M/Sgt. W.F. Podlik

PHILCO

TECHREP DIVISION BULLETIN

1. miller effect

AUGUST
1952

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Several months ago, we distributed a reservation slip to all persons then on the BULLETIN mailing list, to be completed and returned by those readers who wished us to reserve one or more binders for their BULLETIN back issues.

At that time, we indicated that our current appropriation did not allow us to supply the binders free of charge, but that we planned to procure and distribute them at cost, if we received a sufficient number of requests.

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If any information contained herein conflicts with a technical order, manual, or other official publication of the U.S. Armed Forces, the information in the official publication should be used.

Editorial

The "Grass is Always Greener . . ." Myth

By John E. Remich, Manager, Technical Department

It has become increasingly apparent that in electronics engineering, as in most other professions, there are those who are constantly harassed by the feeling that promotion and increased responsibility lie in some other phase of electronics engineering. The variety of engineering positions which are the natural result of the current expansion in electronics facilities and the shortage of engineering talent, have provided an almost irresistible temptation to such persons, with the result that the electronics industry is experiencing a higher-than-average rate of job switching.

To those who find themselves in the category of the "dissatisfied," a word of caution is in order. Evaluate your present position carefully, and examine all its potentialities before assuming that opportunity is greater elsewhere, or that another phase of engineering is more glamorous or offers greater advantages. It is well to remember also that each job has its share of boresome details, frustrations, and disappointments. Too often, the man who changes jobs simply to find more exciting activity, or because of some obscure "need for a change," finds that he has wasted valuable time and that the need for change was actually in his attitude and outlook, rather than in the nature of his job.

We strongly urge that you examine your present duties with an eye to suggestions for improvement which may be obvious to you but which probably have never been brought to the attention of your superior. New ideas and increased efficiency in your present job will be of far greater importance in effecting advancement than changing jobs. It has been repeatedly proved that management in any industry or profession is eager to utilize the ability and initiative of its employees, but that the ability must be demonstrated and the initiative must be made evident through the efforts of the employee, in order to be recognized.

THE MILLER EFFECT

By Gail W. Woodward
Headquarters Technical Staff

A practical explanation of the effects of plate-to-grid interelectrode capacitance in a vacuum tube, and a discussion of several circuits in which Miller effect is used to advantage or cancelled.

THE MILLER EFFECT, which has been one of the many confusion factors inherent in electronics, has been known for a considerable time,[*] but is often misunderstood or overlooked. The result has been some apparently rather weird behavior of electronic circuits.

The unfortunate combination of the effects of tube interelectrode capacitances is responsible for the Miller effect. Figure 1 shows the capacitances involved. Looking into the input circuit, the grid-to-cathode capacitance (C_{gk}) is, of course, immediately encountered. The attenuating effect of this capacitance shunting the input signal is well known. If a signal is applied to the input circuit, an amplified version will appear at the plate of the tube. Since the amplified signal is 180° out of phase with the input signal, the portion coupled back to the input by way of the grid-to-plate capacitance (C_{gp}) will tend to cancel the input signal. This effect is exactly the same as if the C_{gk} were made larger. Thus, the effect of the grid-to-plate capacitance is to increase the input capacitance of the tube.

In order to obtain an equation, consider the circuit shown in figure 2. Consider the total input capacitance as being made up of two values—the equivalent input capacitance caused by feedback, and C_{gk}. The charge on C_{gk} will be:

$$Q_1 = CE = C_{gk}E_g \qquad (1)$$

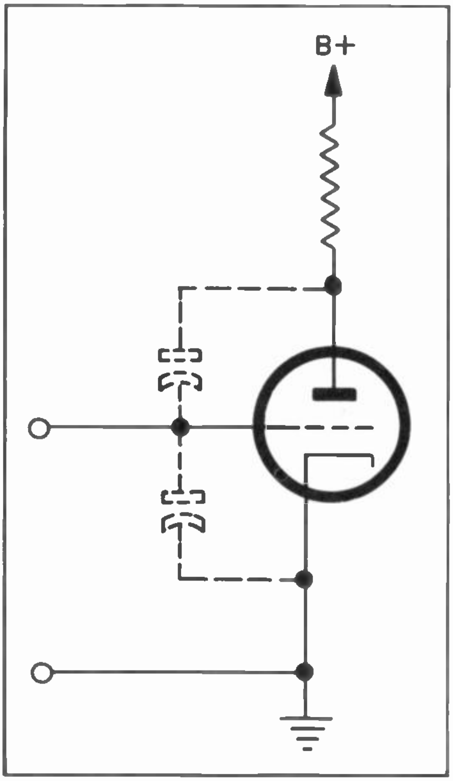

Figure 1. Interelectrode Capacitances Involved in Miller Effect

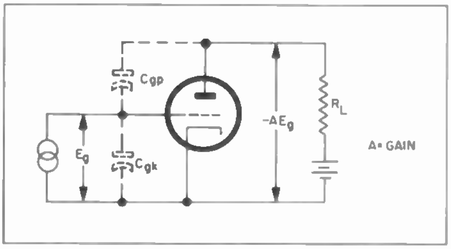

Figure 2. Equivalent Circuit of Triode Amplifier

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[*] J. M. Miller, 1919

$C_{in} = C_{gk} + C_{pg}(1-A)$ For CATH. FOLLOWER

where:

$$E_g = \text{a-c grid voltage}$$

The charge on C_{gp} will be:

$$Q_2 = C_{gp}\,[E_g - (-AE_g)] = C_{gp}E_g(A+1) \qquad (2)$$

where:

$$A = \text{gain of stage}$$

As far as the input circuit is concerned, these two charges will appear additive. Therefore:

$$Q_{in} = Q_1 + Q_2 = C_{gk}E_g + C_{gp}E_g(A+1) \qquad (3)$$

Since Q_{in} is the total charge of the input capacitance (C_{in}), this capacitance will be related by:

$$Q_{in} = C_{in}E_g \qquad (4)$$

Combining equations 3 and 4:

$$C_{in}E_g = C_{gk}E_g + C_{gp}E_g(A+1)$$

Simplifying:

$$C_{in} = C_{gk} + C_{gp}(A+1) \qquad (5)$$

It can be seen from equation 5 that the total input capacitance is determined not only by the distributed capacitances but also by the gain of the stage.

The foregoing action can most readily be illustrated by applying equation 5 to a typical circuit. Assuming the circuit values shown in figure 3, and the published characteristics of the 6SQ7, the stage gain will be:

$$A = \frac{\mu R_L}{R_p + R_L}$$

$$A = \frac{100 \times 220K}{110K + 220K} = 67$$

Substituting the circuit values into equation 5 we obtain:

$$C_{in} = 3.2 + 1.6(67+1) = 112\ \mu\mu f.$$

The tube, itself, has an input capacitance of only 3.2 $\mu\mu$f., but, when used in the circuit shown, the overall effective input capacitance is 112 $\mu\mu$f. —Miller effect accounts for 108.8 $\mu\mu$f. of the total. In fact, the C_{gk} is almost completely overshadowed by the action of Miller effect. This explains the shortcomings of high-gain-triode video amplifiers.

The superiority of the pentode tubes such as the 6SJ7, 6AU6, or 6BA6 can readily be seen by analyzing the circuit shown in figure 4. The circuit constants have been chosen to provide a gain equal to that of the circuit shown in figure 3. Substituting these circuit values into equation 5:

$$C_{in} = 6 + .005(67+1) = 6.34\ \mu\mu f.$$

Thus it can be seen that the increase in capacitance caused by Miller effect is very small in circuits in-

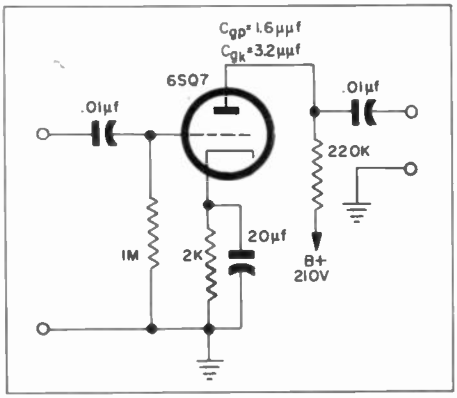

Figure 3. Schematic Diagram of Typical Triode Amplifier

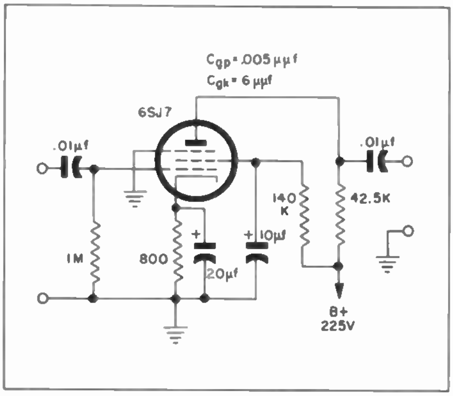

Figure 4. Schematic Diagram of Typical Pentode Amplifier

corporating these pentodes, because of their very low C_{gp}. The effect is more pronounced with such tubes as the 6AK5, 6AG5, or 6AH6.

REACTIVE EFFECTS

The above discussion deals only with the resistive plate load and its effective increase in input capacitance. If the plate load is reactive, the phase of the feedback through C_{gp} will change, and the effect upon the input will no longer be merely capacitive. With a plate load which contains both reactance and resistance, the Miller effect will be equivalent to a resistance as well as a capacitance reflected back into the grid circuit—the resistance being due to the reactive component of the plate load. The grid-circuit resistance caused by Miller effect can be expressed as:

$$R_{in} = -\frac{1}{C_{gp} A \sin \theta} \qquad (6)$$

where:

θ = the phase angle of the load voltage. (θ is considered positive for an inductive load.)

When the reactive plate load is considered, equation 5 is modified as:

$$C_{in} = C_{gk} + C_{gp}(A\cos\theta + 1) \qquad (7)$$

Examination of equation 7 will disclose the fact that a purely inductive load ($\theta = 90°$) will result in an input capacitance which is merely the sum of C_{gk} and C_{gp}. Equation 6 shows that for the same condition, the effect of the resistive component is most pronounced (minimum R_{in}). We now find a very interesting characteristic of equation 6. Since θ is positive for an inductive load, R_{in} will be negative. If θ is negative (capacitive load), R_{in} will be positive.

Consider a tuned circuit in the plate circuit of an amplifier stage. At resonance, the plate circuit will cause a pure capacitance to be reflected into the grid circuit; when the plate circuit is tuned to a frequency below the signal frequency, the reflected grid component is resistive; and, if the plate circuit is tuned to a frequency above resonance, the reflected grid component is a negative resistance. If the negative-resistance component is larger than the positive grid-circuit resistance, oscillation can occur—this is why it is so easy to cause a high gain i-f stage to oscillate by detuning the plate circuit.

APPLICATIONS

If the action of the tuned-plate-tuned-grid oscillator or of the crystal oscillator is examined, it will be found that both of these circuits require that the plate tank be tuned to a higher frequency than the grid circuit. The effect of reflected negative resistance is essential to the function of such circuits. In fact, if the plate tank of either circuit is tuned slightly below resonance, oscillation will cease.

Miller effect is one of the reasons for the practice of aligning a receiver by starting at the output and working back toward the input. If the grid circuit were to be aligned first, adjusting the plate circuit could detune the grid circuit. However, the tuning of the grid circuit will have very little effect upon the plate-circuit tuning.

Another factor to keep in mind during alignment is the action of an a-v-c circuit. If a receiver is aligned with a strong signal, a-v-c voltage is large, and Miller effect is minimum (reduced value of A). Then, when weak-signal reception is attempted, the lower a-v-c voltage allows greater gain, which increases Miller-effect capacitance and causes detuning of the grid tank circuits of each a.v.c.-

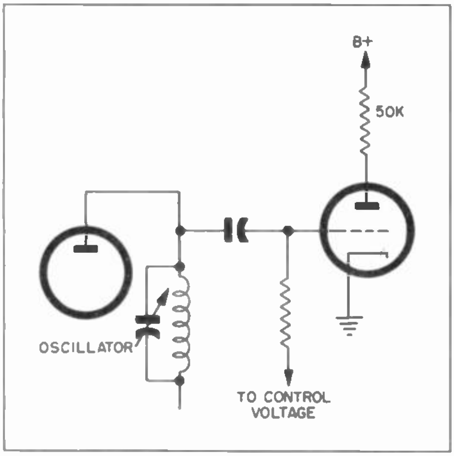

Figure 5. Schematic Diagram of Circuit Which Produces a Variable-Reactance Effect, Using a Triode Tube

controlled stage. For this reason, it is standard practice to perform alignment with the weakest possible signal—thus insuring satisfactory weak-signal operation. (Detuning on strong signals would have virtually no detrimental effect, because a large signal loss could be tolerated.)

The Miller effect can put to good use as a source of variable reactance in a-f-c applications. Figure 5 shows a typical circuit. The plate circuit of V_2 is made resistive, which causes a capacitive grid circuit to be presented to the oscillator (V_1). Thus, the capacitance shunted across the oscillator tank can be varied by any means that would change V_2's gain (term A in equation 5). In the circuit of figure 5, the gain is varied by changing the bias. This same circuit could be used as a frequency modulator by driving the control grid with an audio voltage.

A relatively recent application of the Miller effect is found in its use as a tone-control element. Figure 6 shows a pentode circuit with a resistive plate load. The grid-to-plate capacitance is made very large by the use of an actual capacitor. The capacitance appearing between grid and ground will be very largely a function of the stage gain, which is varied by means of a bias control. This bias control could be a remotely-located potentiometer, or it might be the circuit shown in block form in figure 7.

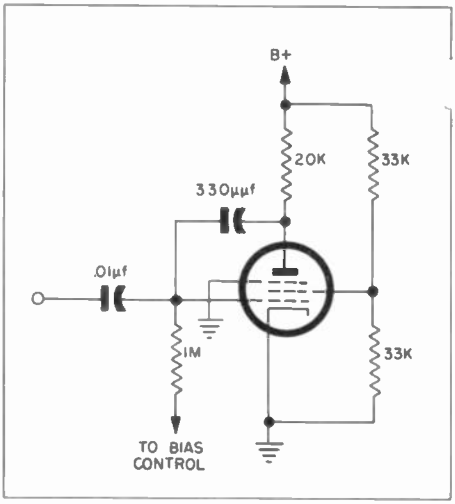

Figure 6. Miller-Effect Tone-Control Circuit

The circuit shown in figure 7 is called a "noise gate" because it has the unique property of closing out record scratch from an audio amplifier. The phonograph pickup feeds a high-pass filter that allows only signals in the scratch-frequency range and higher to pass (above about 3 kc.). The filter output is amplified, rectified, and used to control the gain of a Miller-type tone-control circuit similar to the one shown in figure 6.

If the recorded music or other intelligence contains no *signals* in the scratch-frequency range or higher, the output of the rectifier remains at zero. (The rectifier is negatively biased by a small amount so that the record noise itself does not affect the Miller control tube.) Under these conditions, the gain of the control

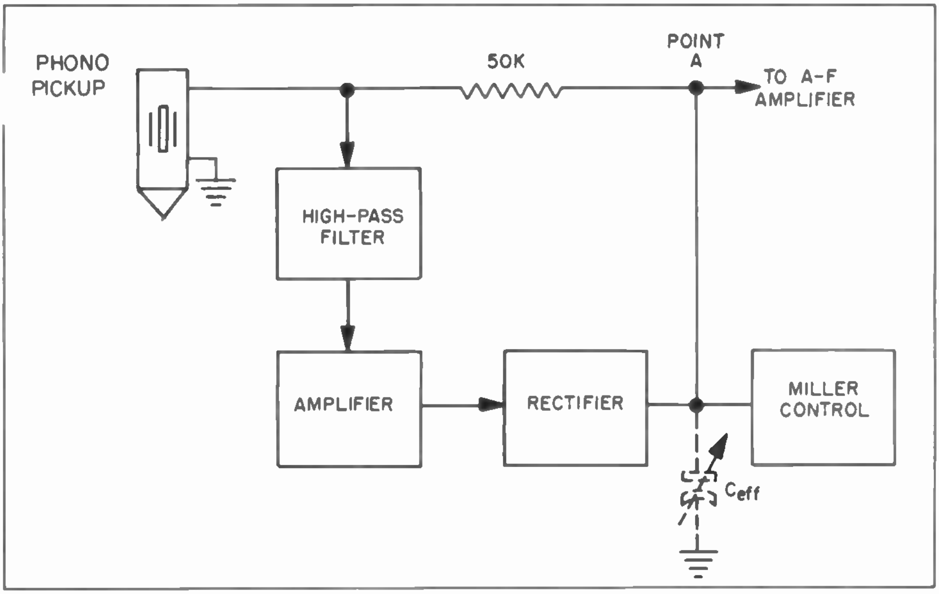

Figure 7. Block Diagram of Automatic "Noise-Gate" Circuit

tube is high, and a large effective capacitance appears between point A and ground. This capacitance, in conjunction with the series 50K resistor, limits the frequency response of the system to the point where record scratch is bypassed.

However, when the recorded intelligence *does* contain components in the frequency band above 3 kc., the high-pass filter passes these components which are amplified, rectified, and applied as bias to the Miller control tube. Under this condition, the capacitance appearing between point A and ground becomes very small, removing the bypassing action and allowing the high-frequency signals to reach the a-f amplifier.

Thus, the only time the "noise-gate" circuit allows wide-range response is when the high-frequency signals are sufficiently pronounced to mask the noise. This circuit is used in the better class of late-model Philco phonograph combinations, because it offers greatly reduced background noise during record reproduction.

Figure 8 shows still another circuit application of the Miller effect. This circuit is used to produce a sawtooth waveform for oscilloscope use. Capacitor C, the grid-to-plate capacitor, is amplified by virtue of the Miller effect, and forms an RC time-constant circuit with resistor R. The

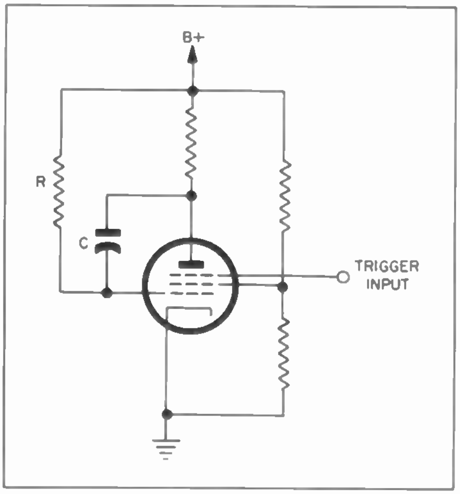

Figure 8. Miller-Effect Sawtooth Generator

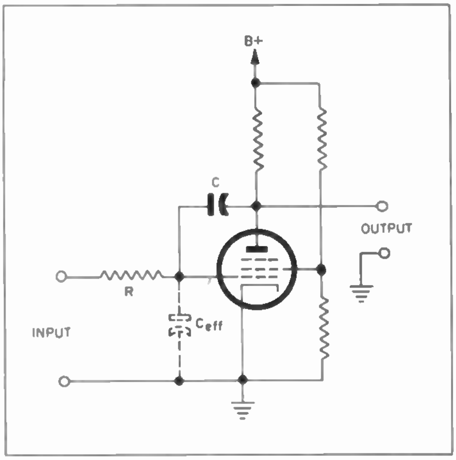

Figure 9. Miller-Effect Integrator

trigger pulse consists of a positive gate pulse which causes the tube to conduct. Because of the large amount of feedback, the plate voltage drops at a relatively slow rate. The effect is the same as if a very large capacitor were connected between grid and ground, and the tube were amplifying the capacitor-charging waveform. This circuit has the advantage of being able to produce very linear sawtooth waveforms of a very long period, with relatively small RC values.

The Miller Integrator (shown in figure 9) makes use of the amplified value of grid-to-plate capacitance C to obtain a large effective value of input capacitance (C_{eff}). R and C_{eff} form the integrator. The tube will also serve as an amplifier of the integrator waveform. As in the sawtooth generator, the large value of negative feedback in the amplifier provides an excellent means of obtaining linearity.

CORRECTION

In many cases, the presence of the Miller effect is very undesirable. For example, the variations in a-v-c voltage in a high-gain, i-f section could cause serious detuning. Another example is found in TV i-f sections where the stray capacitance provides the only circuit tuning.

Several methods have been devised to overcome the effect. One well-known method is to use neutralization in any conventional form. However, most forms of neutralization are resonant. Another method consists of using a large tuning capacitor to "swamp" out the Miller-effect variations—this method is useless at the higher frequencies. Figure 10 shows the most widely used method of eliminating Miller effect. Here, the action of a degenerative cathode resistor is used to cancel the plate-to-grid feedback. Equation 8 gives the optimum value of cathode resistor.

$$R_k = \frac{\Delta C_g + \Delta C_m}{C_{gk} G_m} \qquad (8)$$

where:

ΔC_g = change in input capacitance due to changes in the space charge with bias

ΔC_m = change in input capacitance due to changes in Miller-effect capacitance with bias

G_m = transconductance of tube at maximum gain (minimum a-v-c voltage)

Fortunately, it will be found that the optimum value of R_k is often about 150 to 200 ohms—a value suitable for ordinary cathode bias. Of course, the unbypassed cathode resistor will result in a reduction of gain as expressed in the following equation:

$$A' = A\left[\frac{1}{(1 + G_m R_k)}\right] \qquad (9)$$

where:

A' = gain with unbypassed cathode resistor

A = gain with bypassed cathode resistor

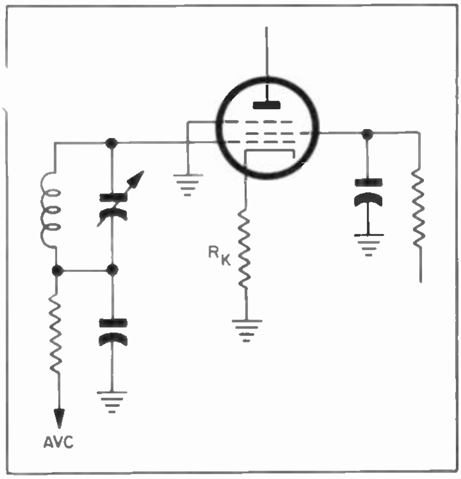

Figure 10. Schematic Diagram Showing Method For Neutralizing Miller Effect

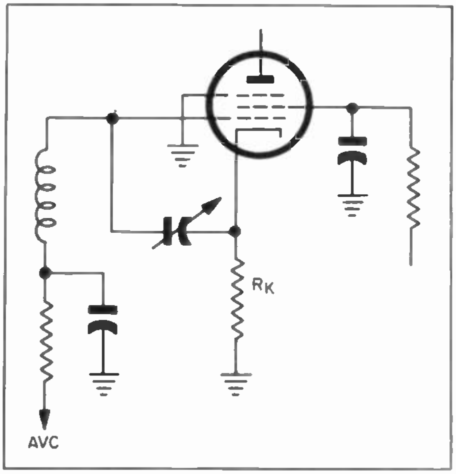

Figure 11. Schematic Diagram Showing Second Method For Neutralizing Miller Effect

For a typical pentode circuit, the loss in gain caused by the unbypassed resistor will be around 30%, but this can usually be made up by using a smaller value of tuning capacitance to obtain a higher tuned-circuit Q (the smaller capacitor can be used because Miller-effect capacitance changes do not have to be swamped out).

An alternate method of neutralizing the Miller effect is shown in figure 11. The unbypassed cathode resistor is used, but the tuning capacitor is returned to the cathode instead of to the ground end of the inductor. This method of connection enables the use of a cathode resistor of only about 20 ohms. This is because the degenerative signal produced by the cathode resistor is amplified by the series-resonant action of the tuned-input circuit before it is applied to the grid of the tube.

CONCLUSION

The Miller effect must be considered by the field engineer—not only in circuit design but also in instructional and maintenance activities. (This is especially true in the case of the triode tube.) The effect can be neutralized (and must be in some cases) but a great many circuits use it to functional advantage.

* * *

STARTING AND OPERATING THREE-PHASE MOTORS ON A SINGLE-PHASE LINE

By Zygmund J. Bara
Philco Field Engineer

Several methods by which three-phase motors may be started and operated with a single-phase power supply, in an emergency.

IN THE FIELD, instances sometime arise in which only three-phase motors are on hand, while the only available power supply for operating the motors is single phase. The purpose of this article is to explain how three-phase motors can be started under such conditions, and how they perform when operated on a single-phase power source.

Any three-phase motor can be converted to a single-phase motor simply by opening one of the stator windings (phases) as shown on figure 1. The two remaining phase windings, "ao" and "ob" are then effectively in series.

It can be shown mathematically that the magnetomotive force in a single-phase field is equivalent to that produced by two rotating fields, rotating in opposite directions. These rotating fields give the rotor a forward acting torque (T_f) and a backward acting torque (T_b). The torque produced by the forward field and rotor currents is expressed mathematically as:

$$T_f = \left(\frac{7.04}{n_s}\right)\left(\frac{I_f^2 r}{s}\right) \qquad (1)$$

The torque produced by the backward field and rotor currents is expressed as:

$$T_b = \left(\frac{7.04}{n_s}\right)\left(\frac{I_b^2 r}{2 - s}\right) \qquad (2)$$

where:

n_s = speed of rotating field = $\frac{120(f)}{\text{poles}}$

s = slip of rotor with respect to rotating field = $\frac{n_s - n}{n}$

I_f & I_b = forward and backward induced currents in rotor winding, referred to stator

f = frequency in c.p.s.

n = r.p.m.

The resultant torque (T_r) = $T_f + T_b$. At standstill (rotor not in motion), n = 0, slip = 1, and $I_f = I_b$. By evaluating formulas 1 and 2, we find that T_f equals T_b, and that the net, or resultant, torque is zero.

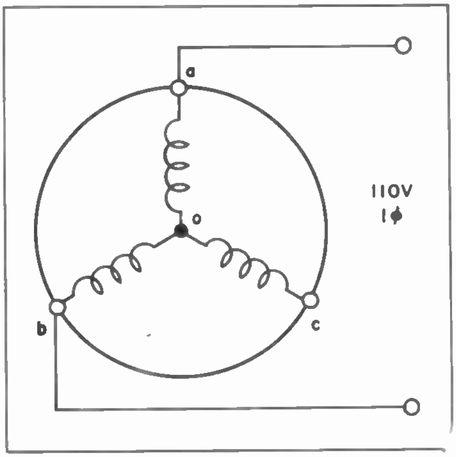

Figure 1. Schematic Diagram of Three-Phase Motor Connected to Single-Phase Power Source

The speed (slip)-vs.-torque curves of a single-phase motor, as shown in figure 2, illustrate the forward, backward, and resultant torque characteristics. Thus, it is shown that at zero speed (when slip = 1), the single-phase windings produce a resultant torque of zero.

It has been shown mathematically and graphically that a single-phase motor at standstill possesses no starting torque. Therefore, methods have to be introduced in order to produce a rotating field, as in a three-phase motor. This rotating field can be obtained by adding: (1) resistance in series with one winding, (2) capacitance in series with one winding, (3) inductance in series with one winding, (4) inductance and resistance in series with one winding, and (5) inductance and resistance across two windings. Thus, by inserting resistance or reactance into the phase winding, the currents in the two windings will be out of phase with each other. This phase difference will produce a rotating field which will be sufficient to provide starting torque. Once the motor has accelerated to near its rated speed, the starting component can be removed from the motor circuit. The five methods of starting are illustrated in figure 3.

Each starting method has its relative advantages and disadvantages.

(1) When resistance is added in series with one winding, the motor starts and accelerates rather quickly. As soon as the motor approaches its rated speed, the resistance can be removed from the circuit. This method is by far the simplest.

(2) A capacitor added in series with a winding gives a high starting torque, and therefore is effective for motors used for driving lathes, etc. If the capacitor is left in the circuit after the motor reaches operating speed, a higher torque is realized, but if the capacitor is switched out, a higher efficiency is realized.

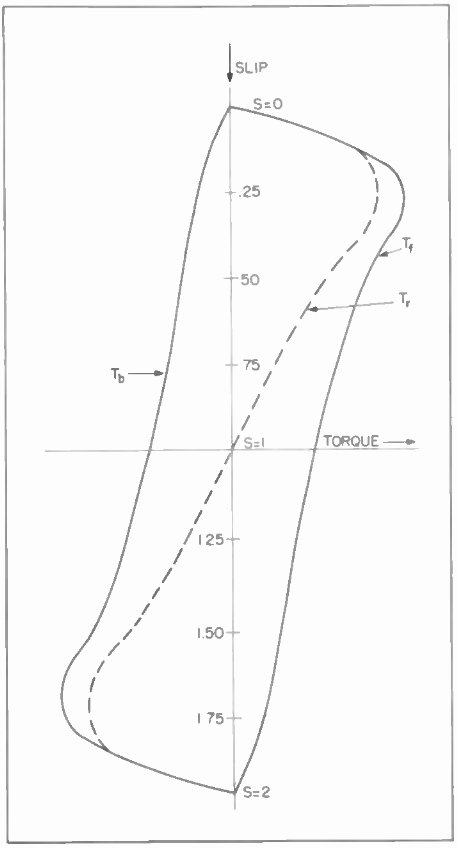

Figure 2. Speed-vs.-Torque Curves of Single-Phase Motor

(3) An inductance in series does not supply so much starting torque as does the capacitor method, but provides more torque and is more efficient than the resistance method.

(4) & (5) Both of these methods provide a relatively slow acceleration. This, however, can be remedied by adjusting values of R and L. Both of these methods provide only about 20% of normal three-phase starting torque, and therefore cannot be used where high starting torque is a requisite.

The characteristic speed-torque

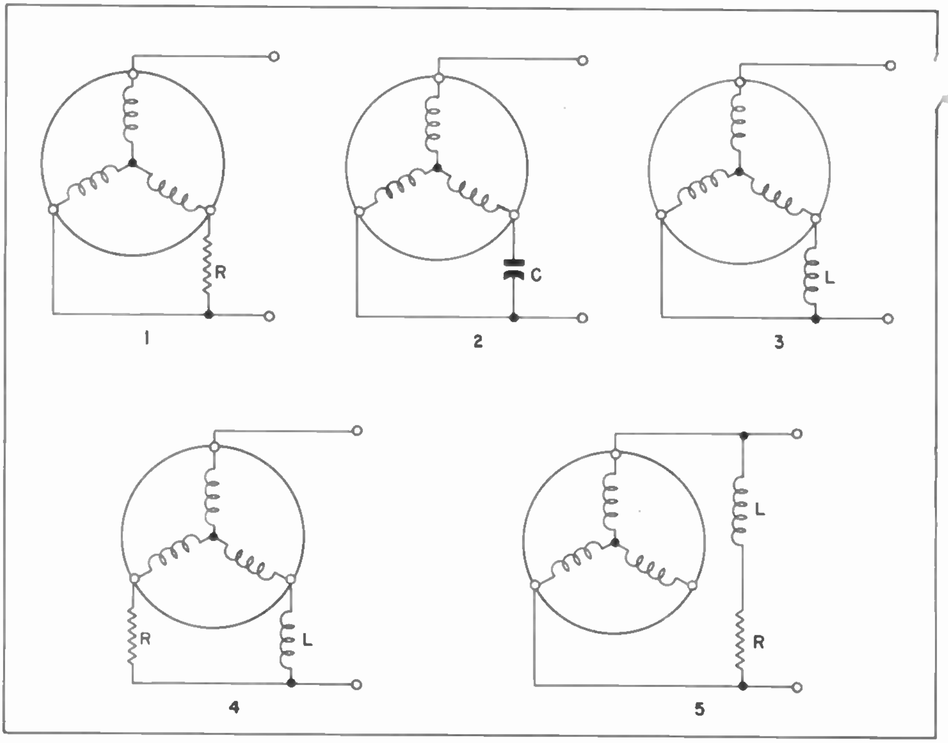

Figure 3. Five Circuits for Providing Starting Torque for Three-Phase Motor on Single-Phase Power Source

comparison curves illustrated in figure 4 show that the pull-out torque (maximum torque) obtained with single-phase operation on a typical three-phase motor was only 37.4% of that obtained with three-phase operation. The data used to plot these curves was based on the operation of a Lewis-Allis 10-hp. squirrel-cage motor.

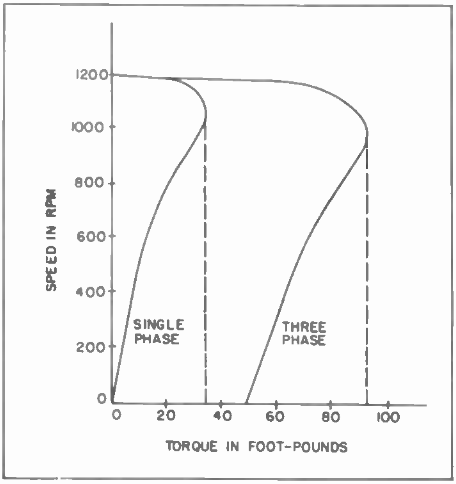

Figure 4. Speed-vs.-Torque Curves for Typical Three-Phase Motor Operated on Single-Phase and Three-Phase Power

The output of a three-phase motor operated on a single-phase line will never exceed 66% of the three-phase value. This is true because one phase is disconnected, and the remaining windings only cover two-thirds of the stator slots. The efficiency of the motor is also decreased with single-phase operation. Since these conditions exist, it is evident that it is not practical to run three-phase motors on single-phase power for a long period of time. In case of emergencies, though, such operation can be and often is practiced.

ZYGMUND J. BARA *was born in South Hadley, Mass. on October 29, 1924. He attended schools in South Hadley and received his diploma from the high school there in June, 1942. He managed to get in a half year at the University of Massachusetts before he was called into the Service in April, 1943.*

While in the Navy, he attended several schools, including the Electronics School, Treasure Island, California. It was here that he acquired his knowledge of electronics. Following this, he acquired practical experience on shipboard electronics while attached to various ship-repair units.

Upon discharge from the Navy, he resumed his education at the University of Rochester, from which he received the degree of Bachelor of Science in Electrical Engineering.

He joined the Philco TechRep Division in July, 1949, and was assigned to AACS. His first assignment took him to Newfoundland, where he remained until January, 1950. At that time, he was transferred to Bermuda, where he still is working with AACS.

TECHNICAL INFORMATION REQUESTS

In recent months, we have received a large number of requests from field personnel for T.O.'s and T.M.'s which have been difficult to obtain through normal supply channels in the field. We have been able to fill most of these requests, but in some cases the requests could not be processed because the writer failed to adequately identify the required publication.

On all such requests, greater speed can be achieved in obtaining requested publications if the writer lists the complete T.O. or T.M. numbers. If these numbers are not available, we can often obtain the necessary technical data if the equipment is completely identified (this is particularly important if it is only a component of a more complex equipment). The name of the manufacturer who built the equipment is useful information also—particularly in those cases where no military publication has ever been prepared for the equipment in question.

Please keep these points in mind, so that we will be able to assist you most efficiently the next time you need help from Headquarters in obtaining a scarce publication.

BASIC MULTIPLEX THEORY

By John Adams

Technical Publications Department

The first of a series of BULLETIN articles on multiplexing. This article serves as an introduction to the subject; future articles will cover specific applications and discuss details of typical circuits.

IN THE LAST DECADE, industrial and Armed Services radio-communications requirements have expanded so rapidly that the h-f and v-h-f portions of the radio spectrum have become crowded and inadequate. This situation has brought about the development of communications equipment which could make use of the vast expanse of the u-h-f and s-h-f bands. The bandpass of such microwave communications equipment is by engineering necessity quite wide (in general, several megacycles wide). However, large bandwidths can easily be tolerated in the vast microwave spectrum. It is obvious that such a wide bandpass would be wasted if only one voice signal or telegraph signal were used to modulate the r-f carrier.

Multiplex, a magic word in the ever-increasing field of communications, according to Webster's definition means: "a system of transmitting several simultaneous messages on the same carrier wave." Multiplex equipment does just that—it combines a number of basic intelligence-carrying signals (voice, telegraph, or combinations of both) into one "composite" signal for transmission.

Multiplex equipments are generally constructed in two sections. One section obtains the signals from various audio, telegraph, or other sources, combines them, and presents the composite signal to a radio transmitter. The other section obtains the composite signal from a radio receiver, separates the basic signals, and presents them to the various reproducing devices. These sections are commonly known as the multiplex transmitter and the multiplex receiver, respectively.

Multiplex equipments have been in use for quite some time; however, the older equipments were limited in the number of channels they could supply, because of the relatively narrow bandpass of the associated radio equipments. An example of this is the AN/TRC-1 communications equipment used by the Armed Forces in the past War. This equipment had a receiver bandpass of approximately 12 kc., which allowed four or six (depending upon the multiplex equipment used) voice-band signals to pass simultaneously.

With modern communications equipments, such as the Philco CLR-6 microwave equipment, a bandpass of *300 kc.* is available, which, with multiplex equipment such as the Philco CMT-4, allows the transmission of up to 24 voice-frequency signals on a single microwave r-f carrier.

METHODS OF MULTIPLEXING

Two methods of multiplexing are in general use at the present time; one is known as frequency division, and the other, time division.

Frequency Division

With frequency division, the entire

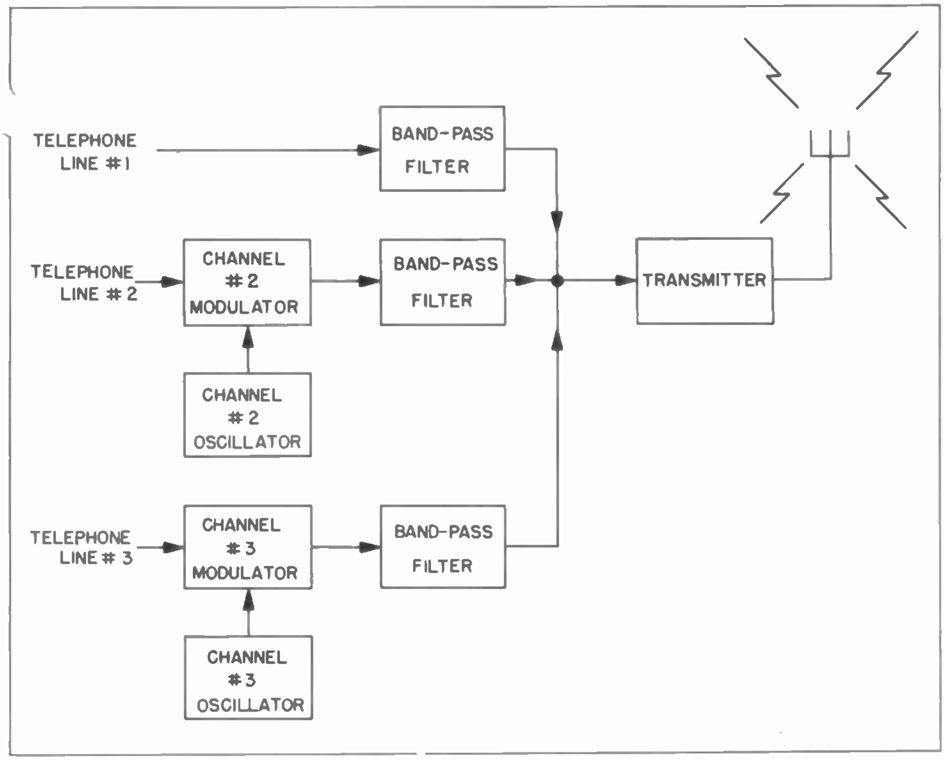

Figure 1. Block Diagram of Frequency-Division Multiplex System

bandpass of the multiplex equipment is divided (in terms of frequency) into channels, with each channel occupying a portion of the frequency spectrum. Each voice-frequency input is heterodyned, by means of a balanced modulator and oscillator, to the appropriate channel frequency, as shown in figure 1. The balanced modulator produces only sideband output, thus providing the feature of oscillator suppression, which means that the adjacent-frequency-rejection characteristics of the associated filter are not too exacting. The combined output of all channels will represent a series of response curves as shown in figure 2. The dashed lines show the frequencies of the associated oscillators. It is evident that the number of channels is limited only by the channel width and the overall bandwidth of the system. The space between channels (called the guard band) is for the purpose of preventing cross modulation between adjacent channels. This is necessary because the filters do not have perfect response curves—the edges tend to slope off to zero.

An example of frequency-division multiplexing is shown in Table I. The equipment operates in the following

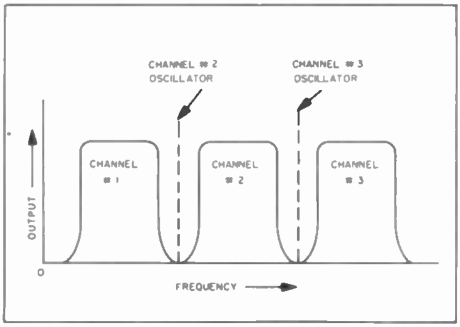

Figure 2. Spectrum Graph of Frequency-Division Multiplex Channels

Table I. Frequency Characteristics of a Typical Frequency-Division Multiplex System

CHANNEL NO.	VOICE FREQUENCY RANGE (c.p.s.)	OSCILLATOR FREQUENCY (kc.)	FILTER RESPONSE (kc.)
1	300 — 2700	NONE	0.3 — 2.7
2	300 — 2700	3	3.3 — 5.7
3	300 — 2700	6	6.3 — 8.7
4	300 — 2700	9	9.3 — 11.7
5	300 — 2700	12	12.3 — 14.7
6	300 — 2700	15	15.3 — 17.7
7	300 — 2700	18	18.3 — 20.7
8	300 — 2700	21	21.3 — 23.7
9	300 — 2700	24	24.3 — 26.7
10	300 — 2700	28	28.3 — 30.7

manner: The frequency spectrum of the equipment is from 300 cycles to 30.7 kc. This spectrum is divided into ten voice-frequency channels (approximately 3 kc. wide), with adequate separation between adjacent channels to prevent cross modulation. The voice signal which is applied to channel 1 (known as the basic voice channel) is subjected only to filtering by the equipment, to keep the signal within the band limits of 300 to 2700 c.p.s. The voice signal applied to channel 2 is heterodyned against a 3000-c.p.s. oscillator. The "sum" frequencies are accepted, while the "difference" frequencies, harmonics, and the original oscillator and input signals are eliminated by the filter, with a resulting signal which ranges from 3300 c.p.s. to approximately 5700 c.p.s. The voice signals applied to the remaining channels undergo the same type of conversion, with the oscillator of each channel operating just above the frequency range of the adjacent lower-numbered channel. At the receiving multiplex equipment, the composite signal is separated by channel filters, heterodyned to its original frequency components by means of an oscillator and modulator similar to the transmitter units, and ultimately applied to appropriate reproducing devices. This system represents what is called a "carrier-telephone" system. Since telegraph signals occupy a very narrow bandwidth, several carrier telegraph (or teletype) signals similarly may be superimposed on each voice channel. (The only additional requirement is that the "current-no current" or "current-reverse current" output of a telegraph or teletype circuit must first be converted to a "tone-no tone" or "tone-other tone" signal prior to being heterodyned, filtered, and combined with other similar signals.) Thus, any given voice channel could be further multiplexed into a number of still-narrower channels.

Time Division

Figure 3 shows an elementary form of time-division multiplexing. The multiplex transmitter consists of a brush-and-commutator arrangement. The brush rotates past a number of commutator segments at a fixed rate. The multiplex receiver has an identical brush-and-commutator system with the brush rotating in synchronism with the transmitter brush. One commutator segment is needed for each multiplex channel.

If synchronism is maintained, it can be seen that, in the position shown, channel number 2 is in operation. As the brush rotates, the successive channels are connected in sequence. Thus each channel is "sampled" once for each brush rotation. If the brush is rotated at a rate above the highest frequency of the intelligence being transferred, it can be seen that each

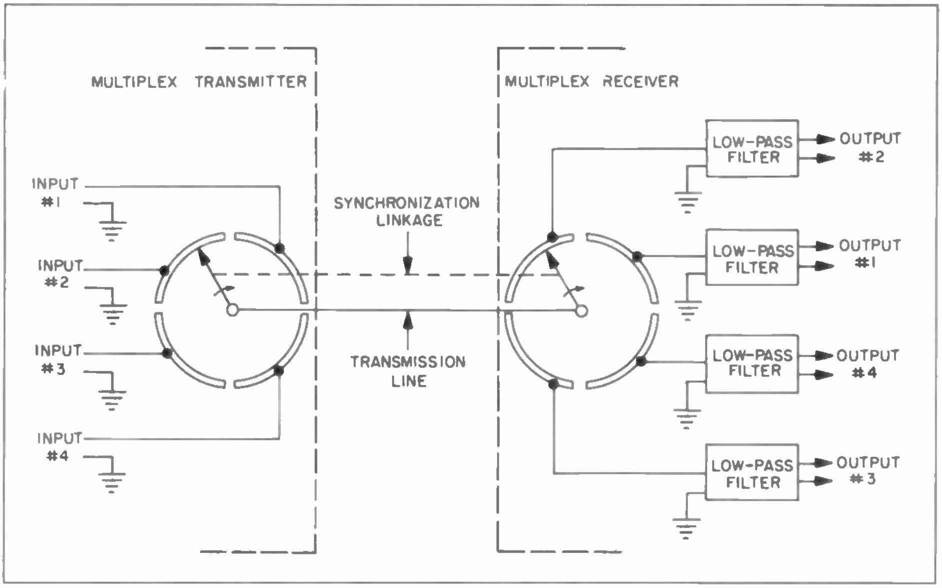

Figure 3. Elementary Form of Time-Division Multiplexer

cycle of the intelligence signal will be sampled at least once.

Figure 4 shows the action of sampling. There are eight samples taken from the 1-kc. sine wave—thus the sampling rate is 8 kc. If this action represented the conditions in figure 3, the 1-kc. sine wave could be considered as being taken apart at the transmitter, passed over the line as pulses, and reassembled again at the receiver. The receiver includes a low-pass filter which effectively removes the sampling-rate signal and restores the original waveform. Of course, other channels are also sampled and their components are carried over the line, but this occurs at different time intervals—thus the signals on each of the channels are split up into pulses which are sent over the line on a time-sharing basis.

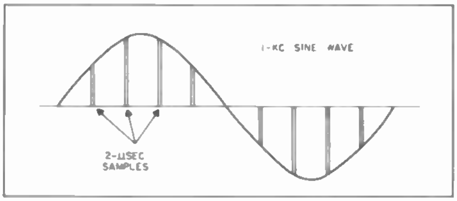

Figure 4. Time-Division Sampling

From figure 4 it is evident that to reproduce both halves of a cycle of intelligence it is necessary to use at least two samples per cycle. This means that the sampling rate must be at least twice the frequency of the highest intelligence frequency. Engineering practice has set the practical ratio of at least 2.4 to 1.

The brush system shown in figure 3 would have to be rotated at a rate of 475,200 r.p.m. to accommodate voice-frequency channels with a bandwidth of 3.3 kc.—this fantastic rate is, of course, impractical. However, the same effect has been obtained by constructing a vacuum tube with a rotating electron beam that strikes a series of plates as it rotates. Hence, no practical limit is encountered in the rate of rotation.

At first glance, it would appear that the number of channels is limited only by the number of commutator segments in use—this number could be made as high as several hundred with no great difficulty. However, it is obvious that as more segments (channels) are added, the width of each segment, and therefore the width of the sample, must be decreased. Conventional pulse theory tells us that as the pulse is made narrower, the bandwidth of the circuit carrying the pulse must be increased. For example, a 1-mc. circuit bandwidth will carry a ½-microsecond pulse, whereas a 0.1-microsecond pulse requires a 5-mc. band width. Therefore, as more channels are added, the required bandwidth increases in much the same manner as was found in frequency-division multiplexing.

The Philco CMT-4 (time-division multiplex) equipment provides 24 audio channels, with an 8-kc. sampling rate per channel, which results in a voice-frequency range of 300 cycles to 3.3 kc. The combined (or overall) sampling rate is 192 kc., which provides a pulse separation of about 5.2 microseconds from the leading edge of one pulse to the leading edge of the next. Since the sampling pulse is only two microseconds wide, this separation is sufficient to prevent crosstalk between adjacent channels.

Thus far, only variation in pulse amplitude has been mentioned as a means of conveying intelligence in the time-division form of multiplexing. Actually, there are many possible modulation systems, which have been classified as indicated in Table II.

Table II. Classifications of Various Time-Division Multiplex Systems

CLASS	NAME	CODE	ACTION OF MODULATING SIGNAL
A	Pulse-Time Modulation	PTM	Varies some characteristic of pulse with respect to time
	Pulse-Position Modulation	PPM	Varies position (phase) of pulse on time base
	Pulse-Duration Modulation	PDM	Varies width of pulse (also called PWM, or Pulse-Width Modulation)
	Pulse-Shape Modulation	—	Varies shape of pulse
	Pulse-Frequency Modulation	PFM	Varies pulse recurrence frequency
B	Pulse-Amplitude Modulation	PAM	Varies amplitude of pulse—consists of two types: one uses unipolar pulses, the other uses bipolar pulses (as in Philco CMT-4)
C	Pulse-Code Modulation	PCM	Varies the makeup of a series of pulses and spaces. Individual systems are classified as follows: Binary—pulses and spaces, or positive and negative pulses Ternary—positive pulses, negative pulses, and spaces N-ary—more complex combinations of pulses and spaces
D	Composite form of two or more of the above classes		

SUMMARY

Multiplexing is a method of combining a series of narrow-band signals into one wide-band signal for transmission. This action conserves the radio spectrum, and allows one transmitter to serve for a number of modulating signals, with a resulting reduction in equipment and costs.

The basic multiplex action divides a specific portion of the spectrum into a number of voice channels which can be further multiplexed (by either method) into a number of still-narrower channels which can be used for telemetering, telegraph, teletype, or facsimile. If required, two or more voice channels can be combined to provide the additional bandwidth required by high-fidelity audio service or even television service.

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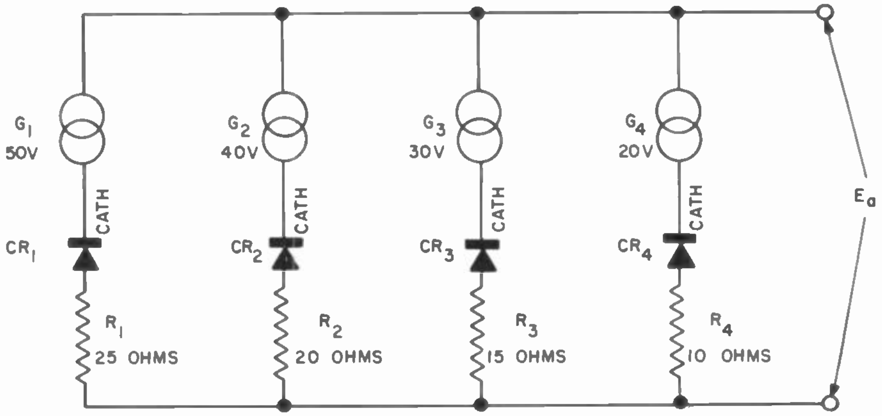
What's Your Answer?

This month's problem was submitted by Mr. Tefius Dectrow, of the H. L. Yoh Company, Philadelphia, Pa.

The schematic shows four a-c generators operating in phase—each with a series-connected selenium rectifier. The associated resistors represent the total internal impedance of each branch.

The problem is to find the total output voltage E_a.

One hint—you communications experts will find the circuit useful as well as interesting.



LIGHTNING PROTECTION OF RADIO TRANSMITTERS AND ANTENNAS

By Herbert M. Lee
Former Philco Field Engineer

A discussion of the protective devices needed at a transmitter installation.

PROTECTIVE SYSTEMS for radio transmitters and antennas are important parts of any transmitter installation. Without such protection during storms, the station might be forced to go off the air, or valuable equipment might be damaged.

This problem of lightning protection which the radio engineer must solve is more complex for a transmitter than for a receiver, since higher power is involved and transmitting antennas are usually larger and more complex. As a result, devices to protect against high voltages generated directly or indirectly on the antenna as a result of lightning, as well as special grounds and circuits to prevent or quench arcs must be included in the installation by the engineer.

HORN GAPS

The transmission system engineer looks askance at the use of spill gaps for protection against lightning damage. As Beck and McCann[1] state, "Viewed from either the standpoint of protection or materials involved, spill gaps are not good substitutes for lightning arresters or protection tubes. The spill gap does not provide as reliable protection . . ." This is so because when a spill gap arcs over on a power line, the high currents available from the power source sustain the arc until some extra device such as a fuse or circuit breaker opens the line.

The problem for the radio engineer is altered in that he does not deal with such large amounts of arc-sustaining power. In this case, the spill gap is reliable, easy to construct, and easy to maintain. Two types of spill gaps exist—the horn gap and the sphere gap. The horn gap[2] is preferred to the sphere gap because the design of the horn gap is such that the arc clears itself automatically, whereas the sphere gap has much less tendency to clear, especially if the spheres are mounted in a vertical line. Figure 1 shows a typical horn gap.

Horn gaps are used at various places in antenna and feeder systems. In the case of a series-fed tower, the base insulator should be protected by a gap. It is also necessary to protect the line-terminating equipment. To increase the effectiveness of the gap it is advisable to insert a small choke coil in series with the feeder on the transmitter side of the gap. This choke can consist of two turns of about a four-inch diameter. Number-four wire or 3/16-inch tubing makes a rigid self-supporting coil. It is necessary to "gap" grounded tower installations as well as ungrounded towers, since the section of the tower below the feeder tap will present considerable impedance to a lightning surge. As additional protection to coaxial transmission

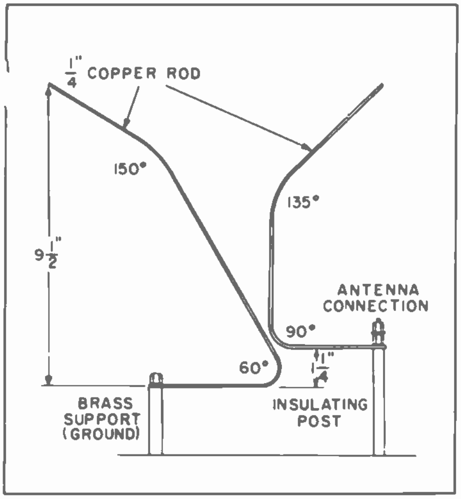


Figure 1. Horn Gap

line (which is especially vulnerable to damage from lightning surges), it is desirable to install a surge choke and horn gap at the tuning-house end of the coaxial transmission line. To protect the transmitter building and its contents, a choke and gap should be installed where the transmission line enters the building.

Gaps are usually supplied with the installation, but proper adjustment of them determines their effectiveness in protecting the equipment. One method of adjusting the gap is to decrease the spacing to the point where it just flashes when the transmitter is heavily modulated, and then to double the spacing for normal operation. The gap electrodes should be cleaned and polished occasionally, especially after storms, so that the breakdown settings will not change.

DRAIN CHOKES

There should be a d-c path between the antenna system and ground to drain off charges that develop on the system. Nearby lightning strokes can have considerable effect. Lewis[3] points out that ". . . under the most unfavorable conditions of high stroke current, high transmission structure, and a stroke to the ground near the structure, initial crest voltages in the order of 1000 kv. may be induced on the conducters." Successive surges might charge up a "floating" system to successively higher voltages which eventually would cause a flashover. Also, the friction of wind, sand, or snow blowing against the antenna can charge the system to extremely high potentials unless some drain is provided.[4] This d-c path may be through the transmitter output circuit or through the tower lighting circuit. Otherwise, a metallic path can be provided by connecting a drain choke from the system to ground.

The design of the choke is not critical; it can be made of number twenty d.c.c. wire closely wound on a non-hygroscopic form. However, because of an effect similar to the uneven distribution of voltage over a string of power-line insulator disks, the first ten turns at the "hot" end of the choke should be triple-spaced to reduce the possibility of flashover during surges. The choke should be rather long and slender in order to keep the voltage per turn low and the distributed capacitance low. To assure minimum detuning of the antenna circuit, the choke should be far from resonant at the operating frequency. The inductance of the choke can be calculated from formulas or charts, and its distributed capacitance determined from the approximate empirical equation[5]:

$$C = 1.8 D$$

in which C is the distributed capacity in micromicrofarads, and D is the diameter of the coil in inches.

Figure 2 shows the location of horn gaps and surge chokes in an antenna system, as well as the drain choke which is required when the system is otherwise "floating." The position of the drain choke is not critical.

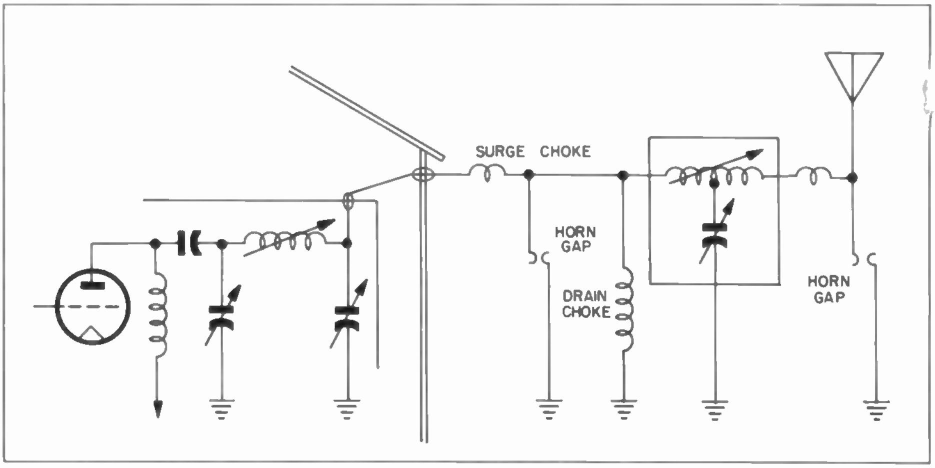


Figure 2. Simplified Schematic Diagram of Typical Transmitter Installation, Showing Connection of Surge Choke, Horn Gaps, and Drain Choke

GROUNDS

Probably the most important part of a protective system is the ground; in any case, it is of the utmost importance that a low-resistance ground be secured. Actual contact must be made with the ground, and this is accomplished by driving rods or burying conducting material in the damp strata of the soil. Total resistance of the "ground" is made up of: (1) resistance of the electrode, (2) contact resistance between the electrode and the soil, and (3) the resistance of the soil itself. Contrary to supposition, the first two factors are usually negligible. Since the major portion of the resistance is in the earth closest to the electrode, it is highly desirable to make the contact area as large as possible. Thus, buried plates or grids are more effective than slender rods, even though the latter may be deeper in the earth.

There are very great differences in the resistivity of natural soil. Factors which affect the resistivity most are temperature, moisture content, and the presence of soluble salts. The water system in the Engineering Building at Duke University was measured and found to have a ground resistance of less than 1/2 ohm. The resistance of a six-foot ground rod in the soil behind the building was about 15 ohms. Morris[6] reports that station grounds with resistances as high as 16,000 ohms have been measured, and it is common to find ground resistances of 1000 ohms. In some areas along the eastern seaboard, an ordinary six-foot ground rod seldom provides a ground with a resistance of less than 100 ohms.

In order to obtain low ground resistance in soil of high resistivity it is often necessary to provide a considerable number of driven rods or buried conductors distributed over an extended area; such an arrangement is called a ground "bed." Because closely spaced electrodes experience an increase of ground resistance through mutual interference of current distribution, ground rods should be spaced about ten feet from each other.

SPECIAL CIRCUITS

Normally, the moderate tendency of the transmitter to maintain an arc-over condition is overcome by the self-clearing horn gap discussed previously. However, weather conditions

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He acquired his first knowledge of electronics in the Navy, and gained considerable experience as a Navy Aviation Electronics Technician before his discharge in 1946. Following this, he continued in communications maintenance work with Pan American Airways and Lockheed Air Service.

In 1947, he returned to Duke University, where he majored in Electrical Engineering. In 1949, he joined Philco as a Field Engineer, and was sent to Alaska, where he served with AACS. After 13 months in Alaska, he returned to the States and further work with AACS. In September, 1951, he left Philco to complete his work for an engineering degree at Duke University.

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such as wind and humidity may cause the arc to be slow in breaking. In addition to causing long off-the-air periods, this can allow extremely high voltages to appear at various points in the system. It is desirable to provide a means of extinguishing the arc quickly and surely.

Since the arc is a low-resistance path, one method uses the arc itself as a conductor for d.c. which energizes a relay and cuts off the transmitter. This is called the *conduction* method of clearing arcs.

Another method depends on the resulting drop in antenna signal to actuate a tripping relay. This is called the *carrier-drop* method.

Figure 3 shows the circuit using the conduction method. Several features of this circuit are noteworthy. The bottom of the antenna coil is placed at r-f ground by the low reactance of capacitor C_1 for the protection of the d-c circuit. R-f choke L also keeps r-f voltages out of the relay and its d-c source. In this case, a drain choke should not be connected to the antenna system, since the drain path is provided through the protective circuit. The indicating device could be a supervisory light as shown, or it could be a bell at the transmitter site and a light in the studio control room. The indicating devices continue to operate until reset, even though normal operation may have been resumed.[7] In the transmitter-cut-off operation, the RC combination in the screen-grid circuit of the intermediate power amplifier has the secondary effect of smoothing out the switching transient, and thus preventing application of a sharp pulse to the final. Of course, all stages past the stage switched off must be fixed-biased to near cut-off. In the G.E. Type BT-25A Transmitter,[8] which uses this circuit, an additional set of contacts on K_1 insert a 15-db pad across the audio line to protect the modulation transformer.

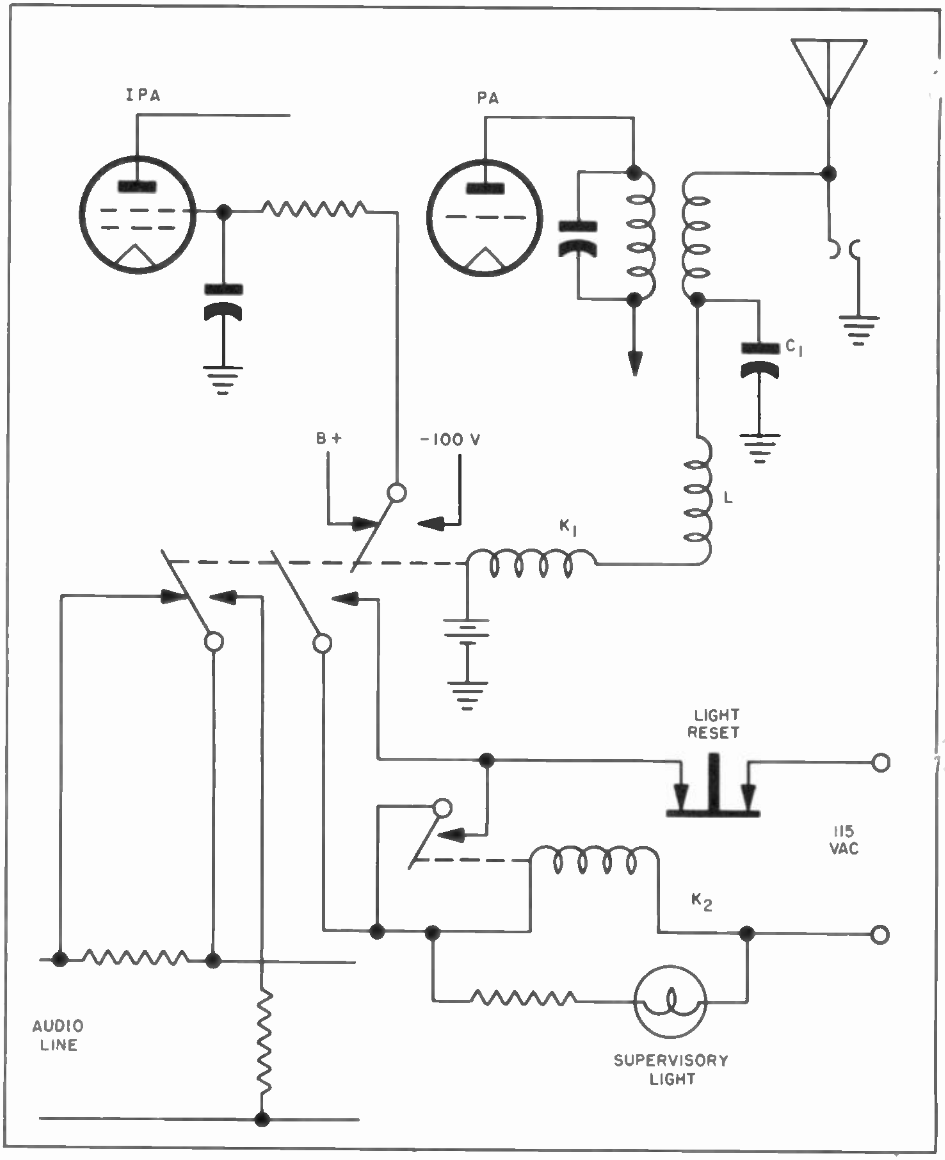

Figure 3. Protection Circuit Utilizing "Conduction" Method

Figure 4 shows the circuit which uses the carrier-drop principle for clearing arcs. Control relay K_1 has two opposing windings which neutralize each other during normal operation. If the signal from the antenna is reduced as a result of a lightning arc-over, the relay becomes unbalanced and is actuated. The contacts perform the same functions as those in the circuit using the conduction method. Actually, the circuits operate so fast that the interruption is scarcely noticeable on the air.

Sometimes a lightning surge on the antenna appears as a momentary overload and trips a circuit breaker. In such a case, it is desirable to get back on the air with a minimum of

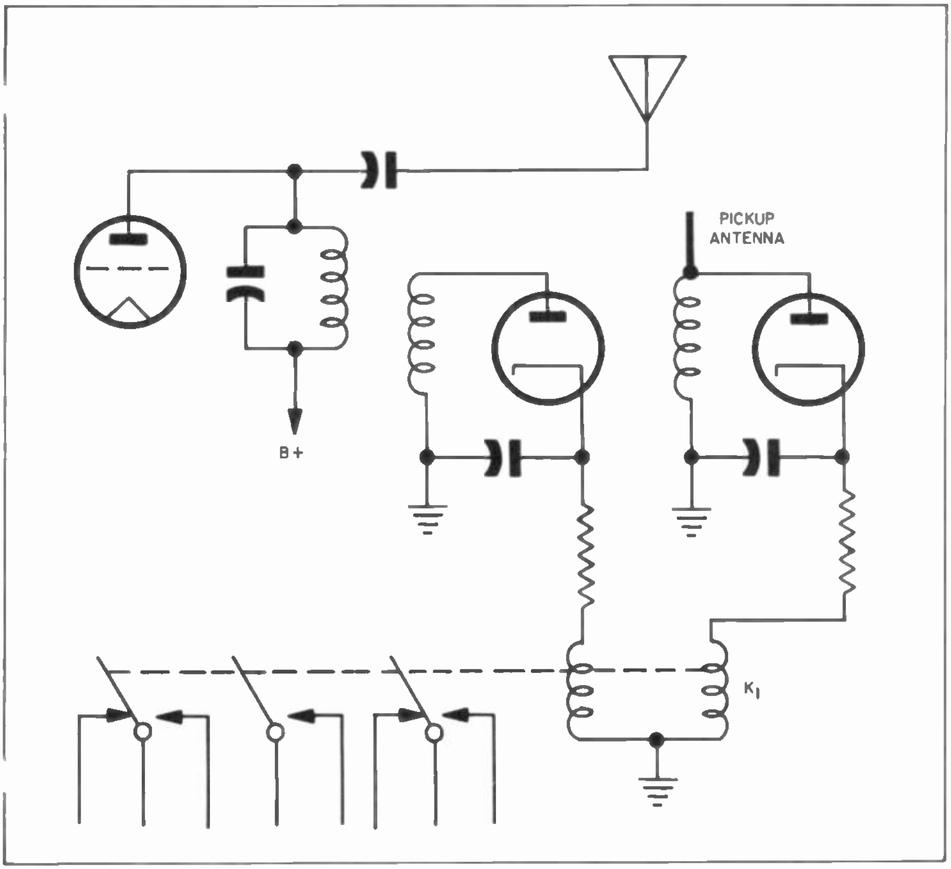

Figure 4. Protection Circuit Utilizing "Carrier-Drop" Method

lost time. Of course, if the overload is sustained or repeating, the equipment should be protected by holding the power off. In the G.E. Type BT-25A, a multi-shot type of automatic reclosure circuit permits two quick reclosures before locking out. A time-delay relay resets the circuit to "zero" after ten seconds if the fourth (lock-out) position has not been reached. This prevents overloads from "adding up" on the reset relay.

In case a momentary line drop, such as is caused by the operation of power-line lightning protectors, allows the filament time-delay relay to drop out, it is desirable to return to operation as soon as possible, and to avoid the normal filament-heating period. Of course, if the drop lasts long enough for the filaments to cool, they should have the protection of being allowed to reheat before a load is applied. Figure 5 shows the circuit which serves these requirements in the G.E. Type BT-25A. When the control voltage is first applied, one set of K_1's contacts closes immediately, and after about one minute, the time-delay contacts close. The latter energize K_2, which closes contacts in series with the instant contacts of K_1 to energize K_3. Contacts of K_3, in series with the interlock circuit, energize the main plate contactor. If the line voltage drops momentarily and is quickly reapplied, the time-delay contacts of K_1 open for one minute,

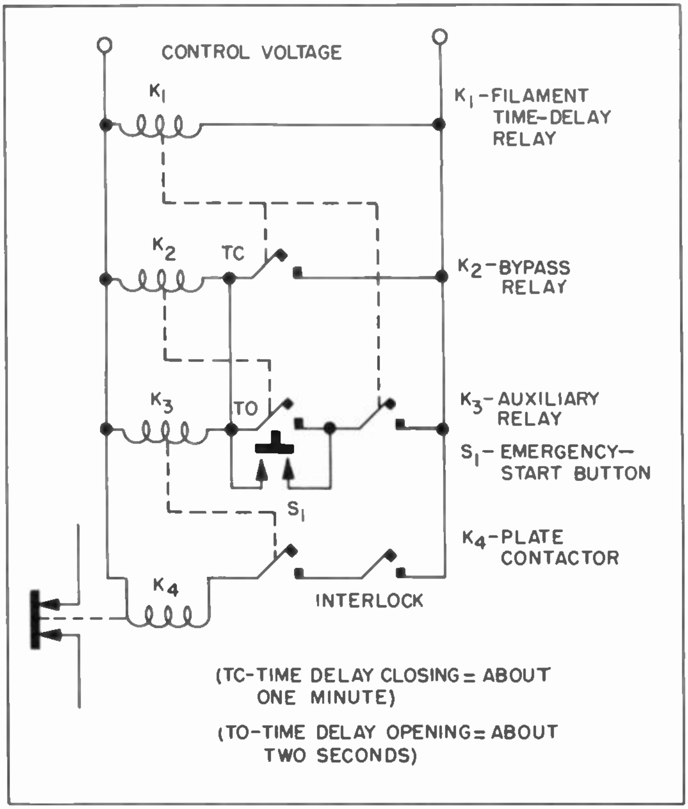

Figure 5. Power-Control System Used in Typical Broadcast Transmitter

but the instant contacts of K_1 are closed. K_2 is a slow-breaking relay of about two seconds delay, and if the instant contacts of K_1 are reclosed before K_2 breaks, K_3 is immediately re-energized, and the same circuit locks in K_2. Contacts of K_3 energize K_4 as before. Emergency-start button S_1 is provided for manually bypassing the time-delay period, but caution should be used in operating this switch, or the tubes may be damaged. A good rule is to wait approximately one and one-half times the length of time that the filament power was off before using the emergency-start button.

The antenna ammeter is another piece of equipment likely to be damaged by lightning. Most r-f ammeters are of the thermocouple type, and because the thermocouple has a very low resistance, it is not feasible to short the meter out of the circuit for its protection. A better method is to disconnect the ammeter from the circuit, or at least disconnect the load side from the circuit. A make-before-opening switch is desirable for this purpose, but if a conventional single-pole-single-throw switch is used, the r-f arc drawn upon opening the switch will sustain the circuit until the switch is closed.

INSTALLATION AND MAINTENANCE

For maximum benefit, the protection system must be properly installed and maintained. This is particularly applicable to the ground system. As Beck[9] points out, "Improper materials used as conductors, haphazard coursing, carelessly made splices and joints, and ineffective or inadequate grounds can render the whole system worthless." It is important to make a detailed study of ground connections before beginning the installation.[10] Many details involving the use of special tools and skills indicate that the job is best done by experienced men. "If (the job) is undertaken by the station personnel, it is usually at the expense of technical aspects of the installation," says *TeleTech.*[11]

As pointed out in the discussion of horn gaps, preventive maintenance is necessary to keep any protection system effective. A regular plan of inspection and maintenance is as important as the careful design and installation of the components of the system.

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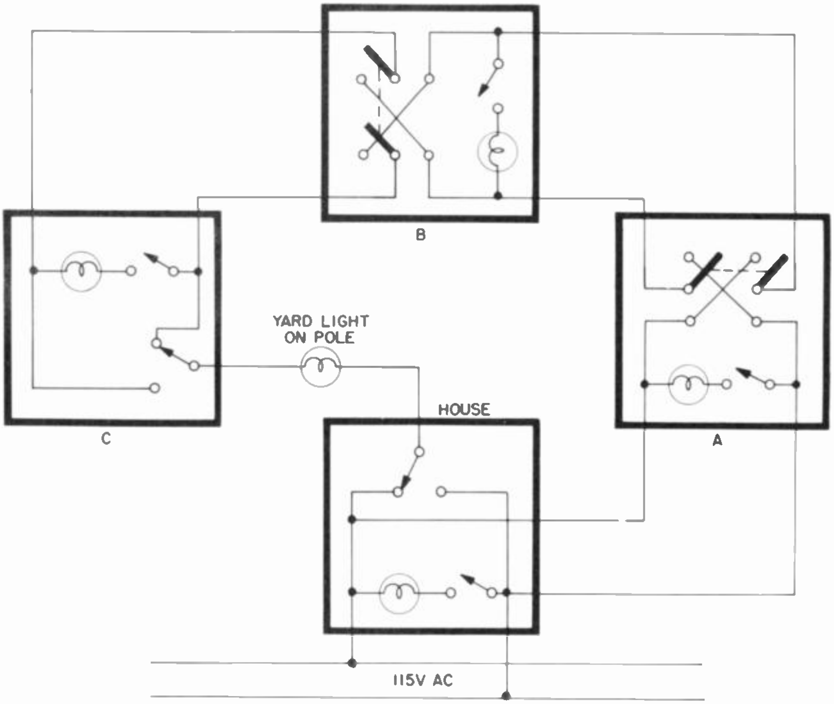
Solution to . . .

Last Month's "What's Your Answer?"

Using two d-p-d-t switches and two s-p-s-t switches, the yard light can be wired as follows:



In Coming Issues

We are pleased to announce that we are preparing to publish a most significant historical article by Brigadier General E. Blair Garland, Commanding General, AACS. The article, titled "Radar in E.T.O. Air-Ground Operations," was originally written for SIGNALS magazine, a bi-monthly publication of the Armed Forces Communications Association, and appeared in the March-April, 1949 issue of that publication.

Also planned for early release, is an excellent discussion of "Constant-Current Voltage Regulation," by Philco Field Engineer Robert G. Nevitt. The article contains a comprehensive summary of such circuits, and presents several new regulator circuits developed by the author.

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