condenser" used interchangeably, but they mean the same thing.

Symbols for condensers and capacitors  or 

Capacitance (continued)

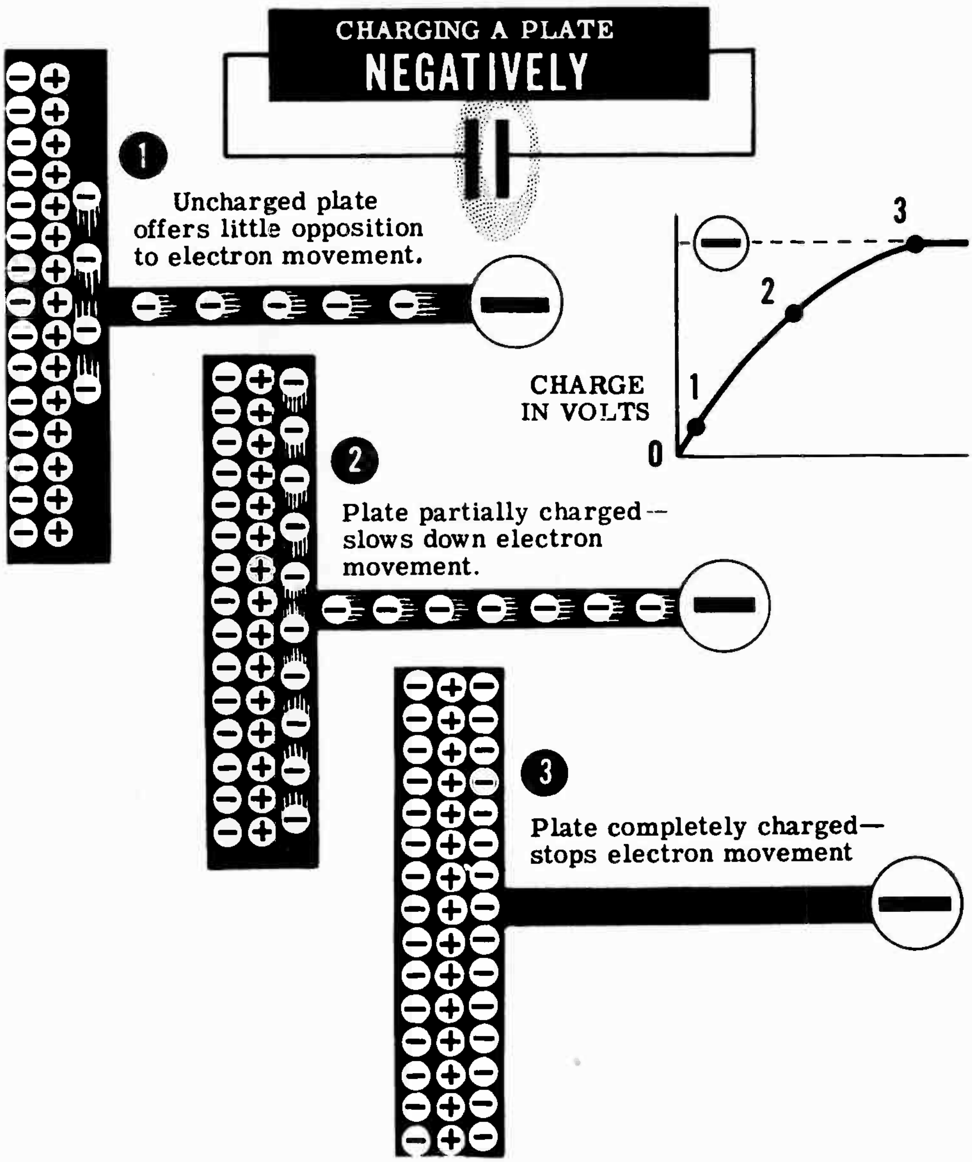
Capacitance exists in an electric circuit because certain parts of the circuit are able to store electric charges. Consider two flat metal plates placed parallel to each other, but not touching. You have already found out —while working with static electricity—that these plates can be charged either positively or negatively, depending on the charge which you transfer to them. If charged negatively, a plate will take extra electrons, but if charged positively it will give up some of its electrons. Thus the plates may have either an excess or lack of electrons.

The plates may be charged independently with either plate being charged positively, negatively, or having no charge. Thus they may both have no charge, one plate only may be charged, both plates may have the same type of charge, or the two plates may have opposite charges.



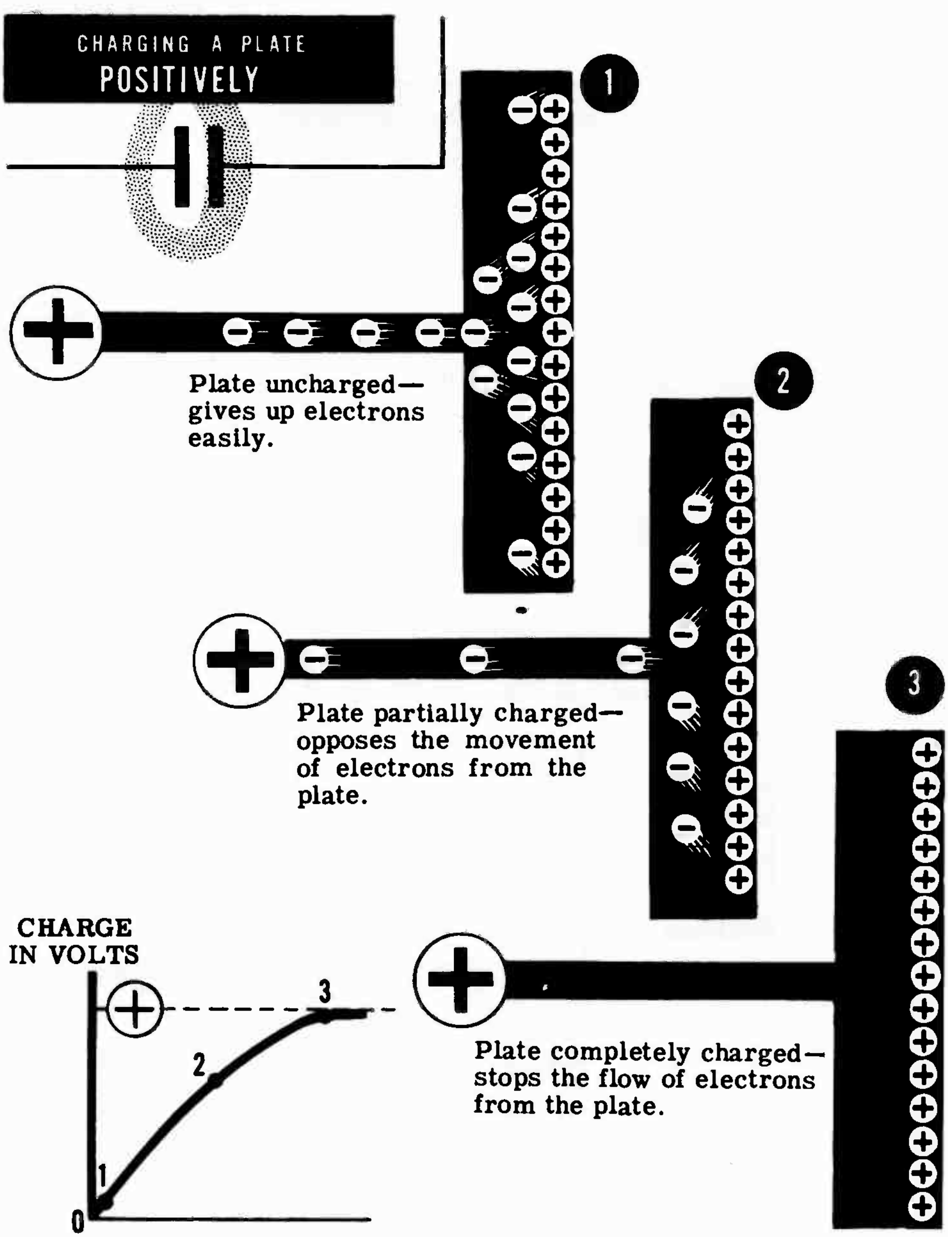
Capacitance (continued)

In order to charge the plates, an electrical force is required. The greater the charge to be placed on each plate, the greater the electrical force required. For example, to charge a plate negatively, you must force extra electrons onto it from a source of negative charge. The first few extra electrons go onto the plate easily but once there, they oppose or repel any other electrons which try to follow them. As more electrons are forced onto the plate, this repelling force increases, so that a greater force is required to move additional electrons. When the negative repelling force equals the charging force, no more electrons will move onto the plate.



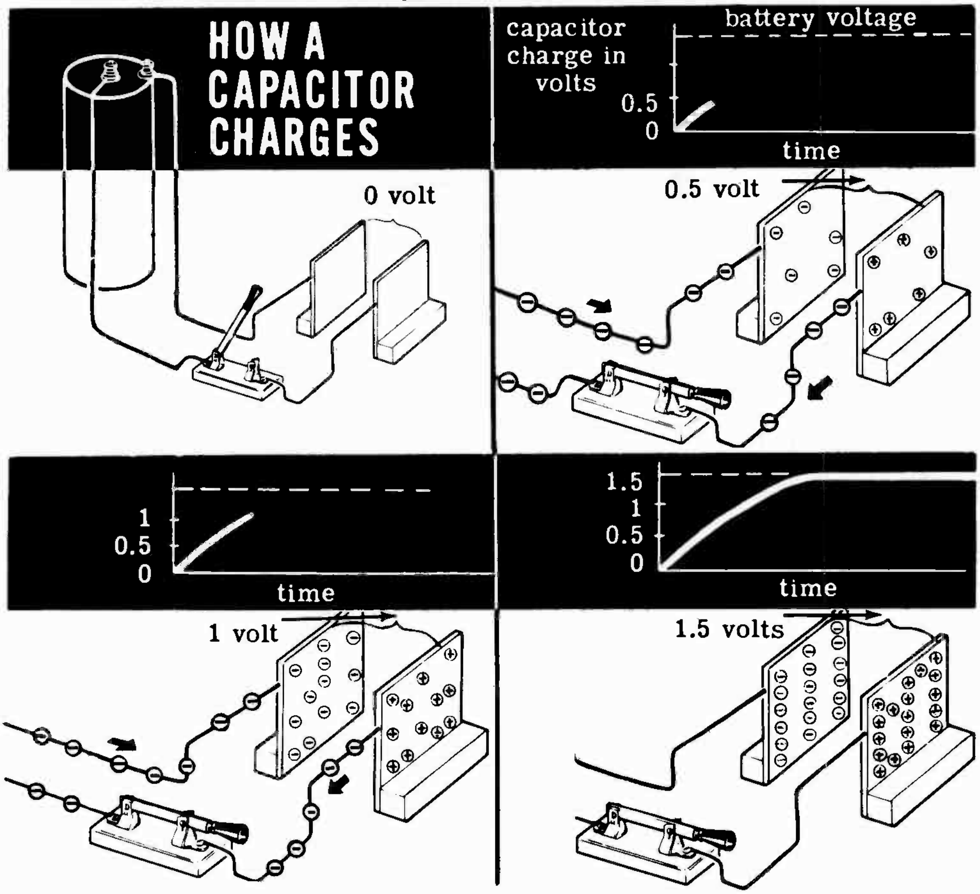
Capacitance (continued)

Similarly, if electrons are removed from a plate by the attraction of a positive charge, the plate is positively charged. The first few electrons leave quite easily; but, as more electrons leave, a strong positive charge is built up on the plate. This positive charge attracts electrons and makes it more difficult to pull them away. When this positive attracting force equals the charging force, no more electrons leave the plate.



Capacitance (continued)

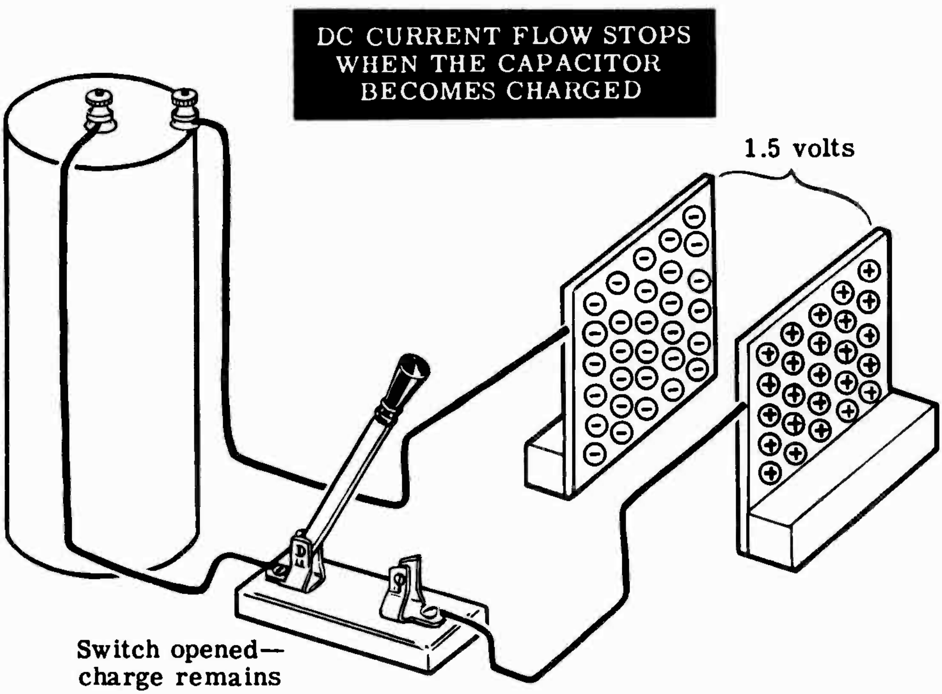
To see how capacitance affects the voltage in a circuit, suppose your circuit contains a two plate capacitor, a knife switch and a dry cell as shown below. Assuming both plates are uncharged and the switch is open, then no current flows and the voltage between the two plates is zero.



When the switch is closed, the battery furnishes electrons to the plate connected to the negative terminal and takes electrons away from the plate connected to the positive terminal. The voltage between the two plates should equal the voltage between the cell terminals, or 1.5 volts. However, this does not occur instantly because, in order for a voltage of 1.5 volts to exist between the two plates, one plate must take excess electrons to become negatively charged, while the other must give up electrons to become positively charged. As electrons move onto the plate attached to the negative terminal of the cell, a negative charge is built up which opposes the movement of more electrons onto the plate; and similarly, as electrons are taken away from the plate attached to the positive terminal, a positive charge is built up which opposes the removal of more electrons from that plate. This action on the two plates is called "capacitance" and it opposes the change in voltage (from zero to 1.5 volts). It delays the change in voltage for a limited amount of time but it does not prevent the change.

Capacitance (continued)

When the switch is opened the plates remain charged, since there is no path between the two plates through which they can discharge. As long as no discharge path is provided, the voltage between the plates will remain at 1.5 volts and, if the switch is again closed, there will be no effect on the circuit since the capacitor is already charged.



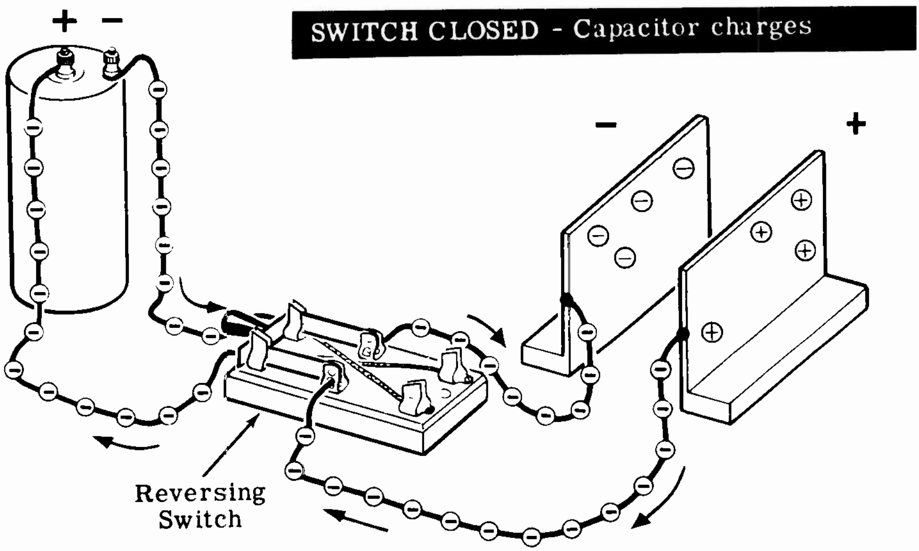
With a DC voltage source then, current will flow in a capacitive circuit only long enough to charge the capacitor (often called a "condenser"). When the DC circuit switch is closed, an ammeter connected to read circuit current would show that a very large current flows at first, since the condenser plates are uncharged. Then as the plates gain polarity and oppose additional charge, the charging current decreases until it reaches zero—at the moment the charge on the plates equals the voltage of the DC voltage source.

This current which charges a capacitor flows only for the first moment after the switch is closed. After this momentary flow the current stops, since the plates of the capacitor are separated by an insulator which does not allow electrons to pass through it. Thus capacitors or condensers will not allow DC current to flow continuously through a circuit.

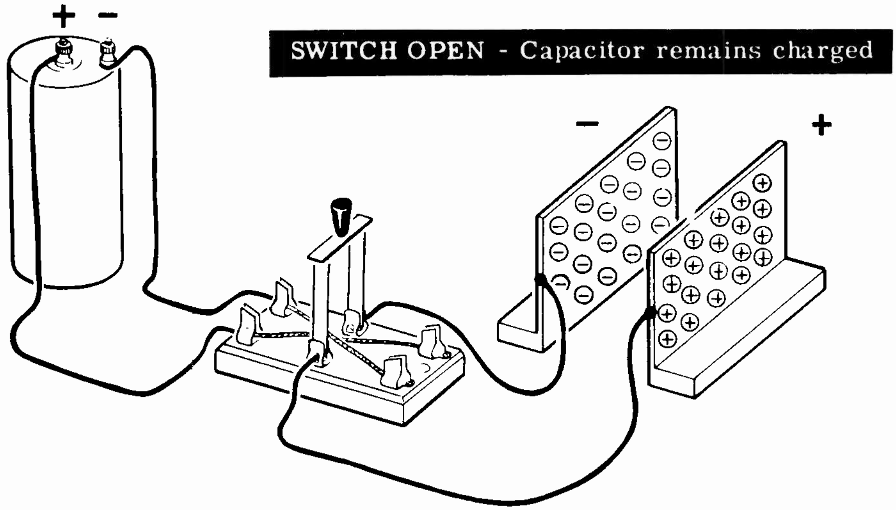
Capacitance (continued)

While a capacitor blocks the flow of DC current it affects an AC circuit differently, allowing AC current to flow through the circuit. To see how this works, consider what happens in the DC circuit if a double-throw switch is used with the dry cell so that the charge to each plate is reversed as the switch is closed—first in one position and then in the other.

When the switch is first closed the condenser charges, with each plate being charged in the same polarity as that of the cell terminal to which it is connected.



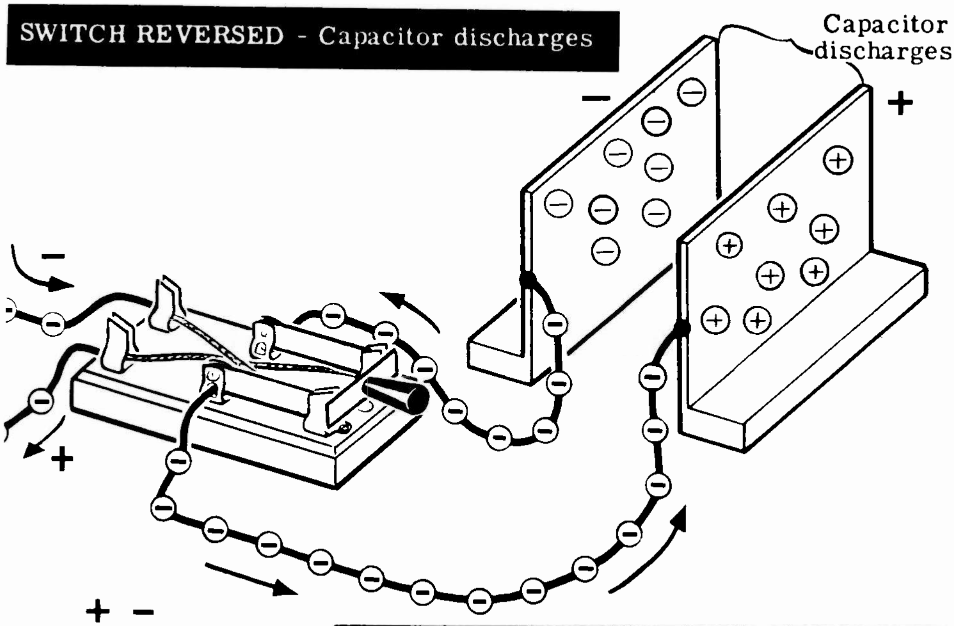
Whenever the switch is opened, the condenser retains the charges on its plates equal to the cell voltage.



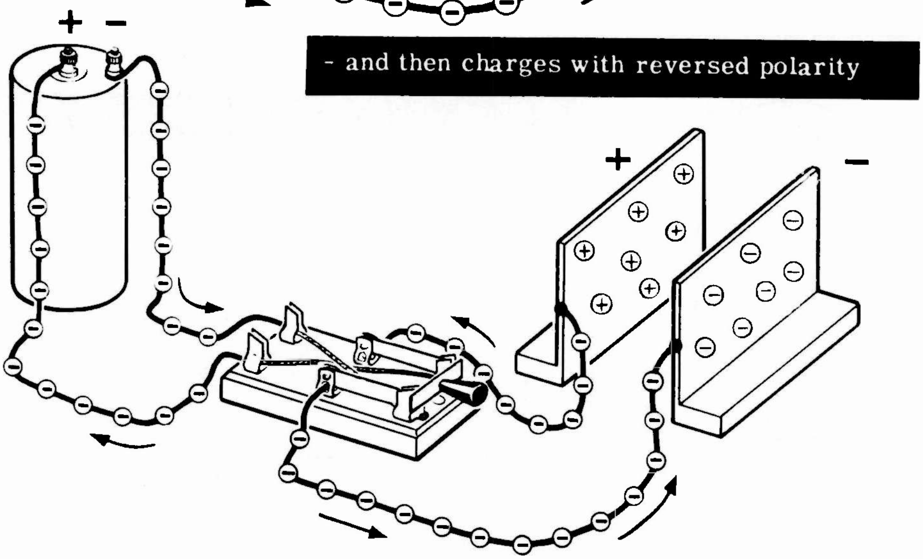
Capacitance (continued)

If the switch is then closed in its original position no current flows, since the condenser is charged in that polarity. However, if the switch is closed in the opposite direction, the condenser plates are connected to cell terminals opposite in polarity to their charges. The positively charged plate then is connected to the negative cell terminal and will take electrons from the cell—first to neutralize the positive charge, then to become charged negatively until the condenser charge is in the same polarity and of equal voltage to that of the cell. The negatively charged plate gives up electrons to the cell, since it must take on a positive charge equal to that of the cell terminal to which it is connected.

SWITCH REVERSED - Capacitor discharges



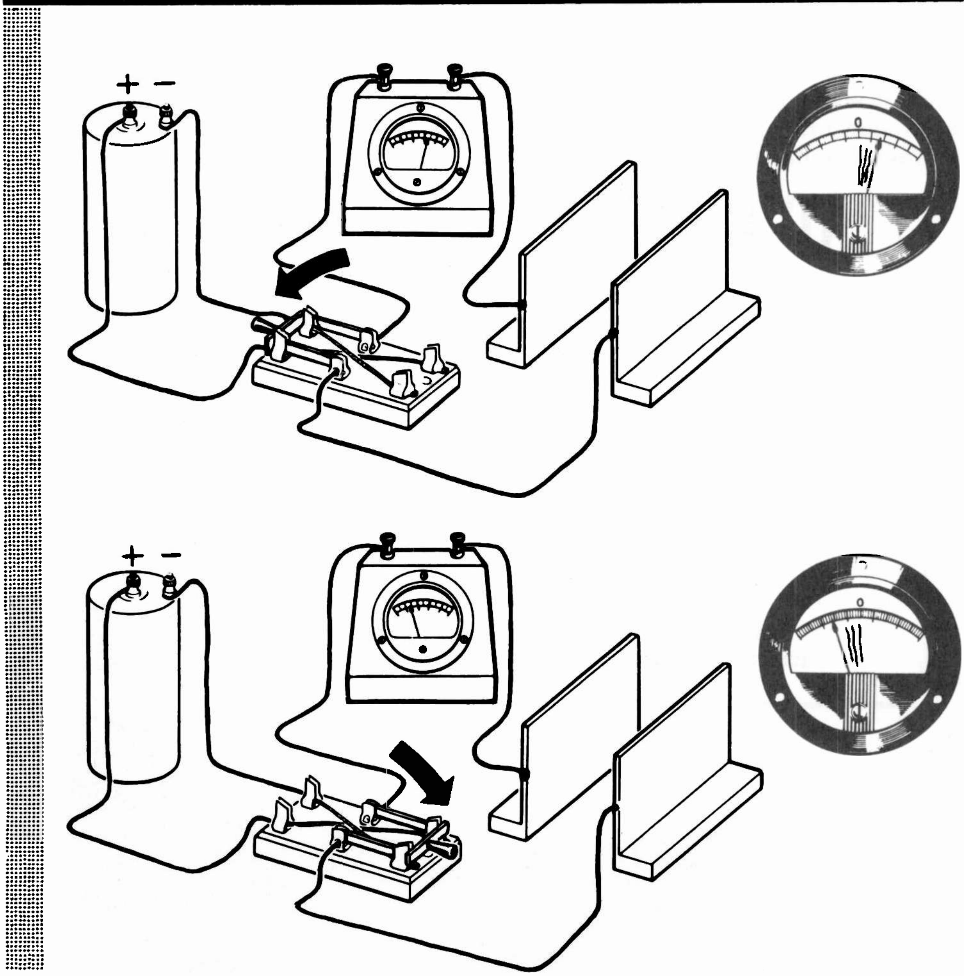
- and then charges with reversed polarity



Capacitance (continued)

If a zero-center ammeter which can read current flow in both directions is inserted in series with one of the capacitor plates, it will indicate a current flow each time the plate is charged. When the reversing switch is first closed, it shows a current flow in the direction of the original charge. Then, when the cell polarity is reversed, it shows a current flow in the opposite direction as the plate first discharges, then charges in the opposite polarity. The meter shows that current flows only momentarily, however, each time the cell polarity is reversed.

CHARGE AND DISCHARGE CURRENT OF A CAPACITOR AS THE SOURCE VOLTAGE REVERSES



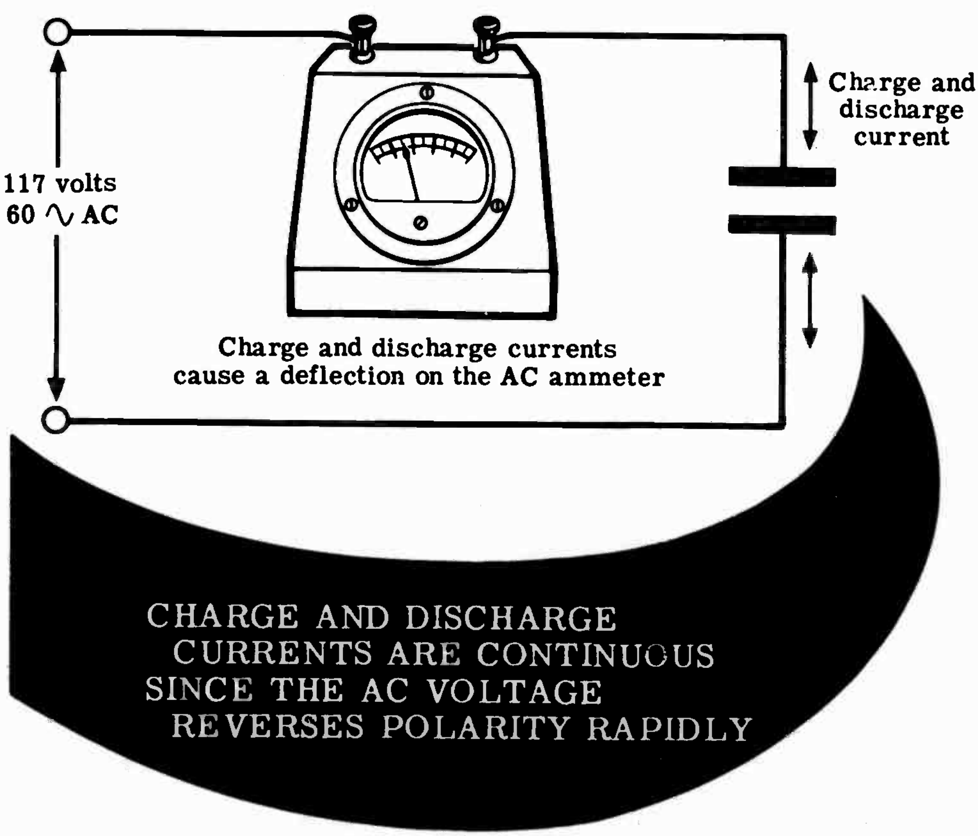
Suppose you switch the cell polarity fast enough so that at the instant the condenser plates become charged in one polarity, the cell polarity is reversed. The meter needle now moves continuously—first showing a current flow in one direction, then in the opposite direction. While no electrons move through the air from one plate to the other, the meter shows that current is continuously flowing to and from the condenser plates.

Capacitance (continued)

If a source of AC voltage is used instead of the dry cell and reversing switch, the polarity of the voltage source is automatically changed each half cycle. If the frequency of the AC voltage is low enough, the ammeter will show current flow in both directions, changing each half cycle as the AC polarity reverses.

The standard commercial frequency is 60 cycles so that a zero-center ammeter will not show the current flow, since the meter pointer cannot move fast enough. Even though it did, you would not be able to see the movement due to its speed. However, an AC ammeter inserted in place of the zero-center ammeter shows a continuous current flow when the AC voltage source is used, indicating that in the meter and in the circuit there is a flow of AC current. Remember that this current flow represents the continuous charging and discharging of the capacitor plates, and that no actual electron movement takes place directly between the plates of the capacitor. Capacitors are considered to pass AC current, because current actually flows continuously in all parts of the circuit except the insulating material between the capacitor plates.

AC CURRENT in a capacitive circuit



CAPACITANCE IN AC CIRCUITS

Units of Capacitance

The action of capacitance in a circuit is to store a charge and to increase its charge if the voltage rises, or discharge if the voltage falls. Every circuit has some capacitance, with the amount depending on the ability of the circuit to store a charge.

The basic unit of capacitance is the farad, but the storage capacity of a farad is much too great to use as the unit of capacitance for practical electrical circuits. Because of this, the units normally used are the microfarad (equal to one-millionth of a farad) and the micromicrofarad (equal to one-millionth-millionth of a farad). Since electrical formulas use capacitance stated in farads, it is necessary that you are able to change the various units of capacitance to other units. Again the method of changing units is exactly like that used for changing units of voltage, current, ohms, etc. To change to larger units, the decimal point moves to the left; while to change to smaller units, the decimal is moved to the right.

CHANGING UNITS OF CAPACITANCE

MICROFAROADS TO FARADS
Move the decimal point 6 places to the left
120 mfd equals 0.000120 farad

FARADS TO MICROFARAD
Move the decimal point 6 places to the right
8 farads equals 8,000,000 mfd

MICROMICROFARADS TO FARADS
Move the decimal point 12 places to the left
1500 mmf equals 0.000000001500 farad

FARADS TO MICROMICROFARADS
Move the decimal point 12 places to the right
2 farads equals 2,000,000,000,000 mmf

MICROMICROFARADS TO MICROFARADS
Move the decimal point 6 places to the left
250 mmf equals 0.000250 mfd

MICROFARADS TO MICROMICROFARADS
Move the decimal point 6 places to the right
2 mfd equals 2,000,000 mmf

In electrical formulas the letter C is used to denote capacitance in farads. The circuit symbols for capacitance are shown below. These symbols are also used to indicate capacitors, both fixed and variable. Most circuit capacitance is due to capacitors (condensers).

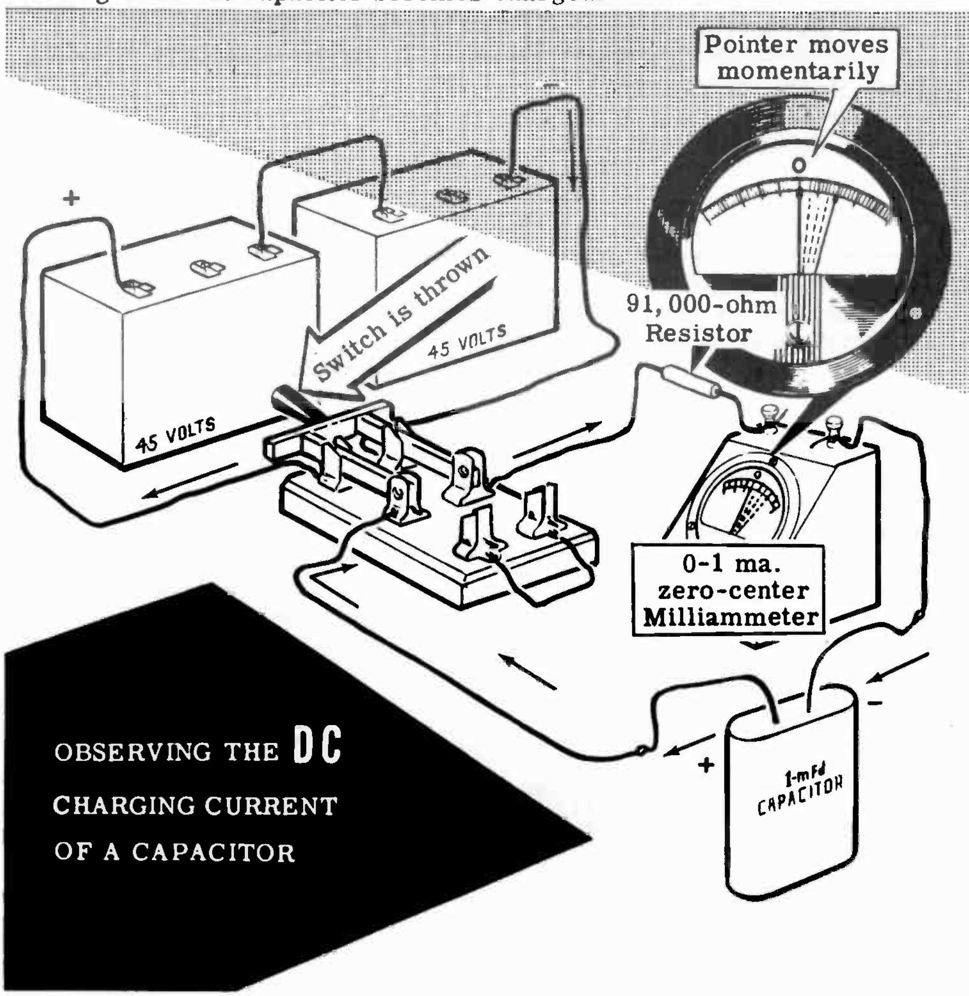
CAPACITOR SYMBOLS

Fixed Capacitors

Variable Capacitors

Demonstration—Current Flow in a DC Capacitive Circuit

In circuits containing only capacitance, both the charge and discharge of a capacitor occur in a very short period of time. To show the circuit current flow during the charge and discharge of a capacitor, the instructor connects two 45-volt batteries in series to form a 90-volt battery. Next he connects the leads from this battery to two of the end terminals of a double-pole, double-throw switch. With the switch open, he then connects the 0-1 ma. zero-center milliammeter and the 1-mfd capacitor in series with the resistor to the switch as shown. Finally, he connects the other two end terminals together with a length of wire. The purpose of the 91,000-ohm resistor is to limit large current surges which may damage the meter. When the instructor moves the switch to the shorted terminals, you see that there is no current flow since the capacitor is initially uncharged. Then, when he moves the switch to the battery terminals, you see that the meter pointer momentarily registers a current flow, but drops quickly to zero again as the capacitor becomes charged.

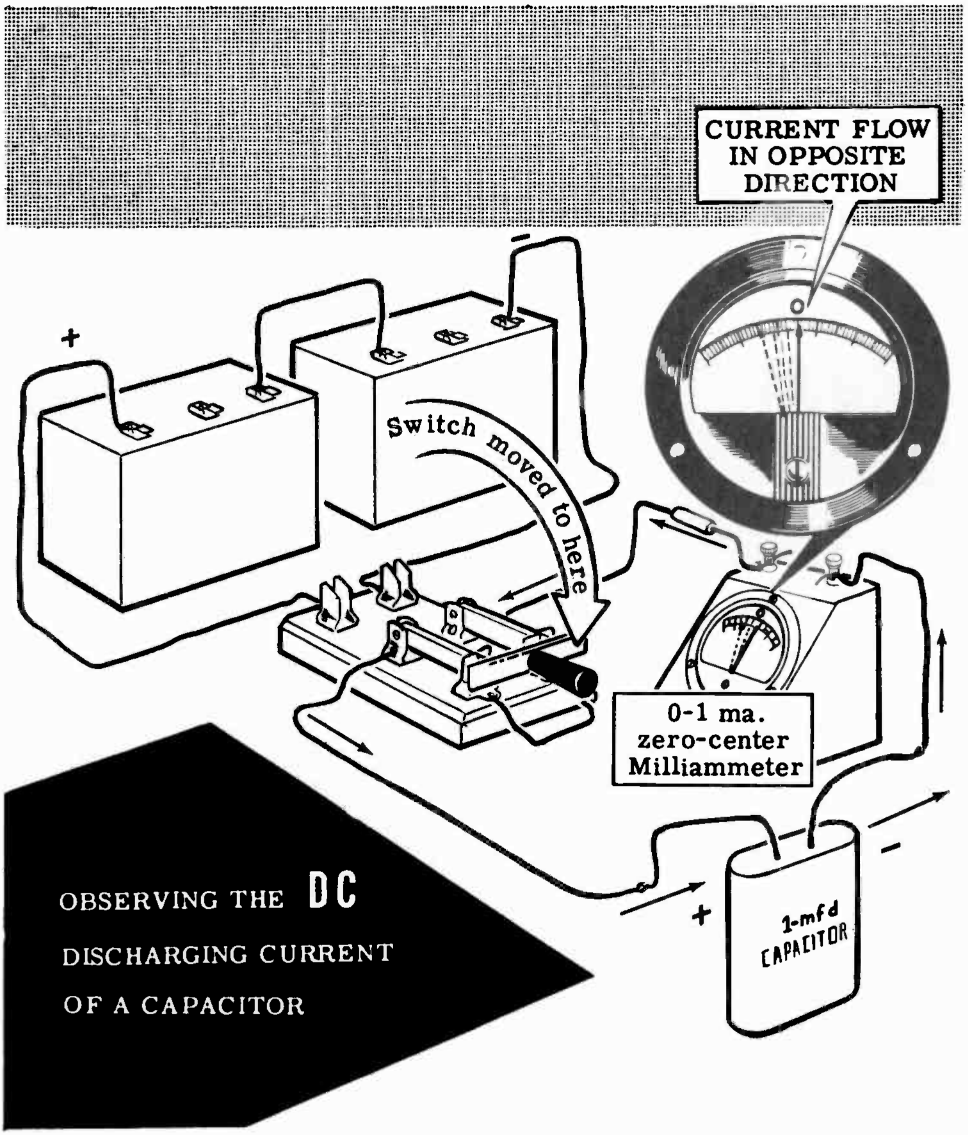


OBSERVING THE DC CHARGING CURRENT OF A CAPACITOR

Demonstration—Current Flow in a DC Capacitive Circuit (continued)

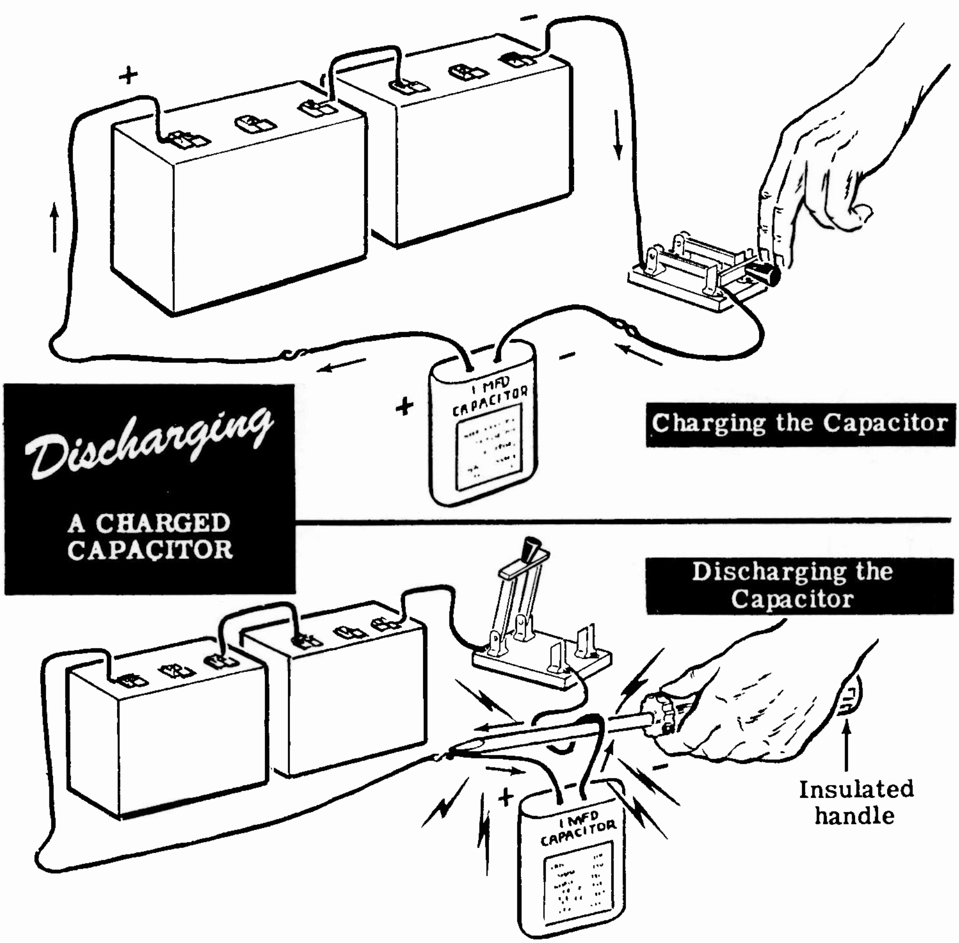
If the instructor opens the switch and then moves it to the shorted terminals, the meter pointer indicates a momentary current flow in the opposite direction when the switch is closed, indicating the discharge of the condenser.

The instructor then charges the capacitor as before, and you notice the instantaneous current flow. He then opens the switch and returns it to its initial position. You notice no current flow, since the capacitor is already charged. When he moves the switch to the shorted terminals, the current flow in the opposite direction again shows the discharge of the condenser.



Demonstration—Current Flow in a DC Capacitive Circuit (continued)

Next the instructor connects the battery to the capacitor and switch in series. The capacitor is charged by closing the switch. He then opens the switch and shorts across the capacitor terminals with a screwdriver blade, making certain to hold the screwdriver only by means of the insulated handle. Notice that the capacitor discharge causes a strong arc. If you were to discharge the capacitor by touching the two terminals with your hands, the resulting electric shock—while not dangerous in itself—might cause a serious accident by making you jump.



As the instructor repeatedly charges and discharges the capacitor, you see that the resulting arc is the same each time. This shows that the charge left in a capacitor when the circuit voltage is removed is always maximum in a DC circuit. CAUTION: Never discharge a capacitor while it is connected to the circuit voltage, whether the voltage source is a battery or AC power line.

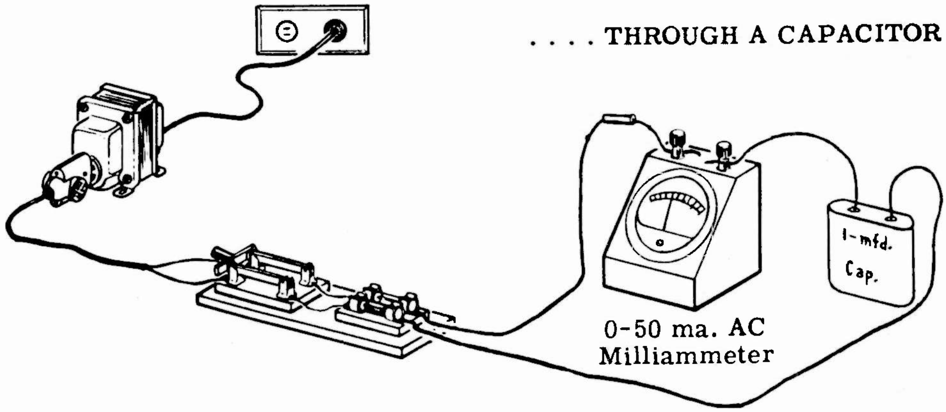
Demonstration—Current Flow in an AC Capacitive Circuit

After disconnecting the DC circuit, the instructor connects the capacitor to show that AC current flows continuously in an AC capacitive circuit. One lead of the line cord is connected to a terminal of the capacitor through the switch and fuses, while the other line cord lead is connected to the remaining capacitor terminal through the 0-50 ma. AC milliammeter. When the transformer is plugged into the AC power line outlet, and the switch is closed, you see that a continuous flow of current is indicated on the milliammeter.

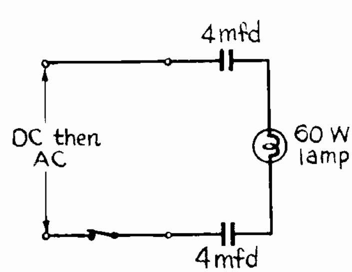
The milliammeter shows that approximately 22 ma. of AC current is flowing continuously. This continuous flow of circuit current is possible since the capacitor is continuously charging and discharging as the AC voltage reverses its polarity. After the instructor opens the switch, he shorts out the terminals of the capacitor with a screwdriver. Again you see that the capacitor retains a charge when the voltage is removed from the circuit. However, as the power is applied and removed several times in succession and the capacitor is discharged each time, you see that the sparks vary in size and intensity. This occurs because the amount of charge retained by the capacitor when used in an AC circuit is not always the same, since the circuit voltage may be removed while the capacitor is discharging or not yet charged.

OBSERVING **AC CURRENT FLOW..**

. . . . THROUGH A CAPACITOR



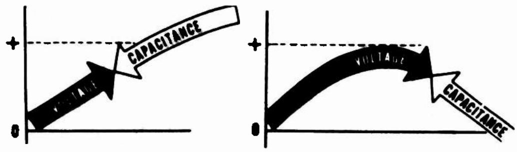
To prove that capacitors appear to block DC but permit AC to pass, the instructor sets up the circuit shown to the right. When DC is applied the lamp will not glow and a DC voltmeter across the lamp will read zero volts. When AC is applied the lamp will glow and an AC voltmeter across the lamp will give a reading.



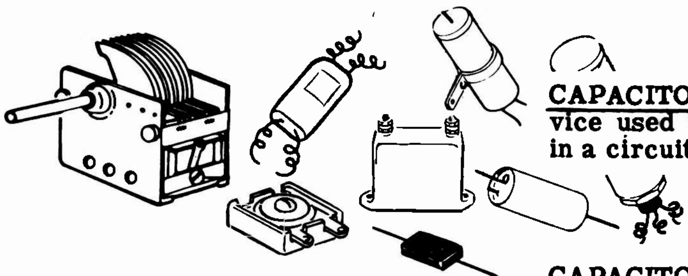
CAPACITANCE IN AC CIRCUITS

Review of Capacitance in AC Circuits

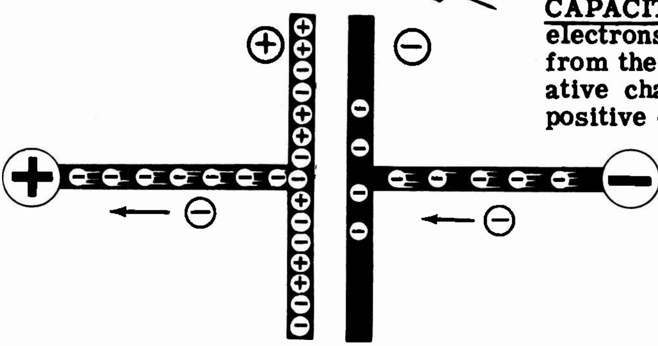
You have found out about capacitance and have seen how it affects the flow of current in electric circuits. Now you are ready to perform an experiment on capacitance to find out more about it and its effects. Before performing the experiment, suppose you recall what you have found out about capacitance.



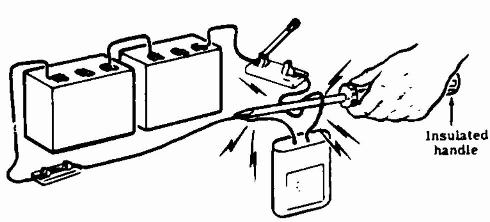
CAPACITANCE — The property of a circuit which opposes any change in the circuit voltage.



CAPACITOR — An electrical device used to supply capacitance in a circuit.



CAPACITOR CHARGE — Flow of electrons into one plate and away from the other, resulting in a negative charge on one plate and a positive charge on the other.



CAPACITOR DISCHARGE — Flow of electrons from the negatively charged plate of a capacitor to the positively charged plate, eliminating the charges on the plate.

FARAD — Basic unit of capacitance used in electrical formulas.

$$1 \text{ mfd} = \frac{1}{1{,}000{,}000} \text{ farad}$$

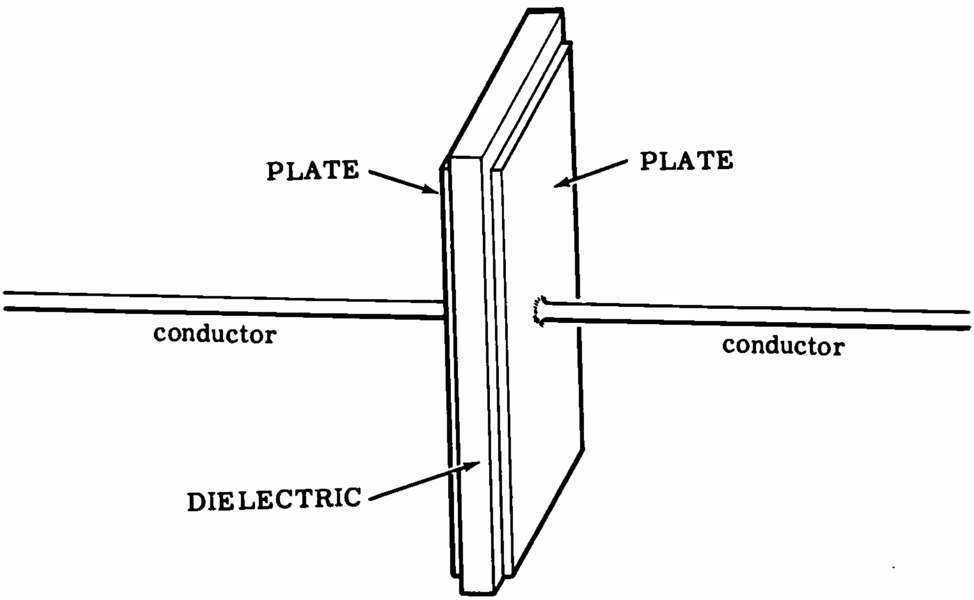
$$1 \text{ mmf} = \frac{1}{1{,}000{,}000{,}000{,}000} \text{ farad}$$

PRACTICAL UNITS OF CAPACITANCE — Microfarad (one-millionth farad) and micromicrofarad (one-millionth-millionth of a farad).

Capacitors

Basically, capacitors consist of two plates which can be charged—separated by an insulating material called the "dielectric." While early condensers were made with solid metal plates, newer types of condensers use metal foil, particularly aluminum foil, for the plates. Dielectric materials commonly used include air, mica and waxed paper.

Capacitors CONSIST OF **Two Plates** AND THE **Dielectric**



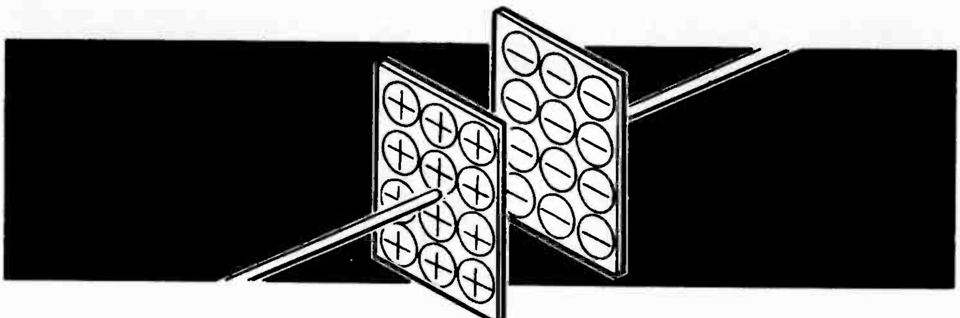
Plates are made of solid metal or metal foil.

Dielectric materials are: air, mica and waxed paper.

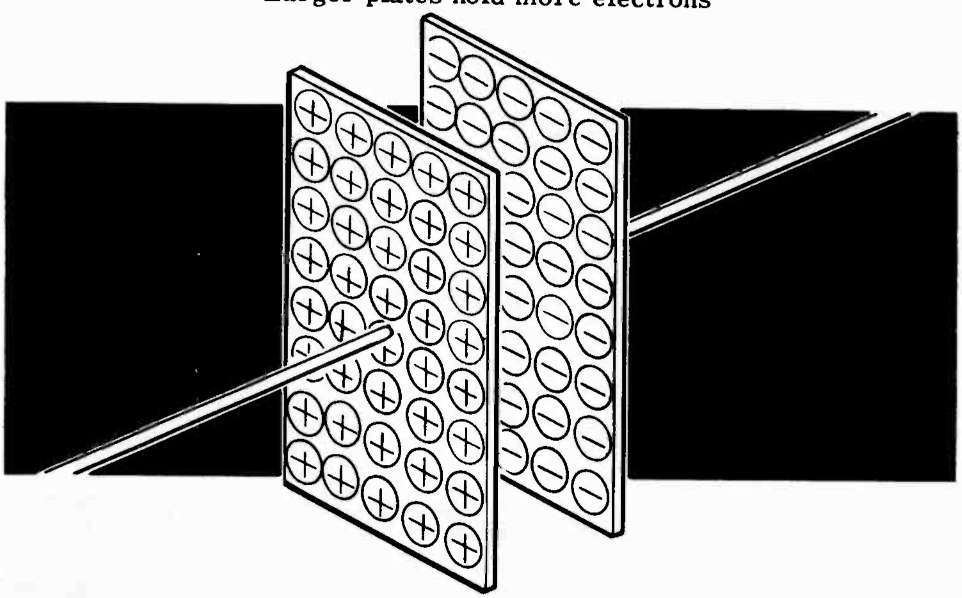
Three basic factors influence the capacity of a capacitor or condenser—the area of the plates, the distance between the plates (thickness of the dielectric) and the material used for the dielectric.

Factors Which Affect Capacitance

Plate area is a very important factor in determining the amount of capacitance, since the capacitance varies directly with the area of the plates. A large plate area has room for more excess electrons than a small area, and thus it can hold a greater charge. Similarly, the large plate area has more electrons to give up and will hold a much larger positive charge than a small plate area. Thus an increase in plate area increases capacitance, and a decrease in plate area decreases capacitance.



Larger plates hold more electrons



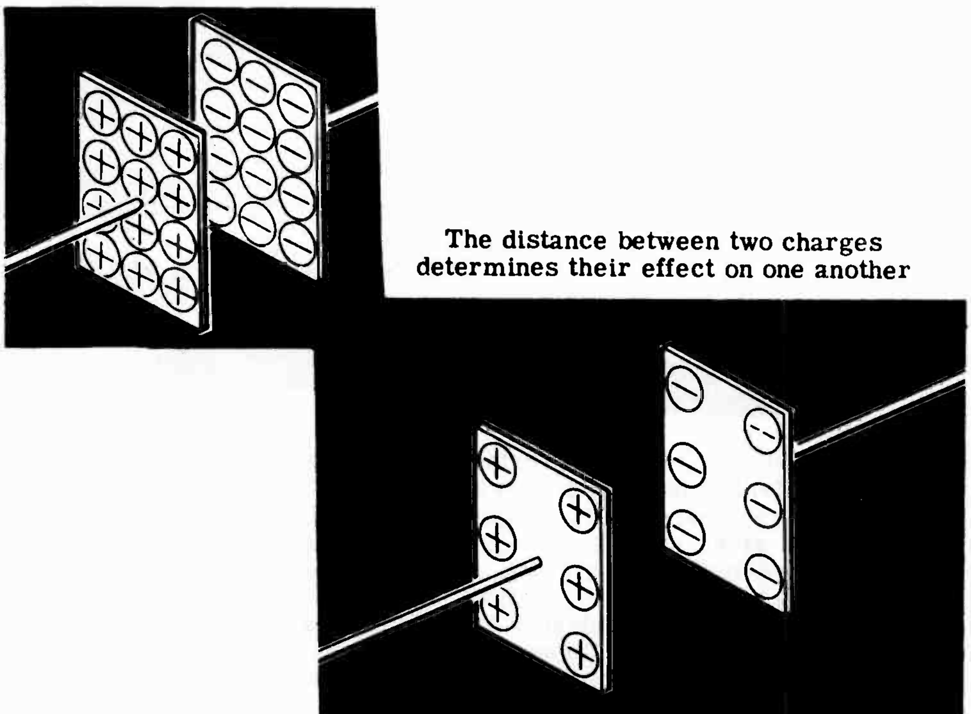
INCREASED PLATE AREA INCREASES *Capacitance*

Factors Which Affect Capacitance (continued)

The effect two charged bodies have on each other depends on the distance between the two. Since the action of capacitance depends on the two plates and the difference in their charges, the amount of capacitance changes when the distance between the plates changes. The capacitance between two plates increases as the plates are brought closer together and decreases as the plates are moved apart. This occurs because the closer the plates are to each other, the greater the effect a charge on one plate will have on the charge of the other plate.

When an excess of electrons appears on one plate of a condenser, electrons are forced off the opposite plate, inducing a positive charge on this plate. Similarly, a positively charged plate induces a negative charge on the opposite plate. The closer the plates are to each other, the stronger the force between them, and this force increases the capacitance of a circuit.

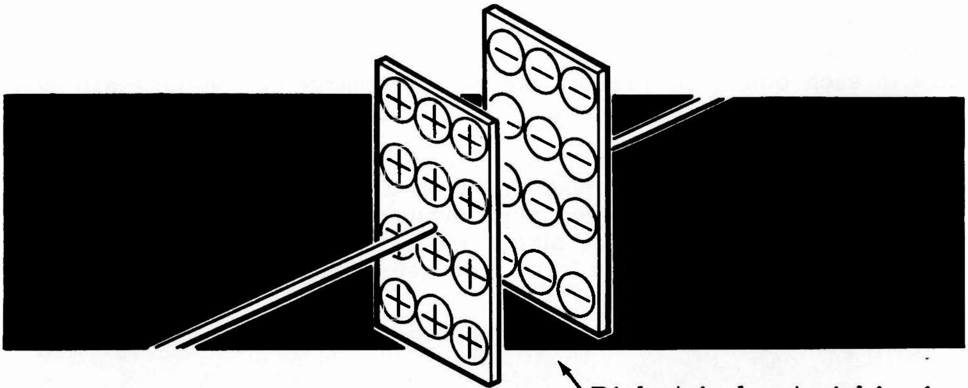
INCREASING THE DISTANCE BETWEEN THE PLATES *Decreases Capacitance*



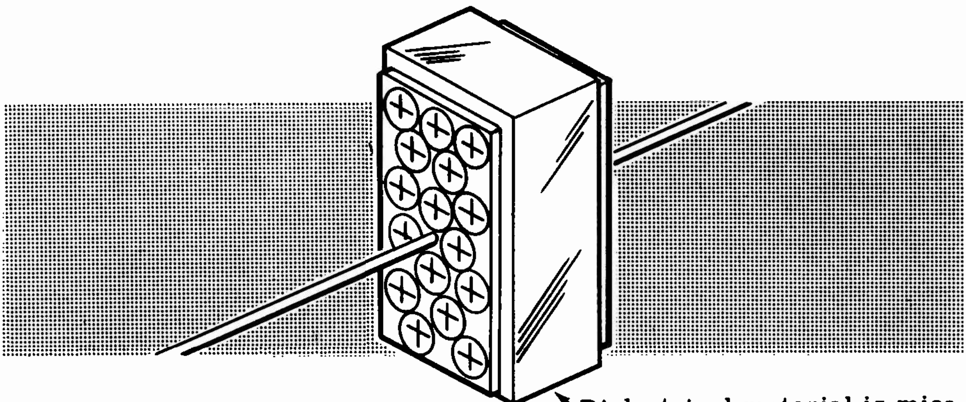
The distance between two charges determines their effect on one another

Factors Which Affect Capacitance (continued)

CHANGING THE *Dielectric* MATERIAL CHANGES THE CAPACITANCE



Dielectrical material is air



Dielectrical material is mica

Mica dielectric increases the capacitance.

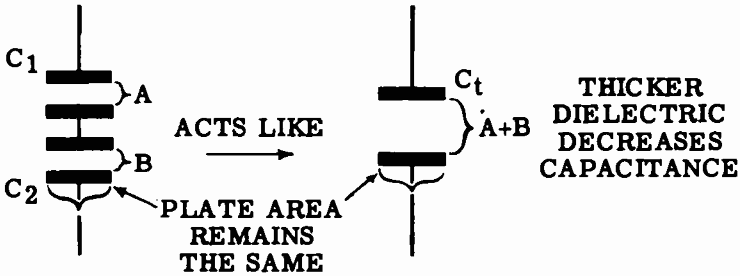
Using the same plates fixed a certain distance apart, the capacitance will change if different insulating materials are used for the dielectric. The effect of different materials is compared to that of air—that is, if the condenser has a given capacitance when air is used as the dielectric, other materials used instead of air will multiply the capacitance by a certain amount called the "dielectric constant." For example, some types of oiled paper have a dielectric constant of 3 and, if this waxed paper is placed between the plates, the capacitance will be 3 times greater than air used as the dielectric. Different materials have different dielectric constants, and thus will change the capacitance when they are placed between the plates to act as the dielectric.

Capacitors in Series and Parallel

When you connect capacitors in series or in parallel, the effect on the total capacitance is opposite to that for similarly connected resistors.

Connecting resistors in series increases the total resistance because it lengthens the resistance path through which current flows, while connecting capacitances in series decreases the total capacitance since it effectively increases the spacing between the plates. To find the total capacitance of series-connected capacitors, a formula is used similar to the formula for parallel resistances.

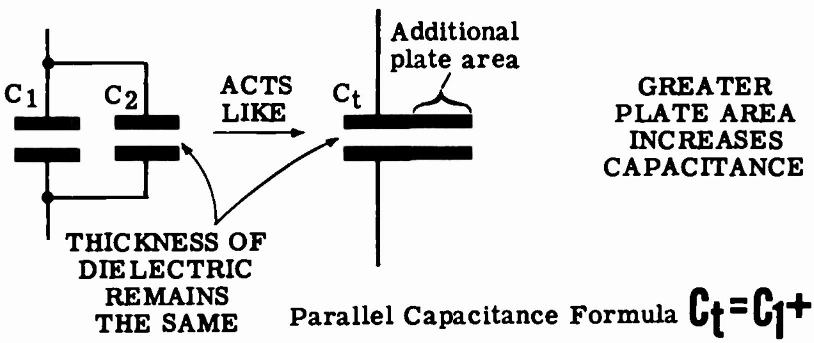
Series Connection INCREASES THE THICKNESS OF THE DIELECTRIC



Series Capacitance Formula

$$C_t = \frac{C_1 \times C_2}{C_1 + C_2}$$

Parallel Connection INCREASES THE PLATE AREA



Parallel Capacitance Formula $C_t = C_1 + C_2 + C_3$

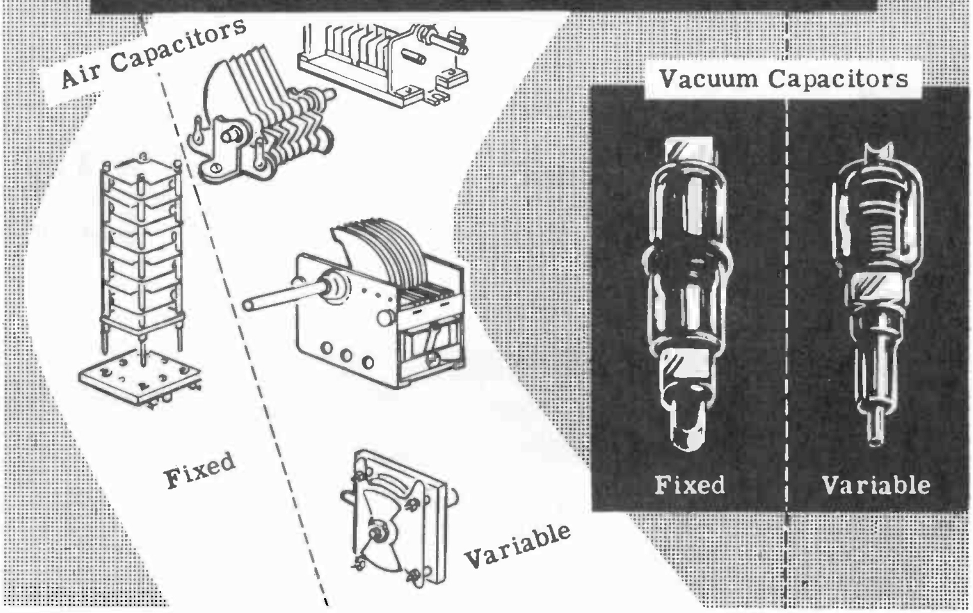
When resistors are connected in parallel, the total resistance decreases since the cross section through which current can flow increases. The reverse is true of parallel-connected capacitors. The total capacitance increases, since the plate area receiving a charge increases. The total capacitance for parallel-connected capacitors is found by adding the values of the various capacitors connected in parallel.

Types of Capacitors

Many kinds of capacitors are used in electricity and electronics. In order to choose the best type for a particular job, you should know how they are made and operate. You also should be familiar with the symbols used to indicate certain special types of capacitors. Condensers (capacitors) are generally classified according to their dielectric material.

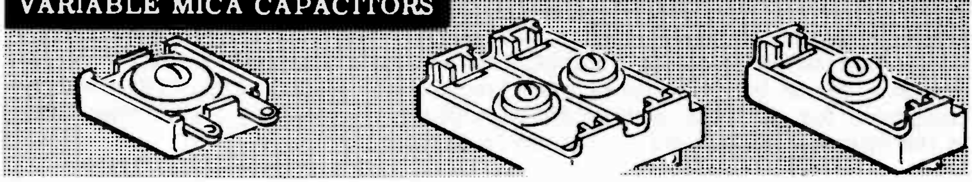
The most basic type of capacitor (which may be either fixed or variable) is the air condenser, constructed of metal plates with air spaces between them. A similar type of condenser is the vacuum condenser, which consists of two plates separated by a vacuum—the vacuum being the dielectric. Because the plates must be rather widely spaced apart to prevent arcing, the capacitance of air and vacuum condensers is low, usually between 1 mmf and 500 mmf.

FIXED AND VARIABLE AIR AND VACUUM CAPACITORS



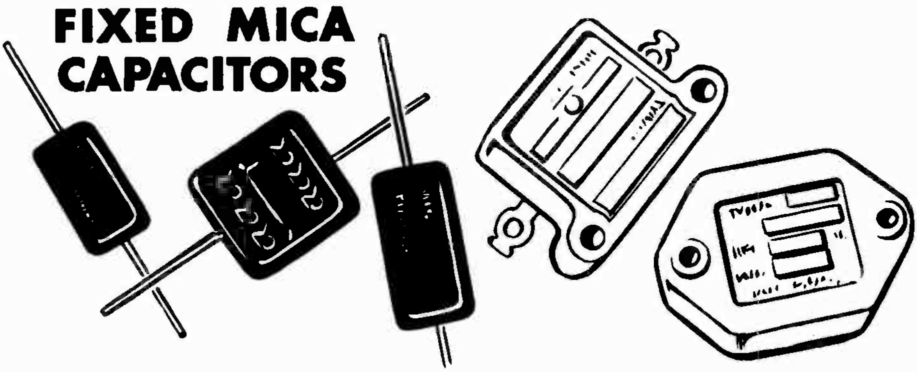
A special type of mica condenser, which is variable and usually has a maximum value of less than 500 mmf, consists of two plates with a sheet of mica between them. A screw adjustment is used to force the plates together, and adjustment of this screw varies the capacitance of the condenser. Several layers of plates and mica are used in larger condensers of this type. This kind of condenser is sometimes built onto a large variable air condenser, to be used in parallel with the larger variable condenser and provide a finer adjustment of capacitance.

VARIABLE MICA CAPACITORS

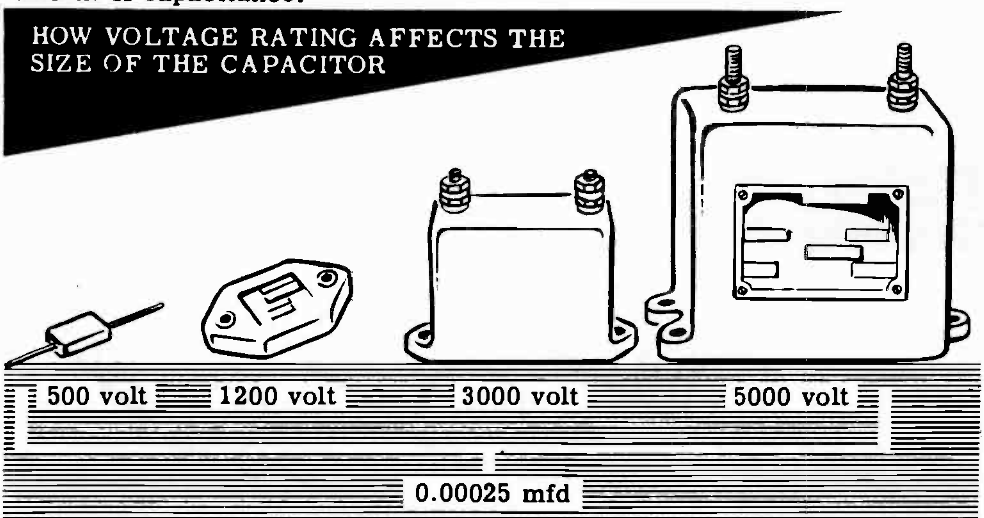


Types of Capacitors (continued)

Fixed mica capacitors consist of thin metal foil plates separated by sheet mica and molded into a plastic cover. These capacitors are made in a capacity range between 10 mmf and 0.01 mfd. Various types of terminals are used to connect mica capacitors into circuits, and these terminals are molded into the plastic with the capacitor plates and dielectric. By molding the capacitor parts into a plastic case, corrosion and damage to the plates and dielectric are prevented in addition to making the capacitor mechanically strong.

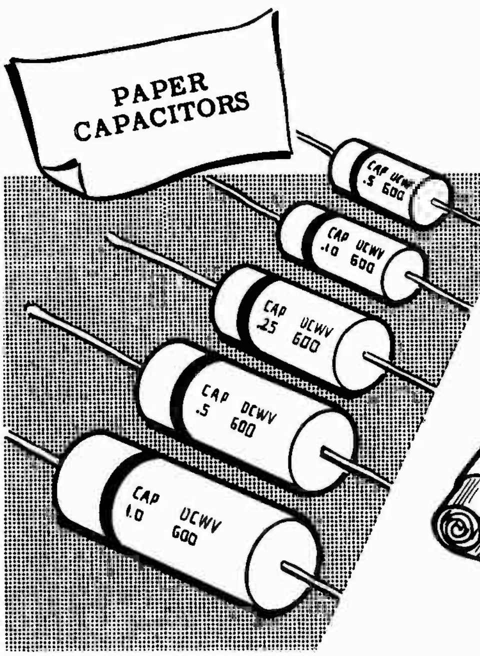


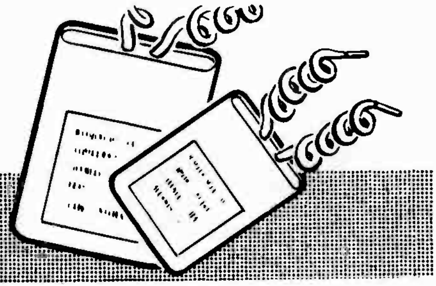
The voltage applied across the plates of a capacitor is determined by the thickness of the dielectric material which acts as an insulator between the two plates. Capacitors of exactly the same capacitance may have different voltage rating due to a difference in the thickness of the dielectric. If the dielectric thickness is increased the plates will be further apart, reducing the capacitance so that the plate areas must be increased to make up for this loss. Thus capacitors of higher voltage ratings are larger in physical size, since the plates are both larger and further apart. This is true of all types of capacitors regardless of the dielectric used. Shown below are typical mica capacitors having various voltage ratings but the same amount of capacitance.



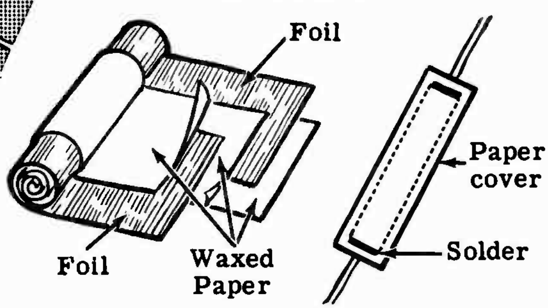
Types of Capacitors (continued)

Paper capacitors use strips of metal foil as plates, separated by strips of waxed paper. Paper capacitors range in value from 250 mmf to 1 mfd for most uses, although larger paper capacitors are made for special applications. Since very long strips of paper are required to obtain a usable capacitance, the strips of foil and waxed paper are rolled together to form a cartridge. This cartridge, including leads attached to the plates, is sealed in wax to prevent moisture leakage and corrosion of the plates. Many different kinds of outer covering are used for paper capacitors, the simplest being a tubular cardboard.

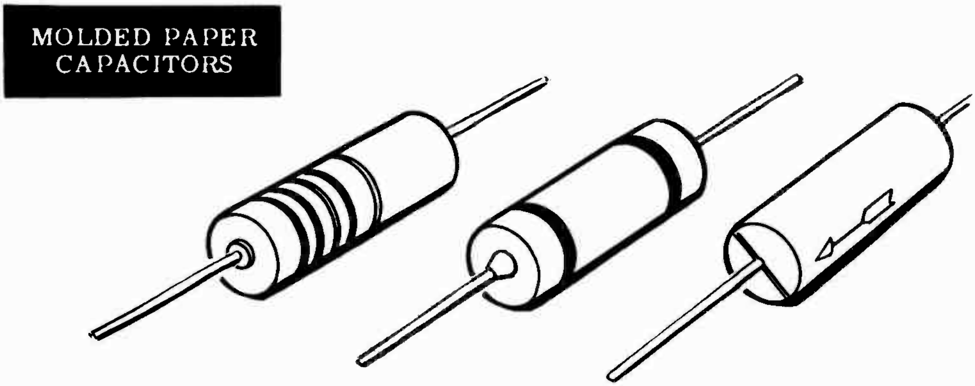




Construction of the Tubular Paper Capacitor

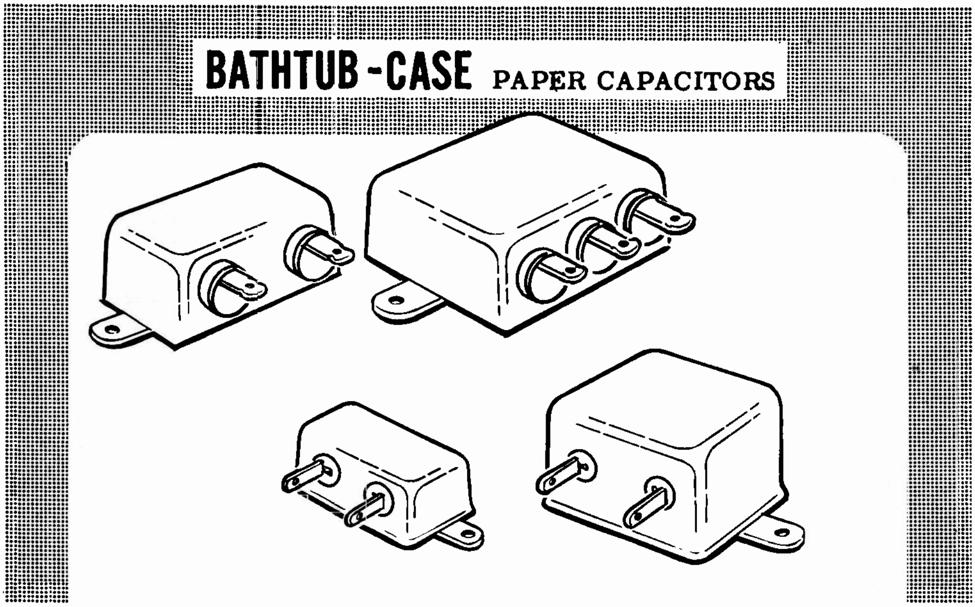


Some types of paper capacitors are encased in a mold of very hard plastic. Capacitors which are so constructed are very rugged and may be used over a much wider temperature range than the cardboard case type, since the wax used in the tubular cardboard type melts at high temperatures and escapes through the open ends of the cardboard case.

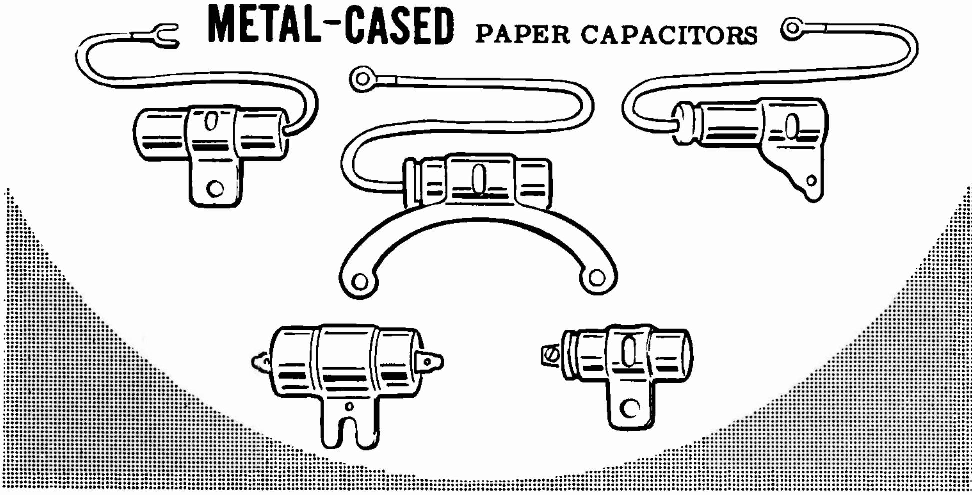


Types of Capacitors (continued)

Bathtub style capacitors are paper capacitor cartridges hermetically sealed in a metal container. The metal container is sometimes used as one terminal and, if not, it acts as a shield against electrical interference. Also, quite often a single terminal is the common terminal used for several different capacitors sealed in one bathtub case.



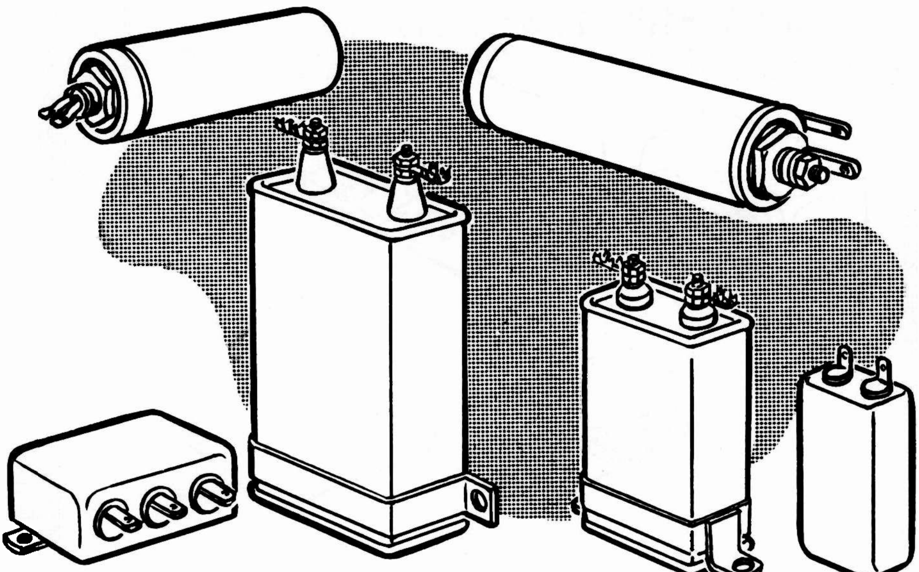
Capacitors used in automobile ignition systems are paper capacitor cartridges and are metal-cased, with the case serving as both a shield and terminal connection. Metal cases are necessary because automobile capacitors must be exceptionally rugged and able to withstand the effects of mechanical shock and the weather.



Types of Capacitors (continued)

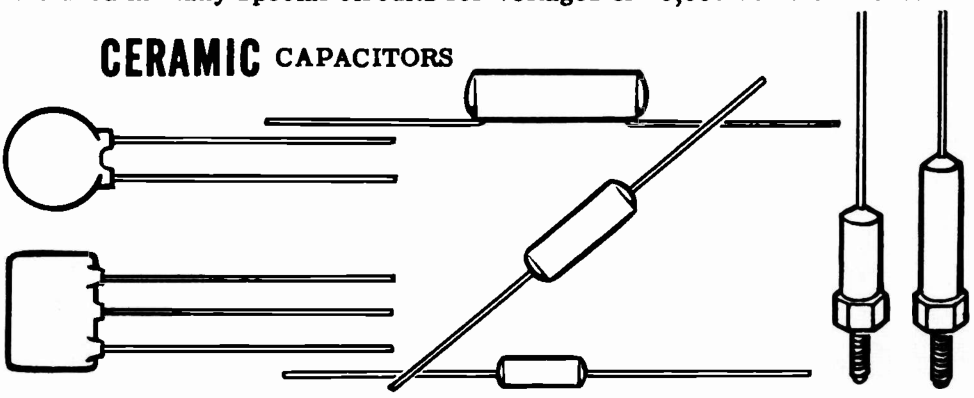
Paper capacitors used for high voltage circuits (600 volts and higher) are impregnated with oil and oil-filled. The metal container is hermetically sealed and various types of terminal connections are used.

OIL-FILLED HIGH VOLTAGE PAPER CAPACITORS



A recently developed type of extremely small capacitors—both fixed and variable—use ceramic as the dielectric and a film deposit of silver for the plates. Ceramic capacitors usually range in value between 1 mmf and 0.01 mfd. They are constructed in various shapes, the most common being disk and tubular shapes. Variable ceramic capacitors have one fixed plate of silver film and a movable metal plate which is silver-plated. Although ceramic capacitors have a dielectric which will insulate against voltages above 2,000 volts, they are quite small and take up little space, so that they are used in many special circuits for voltages of 10,000 volts or more.

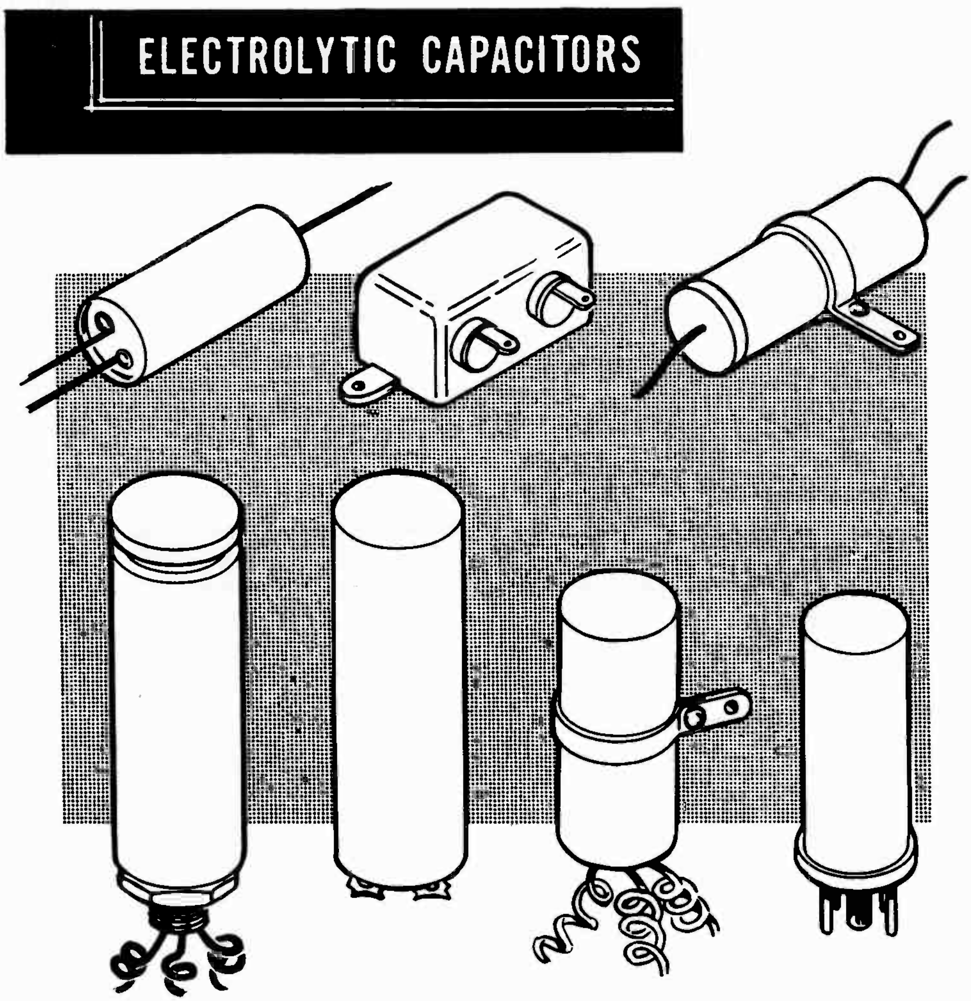
CERAMIC CAPACITORS



Types of Capacitors (continued)

For values of capacitance greater than 1 mfd, the physical size of a paper or a mica capacitor becomes excessive. Electrolytic capacitors are used for such values of capacitance, ranging from 1 to 1,000 mfd. Unlike other types of capacitors the electrolytic capacitor is polarized and, if connected in the wrong polarity, it will break down and act as a short circuit. A special type of electrolytic capacitor is made which compensates for changing polarity, and may be used on AC.

Electrolytic capacitors are constructed in a wide variety of shapes and physical sizes, using either cardboard or metal cases and various types of terminal connections. Remember that unless an electrolytic is designed for use on AC, such as a motor-starting capacitor, you must always be careful to connect it only in a DC circuit and to observe the correct polarity.



Capacitor Color Code

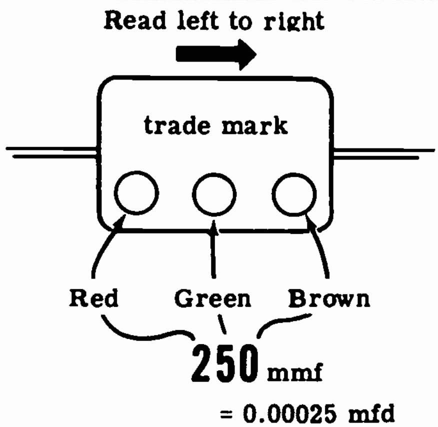
The capacitance value and voltage rating of most capacitors is printed or stamped on the body of the capacitor, together with the polarity in the case of electrolytics. Voltage ratings marked on the body of a capacitor usually refer to the maximum DC voltage which can be applied across the terminals without a breakdown of the dielectric insulation. Many capacitors are marked with a color code similar to the resistor color code, and the corresponding colors and numbers are the same for the two codes. Suppose you review the colors and numbers which are used.

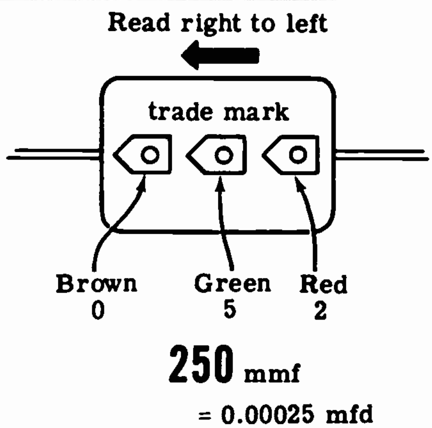
CAPACITANCE COLOR CODE

Color	No.	Tolerance	Voltage Rating	Color	No.	Tolerance	Voltage Rating
Black	0		-	Violet	7	7%	700
Brown	1	1%	100	Gray	8	8%	800
Red	2	2%	200	White	9	9%	900
Orange	3	3%	300	Gold	-	5%	1,000
Yellow	4	4%	400	Silver	-	10%	2,000
Green	5	5%	500	No Color	-	20%	-
Blue	6	6%	600				

The order in which these colors are used by the different manufacturers varies. The simplest color code marking uses three dots of color which give the value of capacitance in mmf. The first two dots represent the first two numbers and the last dot the number of zeros to be added. All color coded values are in mmf and must be changed to mfd if the answer in mfd is desired. If no arrows are present, the capacitor is placed in such a position that the trademark can be read correctly; and the three dots of color are read from LEFT to RIGHT. When each dot is placed on a small arrow, they are read in the direction of the arrows. If the dots are red, green and brown, reading in the proper direction the capacitance is 250 mmf or 0.00025 mfd as shown below. If no tolerance and voltage ratings are indicated, they are assumed to be ± 20% at 500 volts.

HOW TO USE THE CAPACITOR COLOR CODE FOR CAPACITORS MARKED WITH THREE COLORS

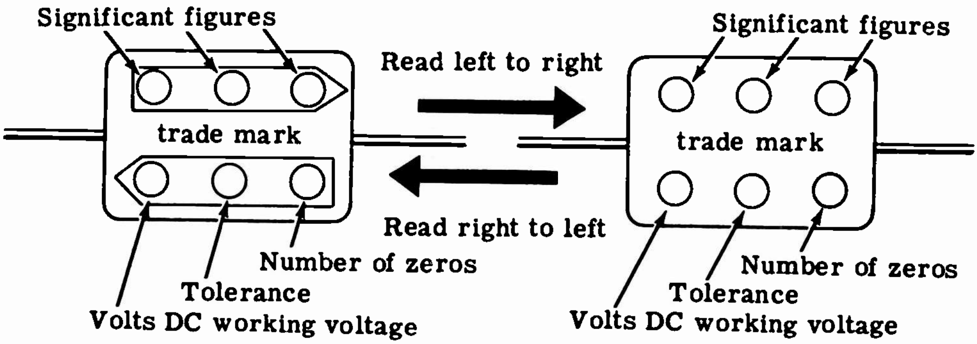




Capacitor Color Code (continued)

Capacitors which are marked with six dots of color are coded for percentage of accuracy (tolerance) and voltage rating, in addition to the capacitance value. The top row of dots is read from LEFT to RIGHT, and the bottom row is read from RIGHT to LEFT. In this type of marking, 3 digits are obtained from the top row of dots; and from the bottom row from RIGHT to LEFT in order are read the number of zeros, the percentage tolerance and the voltage rating.

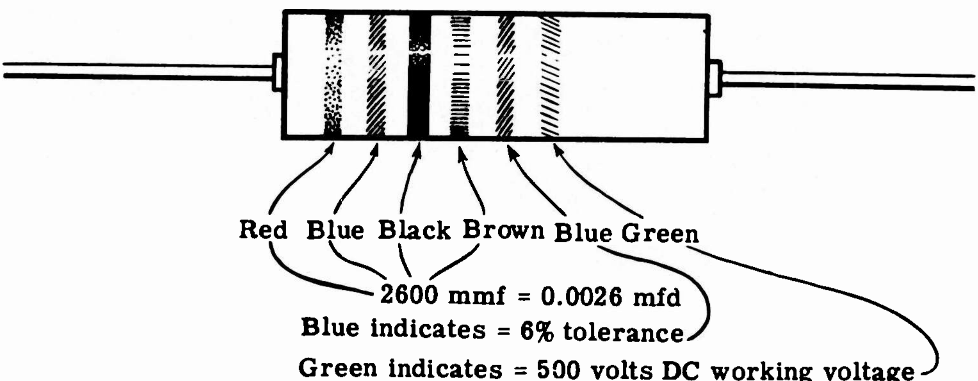
HOW TO USE CAPACITOR COLOR CODE FOR CAPACITORS MARKED WITH SIX COLORS



Suppose the six dots read in the correct order are brown, orange, green, red, silver and blue. The capacitor then has a capacitance of 13,500 mmf, a tolerance of 10 percent and a voltage rating of 600 volts.

Color code marking is not only used on mica or ceramic capacitors, but is also used with molded tubular paper capacitors. The marking then is done with bands of color which are read from the band nearest one end of the capacitor in order toward the center. The colors are read in the same manner as the six-dot system with the first 3 bands denoting digits, the fourth band giving the number of zeros, the fifth band the tolerance and the sixth band the voltage rating.

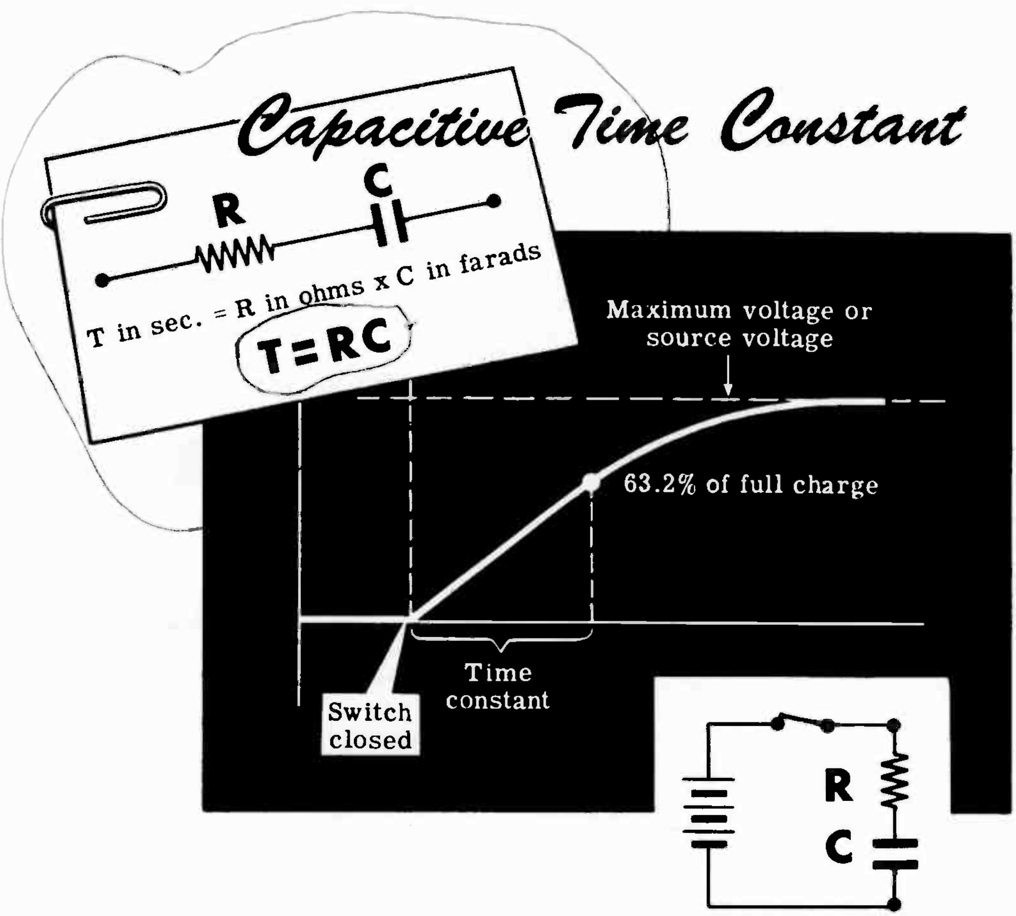
BAND MARKING OF MOLDED PAPER CAPACITORS



Capacitive Time Constant

When a voltage is applied across the terminals of a circuit containing capacitance, the voltage across the capacitance does not instantaneously equal the voltage applied to the terminals. You have already found that it takes time for the plates of a capacitor to reach their full charge, and that the voltage between the plates rises to equal the applied voltage in a curve similar to the current curve of an inductive circuit. The greater the circuit resistance, the longer the time required for the capacitor to reach its maximum voltage since the circuit resistance opposes the flow of current required to charge the capacitor.

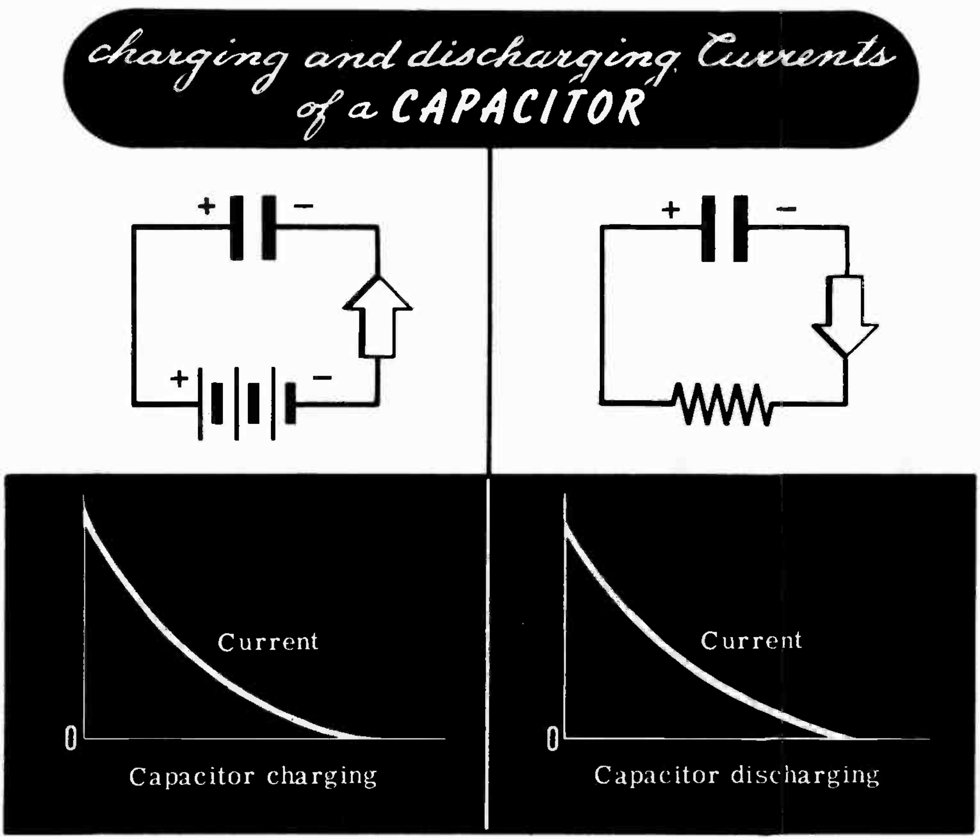
The time required for the capacitor to become fully charged depends on the product of circuit resistance and capacitance. This product RC—resistance times capacitance—is the "time constant" of a capacitive circuit. The RC time constant gives the time in seconds required for the voltage across the capacitor to reach 63.2 percent of its maximum value. Similarly, the RC time constant equals the time in seconds required for a discharging capacitor to lose 63.2 percent of its full charge.



Capacitive Reactance

Capacitive reactance is the opposition to current flow offered by the capacitance of a circuit. When a DC source is used, current flows only to charge or discharge the capacitor. Since there is no continuous flow of DC current in a capacitive circuit, the capacitive reactance to DC is considered infinite. AC continuously varies in value and polarity; therefore the capacitor is continuously charging and discharging, resulting in a continuous circuit current flow and a finite value of capacitive reactance.

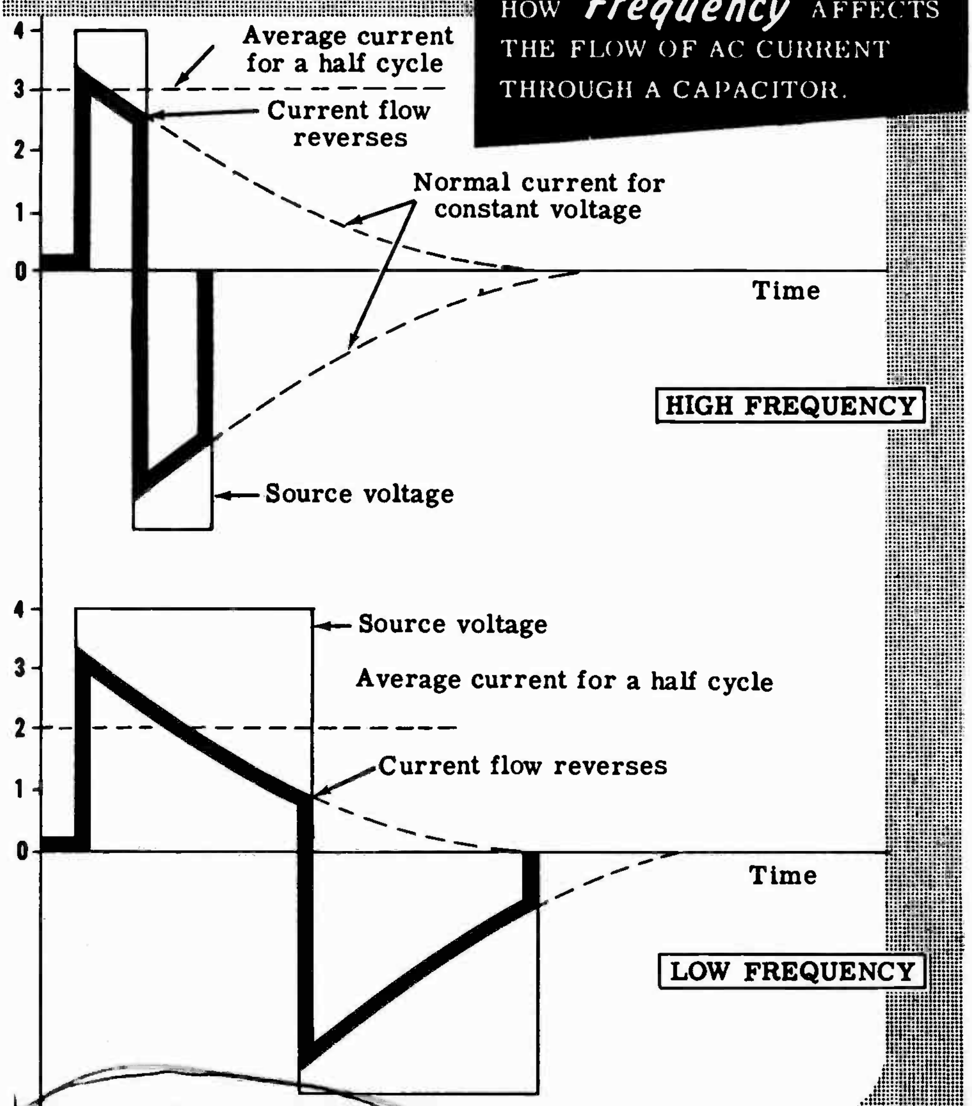
The charge and discharge currents of a capacitor start at a maximum value and fall to zero as the capacitor becomes either fully charged or discharged. In the case of a charging capacitor, the uncharged plates offer little opposition to the charging current at first, but as they become charged they offer more and more opposition, reducing the current flow. Similarly, the discharge current is high at beginning of the discharge since the voltage of the charged capacitor is high but, as the capacitor discharges, its charge voltage drops resulting in less current flow. Since the charging and discharging currents are highest at the beginning of the charge and discharge of a capacitor, the average current is higher if the polarity is reversed rapidly, keeping the current flowing at high values.



Capacitive Reactance (continued)

For a given value of capacitance the amount of current flow in an AC circuit depends on the frequency of the AC voltage. The higher the frequency, the greater the current flow since the charging current in each direction will be reversed before it has time to drop to a low value. If the source voltage is low in frequency, the current will drop to a low value before the polarity reverses, resulting in a lower average value of current flow.

HOW *Frequency* AFFECTS THE FLOW OF AC CURRENT THROUGH A CAPACITOR.

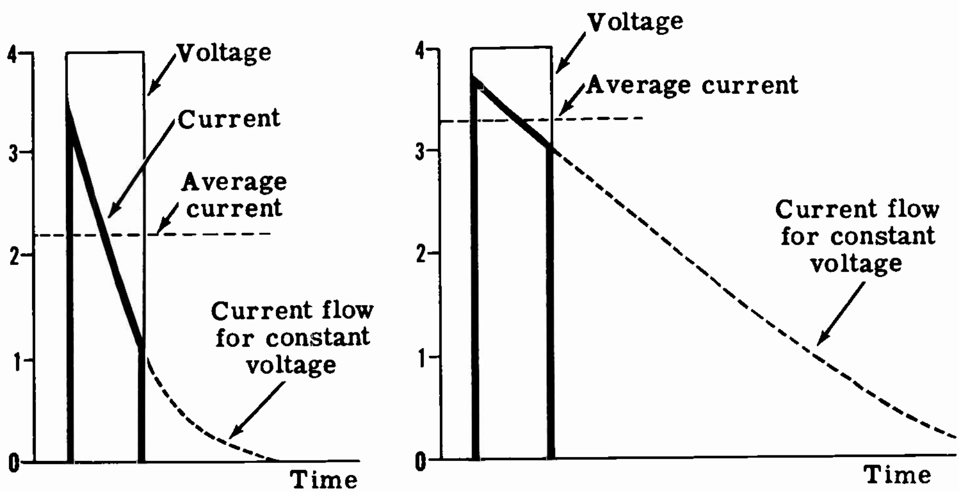


The lower the frequency, the lower the average current.

Capacitive Reactance (continued)

Comparing the charge current curves for different values of capacitance, you see that the larger the capacitance the longer the current remains at a high value. Thus, if the frequency is the same, a greater average current will flow through a larger capacitance than a small capacitance. This holds true only if the circuit resistances are equal, however, because the charge curve of a capacitance depends on the RC time constant of the circuit.

HOW CAPACITANCE VALUES AFFECT CAPACITIVE *Reactance*



SMALL CAPACITANCE

Low average current high reactance

LARGE CAPACITANCE

High average current low reactance

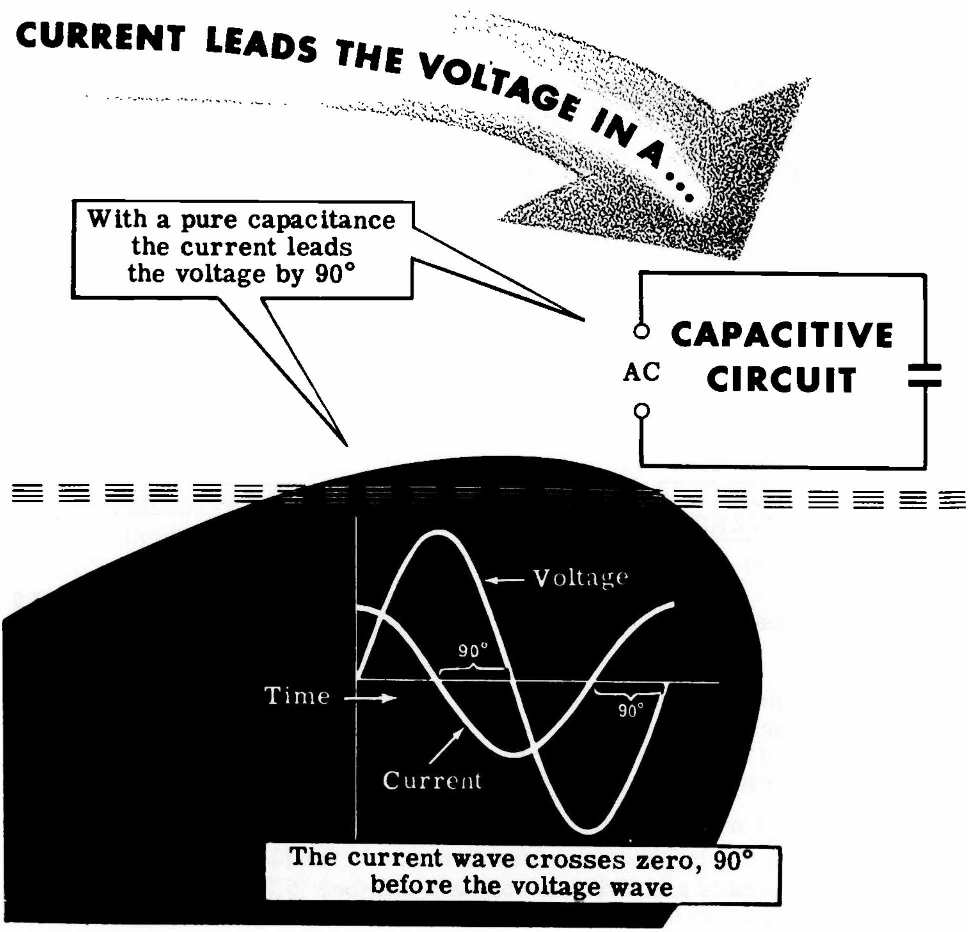
The smaller the capacitance— the lower the average current.

The current flow in a capacitive circuit, assuming that there is no change in the resistance, increases with an increase in either frequency or capacitance. Then capacitive reactance—the opposition to current flow through a capacitance—must decrease when the frequency or capacitance increases. The formula used to obtain capacitive reactance is $X_C = \frac{1}{2\pi fC}$. In this formula X_C is capacitive reactance, f is frequency in cycles, C is capacitance in farads and 2π is a constant number (6.28). Since X_C represents opposition or resistance to current flow, it is expressed in ohms.

Capacitive Reactance (continued)

The phase relationship between current and voltage waves in a capacitive circuit is exactly the opposite to that of an inductive circuit. In a purely inductive circuit the current wave lags the voltage by 90 degrees, while in a purely capacitive circuit the current wave leads the voltage by 90 degrees.

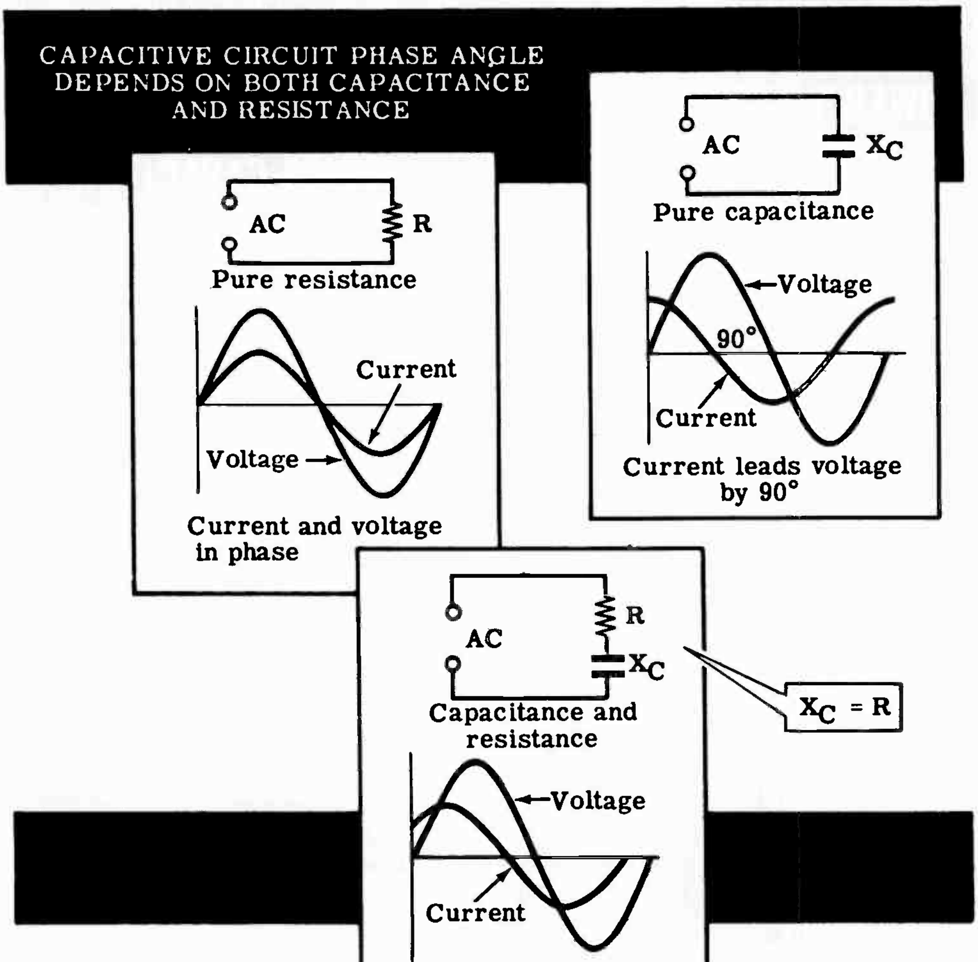
In a theoretical circuit of pure capacitance and no resistance, the voltage across the capacitance exists only after current flows to charge the plates. At the moment a capacitance starts to charge, the voltage across its plates is zero and the current flow is maximum. As the capacitance charges, the current flow drops toward zero while the voltage rises to its maximum value. When the capacitance reaches full charge, the current is zero and the voltage is maximum. In discharging, the current starts at zero and rises to a maximum in the opposite direction, while the voltage falls from maximum to zero. In comparing the voltage and current waves, you can see that the current wave leads the voltage by 90 degrees or, in opposite terms, the voltage wave lags the current by 90 degrees.



Capacitive Reactance (continued)

Resistance affects capacitive circuits similarly to the way it affects inductive circuits. Remember, in an inductive circuit containing both inductance and resistance, the current wave lags the voltage wave by an angle between zero degrees and 90 degrees, depending on the ratio of inductive reactance to the resistance. For a purely capacitive circuit, current leads the voltage by 90 degrees; but, with both resistance and capacitance in a circuit, the amount of lead—"phase angle"—depends on the ratio between the capacitive reactance and the resistance.

If the capacitive reactance and resistance are equal, they will have an equal effect on the angle of lead resulting in a "phase angle" of 45 degrees leading. As shown below, the current wave then leads the voltage wave by 45 degrees.



Power in a Capacitive Circuit

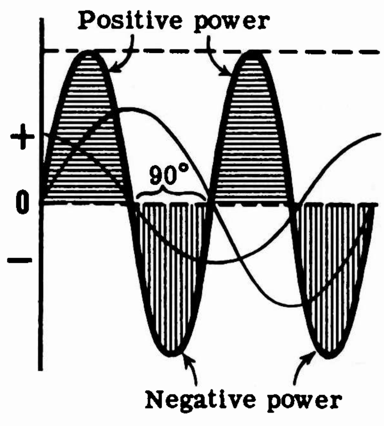
In a capacitive circuit as in an inductive circuit, the true power used is less than the apparent power of the circuit. Current leads the voltage in a capacitive circuit. The power waveform again is obtained by multiplying the corresponding values of voltage and current to obtain the instantaneous values of power. The power wave of an AC circuit consisting of pure capacitance is shown below and, like the power wave of a purely inductive circuit, its axis is the same as that of the voltage and current, while its frequency is twice that of the voltage and current. For this circuit the phase angle between the current wave and voltage wave is 90 degrees, and the negative power equals the positive power. The formula for power factor for a capacitive circuit is the same as that used for an inductive circuit.

When resistance is added to a capacitive circuit the phase angle decreases, and the positive power becomes greater than the negative power. Because the voltage and current are out of phase, power in watts does not equal apparent power, and power factor is between zero and 100 percent.

POWER WAVE

OF A CIRCUIT CONTAINING ONLY **CAPACITANCE**

Phase angle
90° leading

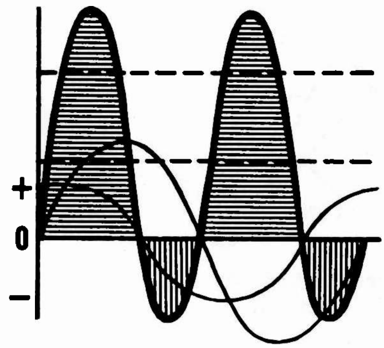


Apparent power E X I

True power is zero

$$P.F. = \frac{T.P.}{A.P.} = 0\%\ (90°)$$

Adding resistance decreases phase angle—increases true power



Apparent power E X I

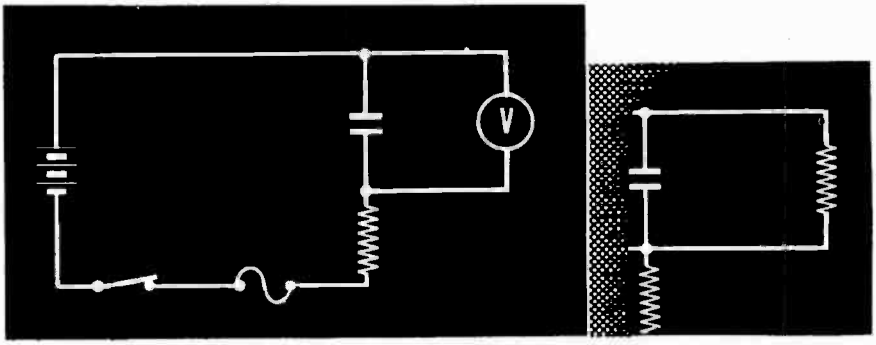
True power—power-wave axis

$$P.F. = \frac{T.P.}{A.P.} = 70\%\ (45°)$$

Demonstration—RC Time Constant

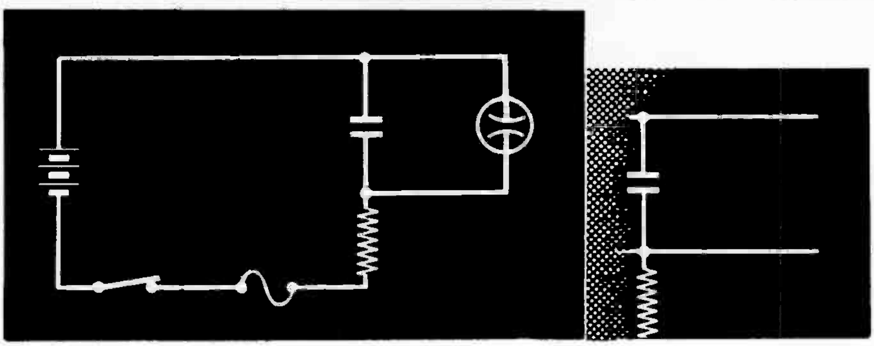
In an RC circuit the charging current for the capacitor is limited by the resistance, and the voltage across the capacitor builds up slowly at a rate determined by the RC time constant. If a voltmeter is used to measure the voltage across a capacitor to show the rise in voltage as the capacitor charges, the plates of the capacitor are connected together through the resistance of the voltmeter. This prevents the capacitor from reaching full charge and, since the meter completes the circuit across the capacitor, it will not show the rise in voltage across the capacitor.

A VOLTMETER CONNECTED ACROSS A CAPACITOR
ACTS AS A **RESISTOR**



To show how voltage builds up across a capacitor, a device which will indicate voltage but will not connect the capacitor plates together is needed. A neon lamp may be used for this purpose, since it is an open circuit until the voltage across its terminals reaches a predetermined value. The lamp does not accurately measure voltage, nor show the actual building up of the voltage as the capacitor charges. However, if connected across a capacitor which is being charged, it does show that the build-up of voltage across a capacitance is delayed, since the neon lamp does not light immediately when the charging voltage is applied to the capacitor circuit. The lamp lights only after the voltage between the capacitor plates reaches the starting voltage of the lamp.

A NEON LAMP IS AN OPEN CIRCUIT
UNTIL ITS STARTING VOLTAGE IS REACHED

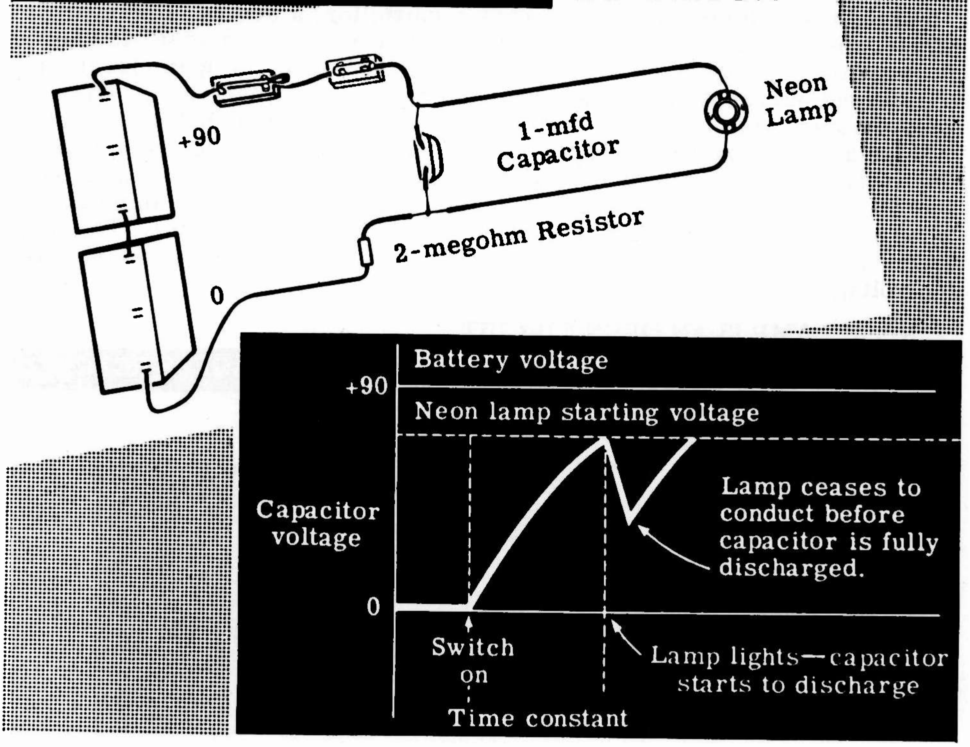


Demonstration—RC Time Constant (continued)

To show how a neon lamp may be used to indicate the time delay in the rise of voltage across a capacitor, the instructor connects a 1-mfd capacitor in series with a 2-megohm resistor. A neon lamp socket is connected across the capacitor and a neon lamp is inserted in the socket, completing the circuit except for a source of voltage. The unconnected end of the resistor is connected to the negative terminal of a 90-volt battery—two 45-volt dry cell batteries in series.

When the instructor closes the switch, you observe that after a momentary delay the neon lamp flashes, indicating that the voltage across the capacitor terminals has reached the starting voltage of the lamp. Notice that the neon lamp continues to flash at intervals of about one second. Each time that the capacitor charges to a voltage equal to the starting voltage of the lamp, the lamp lights—providing a path for current flow between the capacitor plates and discharging the charge which has been built up. When the capacitor discharges through the lighted lamp, its voltage drops to a value which is too low to operate the lamp, the lamp ceases to conduct and again becomes an open circuit. The capacitor then begins to charge again. You see that the lamp lights repeatedly, since each time that the voltage across the capacitor reaches the lamp's starting voltage, the lamp lights, discharging the capacitor.

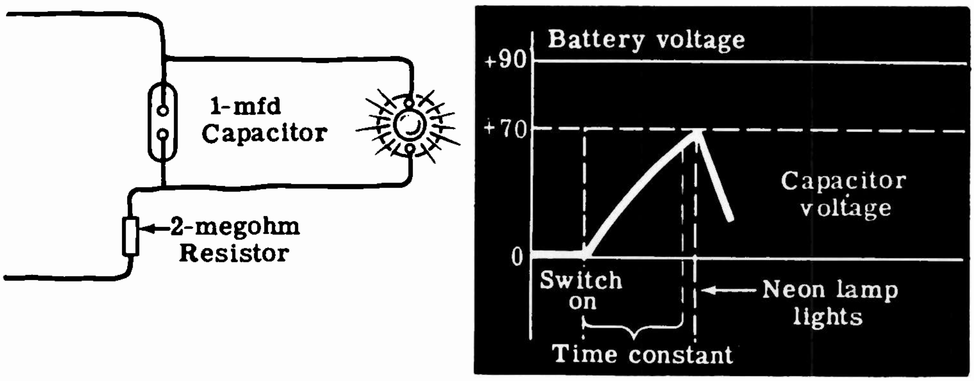
OBSERVING THE TIME DELAY OF AN RC CIRCUIT



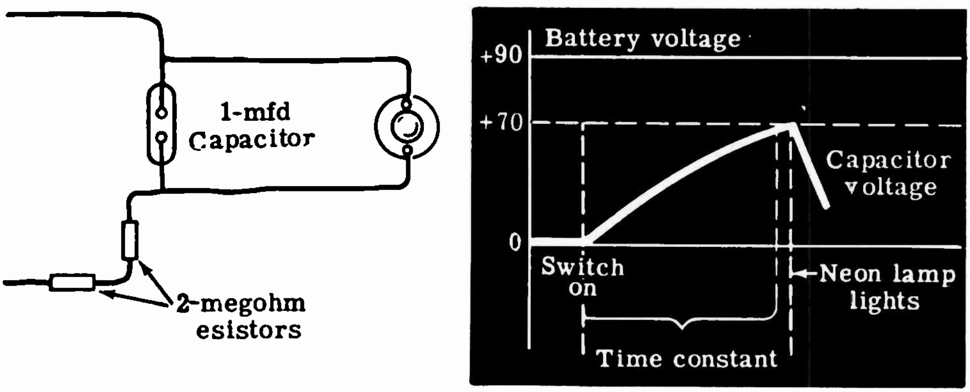
Demonstration—RC Time Constant (continued)

In order to demonstrate the effect of resistance on the time required for the capacitor to charge, additional resistors are added in series with the 2-megohm resistor. Observe that, when the resistance is doubled, the time required for the capacitor to charge is also doubled.

You already know that the RC time constant gives the time in seconds required for the voltage of a charging capacitor to reach 63.2 percent of the voltage applied to the circuit. The starting voltage of the neon lamp is between 65 and 70 volts, or about 75 percent of the total battery voltage used. However, there is a difference between the computed time constant and the observed time constant. If the circuit resistance is 4 megohms, according to the computed time constant the neon lamp should flash 15 times per minute (4 megs x 1 mfd = 4 sec); but you actually see about 30 flashes per minute. The reason for this is that the lamp does not light at exactly 63.2 percent of charge because the capacitor does not fully discharge each time the lamp flashes. As various values of resistance are used, compare the time required to light the lamp with the computed time constant of the circuit.

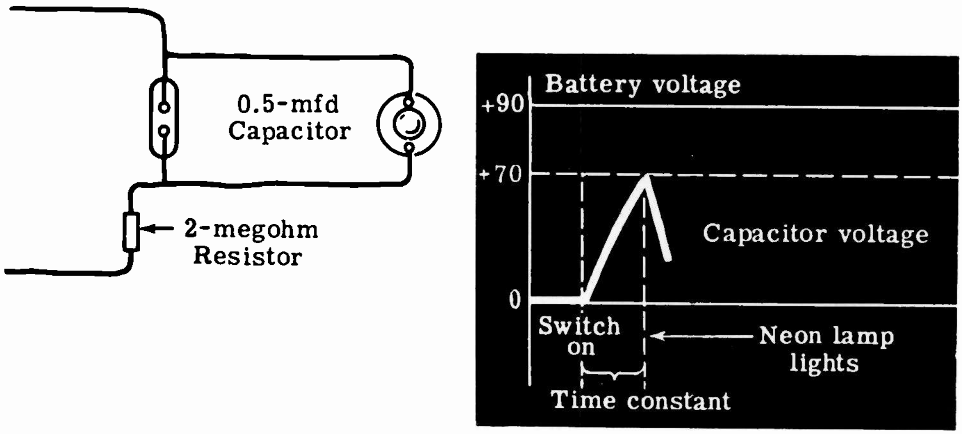


A CHANGE IN RESISTANCE CHANGES THE RC TIME CONSTANT

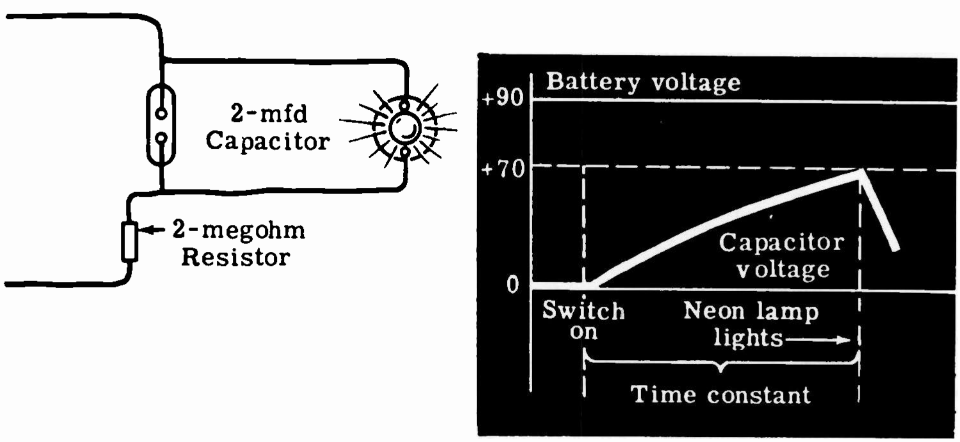


Demonstration—RC Time Constant (continued)

Next, all of the resistors are removed except the single 2-megohm resistor, and various values of capacitance are used. Notice that changes in the value of capacitance have the same effect on the circuit time constant as changes of resistance. When low values of capacitance are used, the time constant is shorter and the flashes occur so rapidly that the light appears to be steady rather than flashing.



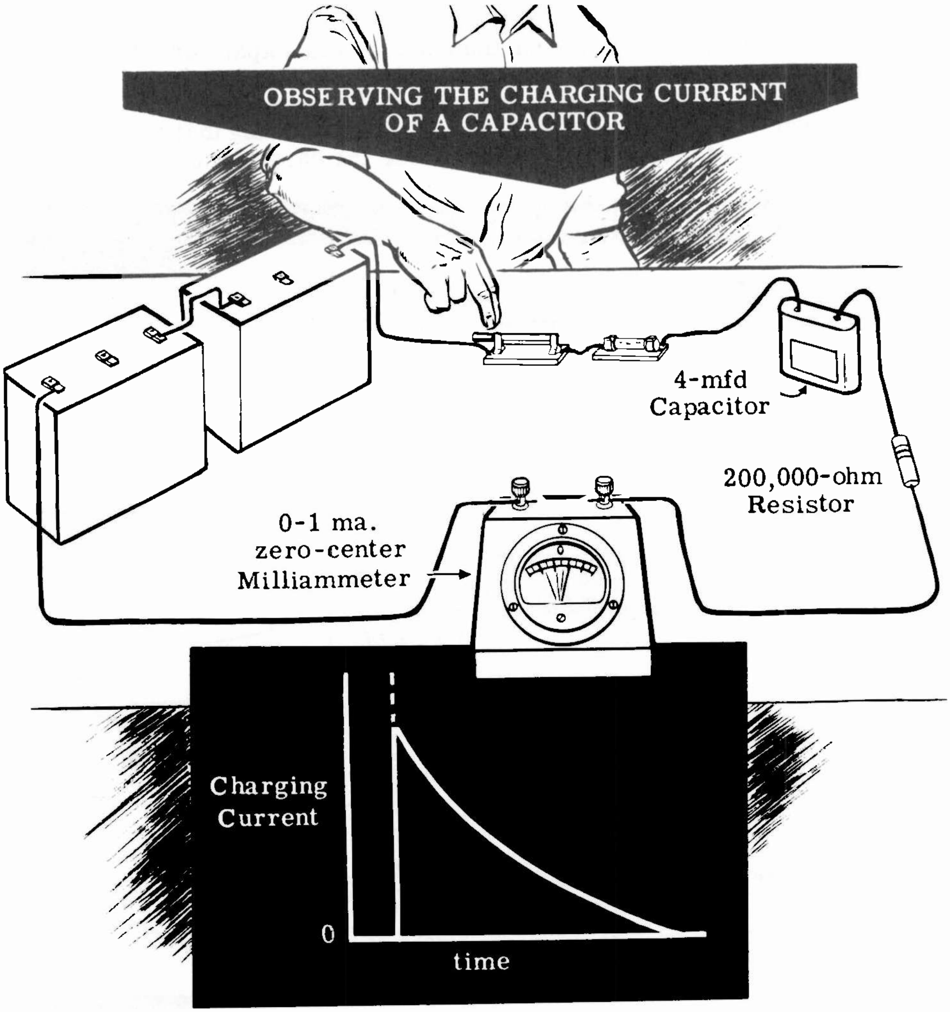
A CHANGE IN CAPACITANCE CHANGES THE RC TIME CONSTANT



Demonstration—RC Time Constant (continued)

Current flow in charging a capacitor is next demonstrated. A 0-1 ma. zero-center milliammeter, a 200,000-ohm resistor and a 4-mfd capacitor are series-connected in the circuit shown below.

At the moment the switch is closed, you see that the meter indicates a large current flow and, as the capacitor charges, the meter reading falls toward zero. Observe that once the current reaches zero (indicating a full charge on the capacitor plates) opening and closing the switch causes no further current flow. The instructor then opens the switch and discharges the capacitor by shorting its terminals with the screwdriver. Now, when the switch is closed, the meter will indicate a charging current.



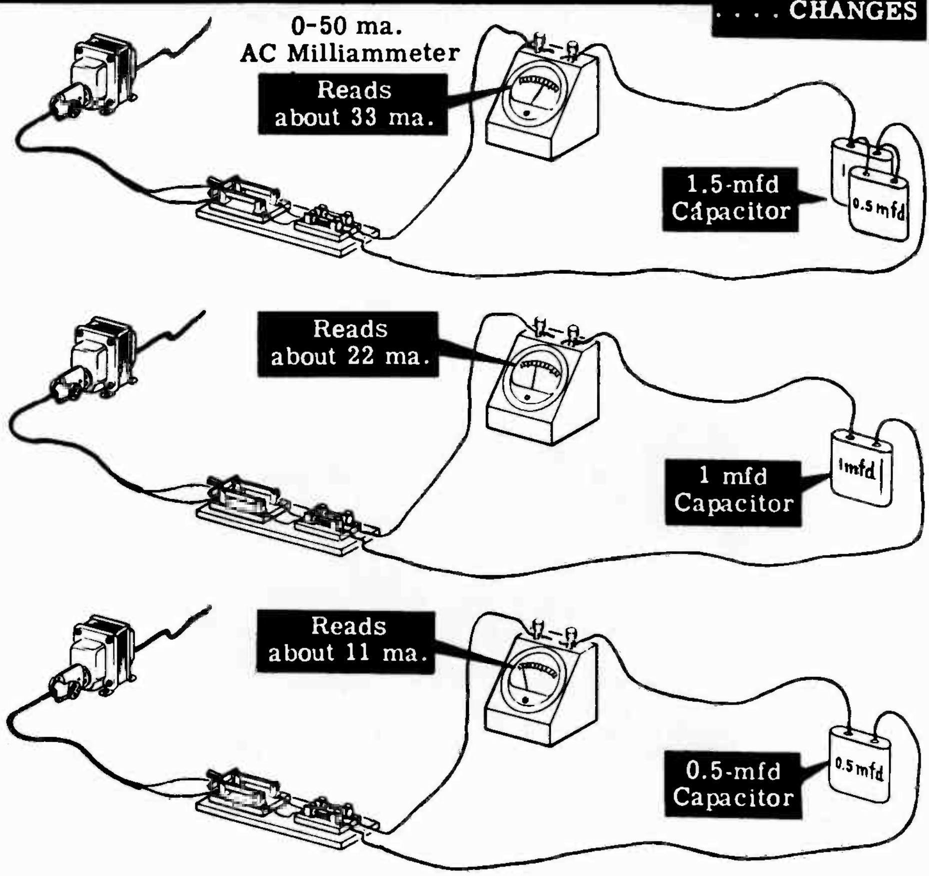
Substituting capacitors having various values, the instructor shows that the current flow lasts longer when charging larger capacitors. Notice that, for small values of capacitance, the time required to charge them is so short that it is difficult to read the current indicated on the meter.

Demonstration—Capacitive Reactance

You have already found out that AC current can flow through a capacitive circuit and that the opposition to current flow in such a circuit depends on the capacitance, provided the frequency remains constant. Using the 117-volt AC power line connected through the step-down autotransformer as a voltage source (thus obtaining a constant voltage of 60 volts and a 60-cycle frequency), the instructor connects the 0-50 ma. AC milliammeter in series with the parallel-connected 1-mfd and 0.5-mfd paper capacitors. When the transformer is plugged in and the switch is closed, you see that a current flow is indicated on the AC milliammeter.

To show the effect of changing the value of capacitance on the opposition offered to the flow of AC current, the instructor replaces the 1.5-mfd capacitor with first a 1-mfd and then a 0.5-mfd capacitor. Notice that each time the capacitor is changed, he first opens the switch and then discharges the capacitor with a screwdriver. You see that increasing the value of capacitance increases the current flow, showing that the opposition or capacitive reactance decreases whenever the capacitance increases.

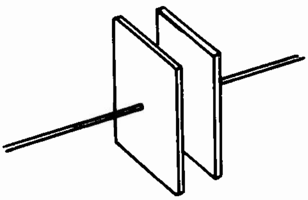
OBSERVING THE CAPACITIVE REACTANCE AS THE CAPACITANCE. . . . . . CHANGES



CAPACITORS AND CAPACITIVE REACTANCE

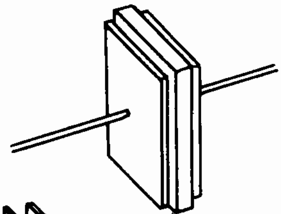
Review of Capacitors and Capacitive Reactance

Before performing the experiment on capacitive circuit time constants, you should review some of the facts you have found out concerning capacitors, capacitive reactance and RC time constant.

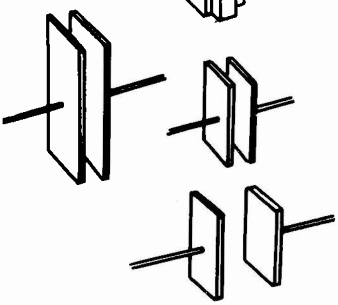


CAPACITOR PLATES — Metallic or metallized plates which can be charged.

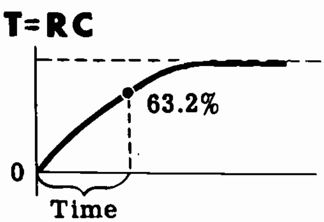
Time = Resistance X Capacitance



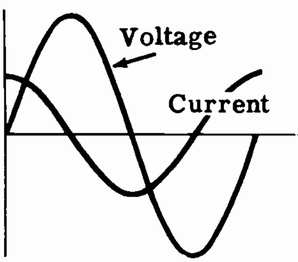
DIELECTRIC — Insulating material between the plates of a capacitor.



FACTORS OF CAPACITANCE — Plate area, the distance between the plates and the dielectric material determine capacitance.



CAPACITIVE TIME CONSTANT — The product of RC which gives the time in seconds required for a capacitance to reach 63.2 percent of full charge.



CAPACITIVE REACTANCE — The action of capacitance in opposing the flow of AC current and in causing the current to lead the voltage.

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(Note: A cumulative index covering all five volumes in this series will be found at the end of Volume 5.)

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