Hbd. Arrears

TM 11-455

U.S. WAR DEPARTMENT

TECHNICAL MANUAL

RADIO FUNDAMENTALS

July 17, 1941

TECHNICAL MANUAL No. 11-455

WAR DEPARTMENT,
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RADIO FUNDAMENTALS

Prepared under direction of the
Chief Signal Officer

SECTION I

GENERAL

1. Introduction.—The basic laws which govern electrical phenomena in radio communication systems are the same as in power systems. A discussion of these basic principles of electricity is presented in TM 1-455, and it is presumed that the student is acquainted with the material contained therein. TM 1-455 includes a study of the current and voltage relations in elementary direct current (d. c.) and alternating current (a. c.) circuits with applications to power equipment and to measuring instruments. This manual presents a discussion of applications of these basic principles to radio transmitters and receivers. A knowledge of the fundamentals of radio enables a radio operator or radio technician to understand the equipment he handles and to obtain the best results in its employment.

2. Communication frequencies.—Communication frequencies are divided generally into two broad groups, audio frequencies and radio frequencies.

a. Audio frequencies are those between, roughly, 20 and 15,000 cycles per second. Sound waves with frequencies in this range are those to which the human ear normally responds. Sounds which occur at frequencies below 20 cycles per second, such as the staccato tappings of a woodpecker, are recognizable more as individual impulses than as tones. The frequencies that are most important in rendering human speech intelligible fall approximately between 200 and 2,500 cycles per second; that is, vibrations per second. The fundamental range of a pipe organ is from about 16 to 5,000 cycles, and the highest fundamental note of the flute is about 4,000 cycles. Speech and music actually consist of very complicated combinations of vibration frequencies of irregular and changing shape; harmonics, or overtones, which are multiples of the fundamental tones, give individual characteristics to sounds of the same fundamental frequency from different sources. It has been determined by experiment that the human ear responds best to sounds of about 2,000 cycles. Sound waves around 15,000 cycles per second, such as those due to very high pitched whistles, are likely to be inaudible to the average ear.

b. Frequencies from, roughly, 50 kilocycles per second to 500 megacycles per second are referred to as radio frequencies. These are the frequencies employed in the propagation of radio waves. Frequencies below 500 kilocycles (per second) are employed for some army and marine services; frequencies between 500 and 1,500 kilocycles are used for standard broadcasting; and frequencies above 1,500 kilocycles are used for many types of operation, including amateur, police, general commercial, and army radio communication.

3. Distributed inductance and capacitance.—*a.* In addition to the inductance and capacitance included in inductors and capacitors, there are distributed, or stray, inductance and capacitance effects present in miscellaneous components of radio instruments, as in connecting wires, switches, and sockets. These become of considerable concern at radio frequencies.

b. Capacitive reactance is inversely proportional to the frequency $\left(X_C=\frac{1}{2\pi fC}\right)$. This means that as the frequency of an applied voltage is increased, the capacitance of the circuit offers less opposition to the flow of current, so that at high frequencies undesirably large currents may appear where negligible currents would flow at low frequencies. The inherent capacitance which occurs between adjacent elements of a vacuum tube or between adjacent turns of a coil presents a large capacitive reactance at the lower frequencies. However, at radio frequencies the reactance may become sufficiently small that the increased magnitude of the current flowing across it determines the upper frequency limit for the usefulness of the associated circuit.

c. Inductive reactance increases proportionally to frequency $(X_L=2\pi fL)$, which means that as the frequency of an applied voltage is increased, the inductance of the circuit offers more opposition to the flow of current. A simple connecting wire, the inductive reactance of which may be insignificant at low frequencies, may have a sufficiently large inductive reactance at higher frequencies to render an instrument inoperative.

4. Effective a. c. resistance.—Fundamentally, a measure of the resistance of a circuit is given by the power dissipated as heat when unit current is flowing in the circuit. In its broadest sense, the term "resistance" is taken to mean all effects leading to a dissipation of energy in any form such that the energy is not recoverable for any useful purpose within the immediate system. Thus a radio antenna for transmitting is said to have a radiation resistance associated with radiative "losses," that is, with the energy which is radiated into space; and a particular transmitter or receiver circuit may be said to exhibit certain "reflected" resistance because of the power consumed by other circuits which it directly or indirectly supplies. With alternating current, for a given current magnitude, considerably more electrical power may be consumed than is required by the same circuit with direct current. The resistance which is indicated by a. c. power consumption is called "effective" a. c. resistance. Part of this additional power is required to maintain the heat losses accompanying parasitic circulating currents (eddy currents) which are induced in conductors of the circuit (in particular, in transformer cores) by the varying magnetic field. Another source of a. c. electrical power dissipation is represented by dielectric and hysteresis losses. In the presence of an electric field a dielectric polarizes, that is, the constituent atoms of the dielectric are alined in the direction of the field, being reversed as the field reverses. With rapidly changing fields such as are encountered in radio, the energy expended during the polarization is often appreciable. This energy appears as heat and is not recoverable in useful form, so it constitutes a definite loss. A similar effect that occurs in a magnetic material which finds itself in a varying magnetic field, for example in transformer cores, is referred to as hysteresis loss. A further factor which makes for more required power for a given magnitude alternating current is the "skin effect," the tendency of alternating currents to travel with greater density near the surface of the conductor than at the center. This tendency increases with frequency. The magnetic field about a current-carrying conductor is more intense at the center of the conductor than it is near the surface of the conductor. Thus the back voltage set up by the rising and falling magnetic field (Lenz's Law) is greater at the center than near the surface, and practically all of the current through a wire at high frequencies is confined to the outer surface of the conductor. The result is increased heating for the same current, that is, higher resistance. The nonuniform distribution of current throughout the cross section of a conductor at high frequencies is more pronounced if the conductor is wound into the form of a coil than it is if it is used as a straight wire. At radio frequencies the effective a. c. resistance of a coil may be 10 or 100 times its true d. c. resistance. Wherever alternating cirrents are studied, it is generally understood, if not specifically stated, that "resistance" means effective a. c. resistance.

5. Insulators.—Insulators which are satisfactory for power purposes may not be suitable for radio work. In radio circuits which operate with microwatts of energy, dielectric losses, which appear, for example, in the dielectric bars which insulate the stator plates from the frame of a variable air capacitor, are of definite concern. Also of interest are the minute leakage currents on insulator surfaces, for example, tube bases and sockets. It is well to keep radio insulators away from strong electric fields, and to maintain all insulators dry and clean.

SECTION II

RESONANT CIRCUITS

6. Vector representation of voltage and current.—*a.* The simplest type of recurrent voltage or current is a sine wave type, that is, one whose instantaneous magnitude may be graphically represented as varying with time in accordance with the sine curve of figure 1. A current or voltage varying in exactly this manner is rarely, if ever, attained in practice. However, the sine wave is a convenient simplification for analysis, and its use in this connection is justified by the fact that any regularly recurrent voltage or current may be regarded as a composite of individual sine waves. For all purposes of circuit analysis only sine wave currents and voltages will be considered, the actual resultant effect in any case being a composite of the individual effects so considered. (See TM 1-455.)

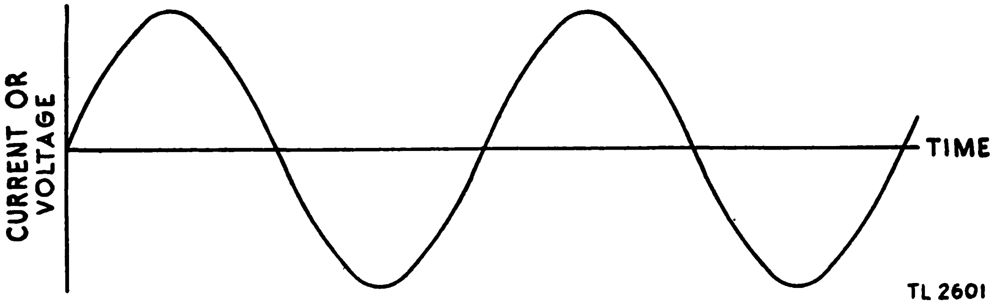

FIGURE 1.—Sine current or voltage.

b. To facilitate representation, a sine curve such as that of figure 1 may be indicated as in figure 2 by an arrow of unit length which rotates at a uniform rate. The vertical projection, *S*, of the arrow represents instantaneous magnitude of the sine action. Consider that the arrow begins rotation when it is pointing horizontally to the right (figure 3①). After it has rotated 30° the arrow is at *B*, and the vertical projection is at *B′* as shown in figure 3②. Rotating another 30° brings the arrow to *C* and the projection to *C′*. A complete rotation of the arrow is accompanied by the corresponding curve traced out by the projection as shown in figure 3③. Continuous rotation produces the repeated sine wave of figure 3④.

c. Had the arrow started rotating when it was pointing up, figure 3⑤, that is, 90° ahead of its former starting position, the accompanying sine curve would have appeared as in figure 3⑥. The sine curves of ⑥ and of ③ differ in phase by 90°; the former is said to be "leading" the latter by 90°, the latter "lagging" the former by 90°.

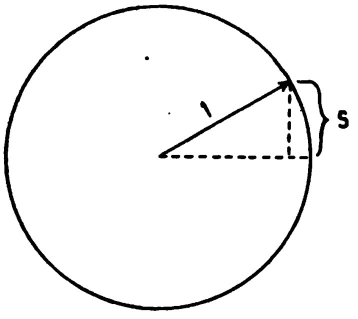

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FIGURE 2.—Uniformly rotating vector. Projection *S* develops a sine action.

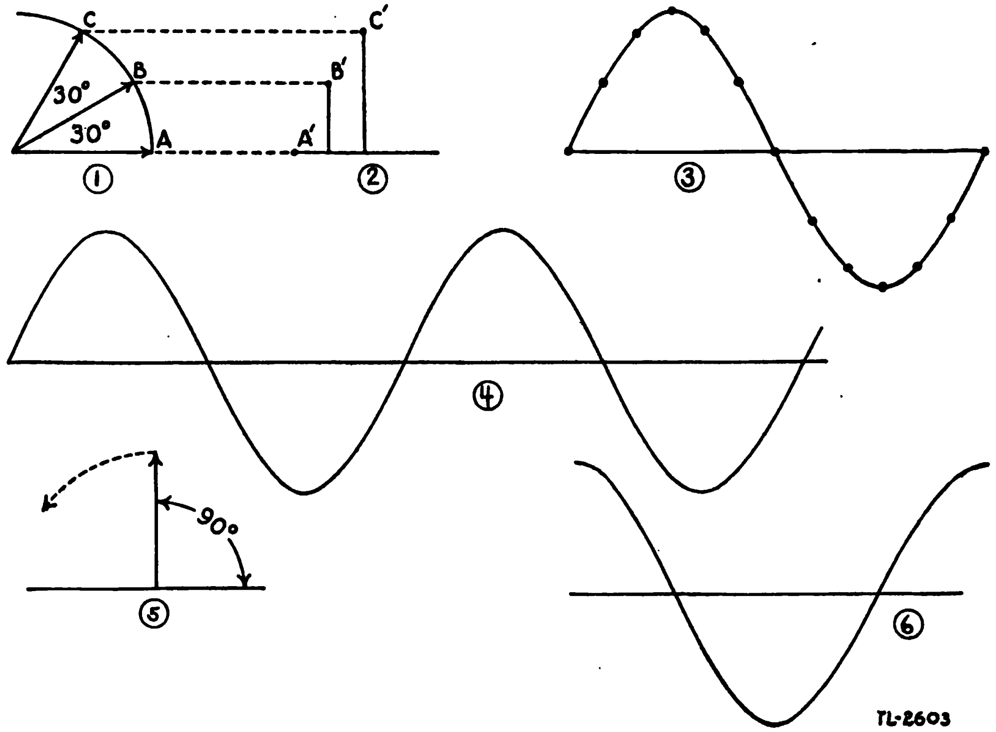

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FIGURE 3.—Development of sine curves.

The curves of ⑥ and of ③ might represent sine waves of current of the same amplitude and frequency which differ in phase by 90°.

Or, if the curve of ③ is taken to represent the wave of alternating voltage across a capacitor, ⑥ may be employed to represent the wave of (leading) current. More simply, the current and voltage could be represented by their corresponding vectors, *i* and *e* of figure 4①. The vectors are "photographs" of the rotating arrows at any particular instant. The particular instant represented by figure 4① is that at the beginning of the rotation. Figure 4② shows the same arrows a quarter cycle later. Either the sine curve or the vector representation presents an adequate picture of the phase relationship between the current and voltage. In a vector picture the magnitudes of the current and the voltage are indicated by the relative lengths of the corresponding vectors. Let us assume that figures 4① and ② represent a voltage of 1 volt maximum and a current of 1 ampere maximum. On this scale, figure 4③ would then represent a voltage of 3 volts maximum and a 90° leading current of 2 amperes maximum.

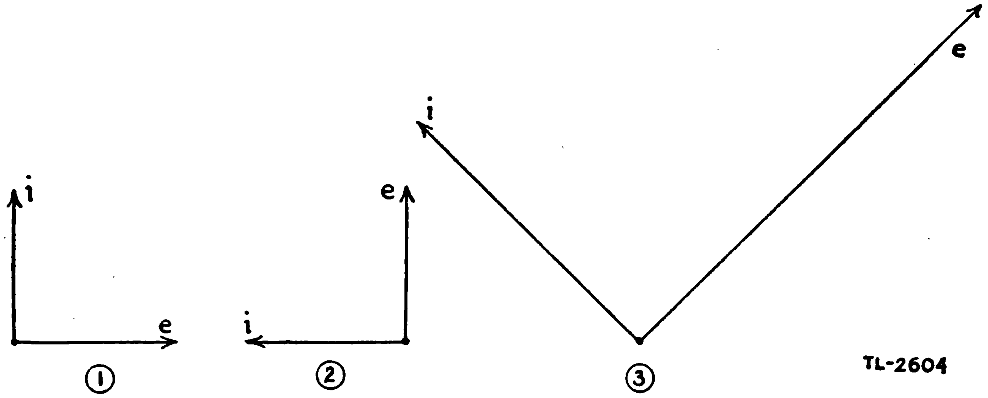


FIGURE 4.—Vector representation of currents and voltages.

d. Figure 5 is a vectorial representation of the current (*i*) and voltage (*e*) in a resistor (both "in phase"). The lengths of the vectors are independent of each other and depend upon the scales selected for each.

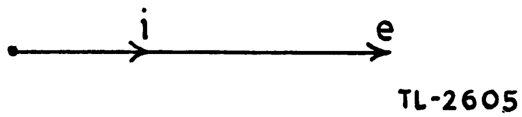
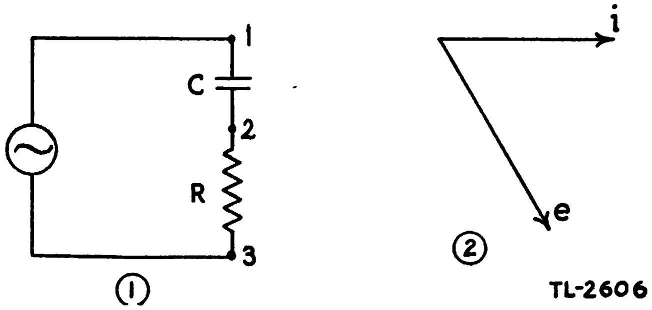


FIGURE 5.—Current and voltage in phase.

e. For the capacitor-resistor combination of figure 6①, figure 6② gives the vectorial representation of the current through the circuit and of the voltage across the circuit (voltage lagging the current by less than 90°). The current is uniform throughout the circuit. The voltage at any instant between points 1 and 3 of figure 6① is the algebraic sum of the voltages existing between 1 and 2 and between 2 and 3. The voltage between 1 and 2 is represented in sine form by the curve marked e_C of figure 7, that between 2 and 3 by the curve marked e_R, and the additive resultant, which is the voltage at the generator terminals, by the curve marked e. It is left as an exercise for the student to demonstrate graphically that the vectorial addition of the voltages as shown in figure 8 is equivalent to the detailed addition pictured in figure 7. In general it may be shown that the sum resultant of any two voltage vectors (or of any two current vectors) is represented correctly, both in magnitude and in phase, by the diagonal of the parallelogram formed from the component vectors as in figure 9①, ②, and ③.



① A. c. generator with capacitance-resistance load.
② Current and voltage vectors for circuit of ①

FIGURE 6.

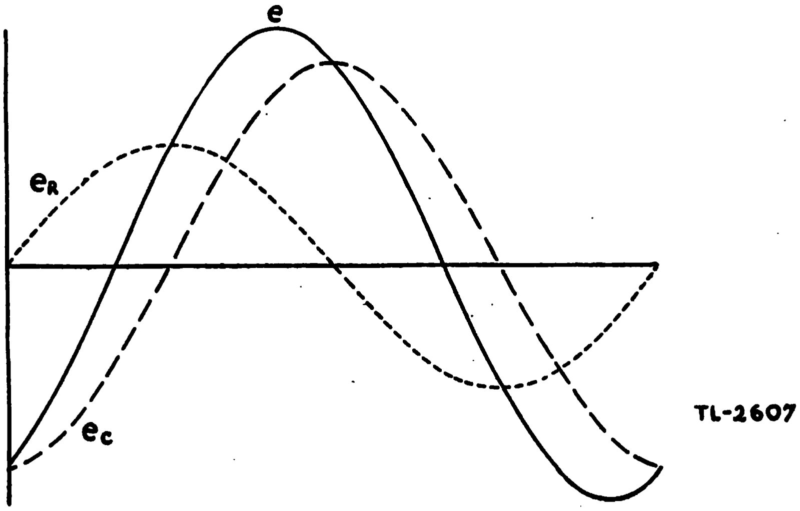


FIGURE 7.—Voltage across capacitor and resistor in series combination in circuit of figure 6①.

7. Circuit containing inductance and capacitance in series.—Among the most important radio circuits is one containing inductance (L) and capacitance (C) in series (fig. 10①). The voltage and current relations which exist in such a circuit are represented vectorially in figure 10②. In magnitude e_L is equal to iX_L, and e_C in magnitude is equal to iX_C. The conditions represented in figure

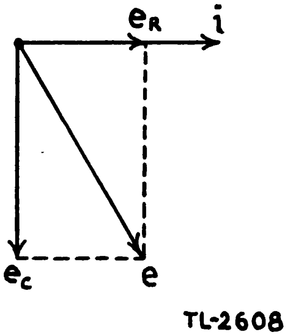


Figure 8.—Vector representation of addition corresponding to figure 7.

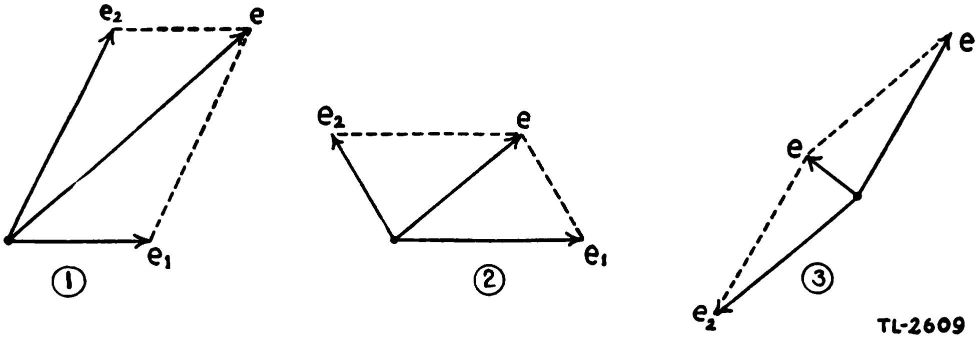
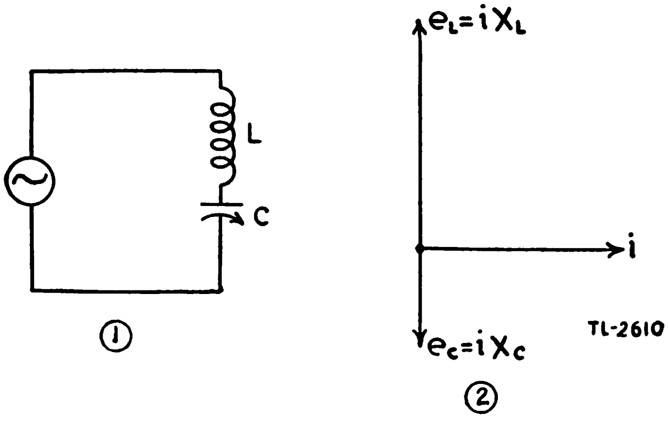


Figure 9.—Vector addition of voltages.



① A. c. generator with inductance-capacitance load.
② Current and voltage vectors for circuit of ① under condition of X_L greater than X_C.

Figure 10.

10 are such that X_L is greater than X_C; hence e_L is greater than e_C and the net effect in this case is that the series inductance-capacitance combination acts as an inductance alone. This is evident on compounding the two voltages to obtain the resultant leading voltage, as in figure 11. If the capacitance is decreased so that the capacitive reactance is increased and the consequent voltage across the capacitor increased as in figure 12, then the net effect of the circuit is that of a capacitance alone. In this manner, the react-

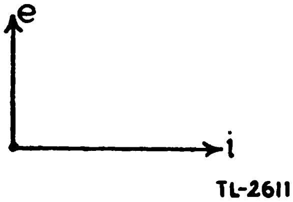


FIGURE 11.—Over-all current and voltage in circuit of figure 10①.

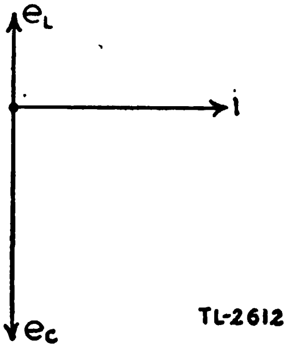
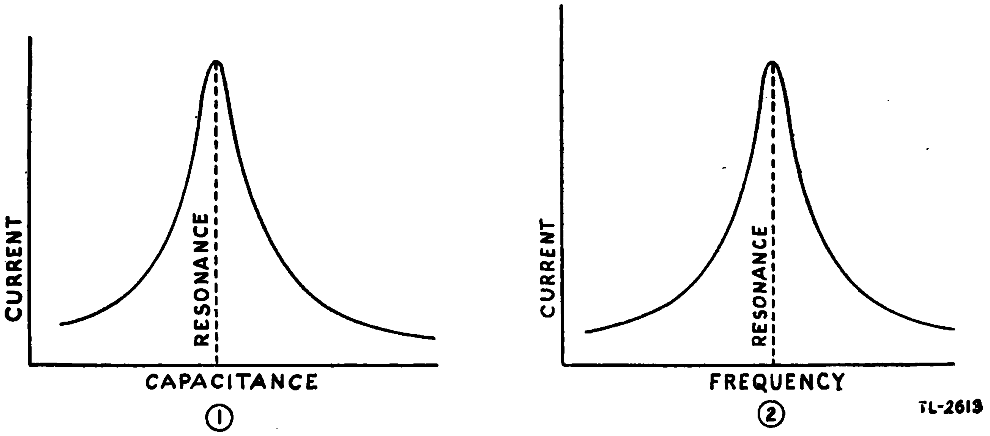


FIGURE 12.—Current and voltage vectors for circuit of figure 10① under condition of X_C greater than X .



① Capacitance varied, inductance and frequency constant.
② Frequency varied, capacitance and inductance constant.

FIGURE 13.—Resonance in series circuit.

ance of the circuit can be varied from inductive to capacitive. When the capacitive and inductive reactances are of equal magnitude, the net reactance of the circuit is zero, a condition described as *resonance.*

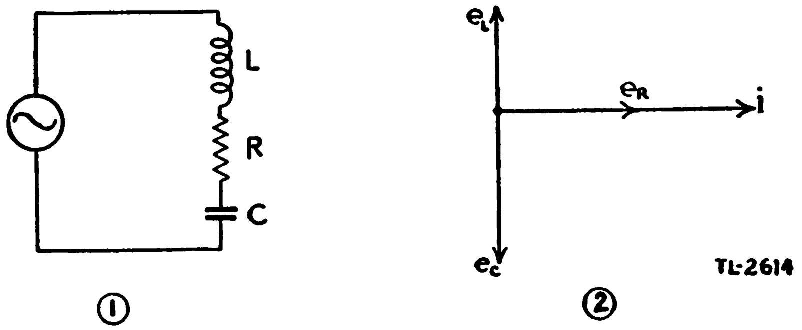
8. Resonance.—*a.* At resonance the current in the circuit of figure 10① becomes infinitely great. This ideal is never attained in practice on account of the presence of resistance. However, even with resistance in the circuit, the current at resonance may reach very large values. As the capacitance (or inductance) is varied either way from resonance, the current falls off as illustrated in figure 13①. Or, if the capacitance and the inductance are fixed, a variation of the frequency of the generator results in a similar variation of current (fig. 13②) with the maximum occurring at that frequency, f_r, for which X_L equals X_C, that is,

$$2\pi f_r L = \frac{1}{2\pi f_r C}$$

This equation gives for the frequency at resonance

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

b. It should be noted that at resonance, although the resultant potential drop across the complete circuit is relatively low, the voltages across the individual inductive and capacitive branches may be very large, often as much as several hundred times the voltage developed by the generator. This feature of a tuned circuit makes it possible to obtain considerable voltage amplification of radio signals of that particular frequency to which the circuit is resonant. In transmitters, the circuit components, in particular the capacitors, must be chosen to withstand high voltages at resonance.



① A. c. generator with inductance-resistance-capacitance load.
② Current and voltage vectors for circuit of ① under condition of X_C greater than X_L

FIGURE 14.

9. Circuit containing inductance, capacitance, and resistance in series.—*a.* When a series resistor is included in the circuit (fig. 14①), the same considerations as in paragraph 7 hold, with such modification as is incurred by the addition of a voltage drop across the resistor in phase with the current (fig. 14②). The resultant voltage of figure 14② is obtained by first compounding e_L and e_C (fig. 15①) and then adding this resultant to e_R (fig. 15②).

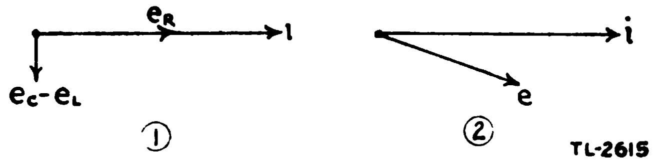


FIGURE 15.—Vectorial addition of voltages of figure 14②.

b. It is convenient to represent reactances in vector form: inductive reactance by an arrow pointing up, capacitive reactance by an arrow pointing down, and resistance by an arrow pointing to the right. Then the net reactance, X, is obtained as the difference between the inductive reactance, X_L, and the capacitive reactance, X_C; the impedance vector, Z ($Z=\sqrt{R^2+X^2}$), is given by the diagonal of the rectangle formed from the vectors X and R. The magnitudes of the individual reactances in the circuit of figure 14① are obtained on dividing the corresponding voltage drops by i:

$$X_C=\frac{e_C}{i}\ X_L=\frac{e_L}{i}\ R=\frac{e_R}{i}$$

The associated vectors are shown in figure 16. The resistance, R, above is the effective a. c. resistance, and is attributed almost entirely to the coil, scarcely at all to the capacitor.

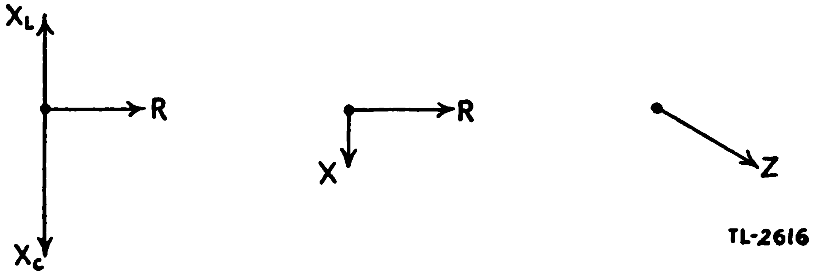


FIGURE 16.—Vectorial addition of reactances to obtain total impedance of circuit of figure 14①.

c. The variation of the net impedance with frequency (L and C fixed) is shown in figure 17. For frequencies below resonance the capacitive reactance is greater than the inductive reactance, and the net effect is that of a capacitance and a resistance in series. At resonance, where the reactances balance, the circuit acts as a pure resistance. For frequencies above resonance the inductive reactance prevails, and the circuit behaves as a simple inductance and a resistance in series.

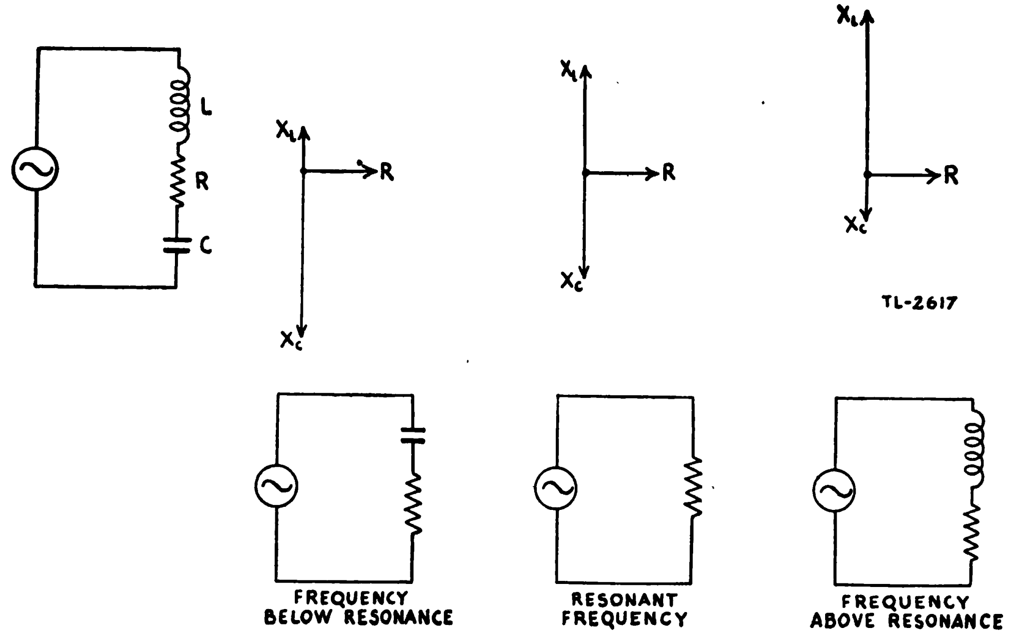


FIGURE 17.—Series circuit. Actual circuit at left. Equivalent circuits for various frequencies below corresponding vector diagrams.

d. It is apparent from figure 18 that if the resistance *R* is very small, the effects of the capacitance and inductance are predominant in determining the net effect of the circuit. At resonance with small cir-

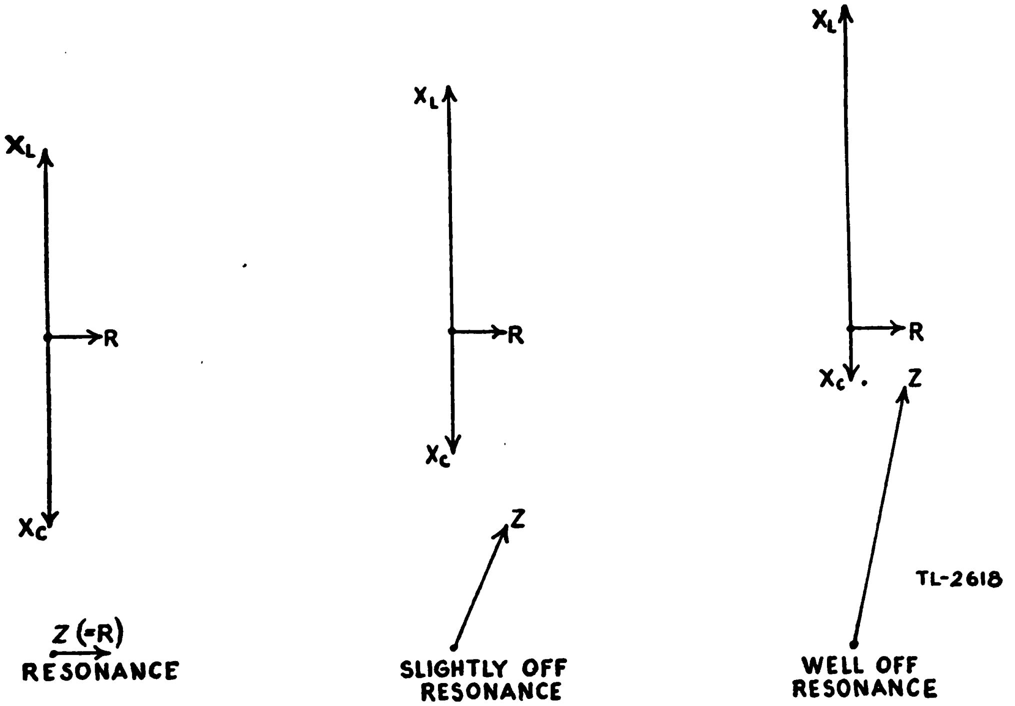


FIGURE 18.—Effect of small resistance on sharpness of resonance for circuit of figure 17. Individual reactances above; net impedance below.

cuit resistance the current is quite large, while slightly off resonance the current drops sharply. On the other hand, if the resistance is large, the resistance predominantly affects the current in the neighborhood of resonance; and the current is only slightly greater at resonance, where the resistance alone is effective, than either side of resonance, where the inductive and capacitive reactances also come into play (fig. 19):

e. Figure 20 illustrates resonance curves for three different values of resistance. These resonance curves demonstrate the practicability of a tuned circuit as a selective device. If voltages of many frequencies are applied to the tuned circuit, the resulting current is principally of frequencies which are approximately equal to the resonant frequency. As resistance is added to the circuit, the current is attenuated in such a manner that a more nearly uniform but reduced response is obtained over an extended range of frequencies in the neighborhood of resonance. The property of a tuned circuit to accept a limited range of frequencies with essential rejection of all others is called selectivity of the circuit. As shown in figure 20, resistance in the circuit acts to reduce the selectivity. It may be shown that the effect of shunt resistance across either the inductor or the capacitor will likewise reduce the selectivity; the lower the resistance, the poorer the selectivity. Occasionally resistance is deliberately introduced into radio circuits for the purpose of broadening the range of frequencies to which they

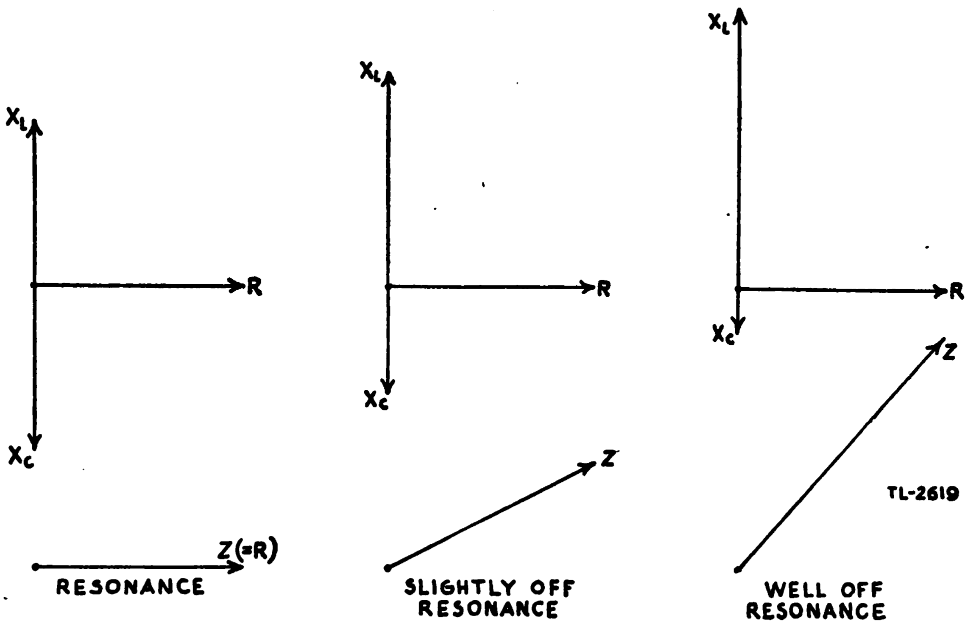


FIGURE 19.—Effect of large resistance on sharpness of resonance for circuit of figure 17. Individual reactances above; net impedance below.

are responsive, although generally their inherent resistance is more than enough for this purpose.

10. Circuit containing inductance and capacitance in parallel.—*a.* Whereas in a series circuit the current is uniform and the voltages across the circuit elements are added to yield the total potential drop across the circuit, in a parallel circuit the voltage across each branch is the same, and the separate branch currents are added to yield the total current through the circuit. Consider the parallel circuit of figure 21. At low frequencies, the reactance in the capacitive branch is high, and consequently the current through that branch is low; at high frequencies the reactance is low, and the current is high. In the inductive branch the opposite relations are true.

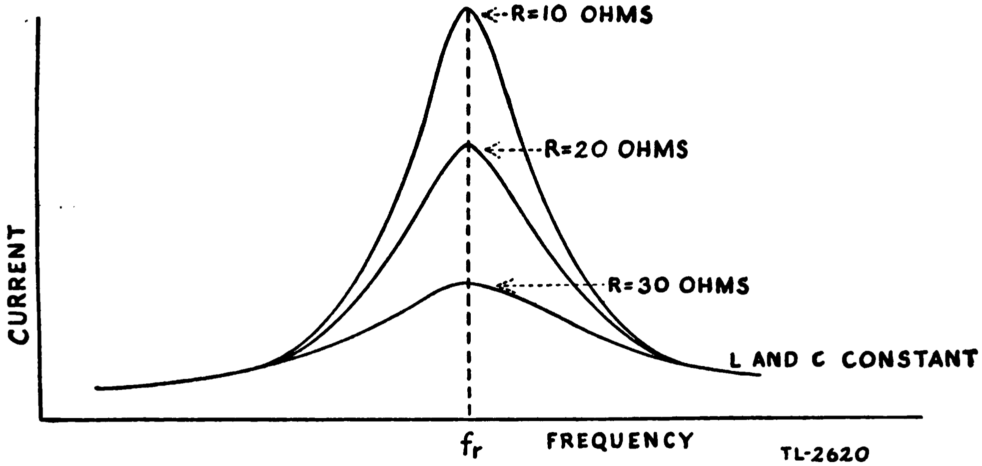


FIGURE 20.—Resonance curves showing broadening effect of series resistance.

b. There are three commonly used conditions for resonance in a parallel circuit. Probably the most common, from a transmitter tuning standpoint, is that resonance is obtained when the line current is a minimum. Another condition is that which makes the impedance of the circuit equivalent to pure resistance. The third condition is that resonance occurs at the frequency for which X_L equals X_C. These three conditions are not identical, but the frequencies obtained by them differ by much less than 1 percent in well proportioned parallel circuits. Therefore, for all practical purposes the resonant frequency of a parallel circuit can be taken as the frequency that satisfies the relation—

$$X_L = X_C$$

or

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

It then follows that the parallel resonant frequency of a tuned circuit is exactly the same as the series resonant frequency of a circuit composed of the same values of *L*, *R*, and *C* in series. The effective a. c. resistance of the capacitor is frequently negligible, but the resistance of the inductor must be taken into account. Diagrams for

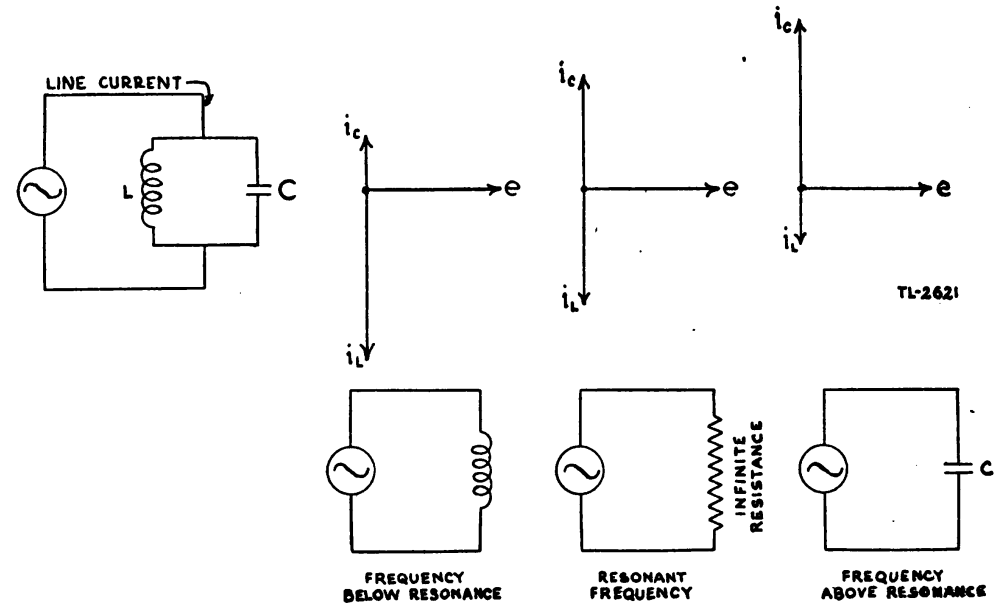


FIGURE 21.—Ideal (no resistance) parallel circuit. Actual circuit at left. Equivalent circuits for various frequencies below corresponding vector diagrams.

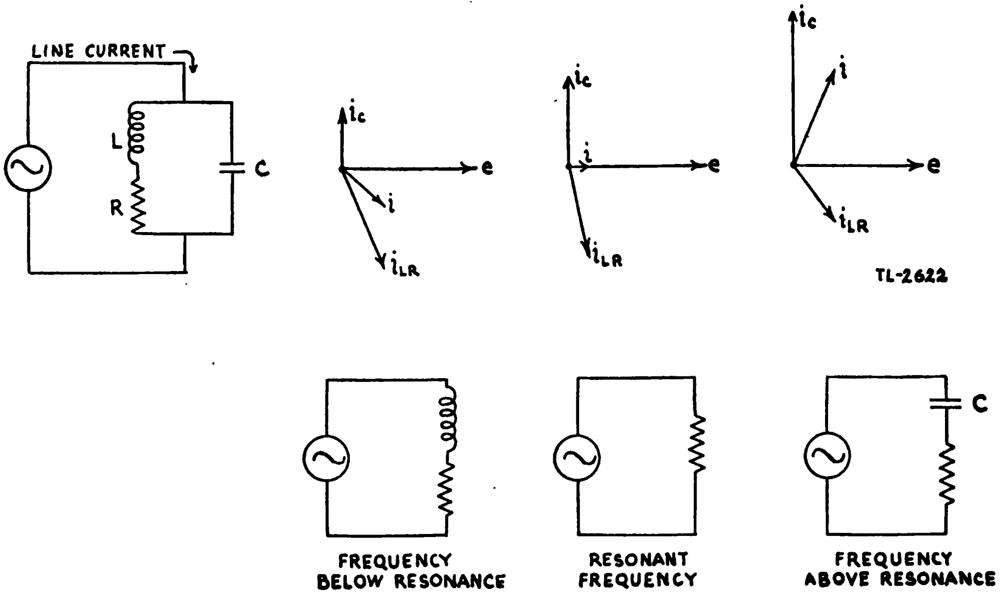


FIGURE 22.—Parallel circuit. Actual circuit at left. Equivalent circuits for various frequencies below corresponding vector diagrams.

this case are shown in figure 22. At frequencies below resonance the net line current may be resolved into an in-phase component and a lagging component; that is, the circuit is equivalent to a simple inductance-resistance series combination. At frequencies above resonance the net current may be resolved into an in-phase component and a leading component; that is, the circuit is equivalent to a simple capacitance-resistance combination. At resonance, that is, for X_L equal to X_C, the net line current, at least in the practical case of R very much smaller than X_L, is essentially in phase with the applied voltage, and the circuit acts substantially as a pure resistance. Due to the presence of resistance the actual lagging current at resonance is very slightly less than the leading current. However, for most practical purposes it is adequate to consider the lagging and leading components as equal at the frequency of resonance.

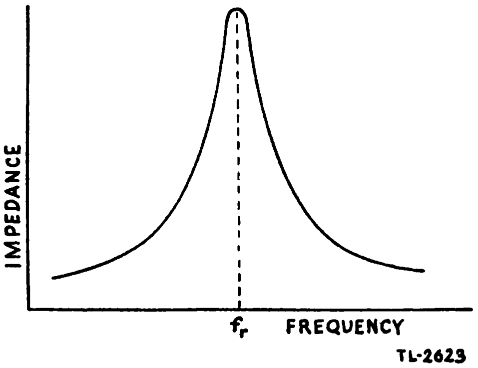


Figure 23.—Resonance curve for a parallel tuned circuit.

c. Resonance in a parallel circuit is often referred to as antiresonance because of the inverse relations as compared with the series case. At resonance the series circuit presents a very low resistance, the parallel circuit a very high resistance; at frequencies below the resonant frequency the series circuit behaves as a capacitance, the parallel circuit as an inductance; and at frequencies above the resonant frequency the series circuit behaves as an inductance, the parallel circuit as a capacitance. The resonance curve of a series circuit in which current is plotted against frequency (fig. 13②) resembles in shape the resonance curve of a parallel circuit in which impedance is plotted against frequency (fig. 23).

d. It will be found that the selectivity of the parallel circuit is inversely related to the resistance in either individual branch of the circuit. Further, the selectivity is adversely affected by a resistance shunted across the entire circuit; the lower the resistance, the broader the response.

e. In a circuit as in figure 24, for a fixed frequency of the generator potential, a variation of the capacitor C is accompanied by a variation of the ammeter reading as the over-all impedance of the circuit changes. Minimum current in the line indicates antiresonance and maximum circulating current within the LC circuit. A parallel resonant circuit in a radio transmitter is tuned in this manner by watching for a dip in the line current or ammeter reading.

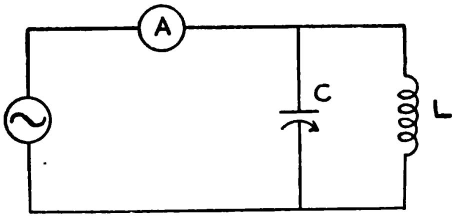


FIGURE 24.—Minimum ammeter reading indicates resonance.

f. For the parallel circuit in the practical case of R relatively small, a detailed study yields for the over-all impedance (resistance) at resonance

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

that is, the net impedance at resonance is equivalent to a resistance, the magnitude of which is directly proportional to the ratio of L to C and inversely proportional to R. The reasonableness of this equation may be attested to, at least, by an examination of the current-voltage relations for special cases. Resonance implies merely $X_L=X_C$. Table I lists some of the possible combinations of L and C which correspond to resonance at a frequency of 10,000 kilocycles. For R equal to zero, R_O is infinite for any L to C ratio. This is apparent on examination of figure 26, which shows vector diagrams for resonance, corresponding ① to $X_L=X_C$ large and ② to $X_L=X_C$

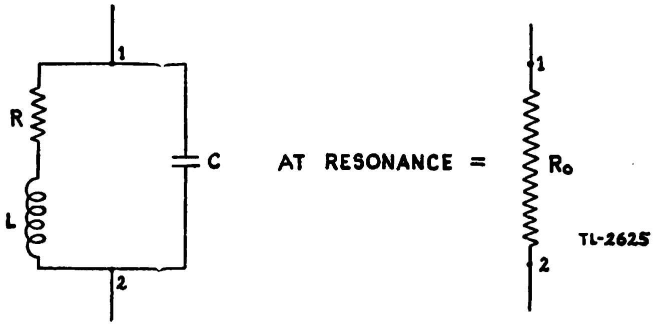
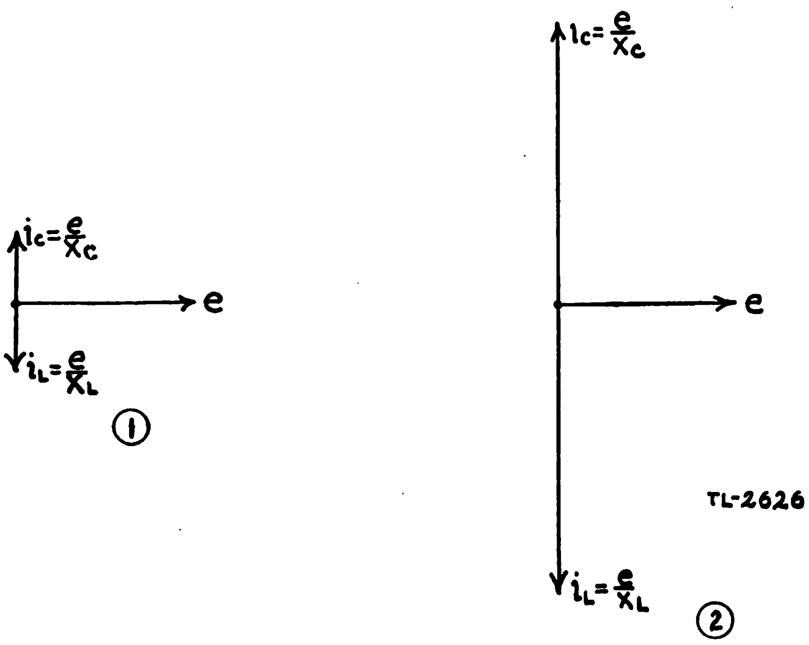


FIGURE 25.—Equivalent circuits at resonance.

small. In either case no current flows from the generator into the tuned circuit regardless of the applied potential; that is, in either case the resistance of the tuned circuit at resonance is infinite. When R is not zero and X_L is large $\left(\frac{L}{C}\text{ large}\right)$, the net current i and consequently the resistive component i_R are small, so that the effective resistance of the tuned circuit is large. When R is not zero and X_L is small $\left(\frac{L}{C}\text{ small}\right)$, i and i_R may be large, indicating a small effective resistance of the tuned circuit.



① High $\frac{L}{C}$. ② Low $\frac{L}{C}$.

FIGURE 26.—Antiresonance in ideal (no resistance) circuit.

TABLE I

L (microhenrys)	C (micromicrofarads)	$X_L = 2\pi f_r L$ (ohms)	$X_C = \frac{1}{2\pi f_r C}$ (ohms)
0. 1	2, 533	6. 28	6. 28
1	253	62. 83	62. 83
10	25. 3	628. 3	628. 3
100	2. 53	6, 283	6, 283

11. "*Q.*"—*a.* The merit of an inductor (coil) in a circuit is most conveniently expressed as the ratio of the inductive reactance to the effective a. c. resistance of the coil. This ratio is so important in the theory of resonant circuits that it is considered as a fundamental property and is usually referred to by the symbol Q. Since the total inductance and resistance of a circuit are almost entirely concentrated in the coil, Q may be represented as follows:

$$Q=\frac{2\pi fL}{R}=\frac{X_L}{R}$$

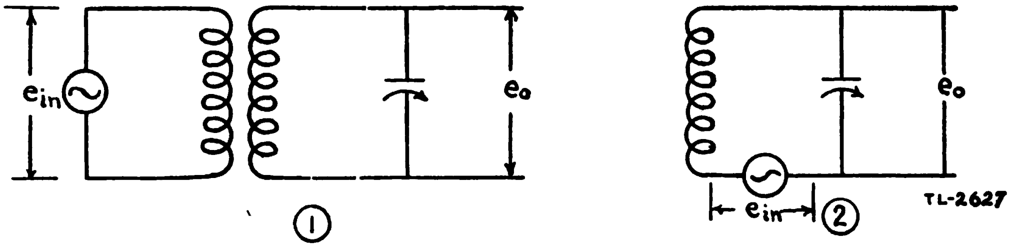
The effective resistance R of the coil includes any dielectric loss which the coil might have; however, in a well-designed coil the R is due almost entirely to skin effect. Two coils of identical shape can have different Q's if their resistances differ; or two coils of the same resistance can have different Q's, if their inductances differ. The Q of any given coil remains practically constant over a wide range of frequencies, because the effective a. c. resistance of a coil is roughly proportional to the frequency, while the inductive reactance is exactly proportional to the frequency. Typical radio inductors have Q's of the order of 100 to 800, depending upon the nature of the service for which they are designed.

b. At resonance in a parallel tuned circuit the net resistance is Q times the reactance of either of the branches. This follows from the equation—

$$R_O=\frac{L}{RC}=\frac{L}{RC}\times\frac{2\pi f_r}{2\pi f_r}=\frac{X_CX_L}{R}=X_CQ=X_LQ$$

Thus the current through either reactor at resonance is Q times the net line current. In the series circuit at resonance the potential across each reactor is Q times the net potential across the complete circuit. This is apparent from the fact that the ratio of the voltages in a series circuit is equal to the ratio of the reactances. Since the net impedence offered by the series circuit at resonance is equal to that of the resistance alone, the potential across either reactor is Q times the net applied line potential. For either parallel or series tuned circuits a high Q, that is, relatively low R, implies good selectivity.

12. Coupled circuits; voltage gain.—*a*. A common form of coupled circuit arrangement for radio receivers is that of figure 27. The voltage gain at the resonant frequency of this circuit, that is, the ratio of output voltage to input voltage, is the product of the individual voltage gains in the transformer and in the tuned circuit. If the voltage gain of the transformer is unity, so that the induced voltage in the secondary is equal in magnitude to the applied voltage in the primary, then the gain of the circuit is equal to Q, as explained in paragraph 11*b*. The voltage gain of this circuit is no violation of the principle of the conservation of energy. Energy is alternately exchanged between the inductor and the capacitor, and the only power dissipated is that which is converted into heat by the inherent resistance of the circuit. This latter is the only power which the primary circuit is called upon to supply. If energy is drawn from the tuned circuit, for example, to supply a third circuit, the potential across the secondary output will drop to a value consistent with the available input power, which in radio receiver circuits is apt to be quite small.



① Common form of coupled circuit arrangement for radio receivers.
② Equivalent circuit for unity coupling.

FIGURE 27.

b. One tuned circuit is frequently coupled to another, as in figure 28. The over-all frequency characteristic—that is, secondary current versus frequency for a given magnitude of applied primary voltage—depends upon the degree of coupling employed. If each circuit is independently tuned to the same frequency and then the circuits are loosely coupled together, the over-all frequency characteristic is similar to the resonance curve for an isolated series circuit (figure 13②). However, if the coupling is sufficiently increased, for instance, by winding the secondary coil directly over the primary coil, the over-all reactance and the effective resistance are so altered that a double-humped frequency characteristic results, one peak occurring on either side of the frequency to which the circuits were individually tuned. A compromise (fig. 29②) is often struck be-

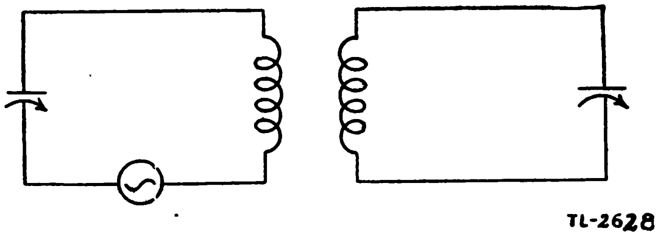
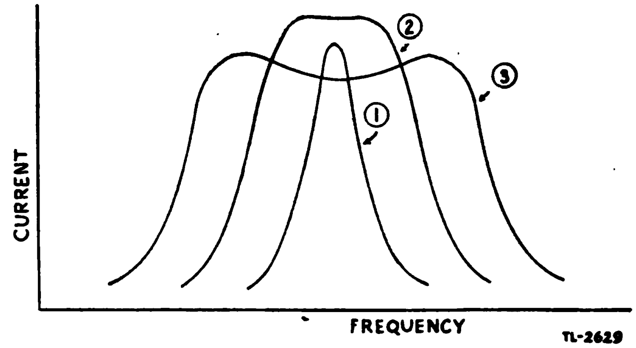


FIGURE 28.—Inductively coupled tuned circuits.

tween very loose (fig. 29①) and very tight (fig. 29③) coupling to permit nearly uniform energy transfer over a particular restricted range of frequencies. The selectivity of a coupled circuit is adversely affected by the presence of resistance across or in series with any part of the circuit. The effect is similar to that for an individual tuned circuit (fig. 20), a high series resistance or a low shunt resistance producing the broadest tuning.



① Loose coupling. ② Intermediate coupling. ③ Tight coupling.

FIGURE 29.—Frequency characteristics of coupled circuits.

SECTION III

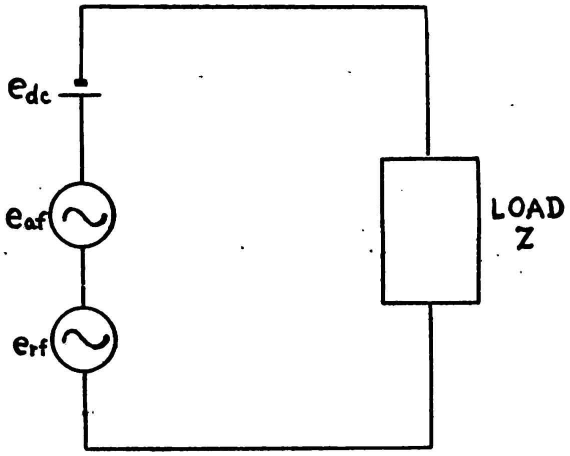
FILTERS

13. Filter action of individual capacitors, inductors, and resistors.—The analysis in section II indicated the feasibility of using resonant circuits for selecting energy at desired frequencies and for rejecting energy at undesired frequencies. Certain other inductor-capacitor arrangements are better adapted to passing or rejecting more or less uniformly a wide band of frequencies.

a. In the circuit of figure 30 the applied potential consists of three components: direct current, e_{dc}; audio frequency alternating current, e_{af}; and radio frequency alternating current, e_{rf}. The current which flows is given by

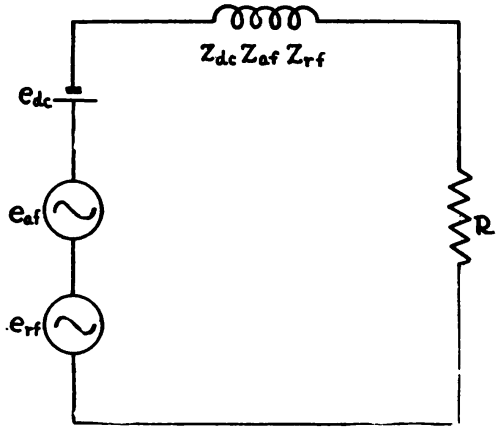
$$i=\frac{e_{dc}}{Z_{dc}}+\frac{e_{af}}{Z_{af}}+\frac{c_{rf}}{Z_{rf}}$$

where Z_{dc} is the impedance (or rather the resistance) of the load to direct current, Z_{af} is the impedance of the load to current of the frequency of e_{af}, and Z_{rf} is the impedance of the load to current of the frequency of e_{rf}. The internal impedance of the source is here neglected. If the load is capacitive, and hence offers infinite impedance to direct current and low impedance to alternating current, the current which flows contains only a. c. components; the magnitude of the audio frequency (a. f.) component is proportional to its frequency, as is the magnitude of the radio frequency (r. f.) component proportional to its frequency. On the other hand, if the load is inductive, the radio frequency and alternating frequency components of current are each inversely proportional to their respective frequencies, and the magnitude of the direct current component is limited only by the inherent small resistance of the inductor.



TL-2630

FIGURE 30.—Potential of three frequency components applied to load.



TL-2631

FIGURE 31.—Low pass filter.

b. In the following circuits take the internal resistance of the source as negligible; the impedances of the inductor, *L*, as: Z_{dc} zero, Z_{af}

very much smaller than R, Z_{rf} very much greater than R; the impedances of the capacitor as: Z_{dc} infinite, Z_{af} very much greater than R, Z_{rf} very much smaller than R. These relative impedances are possible because of the wide difference in frequency between radio frequencies and audio frequencies. Take the potentials, e_{dc}, e_{af}, and e_{rf} as approximately equal in magnitude. The total impedance of the circuit of figure 31 is relatively high to r. f. currents (impedance determined principally by Z_{rf}; R negligible in comparison with Z_{rf} and relatively low to direct and a. f. currents (impedance determined principally by R; Z_{af} and Z_{rf} negligible in comparison with R). Thus the coil, L, effectively serves to "choke" the r. f. current and may be regarded as a simple low pass filter.

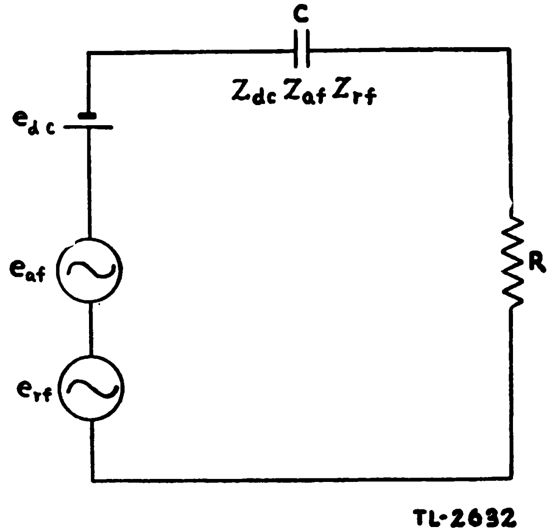


FIGURE 32.—High pass filter.

c. The total impedance of the circuit of figure 32 is infinite to direct current and relatively high to a. f. currents (the effect of R is negligible in either case) and relatively low to r. f. currents (impedance determined principally by R). The capacitor effectively "blocks" direct current and may be regarded as a simple high pass filter.

d. In the circuit of figures 33 and 34 the series resistor R is of the same resistance as the load resistor. In the circuit of figure 33 the impedance of the parallel branch is essentially only R to direct current and to a. f. currents, and Z_{rf} to r. f. currents. The potential e_{dc} is then divided equally, $\frac{e_{dc}}{2}$ across the load resister and $\frac{e_{dc}}{2}$ across the series resistor. A similar division of potential obtains for the audio frequency voltage, e_{af}. However, e_{rf} is almost entirely across the series resistor, because the impedance of the parallel circuit to r. f. currents (essentially Z_{rf}) is very small. Thus only a small fraction of e_{rf} occurs across the load resistor and consequently very little r. f. current flows through the load resistor. The student will find it worth while to demonstrate for himself that the inductor and the series resistor in the circuit of figure 34 act as a high pass filter.

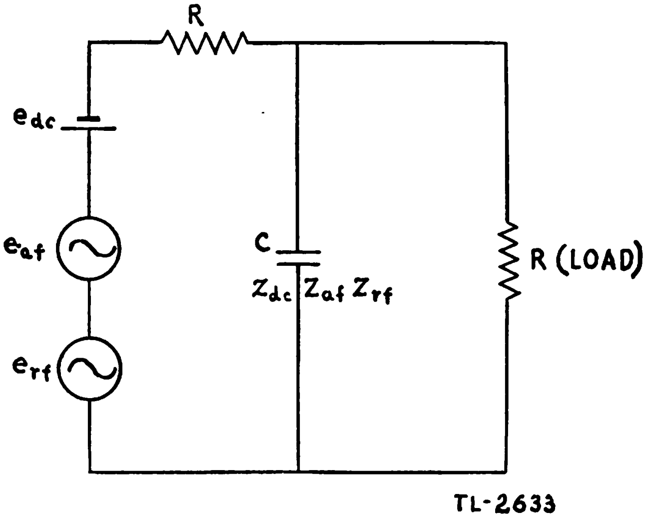


Figure 33.—Low pass filter.

e. Figure 35 presents a pictorial concept of currents which flow in series circuits corresponding to various applied potentials.

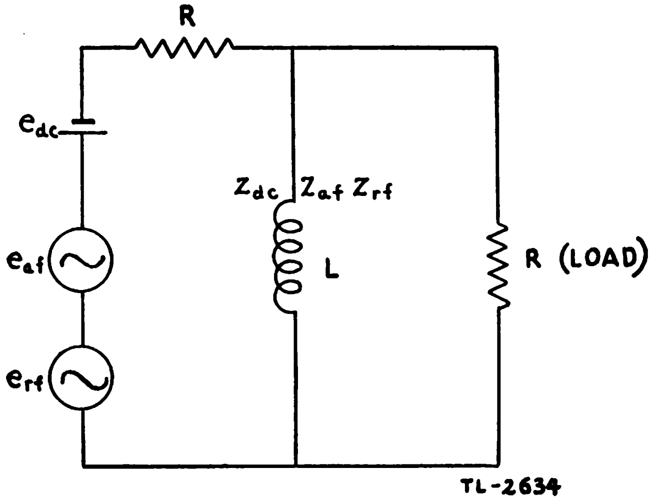


Figure 34.—High pass filter.

14. Filter action of resonant circuits.—Resonant circuits can be made to serve as filters in a manner similar to the individual inductors and capacitors of paragraph 13. The series resonant circuit offers a very low impedance to currents of the particular frequency to which it is tuned, and a relatively high impedance to currents of other frequencies. A series resonant circuit replacing the inductor of figure 31 would act as a band pass filter, passing

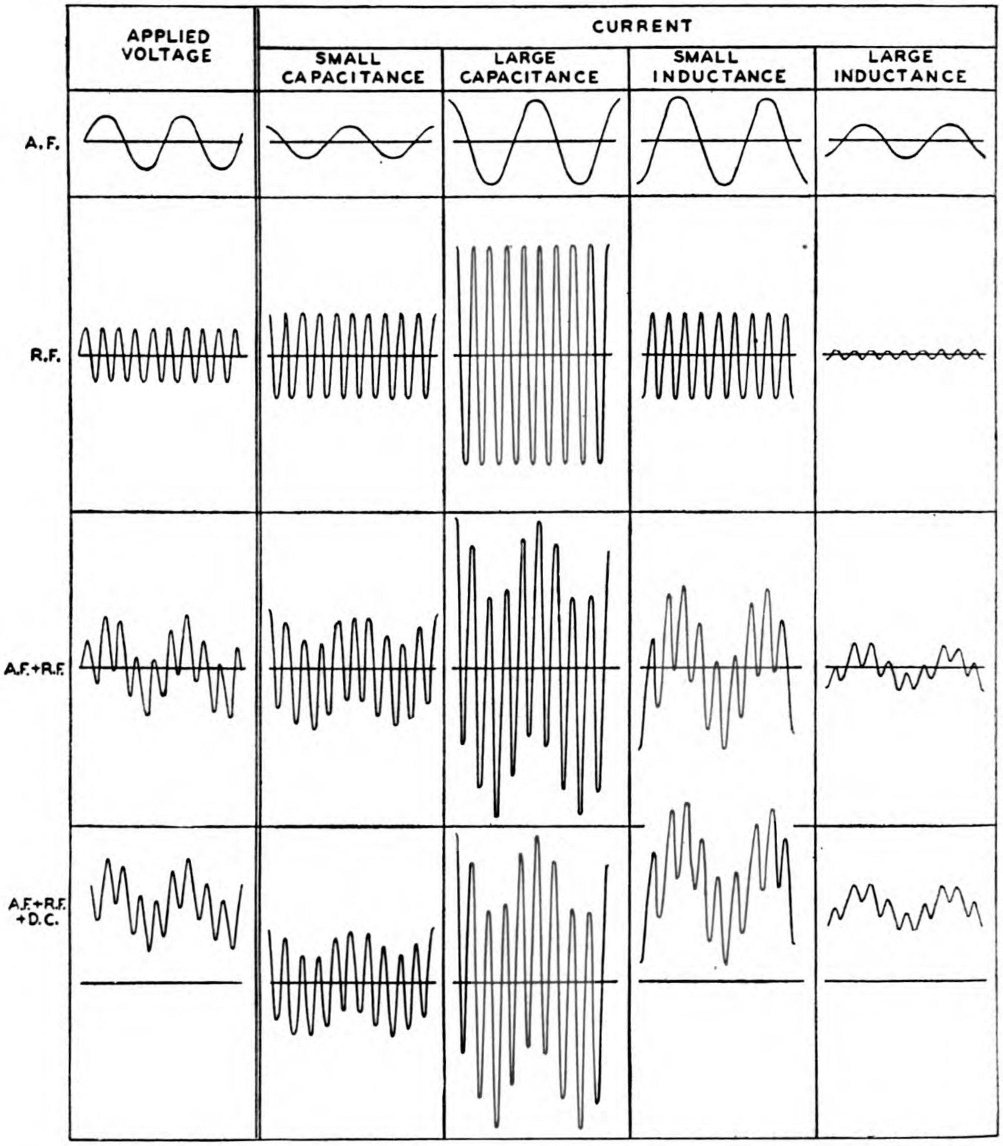


FIGURE 35.—Filter action of individual series capacitances and inductances

currents of frequencies in the neighborhood of its natural frequency and attentuating all others. A series resonant circuit shunted across the load to replace the inductor of figure 34 would bypass currents of its natural frequency. The parallel tuned circuit, on the other hand, offers a very high impedance to currents of its natural frequency and a relatively low impedance to others. In series with a load it acts as a band stop filter; in parallel with a load as a band pass filter.

15. General filter networks.—*a.* Combinations of capacitances, inductances, and resistances are frequently used in networks. The arrangement of figure 36 is commonly employed to "smooth" the output of rectifier tubes supplying plate current for a transmitter or receiver. The capacitors shown are each of 10 microfarads capacitance; and each choke is of 20 henrys inductance with inherent resistance of 100 ohms to direct current and total impedance of 2,000 ohms to 120-cycle alternating current. The load is a 10,000-ohm (d. c. or a. c.) resistance. A semi-quantitive analysis of the action of such a filter may be made as follows. The impressed voltage at *AE* (voltage output of a full-wave rectifier), which is actually shown in figure 37①, may be regarded as roughly equivalent to a superposition of two simple voltages, one a direct voltage and the other a 120-cycle alternating voltage as in figure 37②. That much of the filter which is to the right of *CD* (fig. 36) is of sufficiently high 120-cycle impedance so that its contribution to the total impedance across *CD* is negligible. Thus for studying the ripple component, the filter may be studied in isolated sections as shown in figure 38. The relative alternating voltage drops across the inductance, resistance, and capacitance of the first section are as represented in figure 39. For the first section the ratio of alternating voltage output to input, $\frac{e_{GH}}{eAE}$, may be of the order of 1 percent.

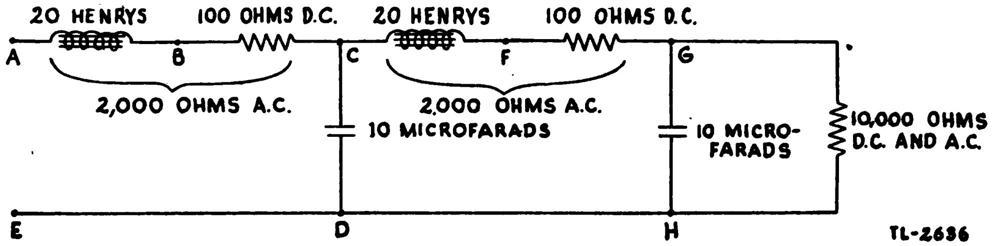
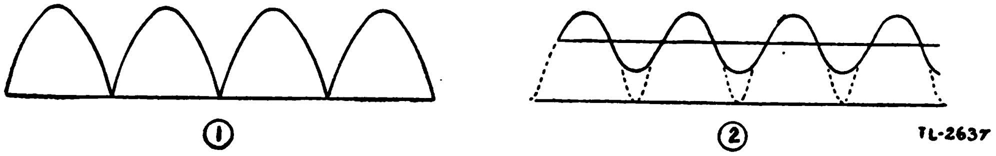


FIGURE 36.—Low pass filter for power supply.



① Actual voltage input filter. ② Approximate equivalent voltage input to filter.

FIGURE 37.

In the output of the second section, that is, in the voltage across the load, any ripple component is negligible. On the other hand, the only d. c. resistance which the complete filter offers is the relatively small total d. c. resistance (200 ohms), so that nearly the full continuous voltage across the filter input is impressed on the load,

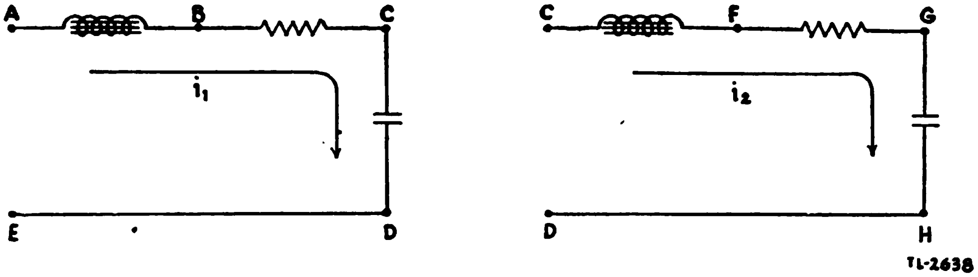


FIGURE 38.—Low pass filter in sections.

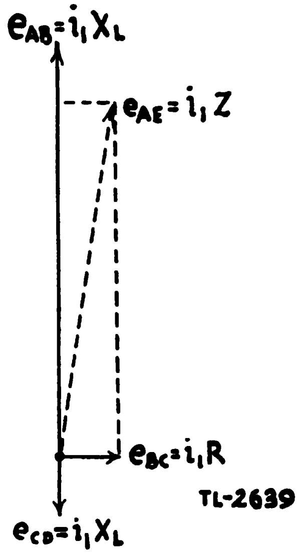
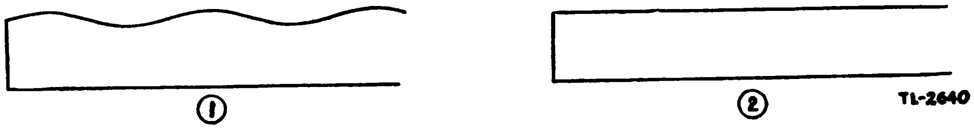


FIGURE 39.—Alternating voltages in first section of low pass filter.

The voltage output of the first section is shown in figure 40①, and the output of the second section in ②.



① First section. ② Second section.

FIGURE 40.—Voltage output of low pass filter sections.

b. A high pass filter is shown in figure 41. Band pass and band stop filters employing resonant circuits are shown in figures 42 and 43 respectively.

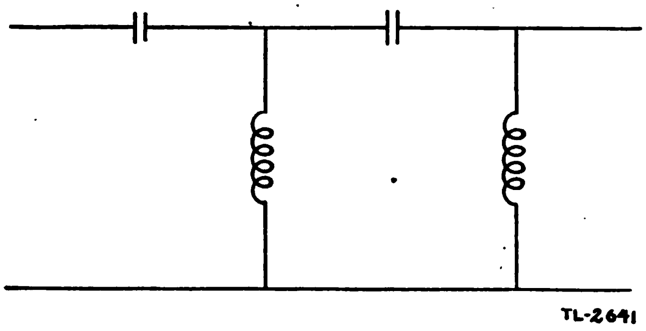


FIGURE 41.—High pass filter.

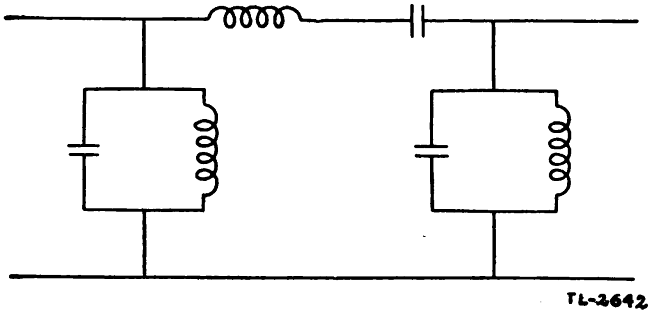


FIGURE 42.—Band pass filter.

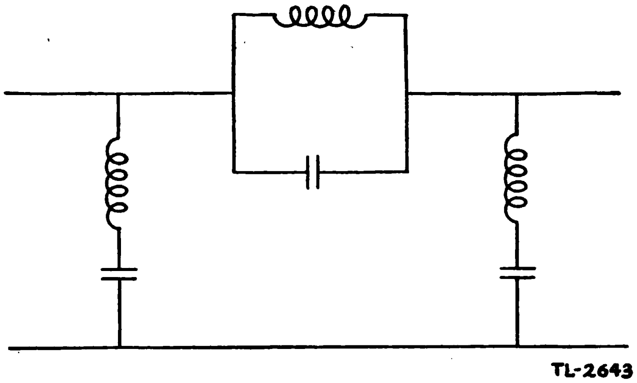


FIGURE 43.—Band stop filter.

SECTION IV

VACUUM TUBES

16. General.—*a.* Tungsten and certain other metals and metallic oxides yield electrons freely when heated to a high temperature in a low-pressure atmosphere. Any isolated positively charged body in the vicinity of an electron emitter attracts the electrons, which then ultimately neutralize the positive charge. The positive charge can be maintained, however, if electrons are removed just as fast as they strike, as, for example, by connecting a source of constant voltage between the positively charged body and the emitter (fig. 44). This is the general arrangement in a two-element vacuum tube (*diode*). The emitter may resemble the familiar incandescent lamp filament heated by passing a current through it. The charged body usually surrounds the emitter and is called the *plate*. The whole assembly is enclosed in an evacuated glass or metal container, called the "envelope." The plate, being the terminal at which current normally enters the tube, is sometimes called the *anode;* the emitter, being the terminal at which current normally leaves the tube, is commonly called the *cathode.*

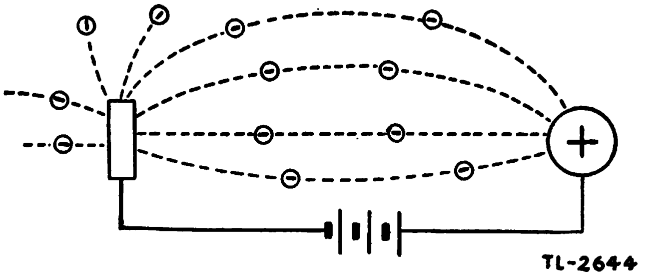


FIGURE 44.—Emitted electrons attracted by positively charged body.

(The conventional direction of current flow is opposite to the direction of electron motion.)

b. The pressure inside a vacuum tube is reduced to such an extent that only about $1/100,000,000$ of the original air in the tube remains. For pressures much above this amount spurious effects are introduced by the presence of gas molecules. The electrons are deflected from their normal paths by collisions with gas molecules; the positive ions formed from the molecules as the result of such collisions make for background noise in a radio receiver; these positive ions further serve to lower the internal resistance and amplifying power of a vacuum tube, and they may lower the effectiveness of an emitter or even destroy it. In general, tubes are evacuated to the highest extent consistent with economical commercial manufacture.

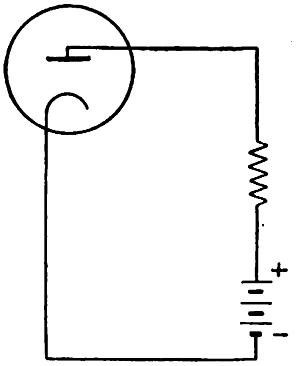


FIGURE 45.—Diode with resistive load.

17. Diode rectifier.—The symbolic representation of a diode with a resistive load is as shown in figure 45. The battery potential controls the magnitude of the current through the load resistance. Increasing the potential increases the rate at which the emitted electrons move to the plate and the rate at which current flows through the load; decreasing the potential decreases the current through the load. Reversing the potential, which makes the plate negative with respect to the emitter, causes repulsion of the electrons from the plate with consequently no current through the load. One immediate application of the vacuum tube is obvious: its use as a rectifier. Thus with an alternating potential applied (fig. 46), current flows through the load only during alternate half cycles; that is, when the plate is positive with respect to the emitter—and only in one direction, from plate to emitter (fig. 46).

18. Characteristic curves.—The load current in the above circuit is not proportional to the applied voltage, as is the case with previously studied circuits. Ohm's Law is strictly applicable only to small increments of currents and voltages, and current-voltage relations in general in vacuum tube circuits are studied by means of experimentally obtained characteristic curves. A plot of the direct current in the load of figure 45 against the plate-to-emitter potential is shown in figure 47. At the lower values of plate potential the accumulated emitted electrons in the neighborhood of the cathode are effective in repelling the electrons nearest the cathode back toward the cathode, and only those electrons which are nearest the plate are attracted to the plate. For intermediate values of plate potential the space charge in the vicinity of the cathode is reduced, owing to the removal of increased numbers of electrons, by the attraction of the positively charged plate, and any increase in plate potential produces an appreciable increase in current. For large values of plate potential, when the space charge is completely removed, the number of electrons reaching the plate per second is limited by the number emitted per second from the cathode, and is independent of

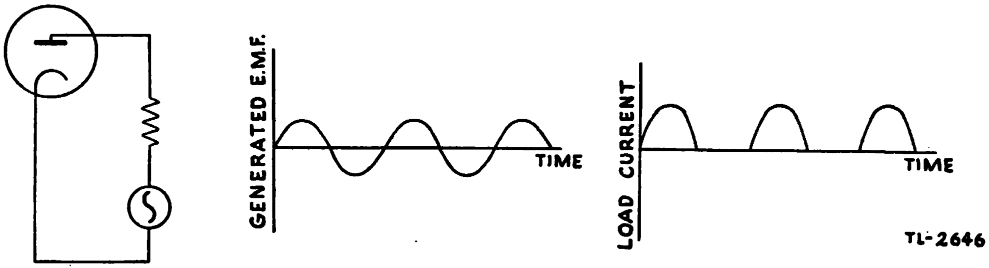


FIGURE 46.—The diode as a rectifier.

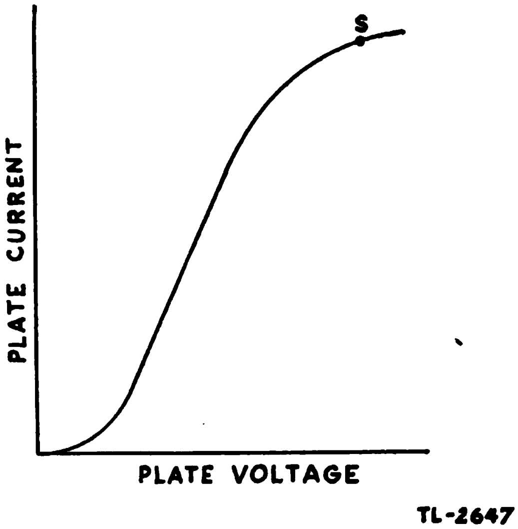
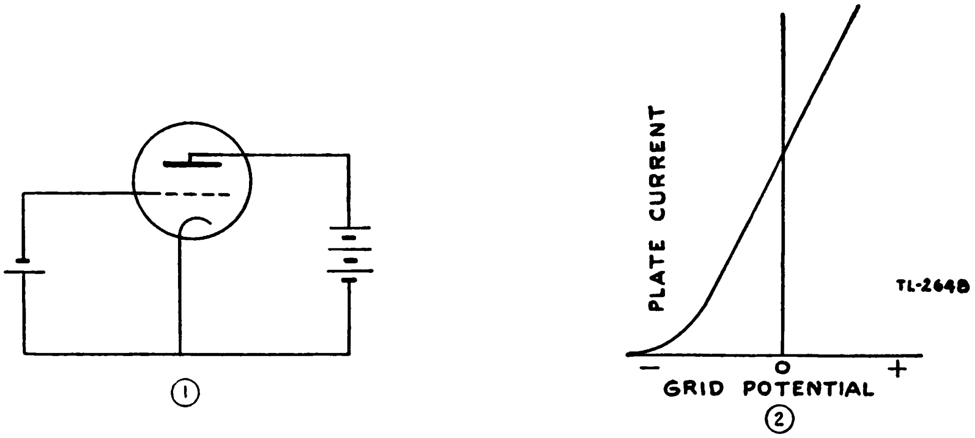


FIGURE 47.—Plate current-plate voltage characteristic of diode.

plate potential. This condition is referred to as saturation, and a point *S* on the knee of the plate current-plate voltage curve is called the saturation point.

19. Triode amplifier.—The plate current of a vacuum tube is conveniently varied by applying a positive (with respect to the cathode) potential to a mesh type element located between the plate and cathode and in the space charge region. Such an element, termed a grid because of its usual gridiron-like structure, tends to reduce the effect of the space charge in a manner similar to the action of the plate. However, due to the highly effective location of the grid in proximity to the cathode and to the space charge center, it is much more efficient than the plate in accomplishing this mission. At the same time, the open structure of the grid permits the ready passage of electrons through it and onto the plate. The net effect is that for a fixed positive plate potential, a small positive grid potential makes for large plate current; and a small negative grid potential is sufficient to counterbalance the positive plate potential and to reduce the plate current to zero. A second application of the vacuum tube is apparent: its use as a relay and amplifier. Large current variations in the load circuit may be made to follow relatively small voltage variations across grid to cathode. The manner in which plate current varies with grid potential is illustrated in the characteristic curve of figure 48 for a three element tube (triode).

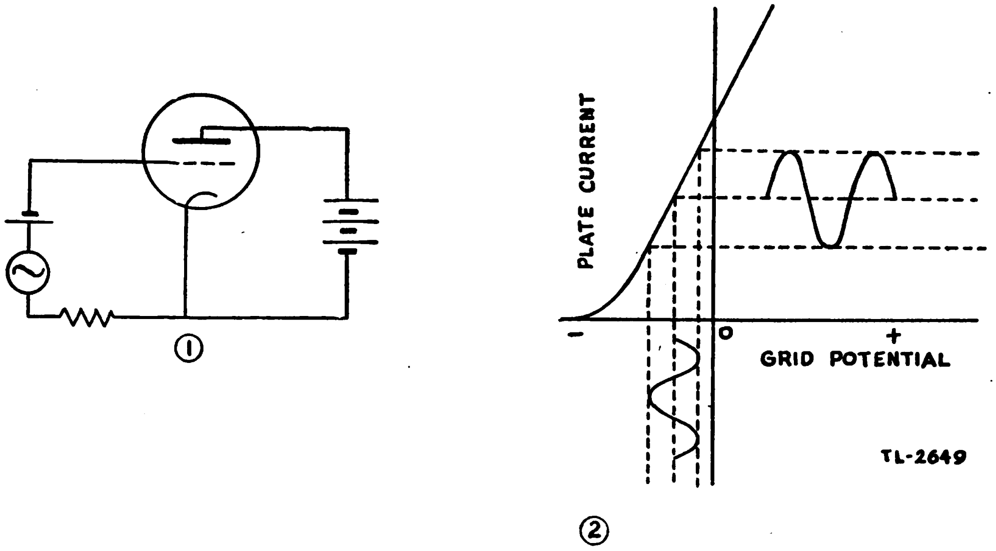


① Basic triode circuit. ② Plate current vs. grid potential characteristic.

FIGURE 48.

20. Distortion.—If in the circuit of figure 48① an alternating voltage (signal voltage) is superimposed on the direct voltage (grid bias) as in figure 49①, the variations in the plate current will follow a pattern similar to the variations in grid voltage (fig. 49②).

Provided the grid potential swing is within the limits of the straight line portion of the characteristic, the plate current will faithfully reproduce the grid potential form. However, if the grid is allowed to go positive so that current flows in the grid circuit, the grid to cathode a. c. potential differs in form from the actual signal potential because of the drop in potential occurring with the flow of current across any impedance which is in the grid circuit. Unless some compensation for the effects of grid current is provided, in order to avoid distortion the grid swing must be restricted not merely to the straight line portion of the characteristic but to only negative values as well.

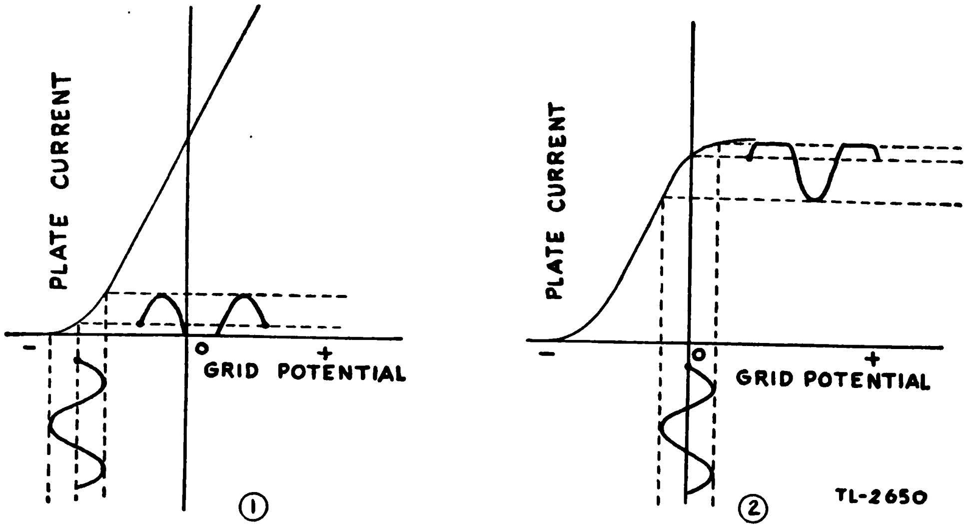


① Triode with impressed signal voltage. ② Output current vs. input voltage.

FIGURE 49.

Distortion also results either if the grid bias is increased excessively as in figure 50①, or if the cathode temperature is lowered so that the emission is insufficient, as in figure 50②. A distorted output is generally, but not always, objectionable, occasionally it is actually desirable.

21. Static and dynamic characteristics.—In figure 51 there are shown for comparison two characteristics of a triode, one for the case of no load in the plate circuit (static characteristic) and the other for the case of a load in the plate circuit (dynamic characteristic). The difference in the slope of the two curves is due to the fact that the plate-to-cathode potential for no load is constant regardless of the plate current, whereas with a load in the plate circuit the potential across the load, and consequently the plate to cathode potential, varies with the current. Take the normal operating point as the same for the tube either with or without external load, that is, regard the operating point as the point of intersection of the two curves of figure 51. Without an external load, as in figure 52①, on a positive swing, of signal potential, *A*, figure 52③, the plate current rises by an amount *B*. With an external load, as in figure 52②, the increase in current which follows a positive grid swing is in turn accompanied by a potential drop (*IR*) across the load (as read by voltmeter V_2). Thus the potential available across plate to cathode within the tube (as read by voltmeter V_1) is reduced; and the consequent increase in current *C* is less than it was under the no load condition. On the negative half cycle of the signal voltage the plate current is reduced, and the potential drop across the load is less than it is under normal operating conditions. Thus the voltage across the tube rises, so that the available plate to



① Effect of high grid bias. ② Effect of low cathode temperature.

FIGURE 50.

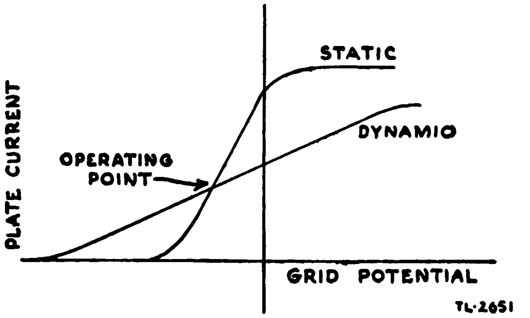
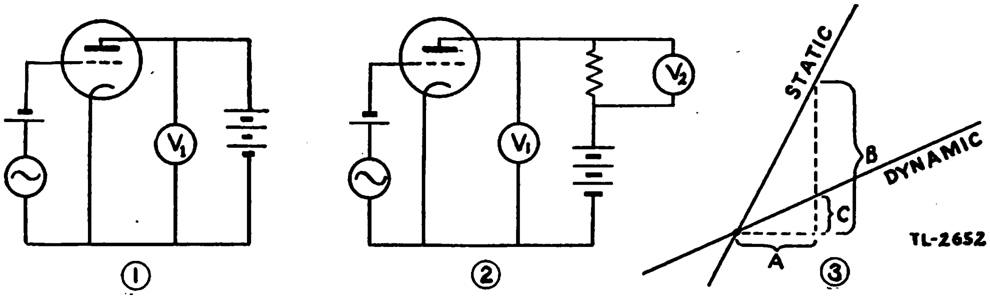


FIGURE 51.—Static and dynamic characteristics of triode.

cathode potential exceeds the corresponding value under the no load condition. The dynamic curve is, incidentally, more nearly linear than is the static curve.

22. Miscellaneous characteristics.—Three dynamic curves are given in figure 53 for various load resistances. A set of static curves is shown in figure 54 for various plate potentials. A set of characteristics frequently useful in circuit design is a group of static plate current-plate voltage curves for various grid potentials as shown in figure 55. Many handbooks on vacuum tubes confine the characteristics illustrated to *families* of curves of this last type.



① With external load. ② Without external load. ③ Corresponding characteristics.

FIGURE 52.—Triode.

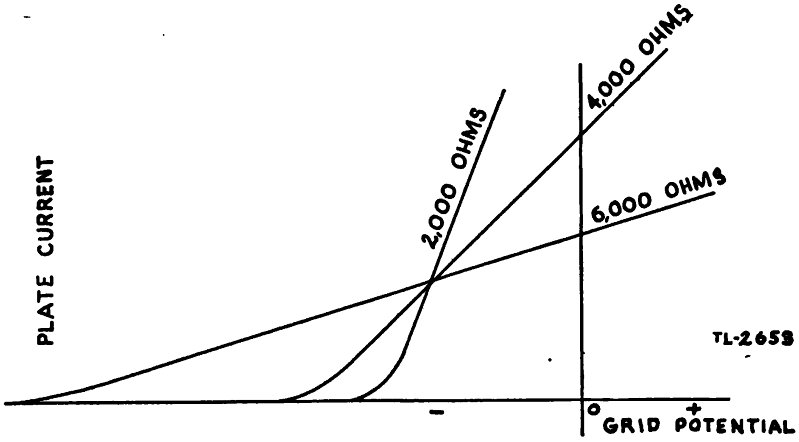


FIGURE 53.—Dynamic characteristics of triode.

23. Families of characteristics used in analysis.—Observe that of the three quantities, grid potential, plate potential, and plate current, any two will determine the third from the set of static characteristic curves of figure 55. Thus corresponding to a plate current of 10 milliamperes and a plate potential of 50 volts, the required grid potential is −8 volts. Suppose it is desired to obtain these same relations—plate current 10 milliamperes, plate potential 50 volts, and grid potential −8 volts—with a load resistance of 4,000 ohms. This requires a total plate supply potential of 50+4000× (10/1000) volts= 90 volts, 50 across the tube and 40 across the load resistance. The current in the load resistance follows Ohm's Law, that is, the current through the resistance is proportional to the potential across it. This proportionality can be represented by a straight line on the current-voltage graph of figure 56. The line is determined by any two points on it, two convenient points being *P* and *Q*, as in figure 56①. *P* is for a current of 10 milliamperes and a voltage drop across the resistance of 40 volts (50 volts across the tube); *Q* is for zero current and zero drop across the resistance (90 volts across the tube). If *P* is taken as the normal operating point, the grid swing due to an impressed signal voltage will cause variations along this load line in both directions from *P*. Corresponding to an instantaneous grid potential of 10 volts, the plate current, plate voltage, and voltage across the load can be found by following the 10-volt characteristic to where it intersects the load line. From the curves of figure 56② this yields 16 milliamperes plate current, 25 volts plate potential, and

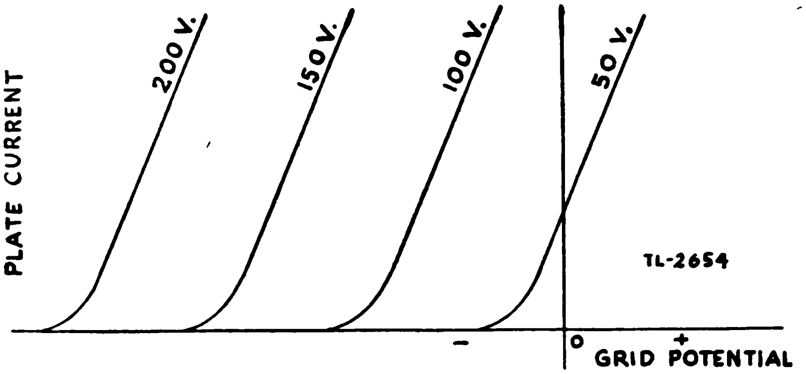


FIGURE 54.—Plate current vs. grid potential curves for triode.

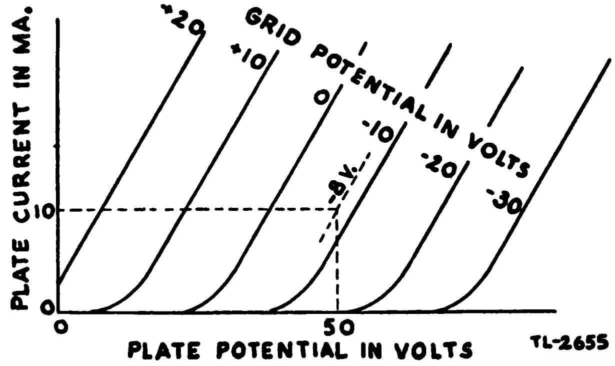
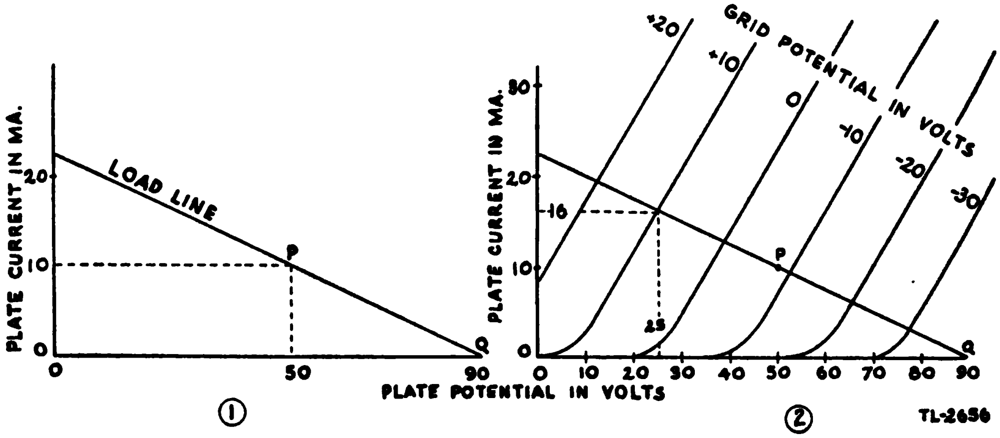


FIGURE 55.—Plate current vs. plate potential curves for triode.

90 − 25 = 65 volts drop across the load. The family of plate current-plate potential curves is thus useful in determining the limitations of a particular tube under various operating conditions. A particular tube can be selected to fit certain circuit constants, or vice versa, with the aid of the information contained in the vacuum tube characteristics.

24. Resistance, amplification factor, and transconductance.—The a. c. internal resistance, R_p, of a vacuum tube is measured by the increase in plate voltage required to produce given increase in plate current. A tube for which a 10-volt plate potential increase is required to produce a 10-microampere increase in plate current has a relatively high internal resistance, $\frac{10}{0.000010} = 1{,}000{,}000$ ohms. A tube which requires a 10-millivolt plate potential increment to produce a 10-microampere plate current change has a relatively low internal resistance, $\frac{0.010}{0.000010} = 1{,}000$ ohms. Low internal resistance is manifested by a steep i_p–e_p characteristic corresponding to large increases in plate current for small increases in plate voltage. The amplification factor, μ, (a Greek letter, "mu") of a tube is a measure of the relative effectiveness of grid and plate potential increments in changing the plate current, and is an indication of the suitability of the tube for voltage amplification purposes. If a 1 milliampere increase of plate current is accomplished either by a 10-volt increase in plate potential or by a 0.1 volt increase in grid potential, the amplification factor is $\frac{10}{0.1} = 100$. Transconductance, G_m, is defined as the ratio of a small change in plate current to the change in grid potential



① Construction. ② Application.

FIGURE 56.—Load line.

producing it, all other voltages remaining constant. Transconductance is a criterion of the suitability of a tube for power amplification purposes, a tube with a high transconductance yielding large plate current variations corresponding to small variations in grid potential. The transconductance of a tube is dimensionally a ratio of amperes to volts and is thus measured in reciprocal ohms or mhos. ("Mho" is "ohm" spelled backwards.) A tube with a high transconductance, perhaps 10,000 micromhos, is evidenced by a steep i_p–e_g characteristic; a tube with a low transconductance, perhaps 10 micromhos is shown by an i_p–e_g characteristic with a small slope. Internal resistance, amplification factor, and transconductance are interrelated, amplification factor being essentially a product of the other two. A tube which has both a high transconductance and a high internal resistance accomplishes the same increase in plate current with a small increase in grid potential alone (due to the high transconductance) as with a large increase in plate potential alone (due to the high internal resistance). In other words, such a tube also has a high amplification factor.

25. Interelectrode capacitance.—The inherent capacitance between grid and plate elements of a triode is of sufficient importance at high frequencies to require special consideration in radio circuits. Where this capacitance is undesirable, it can be counteracted by introducing a neutralizing circuit which presents r. f. potentials equal in magnitude but opposite in phase to those occurring across the interelectrode capacitance, with the result that the effects of the interelectrode capacitance are nullified. The extra circuit complications can generally be avoided by the use of tetrodes or pentodes, four and five element tubes respectively, which are particularly designed to have low interelectrode capacitance. The grid to plate capacitance of an ordinary receiving triode runs about 3 micromicrofarads. This represents a capacitive reactance of 53,000 ohms at 1 megacycle and only 530 ohms at 100 megacycles. Tetrodes and pentodes offer corresponding reactances of about 16,000,000 ohms at 1 megacycle and 160,000 ohms at 100 megacycles.

26. Tetrodes.—The tetrode includes a second grid, called a screen grid, between the regular control grid and the plate. The screen grid is operated at a potential which is positive with respect to the cathode but less positive than the plate. By connecting the screen to the cathode through a capacitance, the screen is at approximately the same potential as the cathode as regards r. f. currents. The screen acts as an electrostatic shield between the cathode and the plate. The effect of the screen thus connected is twofold: the grid to plate capacitance of the tube is considerably reduced (see par. 25) and the amplification factor of the tube is considerably increased. The control grid potential regulates the plate current in much the same manner as in a triode; however, in the screen grid tube the plate potential has very little effect on the plate current. Because of the screening action of the second grid, the same change in plate current which requires a very large change in plate potential is accomplished by a small increment of control grid potential; that is, the amplification factor of the screen grid tube is high. An incidental and generally unwanted effect in tetrodes is the extent of secondary emission, that is, release of electrons from the plate on bombardment by the electrons in the current stream. In a triode these secondary electrons are eventually attracted back to the plate. In a tetrode, however, the positively charged screen competes with the plate for the attraction of these electrons, with the result that when the potential of the plate approaches, or falls below, that of the screen, the screen draws large currents, the plate current is lowered, and the amplification of the tube is reduced.

27. Pentodes and beam tubes.—Pentodes and beam tubes effectively cope with the problem of secondary emission. In the pentode a suppressor grid inserted between the screen grid and the plate, and electrically connected to the cathode, serves to prevent the secondary electrons from moving to the screen grid without otherwise appreciably altering the characteristics of the tetrode. In the beam tube suppression is achieved by a particular design arrangement which provides for a very low intensity electric field midway between the screen grid and the plate. In this region of the low intensity field, electrons are slowed down to such an extent as to accumulate and to present a space charge effect similar to that which surrounds the cathode. The negative charge cloud repels secondary electrons in the same manner as would a suppressor grid. Screen current is minimized in the beam tube by the design of the screen grid, which is such that the constituent wires are in the shadow formed by the control grid of the electron stream from the cathode. The beam tube has a high power sensitivity, that is, high power output for a given signal voltage input.

28. Variable μ tube.—The variable μ tube is a modified tetrode or pentode receiving tube in which the control grid is constructed with some of the grid elements widely separated and others closely spaced. For large negative values of grid bias the closely spaced elements present a high density negative charge to prevent the flow of electrons through them; and the only electrons from the cathode to reach the plate are those passing through the openings between the widely spaced elements. It is possible by means of an auxiliary rectifier circuit to vary the grid bias of the variable μ tube in accordance with the intensity of the incoming signals and thus to provide automatic volume control to compensate for fading.

29. Multipurpose tubes.—Certain types of receiving tubes have two or more complete sets of elements within one envelope which perform various associated functions. For example, the duplex diode has two cathodes and two plates, and it may be used as a full wave rectifier. The possible combinations are numerous. Some of them will be encountered in section X on radio receivers.

30. Directly and indirectly heated cathodes.—*a.* A cathode which is in the form of a filament directly heated by passing a local current through it has the disadvantage of introducing a ripple in the plate current when alternating current is used for heating. The ripple is most objectionable if the plate and grid returns are made to one end of the filament. In figure 57 the resistor *AB* represents a filament which is heated by applying 5 volts of alternating current across it. For no current flowing through the tube the plate is maintained at a potential of 100 volts above that of point *B*. For a 5-milliampere steady plate current the potential across the tube from *B* to the plate is always $100-2000\times\frac{5}{1000}=90$ volts; whereas the potential from *A* to the plate varies from 85 to 95 volts depending upon the potential of point *A* relative to point *B*, and the total plate current rises and falls at the frequency of the filament current. This condition is remedied to a large extent by connecting the grid and plate

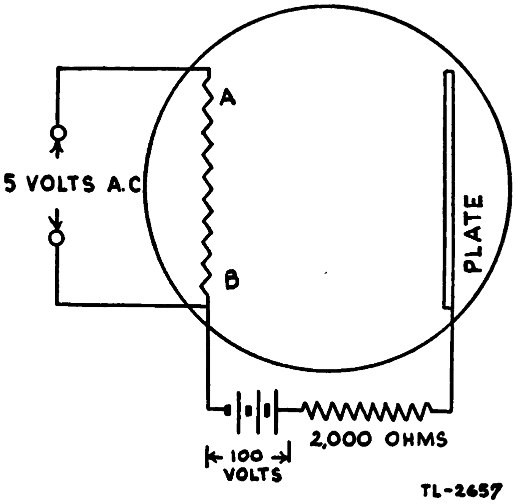
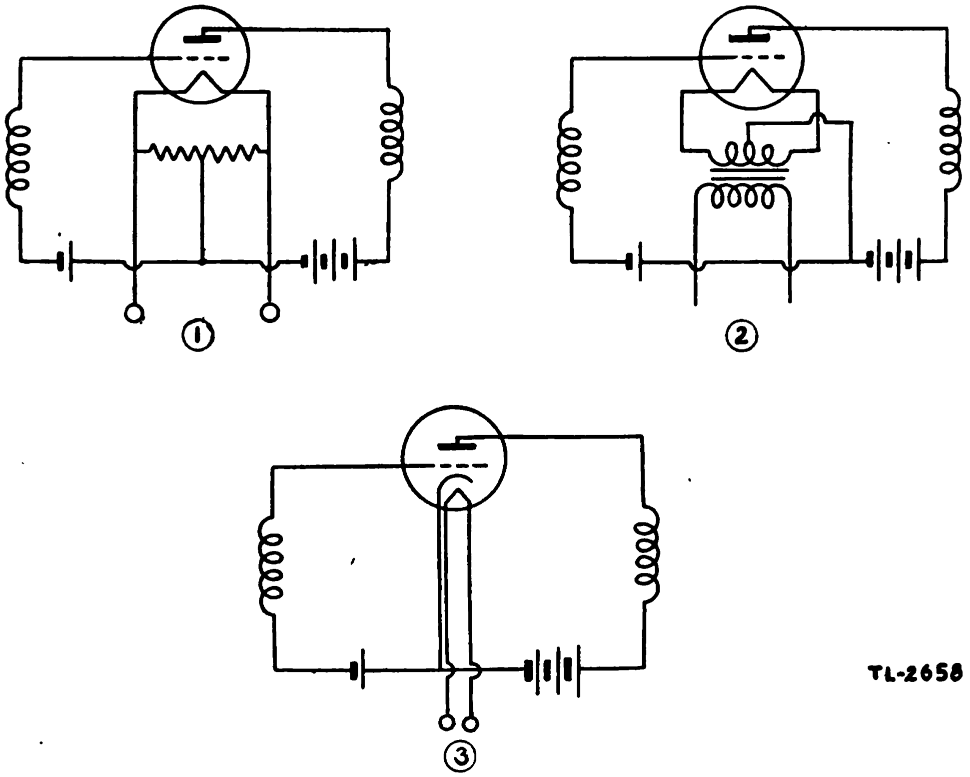


FIGURE 57.—Directly heated cathode.

returns to the electrical center of the filament as in figure 58① or ②. But even with a center return arrangement, for a 60-cycle filament current, there is still present 120-cycle modulation of the plate current. This double frequency ripple arises from the effects on the plate current provided by the intermittent rise and fall of the filament temperature, the voltage drop in the filament, and the alternating magnetic field set up by the filament current. Temperature fluctuations in the filament are ordinarily negligible. The latter two effects, however, may be troublesome. The magnetic field about the filament serves to deflect the electrons from their normal paths and so in effect to reduce the plate current. The resulting plate current is largest when the heating current is zero, that is, at intervals which occur at double the heating current frequency. With a voltage drop in the filament, the space current from the negative half of the filament exceeds that from the positive half because of the manner in which space current varies with the electrostatic field across the tube (space current varies as the three-halves power of the plate potential). The result is that



① Center-tapped resistor.
② Center-tapped transformer.
③ Indirectly heated cathode.

FIGURE 58.—Methods of utilizing a. c. filament supply.

each time the current is a maximum in either direction in the filament, that is, at a frequency which is double the heating current frequency, the space current is increased slightly from the value which obtains during those instants when the current through the filament is zero and the potential of the filament is uniform.

b. In transmitting tubes and in the power stages of a receiver, where the signal currents are large, the double frequency ripple current is neglible in comparison. However, in all other receiver tubes, indirectly heated cathodes (fig. 58③) are necessary wherever a. c. filament operation is desired. An indirectly heated cathode is formed by a metallic sleeve closely surrounding a heated filament and electrically insulated from the filament. The cathode is heated by radiation from the filament. Such an emitter is sometimes referred to as an equipotential cathode, since all parts of it are at the same potential. In general throughout this manual, for simplicity tube heater elements and heater power circuits are not shown in circuit diagrams.

SECTION V

VACUUM TUBE AMPLIFIERS

31. Classification of amplifiers.—Amplifiers are classified according to their general usage as radio or audio frequency amplifiers, and as voltage or power amplifiers; according to the type of coupling between stages as resistance coupled, impedance coupled, or transformer coupled amplifiers; and according to the method of operation as class A, class B, or class C amplifiers. The A, B, and C classifications are based on the following general considerations: class A, high fidelity reproduction; class B, plate circuit rectification; and class C, high efficiency operation.

32. Class A operation.—Class A operation is such that with a single tube in an amplifier stage it is possible to obtain an output plate current wave shape that is a good replica of the input signal voltage wave shape. This requires that the grid and plate potentials applied to the tube confine the operation to within the substantially straight portion of the i_p–e_g* dynamic characteristic as in figure 59. It is generally desirable to prevent positive swings of grid potential because of the accompanying grid current. A tube which does not draw grid current presents an infinite input resistance. On the other hand, a tube which does draw grid current is equivalent to a shunt resistance across the input circuit; the higher the current, the lower the resistance. In r. f. receiver amplifiers, where the grid-to-cathode portion of the tube shunts the preceding tuned circuit, it is in the interest of good selectivity to keep the grid-to-cathode resistance high by operating the tube so as not to draw grid current. A tube which draws grid current suffers distortion of the signal voltage, as indicated in para-

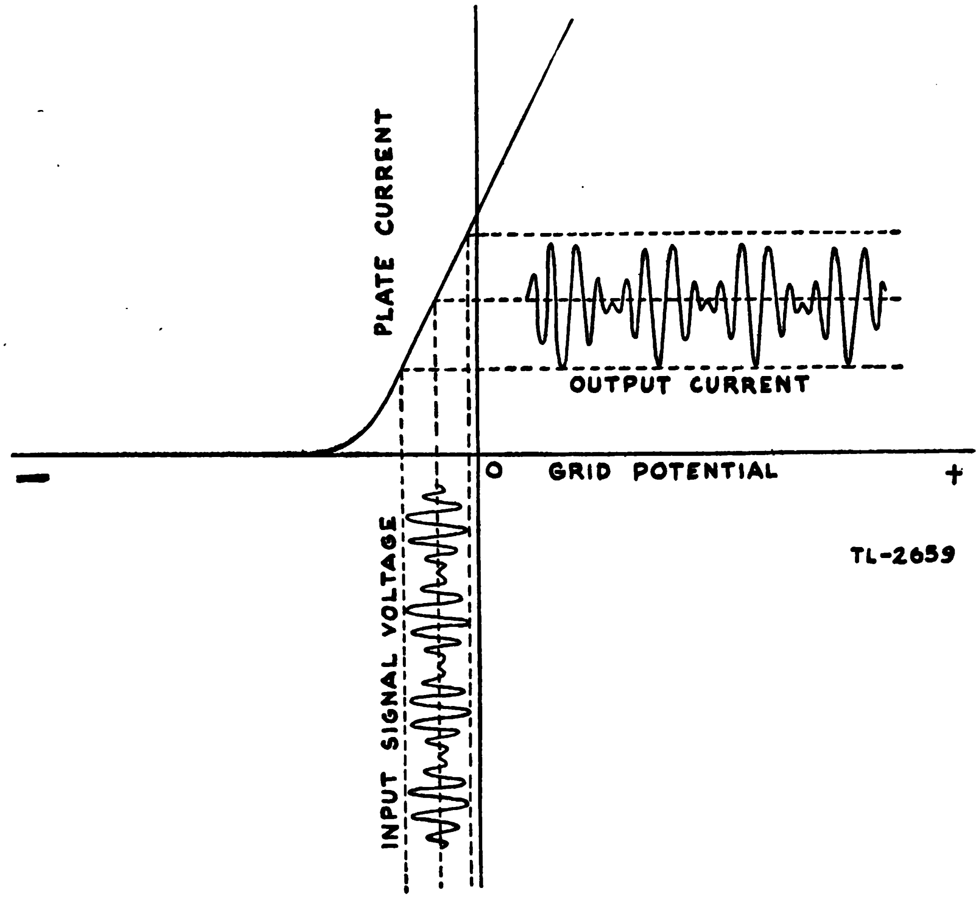


FIGURE 59.—Class A operation.

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*The subscript g and references to grid, unless otherwise specified, will be taken to indicate control grid.

graph 20, and it requires grid power to excite it. In power amplifiers where economy of grid circuit excitation is generally secondary, distortion of the input wave form with a limited amount of grid current is sometimes tolerated in exchange for the higher plate circuit efficiency—$\frac{\text{a.c. plate power output}}{\text{d.c. plate power input}}$—which results. Negative feedback (par. 42) may be employed to counteract the distortion introduced by the grid current.

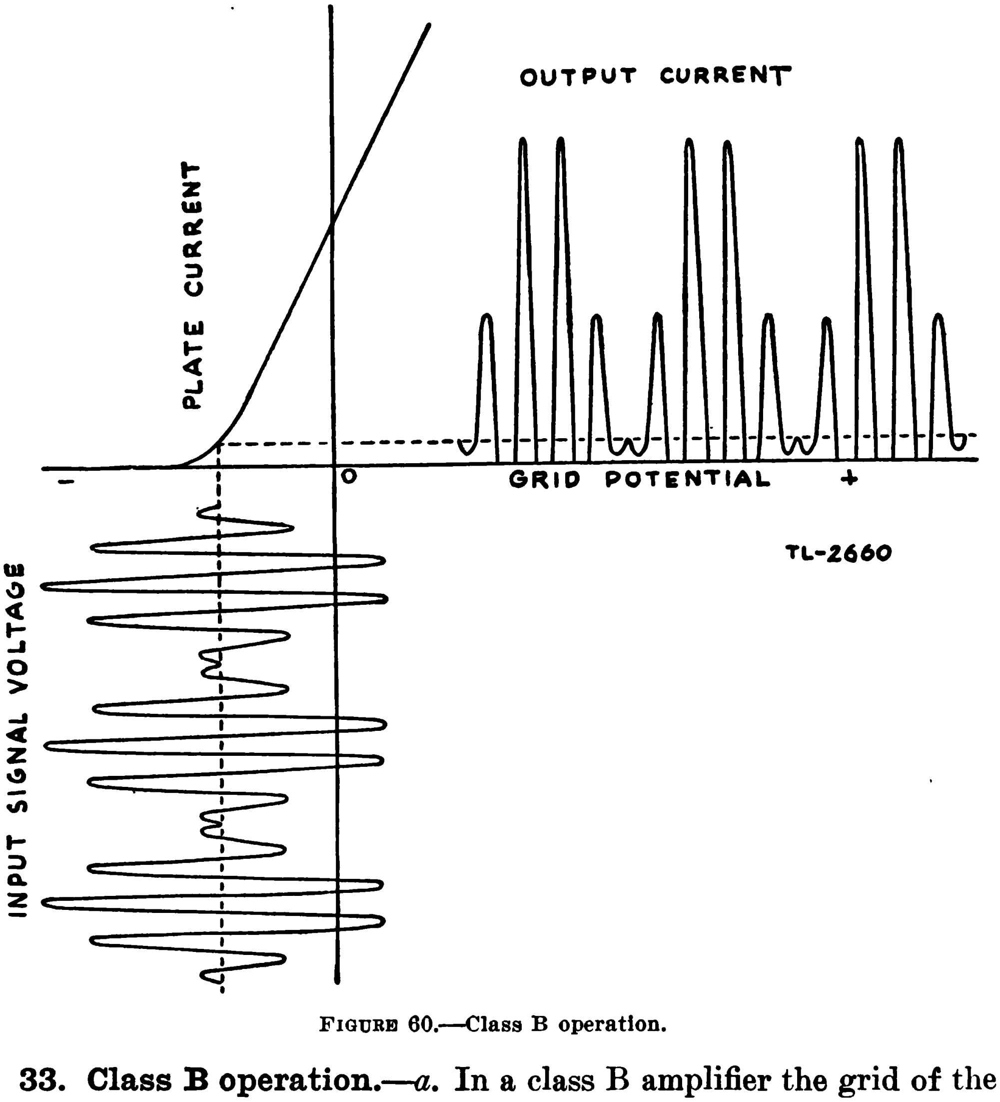


FIGURE 60.—Class B operation.

33. Class B operation.—*a*. In a class B amplifier the grid of the tube is biased approximately to cutoff; that is, for no signal voltage the plate current is very small, and with signal voltage impressed the plate current flows essentially only during the positive half cycles of the signal. The signal voltage is allowed to swing sufficiently that operation occurs over the entire linear portion of the characteristic (fig. 60).

The grid usually draws current during part of the time, and the driving source must supply power to overcome the grid losses.

b. For audio frequency class B amplification two tubes are used in push-pull as shown in figure 61. One tube operates during each half of the cycle with a net effect that is comparable in quality to single-tube class A amplification but with much improved plate circuit efficiency.

c. For radio frequency amplification covering a narrow band of frequencies a single tube serves in an amplifier stage (single-ended amplifier) in conjunction with a tuned circuit. The flywheel effect of the tuned circuit (par. 46*a*) supplies the missing half cycles. Distortion present in the single-ended class B radio frequency amplifier is in the form of components of audio frequencies and of radio frequencies. The radio frequency components of the distortion are of at least twice the frequency of the input signal, so that all of the unwanted components are conveniently suppressed by the filter action of the tuned circuit, and the output contains only the desired signal amplified. This same filter action is not practicable for a single-ended audio frequency class B amplifier, since here the unwanted distortion frequencies overlap the desired frequencies of the original signal.

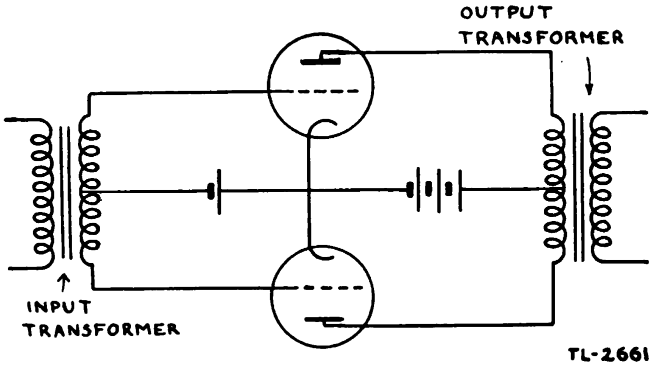


FIGURE 61.—Push-pull amplifier.

d. The output current of a class B amplifier is proportional to the input voltage; thus this type of amplifier is sometimes referred to as a linear amplifier. The class B amplifier is suitable for increasing the output of an amplitude modulated radiotelephone transmitter, the linearity feature preserving the desired wave shape.

e. The plate supply system for a class B amplifier must have good regulation (see par. 77), since the current drawn from the supply varies with the signal amplitude. Further, the driving stage must be of low internal impedance to minimize distortion to the input signal.

34. Class C operation.—A class C amplifier is one which is operated with a negative grid bias which is more than sufficient, under conditions of no signal, to reduce the plate current to zero. The grid voltage usually swings over a wide range, going positive to such an extent as to allow saturation plate current to flow. Distortion is present, even more so than in the class B amplifier, but the flywheel effect and filtering action of a tank circuit make the class C amplifier suitable for developing radio frequency power. The very high efficiency makes it attractive from an economic standpoint. The plate current of the class C amplifier is proportional to the plate voltage, so that this type of amplifier is ideal for modulation by variation of the applied plate potential. Figure 62 illustrates output current vs. input voltage for a class C amplifier.

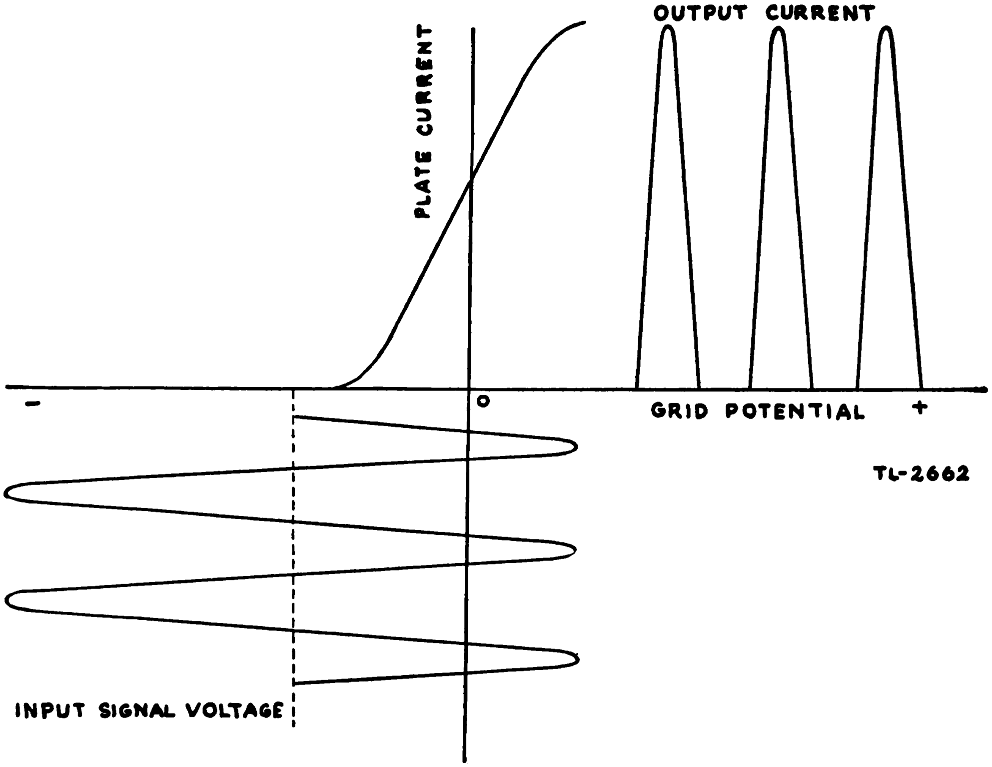
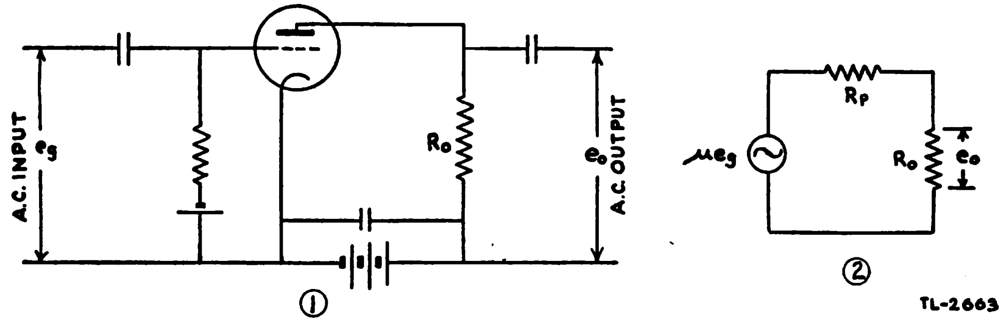


FIGURE 62.—Class C operation.

35. Voltage gain.—An estimate of the gain to be expected from an amplifier stage may be obtained from a study of an equivalent circuit, that is, a circuit which is basically similar to the actual circuit in electrical characteristics but which is sufficiently simple and explicit to be useful for analysis. The equivalent circuit usually takes into account only the a. c. effects, and ignores, for example, parts of the circuit relating to power supply. A single stage of a resistance coupled amplifier is shown in figure 63① with its equivalent circuit in figure 63②. Instead of showing the actual input voltage, its effect in the plate circuit is indicated by an a. c. generator labeled μe_g in series with the internal plate-to-cathode resistance of the tube, R_p, and with the load resistance, R_o. If the plate current is i_p, then



① Single stage of resistance coupled amplifier. ② Equivalent circuit.

FIGURE 63.

$$\mu e_g = i_p R_p + i_p R_o$$

from which

$$e_g = \frac{i_p R_p + i_p R_o}{\mu}$$

The output voltage is

$$e_o = i_p R_o$$

Thus the gain of the amplifier stage is

$$\frac{e_o}{e_g} = \frac{\mu R_o}{R_o + R_p}$$

This shows that for the gain of a resistance coupled amplifier to approach the amplification factor of the tube, R_o must be very large so that R_p is negligible in comparison. However, a practical upper limit to R_o is set by the fact that the potential required to maintain the plate current becomes increasingly large as R_o is increased. The value of R_o is usually compromised on as about the same order of magnitude of R_p.

36. Methods of coupling amplifier stages.—*a.* The resistance coupled amplifier is used extensively for audio frequency applications because of its low cost and relative freedom from distortion. It is occasionally used for certain applications in radio frequency work where an untuned circuit is satisfactory.

b. Figure 64 shows a typical two-stage resistance coupled amplifier. The capacitors *C* couple the output of each stage to the input of the following circuit. Each capacitor serves to block the d. c. plate voltage of one tube from the grid of the next, while at the same time permitting ready transfer of the a. c. signal voltages. The function of the resistor *R* is the same in each stage, in conjunction with the cathode series resistor R_1, to maintain the grid of the tube at the proper bias for class A operation. Normally no current flows through *R*. Thus the potential drop across *R* (potential drop$=I\times R$) is zero; that is, the potential of the grid relative to the cathode is entirely determined by the drop in potential occurring with the flow of plate current through R_1. The coupling capacitor *C* should be large enough to offer a low reactance to the frequencies to be amplified, while the grid leak *R* should have a very large value so that the shunting effect of the grid leak and coupling capacitor upon the coupling resistor R_o is small. This requirement is manifested by an

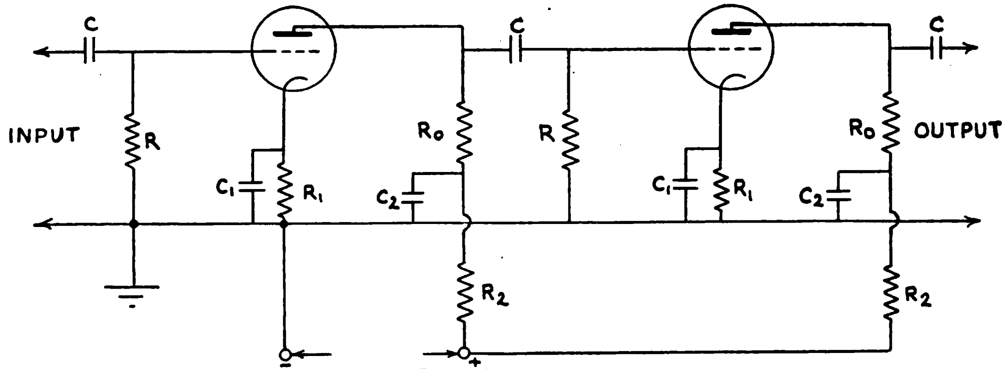


FIGURE 64.—Two-stage resistance coupled amplifier.

examination of figure 65, which is an equivalent circuit of one stage of resistance coupled amplification. It will be recalled from paragraph 35 that the requirement for good voltage gain of the resistance coupled amplifier is a load circuit resistance which is as high as practicable. The capacitors C_1 across the biasing resistors R_1 provide low impedance paths for the a. c. components of plate current, so that grid bias is not varied in accordance with variations in plate current. The reason for the resistors R_2 and capacitors C_2 in the plate circuit of each tube can be seen by a study of the simple circuit of figure 66. The plate current of the second tube, including a. c. and d. c. components, flows through the common plate source. If the plate source contains an internal resistance, the potential across *AB* fluctuates in accordance with the a. c. output of the second tube. Thus the potential applied to the first tube is modulated by the action of the second tube. This interaction, termed feedback, is avoided by the use of a decoupling filter—C_2 and R_2 (fig. 64)—in each plate lead which serves to bypass the a. c. components around the plate potential source.

c. The response of the resistance coupled audio frequency amplifier falls off at low frequencies (below roughly 50 cycles) because of the high reactance of the coupling capacitors. It falls off at high frequencies (above roughly 5,000 cycles) because of the low reactance of the tubes' interelectrode capacitances, which shunt the load resistors. For intermediate frequencies the response is substantially uniform.

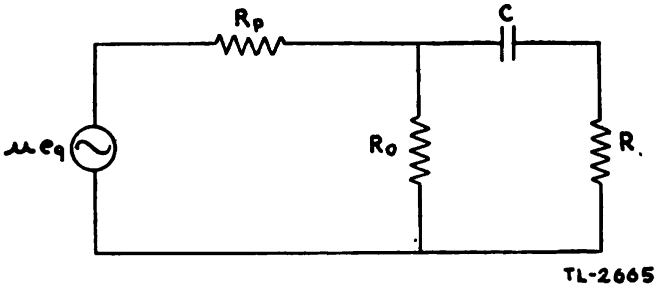


FIGURE 65.—Equivalent circuit of stage of resistance coupled amplifier.

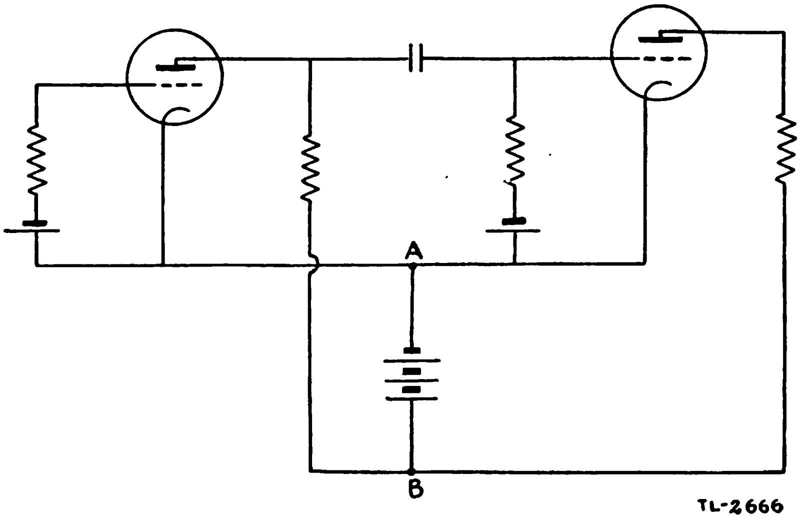


FIGURE 66.—Two-stage amplifier with common plate supply.

d. If large inductors (choke coils) are inserted in place of each plate resistor R_0 in figure 64, an impedance coupled amplifier results. Each inductor offers a high impedance to alternating current, giving a high gain, while at the same time offering low d. c. resistance, thus requiring considerably less supply potential than is needed for the comparable resistance coupled amplifier. The frequency response characteristic of the impedance coupled amplifier is similar to that of the resistance coupled amplifier.

e. If transformers are used as coupling units between adjacent amplifier stages, the coupling capacitors and grid resistors can be omitted. Figure 67 shows a two-stage transformer coupled amplifier. Transformer coupled amplifiers can be made to give more gain than either resistance or impedance coupled amplifiers with the use of step-up transformers. The response falls off at the lower frequencies due to the fact that the reactance of the transformer primary decreases with the frequency. At the upper frequencies a decline in response is associated with the effect of the grid cathode capacitance of the following circuit.

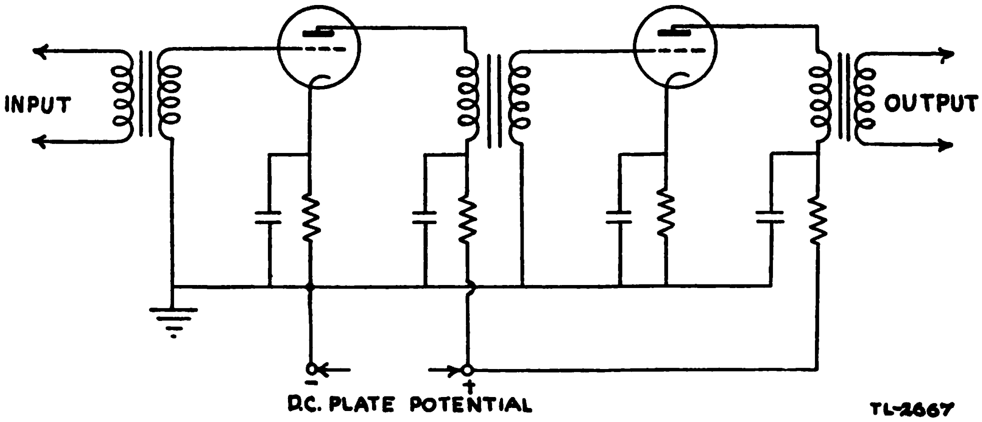


FIGURE 67.—Two-stage transformer coupled audio amplifier.

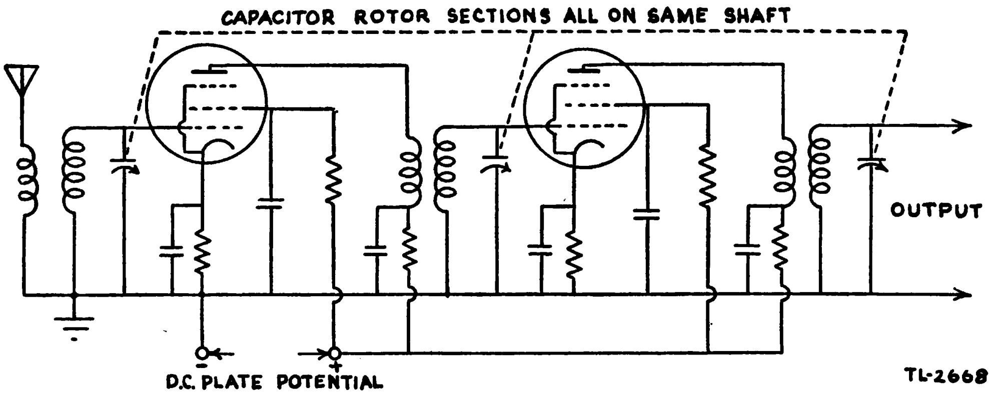


FIGURE 68.—Two-stage r. f. transformer coupled amplifier.

f. An r. f. transformer coupled amplifier employing tuned secondaries and pentode tubes is shown in figure 68. The selectivity (as well as the gain) of such a tuned r. f. amplifier increases with the number of stages in the manner illustrated in figure 69.

37. Bias.—*a.* The choice of a particular type of grid bias depends on the service to which the amplifier is subjected. Most receiver amplifiers use the cathode return resistor bias with shunt capacitor, as in the circuits of figures 64, 67, and 68. Omission of the shunt capacitor, or too small a value of the capacitor, incidentally produces degeneration (par. 42) as a result of the variations of grid bias which then accompany the a. c. pulsations of plate current.

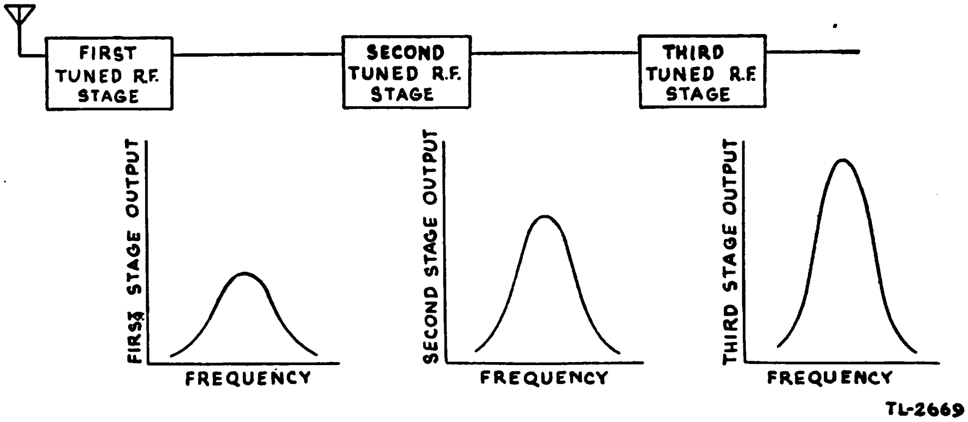
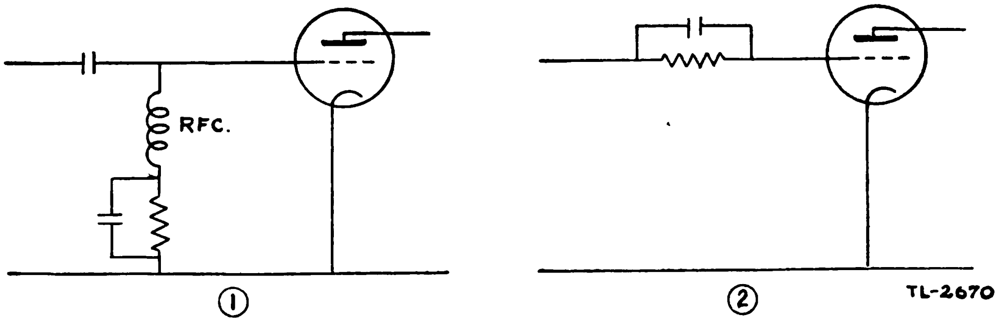


FIGURE 69.—Increase in selectivity with the number of tuned stages in an r. f. amplifier.

b. Grid leak bias (fig. 70) is suitable for use under conditions where grid current flows. This type of bias is economical of power and is thus frequently employed in transmitters. The bias results from the drop in potential across the grid leak (resistor) with the flow of current on positive signal swings. The capacitor across the leak offers a low impedance to a. c., so that the bias is essentially steady in character and is a function of only the magnitude of the grid current. A disadvantage of grid leak bias is that if for any reason the excitation is removed, the bias is removed also, and the



① Shunt arrangement. ② Series arrangement.

FIGURE 70.—Grid leak bias.

plate current may assume dangerous proportions, causing the liberation of gas from internal parts of the tube or even melting the plate.

c. Batteries, or a separate rectifier filter system distinct from the plate power supply, have the advantage of giving practically constant bias voltage under all conditions of excitation. This type of bias, further, offers protection to an amplifier tube in case of excitation failure. To combine the advantages of grid leak and battery bias, transmitter amplifiers often employ a combination of both types in series. Some amplifier tubes are conveniently designed, as regards bias supply, to operate with the grid at cathode potential (zero bias).

38. Distortion.—*a.* Distortion in an amplifier may be broadly classified under three different headings: Frequency distortion, nonlinear distortion, and delay (or phase) distortion. Frequency distortion arises because of the inability of an amplifier to amplify equally all frequencies. Nonlinear distortion is a consequence of operating over a curved (nonlinear) portion of a tube's characteristic, so that harmonic or multiple frequencies are introduced. Delay distortion results from the effects of transmission of different frequencies at different speeds, giving a relative phase shift over the frequency spectrum in the output. Except at the ultrahigh frequencies or in transmission line work, the effects of delay distortion are usually insignificant. Frequency distortion in r.f. transmitter amplifiers is ordinarily of little concern, since these amplifiers operate over only a relatively narrow range of frequencies at any one time.

b. In r. f. receiver amplifiers, various compensating devices are sometimes employed to provide uniform response to a band of frequencies. Figure 71 illustrates one such compensating arrangement. A high inductance primary winding *P*, loosely coupled to the secondary *S*, resonates (due to self-capacitance) at a lower frequency than the lowest for which the amplifier is to operate. This gives high gain at the low end of the band because of the high plate load impedance at the lower frequencies. The small capacitance *C*, due to a loop of wire hooked around the top of the secondary, provides increased coupling at the higher frequencies to improve the response at the upper end of the band.

c. Distortion which arises from operating a vacuum tube over a nonlinear portion of its characteristic consists principally of multiple frequencies (harmonics) and of sum and difference frequencies corresponding to each frequency present in the original signal. Suppose, for instance, that the input signal to a nonlinear radio frequency amplifier is composed of three frequencies: 500,000, 501,000 and 501,025 cycles. The output then contains in addition to the three original frequencies mainly the following distortion frequencies:

(1) Harmonics: 1,000,000, 1,500,000
1,002,000, 1,503,000
1,002,050, 1,006,075
(2) Sum frequencies: 1,001,000, 1,001,025, 1,002,025
(3) Difference frequencies: 1,000,25, 1,025.

The filtering action of a parallel resonant circuit in an amplifier plate circuit which is tuned to about 500,000 cycles minimizes the effects of all these distortion components. The extent of this suppression of the distortion frequency components may be controlled by proper design of the tuned circuit. At frequencies well off resonance the parallel circuit offers essentially the impedance of the lowest impedance branch. In a circuit tuned to 500,000 cycles the impedance offered to currents of frequency 1,000,000 cycles is practically that of the capacitor alone, and the impedance offered to currents of frequency 1,000 cycles is practically that of the inductor alone. Thus a low *L*-to-*C* ratio minimizes the voltages developed across the parallel circuit at the distortion frequencies. Two tuned circuits between which it is desired to transfer energy sometimes employ link coupling as shown in figure 72. In this manner incidental coupling between the two circuits due to the distributed capacitance of the turns is avoided, and the transfer of harmonics from one circuit to the other is avoided.

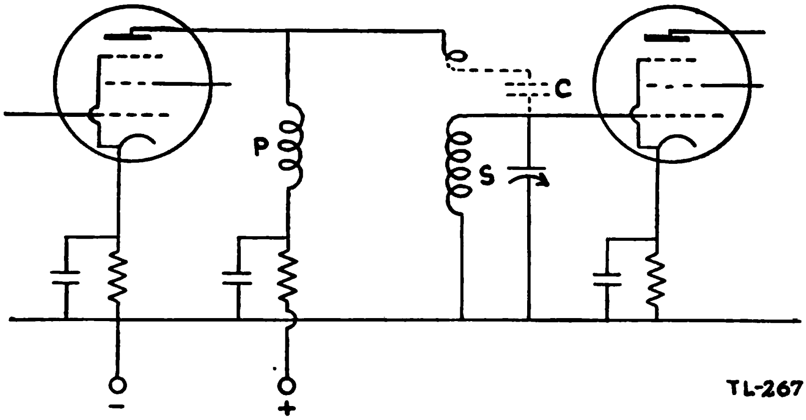


FIGURE 71.—Special circuit arrangement in r. f. amplifier to provide uniform response over a band of frequencies.

d. In an audio frequency amplifier the distortion frequencies corresponding to *c*(1), (2), and (3) above generally overlap components of the desired signal frequencies, so that filtering is not feasible. In the audio frequency case the problem demands prevention rather than cure. Class A operation is one solution. Push-pull arrangements are of further assistance.

e. Of the harmonic frequencies, the second (first overtone) is usually the predominant one. The rest are ordinarily weak. It is the objectionable second harmonic (as well as all other even order harmonics) which is absent in the output of a push-pull amplifier. By way of analysis to see that such is the case, consider the curves of figure 73. Here ① represents a fundamental signal frequency (first harmonic); ② and ③ are multiple frequency curves, second and third harmonics of the signal, respectively. The solid curve of ④ is obtained by adding the fundamental ① and the second harmonic ②. The solid curve of ⑤ is obtained by adding the fundamental ① and the third harmonic ③. Fundamental, second harmonic, and third harmonic are compounded to yield the solid curve of ⑥. The resultant in ⑤ is such that if the negative half cycle of

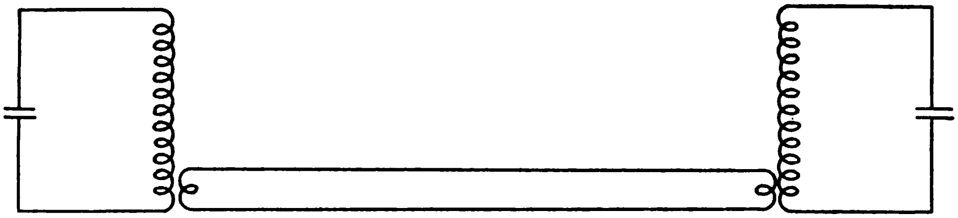

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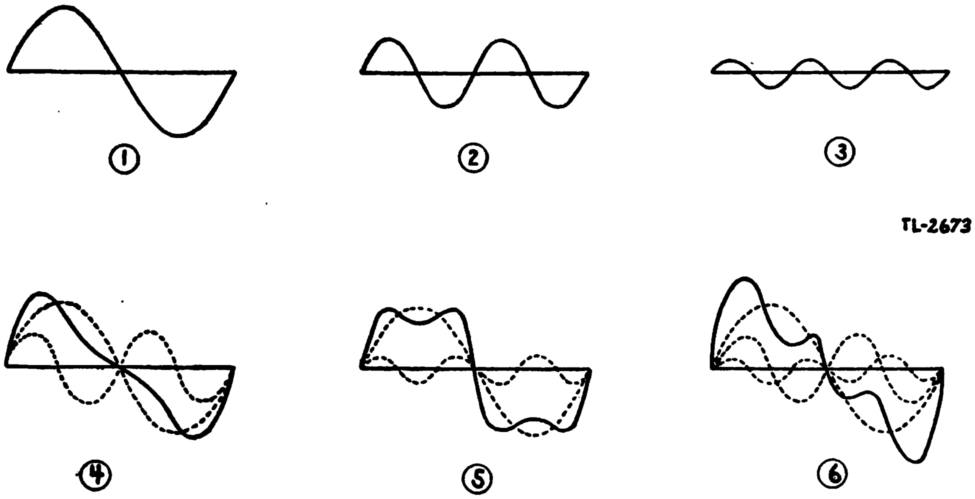
FIGURE 72.—Link coupled tuned circuits.



① Fundamental.
② Second harmonic.
③ Third harmonic.
④ Fundamental plus second harmonic.
⑤ Fundamental plus third harmonic.
⑥ Fundamental plus second and third harmonics.

FIGURE 73.—Harmonic distortion.

the curve is shifted along the abscissa (horizontal axis) so as to be directly below the positive half cycle, the negative half cycle then presents a mirror image of the positive half cycle about the abscissa. It can be shown that any combination of odd-order harmonics possesses this same symmetry; further that any resultant wave formed by a combination of harmonics and which possesses this symmetry cannot contain any even-order harmonic elements. In push-pull action two tubes interchange roles during alternate half cycles such that if the dashed curve of figure 74 represents the output of one tube, the dotted curve of the same figure represents the output of the companion tube. Dissymmetry in the output wave form of each individual tube indicates definite even-order harmonic content; whereas symmetry of the combined wave form shows complete absence of any even-order harmonics.

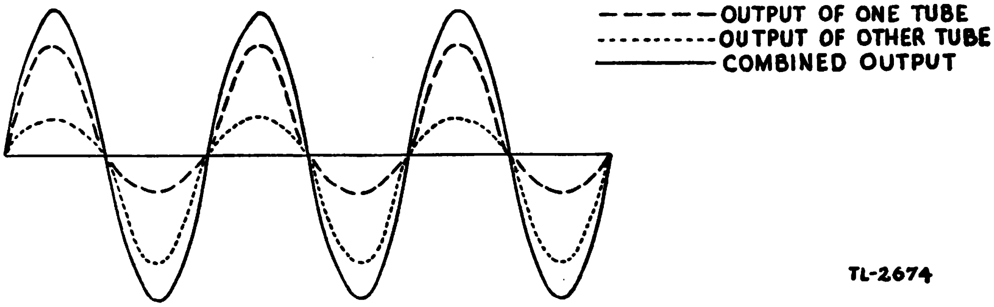


FIGURE 74.—Wave forms in push-pull amplifier.

f. Push-pull operation serves to lessen distortion in other ways. (1) The direct currents present in the two halves of the output transformer primary balance each other in their magnetic effects, so that the core cannot become d. c. saturated. (Saturation is a state of magnetization of the core which obtains for reasonably large currents and such that further increase in current produces only a small increase in magnetic induction.)

(2) Alternating current components of plate supply potential which are due to incomplete filtering produce no effect in the output transformer secondary, since the potentials thus developed across the primary balance each other. Because of the difficulty of obtaining perfect balance, particularly in tubes, the full possibilities of push-pull amplifiers are seldom realized in practice. However, under conditions of moderately good balance, the push-pull amplifier offers a definite improvement in quality over a comparable single-ended amplifier.

g. For doubling the frequency at radio frequencies in a transmitter, with a single-ended amplifier operating into an appropriately tuned

LC circuit, harmonic distortion within the tube is deliberately encouraged.

39. Maximum power transfer.—One basic consideration in the design of amplifiers, or in any radio circuit design, is that of maximum power transfer from a generator into its load, for example, from a vacuum tube into its plate load impedance. A general rule to follow in this respect is that maximum power transfer is effected between a generator and its load when the resistance of the load equals the internal resistance of the generator. The condition of maximum power transfer is not necessarily that of maximum undistorted power transfer nor that of maximum efficiency. However, maximum power transfer, which in many cases is the only function of impedance matching, is frequently chosen as a working criterion.

40. Feedback.—Feedback, the introduction of energy from the plate circuit back into the grid circuit, in an amplifier may occur unintentionally, and so uncontrollably, as with the use of impedances common to two or more stages. Feedback of this nature may or may not adversely affect the amplifier characteristics, but is usually avoided as a precautionary measure. Controlled feedback, on the other hand, may materially improve an amplifier's operation. The feedback is from the output of one stage to the input of the same or of a preceding stage, and may be in the same phase as that of the signal which it supplements (regeneration) or in opposite phase (degeneration). In regeneration a fraction, possibly one percent, of the output is reintroduced into the input, with an over-all increase in the amplification of the stage. In degeneration a fraction of the output is reintroduced in reverse phase. A high gain amplifier can suffer a certain amount of loss of gain due to degeneration and still present a high voltage amplification. The advantage of regeneration is an increase of amplification. The advantage of degeneration is an improvement in quality. Design problems in either case—to obtain exact in-phase or exact out-of-phase feedback relations—are sufficiently involved to warrant simple straight amplification for most amplifiers. The elimination of unwanted feedback is accomplished by introducing compensating voltages in opposite phase (neutralizing) or by preventing the inception of feedback by careful shielding and by the use of such devices as screen grid tubes (with low interelectrode capacitance) and decoupling filters. The magnitude of the feedback can be controlled by regulating the amount of coupling between the output and input circuits. The degenerative feedback voltage is always less than the signal voltage and can never equal the signal voltage. Any attempt to increase the magnitude of the feedback in the hopes of approaching the magnitude of the signal results in a decrease of the difference voltage, which is that applied to the input of the amplifier. Equal signal and feedback would correspond to zero impressed voltage and consequently to zero output. On the other hand, regenerative feedback voltage can, and usually does, exceed the signal voltage.

41. Regeneration.—*a.* To appreciate the manner in which the magnitude of the feedback is controlled by the coupling, consider a practical example of regeneration. Take the following values for the constants of the circuit of figure 75:

Frequency of the signal	1000 kilocycles
Q of the tuned circuit	200 at 1000 kilocycles
Transconductance of the tube	0.0006 mhos
M (mutual inductance)	$\frac{8}{2\pi}$ microhenrys

The particular figure of $\frac{8}{2\pi}$, approximately 1.27, is chosen for the value of M since it simplifies the computations.

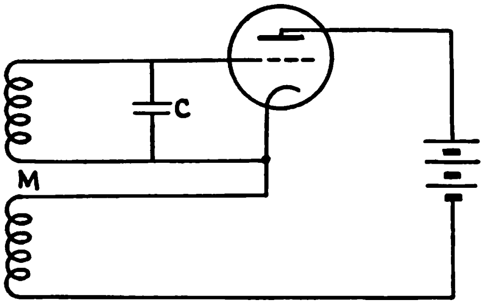


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FIGURE 75.—Feedback amplifier.

b. Suppose a signal of 1 microvolt is induced in L from the preceding circuit (not shown). Then Q times 1, or 200 microvolts, is the corresponding input voltage to the tube. This voltage causes a change of current in the plate circuit equal to the product of the voltage on the grid and the transconductance of the tube: $200 \times 0.0006 = 0.12$ microampere. This plate current, in turn, induces a voltage in L equal to the product of the plate current and the mutual reactance ($2\pi fM$) of the coupled circuits: $0.12 \times 2\pi \times 1000 \times 8/2\pi = 0.96$ microvolt. If the relationships between the windings are such that this voltage adds to that which was induced in L by the original signal, then the net effective impressed voltage in the LC circuit is $1 + 0.96 = 1.96$ microvolts. Computations for the continued process are illustrated in part in table II. The increases in voltage and currents become less with each transfer of energy from the plate to the grid circuit, until, under these particular circumstances, the voltage input to the tuned circuit ultimately becomes and remains 25 microvolts. The complete process occurs almost instantaneously.

TABLE II

Net voltage induced in the tuned circuit (microvolts)	Voltage across capacitor *C* (microvolts)	Radio frequency plate current (microamperes)	Voltage induced in the tuned circuit by the radio frequency plate current (microvolts)
1. 00	200	0. 120	0. 96
1. 96	392	0. 235	1. 88
2. 88	576	0. 346	2. 77
3. 77	753	0. 452	3. 62
4. 62	923	0. 554	4. 43
5. 43			

c. The 25-fold magnification produced by the regeneration might equally well have been produced by a reduction of the tuned circuit resistance to $\frac{1}{25}$ of its original value. Thus the regeneration has the effect of a "negative" resistance in the tuned circuit, the value of which is $\frac{24}{25}$ the actual tuned circuit resistance, and the selectivity and sensitivity of the tuned circuit are increased accordingly.

d. It is to be observed that if, at any time, the original impressed signal is removed, the output is accordingly reduced to zero. This may be seen from table III, which tabulates the results of removing the signal voltage. Only the net input and feedback voltages are herein recorded, since the intermediate steps are not essential to the discussion.

TABLE III

Net input (microvolts)	Feedback (microvolts)
25. 0	24. 0
23. 1	22. 2
21. 3	20. 4
19. 6	18. 8
18. 1	17. 4
16. 7	

e. Less than a 25-time amplification could have been had by reducing the mutual inductance, that is, by reducing the coupling between the output and the input circuits. To study the effects in the case where the coupling is increased to such an extent that the voltage fed back each time exceeds the corresponding net input voltage, consider a situation where M has a value of $\frac{10}{2\pi}$, or approximately 1.59, microhenrys. Corresponding input and feedback voltages for this case are given in part in table IV.

TABLE IV

Net input (microvolts)	Feedback (microvolts)
1. 00	1. 20
2. 20	2. 64
3. 64	4. 34
5. 34	6. 40
7. 40	8. 88
9. 88	

f. It will be noted that the difference between succeeding input voltages increases each time, so that as long as power is available to supply the circuit requirements, the amplification increases indefinitely. Moreover, the original signal no longer exercises control, and the output continues even if the original signal is suppressed. An amplifier in this condition may be made to serve a useful purpose, as a generator, however, rather than as an ordinary amplifier. The functioning of an amplifier in this capacity is described in detail in section VI. For a treatment of the general case of regeneration, see appendix I.

g. The results of this analysis, although illustrated for a radio frequency amplifier, apply with only minor modifications to audio frequency amplifiers.

42. Degeneration.—*a.* The increased quality secured with degeneration is twofold: the amplification is more nearly independent of variations of circuit constants (independent, for example, of variation of impedance of a loud speaker with frequency) and distortion which is not present in the input signal, but which arises from within the amplifier, is reduced. Degeneration finds particular application in audio frequency circuits, and in audio-frequency-modulated r. f. circuits, where fidelity of reproduction is important.

b. The first feature of degeneration noted above is apparent from a simple analysis. Take the input signal to a degenerative amplifier as e and the output as E. If B is the fraction of the output fed back, the degenerative feedback voltage is BE. Then the net input voltage is $e-BE$, and the output is

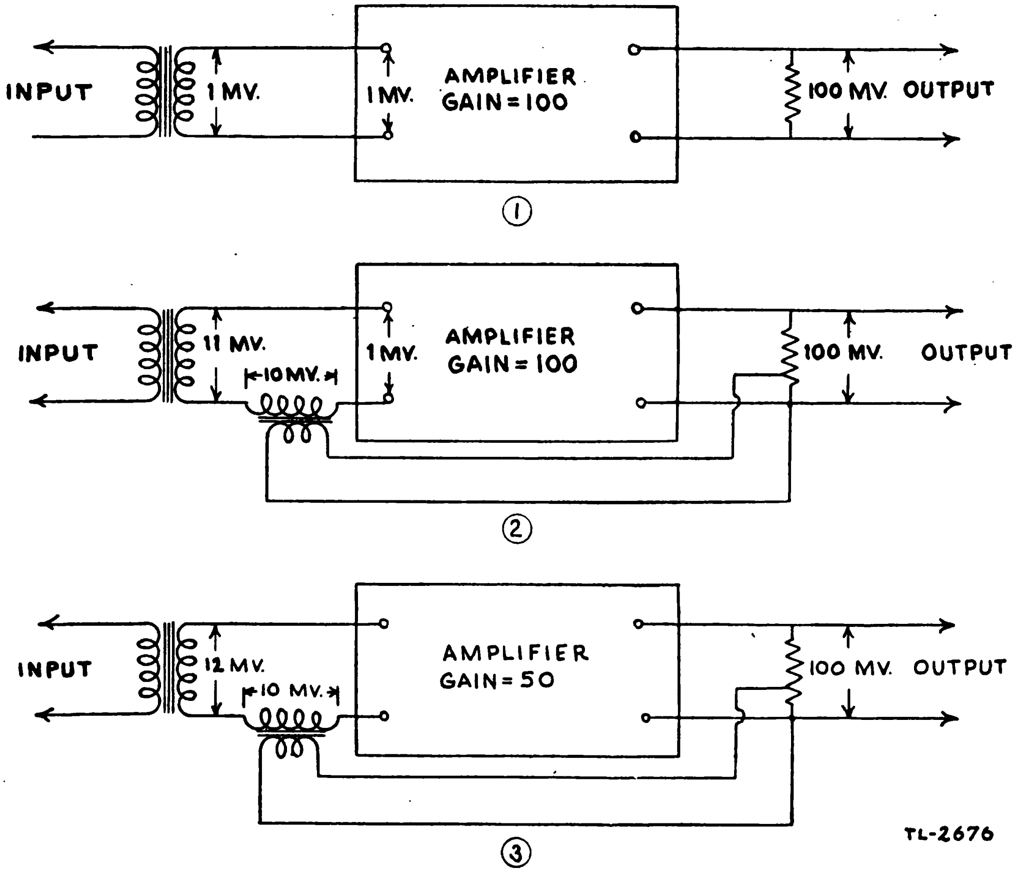
$$E=A\times(e-BE)$$

where A is the normal gain of the amplifier; so that the over-all gain is

$$A_o=\frac{E}{e}=\frac{A}{1+AB}$$

This shows that the gain of the amplifier with degeneration is less than the normal gain without any feedback. Further, for the case of B large enough such that AB is much greater than 1 (perhaps 25 in an amplifier with a normal gain of 100) the over-all gain becomes approximately

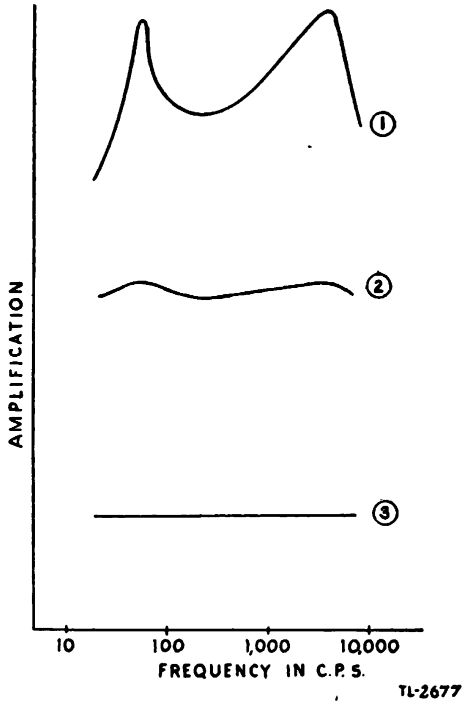
$$A_o=\frac{A}{AB}=\frac{1}{B}$$



① No feedback.
② and ③ Ten percent degenerative feedback.

FIGURE 76.—Effect of degeneration.

that is, the over-all gain is substantially independent of the normal gain of the amplifier. For a specific example to illustrate this effect, consider an amplifier which without any feedback has a normal gain of 100. An input of 1 millivolt gives rise to an output of 100 millivolts (fig. 76①). Suppose degenerative coupling is now provided such that 10 percent of the output is returned to the input. If the output under these circumstances is 100 millivolts, 10 millivolts will be introduced into the input of the amplifier in reversed phase from the signal. In order for the output to remain 100 millivolts, it is necessary that a net input of 1 millivolt in phase with the signal be maintained. A signal of 11 millivolts is necessary to maintain this 1 millivolt net input: 11 millivolt signal − 10 millivolt feedback = 1 millivolt input (fig. 76②). It should be noted how under conditions of degeneration the over-all amplification is considerably reduced. Without degeneration the over-all gain is 100 to 1. With degeneration the over-all gain is now 100 to 11. Suppose now that under some particular circumstances, possibly for some particular frequency range, the normal gain of the amplifier is reduced to 50. It would then require a 2 millivolt net input to give an output of 100 millivolts. For 10 percent degeneration this means a 12 millivolt signal: 12 millivolt signal − 10 millivolt feedback = 2 millivolt input (fig. 76③). The over-all amplifier gain is now 100 to 12. Thus only a very small percentage reduction in over-all amplification, from $^{100}\!/_{11}$ to $^{100}\!/_{12}$ results from a 50 percent reduction in the normal



① Straight amplification.
② Same amplifier with degeneration.
③ Same amplifier with increased degeneration.

FIGURE 77.—Response characteristic of amplifier with loudspeaker load.

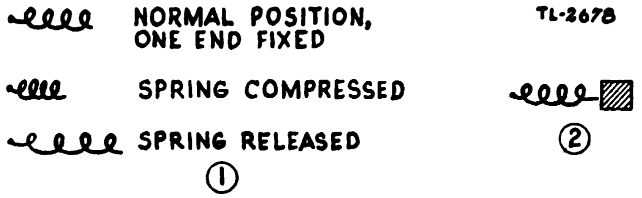
amplifier gain. Actual experimental curves showing response characteristics corresponding to straight operation and to degeneration for the same receiver amplifier with a loudspeaker load are shown in figure 77. The independence of amplifier gain with frequency means an improvement in the quality of the amplifier reproduction. Whereas the amplifier normally might discriminate against certain frequencies and accentuate others, with degeneration all the desired frequencies are amplified nearly uniformly.

c. The second feature of degeneration—reduction of noise produced within the amplifier—depends on the fact that the signal, which is introduced in the grid circuit of the amplifier, receives greater relative magnification than those particular noises which are introduced in the plate circuit. The grid signal is amplified, whereas the plate noise is not; while that portion of the output which is returned out-of-phase to the input is amplified equally for both noise and signal components. The reamplification of this out-of-phase signal component reduces the amplifier gain; the reamplification of the out-of-phase noise component effectively reduces the noise current present. Hence, the cancellation effect of the degeneration combined with the differential effect of straight amplification results in a relative reduction of the noise produced within the tube, at the price of a general reduction in gain. If the feedback can be made into a preceding amplifier stage, where it is presumed that no distortion of the same type occurs, then the degeneration could be controlled so that the output of the first stage consists of the desired signal, and a distortion component sufficient to counterbalance the noise present in the output of the last stage, while at the same time the over-all gain of the two stages is reduced only slightly.

SECTION VI

VACUUM TUBE OSCILLATORS

43. Mechanical oscillations.—Two fundamental requirements of any type of natural oscillation are an inertial element and a restoring force. Consider a coil spring lying horizontally on a table with one end of the spring clamped, as in figure 78①. If a force is applied to the free end so as to compress the spring and then the compressing force is removed, the energy stored in the spring on compression is released to extend the spring back to its normal length. More than likely the spring may actually distend a small amount beyond its normal length and then compress again slightly; that is, the spring may alternately expand and contract so that the free end oscillates a few times about its equilibrium position before coming to rest. What causes the spring to continue beyond its normal length is described as the inertia of the spring and is attributed to its inherent mass. If a large concentrated mass is attached to the end of the spring (fig. 78②), the tendency for the spring to continue past its equilibrium position is more pronounced. Also the period of oscillation, the time for one complete to-and-fro motion, is lengthened. The period is longer for a weaker spring, that is, for one with a weaker restoring force; and it is shorter for a stronger spring.



① Oscillations of a coil spring.
② Spring with mass attached to free end.

FIGURE 78.

44. Electrical oscillations.—Electrical counterparts of the mass and spring are an inductor and a capacitor, furnishing inertia and restoring force, respectively, for electronic transfer. If by some electrical force a separation of charge within the ideal (no resistance) closed circuit of figure 79 is made to occur such that some electrons are taken from the lower plate of the capacitor and transferred to the upper plate, a certain amount of energy is stored in the capacitor in the process. On removal of the electric force the energy stored in the capacitor is free to transfer the electrons back to the lower plate. As the electrons in question are released, their flow through the inductor sets up a magnetic field about it, and this magnetic field, once es-

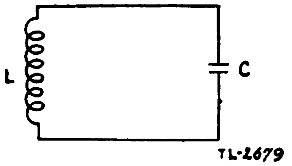


FIGURE 79.—Oscillatory circuit.

tablished, tends to prevent any decrease in the flow of electrons which might be expected after the original charge distribution is reestablished. As a matter of fact, the energy in the electrostatic field of the capacitor is transferred to the magnetic field of the inductor with the flow of charge; and at the instant of resumption of the original charge distribution the total energy of the circuit is associated with the magnetic field. The energy in the magnetic field is now available to transfer even more electrons from the upper plate to the lower, until the energy of the magnetic field is entirely diverted back to the electrostatic field. These energy relations are similar to those in the mechanical example. In the latter situation energy originally stored in the spring is released on removal of the compressing force with an ensuing transfer of energy from potential form in the spring to kinetic form in the mass until, at the instant the spring is expanded to its normal length, the energy—except for heat losses—is completely associated with the motion of the mass. This energy of motion carries the mass past its equilibrium position; and when the mass finally comes to momentary rest at the end of its swing, the energy of its motion has entirely disappeared, and energy is now present as potential energy in the extended spring, ready to send the poised mass in the opposite direction toward its equilibrium position again. At this point in the electrical case the capacitor is recharged exactly to its original magnitude but in opposite polarity, and the discharge proceeds in the opposite direction. The rate of charge and discharge which follows can be controlled by varying the capacitance or inductance, or both, just as the spring vibration frequency is controlled by varying the spring tension and/or the mass. The alternate charge and discharge of the capacitor does not continue indefinitely in an actual circuit, but damps out after a brief interval in the same manner as does the spring-mass combination, and for the same reason, that is, resistance. If the friction between the spring-mass and the table is reduced, perhaps by using a glass table top, the duration of the oscillatory motion is prolonged. If all the friction in the system could conceivably be removed, the oscillations should continue indefinitely. In the electrical circuit resistance develops from the collision of the electrons of the current stream with the constituent entities of the conductor traversed. The energy shared in this manner is ultimately all converted into heat, manifesting itself by a rise in temperature of the conductor and of the surroundings, and being lost for all practical purposes. If the inherent resistance of the oscillatory circuit could be reduced to a small magnitude, just the small amount of energy necessary to replenish that lost in the form of heat on each cycle could probably be delivered periodically in escapement wheel fashion from an external source to sustain the oscillations in the *LC* circuit indefinitely. This is precisely what occurs in a vacuum tube oscillator. The tube and the associated circuit equipment serve as an escapement mechanism to trigger off energy from the power supply at appropriate intervals.

45. Simple oscillator circuit.—A simple scheme to achieve this end is illustrated in figure 80. The voltage across the capacitor *C* of the oscillatory circuit is applied to the grid of a vacuum tube so that variations in the vacuum tube output current correspond exactly with variations of the capacitor potential. This circuit is exactly the same as that employed previously to obtain regenerative amplification of an impressed signal whose frequency was that of the natural frequency of the tuned circuit $\left(f=\frac{1}{2\pi\sqrt{LC}}\right)$ In the regenerative case the feedback was definitely restricted so that the presence of the input signal was essential; that is, the signal served to control the frequency, and amplification followed accordingly. Here the feedback voltage is sufficiently large that the signal voltage is unnecessary (once the action is started); and sustained currents are obtained at a frequency which is controlled only by the natural frequency of the tuned *LC* circuit.

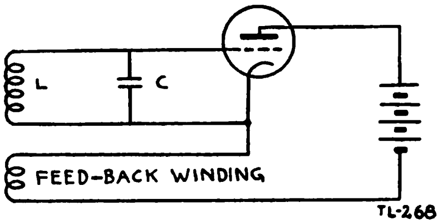


FIGURE 80.—Simple vacuum tube oscillator circuit.

46. Practical oscillator circuit.—*a.* Intermittent feedback impulses as supplied by a class C amplifier are quite adequate for sustaining the oscillations and are more economical of power than is the continuous feedback obtained with a class A amplifier, since with the former there is a smaller proportion of power loss within the tube itself. An arrangement to provide intermittent feedback impulses is shown in figure 81. Here the grid is biased by the voltage developed across the resistor *R* in accordance with the grid current, which in turn is determined by the magnitude (not frequency) of the potential of the capacitor. (See par. 37.) After oscillations are once established, a fixed battery bias to maintain the class C operation would serve. However, to permit self-starting of the oscillations, the bias must be such that some plate current flows initially, since it is the first pulse of plate current that contributes the necessary pulse of potential across the *LC* circuit to set off the oscillatory action. Grid leak bias regulates itself to the requirements ideally. Figure 82 depicts the manner in which grid potential e_g, grid current i_g, and plate current i_p vary as oscillations are initially built up. The persistence of oscillations in the *LC* resonant circuit with only intermittent pulses being released by the tube is commonly referred to as the circuit *flywheel effect*.

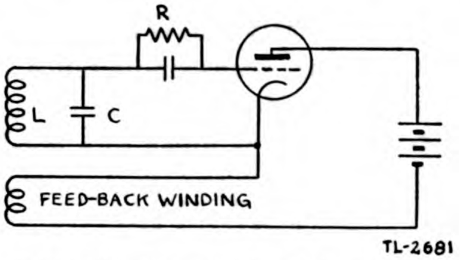


FIGURE 81.—Simple oscillator with grid leak bias.

b. During the build-up of the oscillations, as the amplitudes of the oscillatory current and of the grid and plate currents increase, the accompanying losses increase (and in proportion to current squared). If the direct current source is able to furnish only a limited amount of power, the magnitude of the oscillations is determined by the power available. Otherwise the amplitude of the

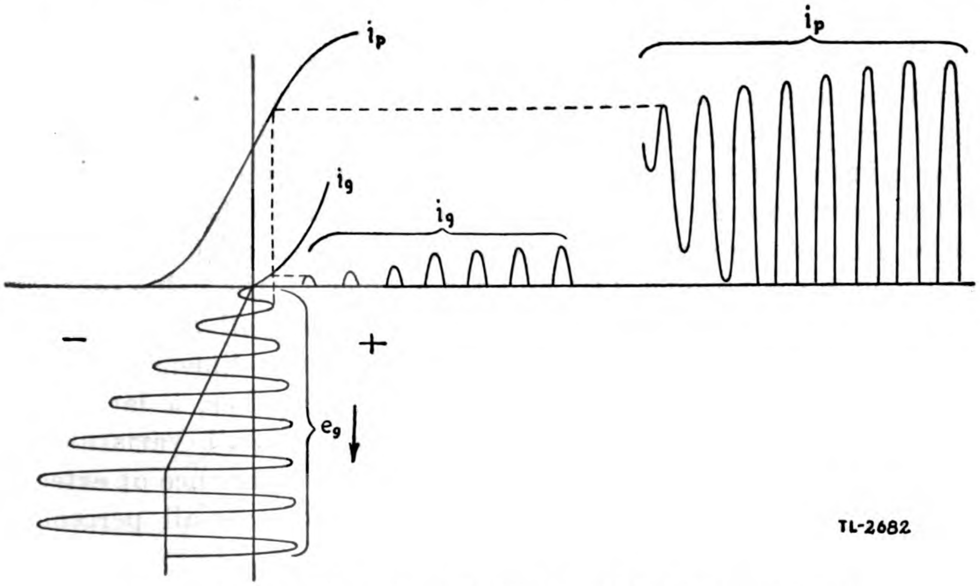


FIGURE 82.—Build-up of oscillations in grid leak bias oscillator.

oscillations increases until the operation extends to the knee of the tube's i_p–e_g characteristic, where the transconductance falls off and with it the output of the amplifier, too. This results in a decreased feedback and so a decreased grid swing, with a consequent increase in the transconductance which affects the peaks of the swing. In this way any tendency for the oscillations to assume a magnitude above or below a certain critical value is counteracted with an opposing effect by the instantaneous transconductance, which acts to keep the level of the oscillations uniform.

c. The frequency of oscillation is given to a good approximation by

$$f=\frac{1}{2\pi}\sqrt{\frac{1+R/R_p}{LC}}$$

where R_p is the internal plate to cathode resistance of the tube; and R is the resistance of the LC circuit, including that resistance which is effectively introduced into the tank circuit when a load is coupled into the tank circuit to draw power from it. Variations in R_p occur with any slight changes in the vacuum tube electrode potentials. R/R_p is usually very much less than 1, so these changes produce only small, probably one part in 10,000, shifts in frequency. Nevertheless, demands on frequency stability are sufficiently exacting to warrant such design as will minimize the effects of plate resistance variation. The equation above suggests the use of the smallest possible value of R and the largest possible value of R_p which are consistent with other factors for good operation. A low R is the result of a low inherent resistance in the tank circuit together with a small load. The load might be the input to a sufficiently biased intermediate amplifier, but it should not be a radiating system, for example. For a particular frequency (which fixes the product LC) and for a given Q, the value of R can be reduced and stability encouraged by using a small L (low L to C ratio); the smaller the inductance, the smaller the dimensions of the coil, and the lower the inherent resistance. Further, a large C in itself is an effective aid to stability because small variations in capacitance due to mechanical vibration or to the presence of external bodies (hand capacitance) produce only a low over-all percentage change in the capacitance of the resonant circuit.

47. Oscillator circuits in general use.—*a.* A number of variations of oscillator circuit design are shown in figure 83. All of them are fundamentally alike, differing principally in the disposition and in the manner of coupling of elements. The feedback in the tuned-plate tuned-grid circuits is through the plate-to-grid capacitance within the tube.

b. An oscillator circuit is usually required merely to control the frequency and not to deliver any appreciable amounts of power. Power is developed by amplification in the succeeding circuits, where load changes have a much smaller effect on frequency. The electron coupled oscillator combines the functions of oscillator and power amplifier with one tube. The cathode, control grid, and screen grid of the tube serve as a triode oscillator. The coupling between the oscillator and amplifier circuits is through the electron stream. Capacitive coupling is reduced to a minimum by operating the screen at ground potential as far as r. f. currents are concerned. This effectively isolates the output from the input circuit, so that the frequency of oscillation is relatively independent of load variations. Further, an increase of plate potential causes a frequency shift in one direction, whereas an increase in screen potential causes a frequency shift in the opposite direction.

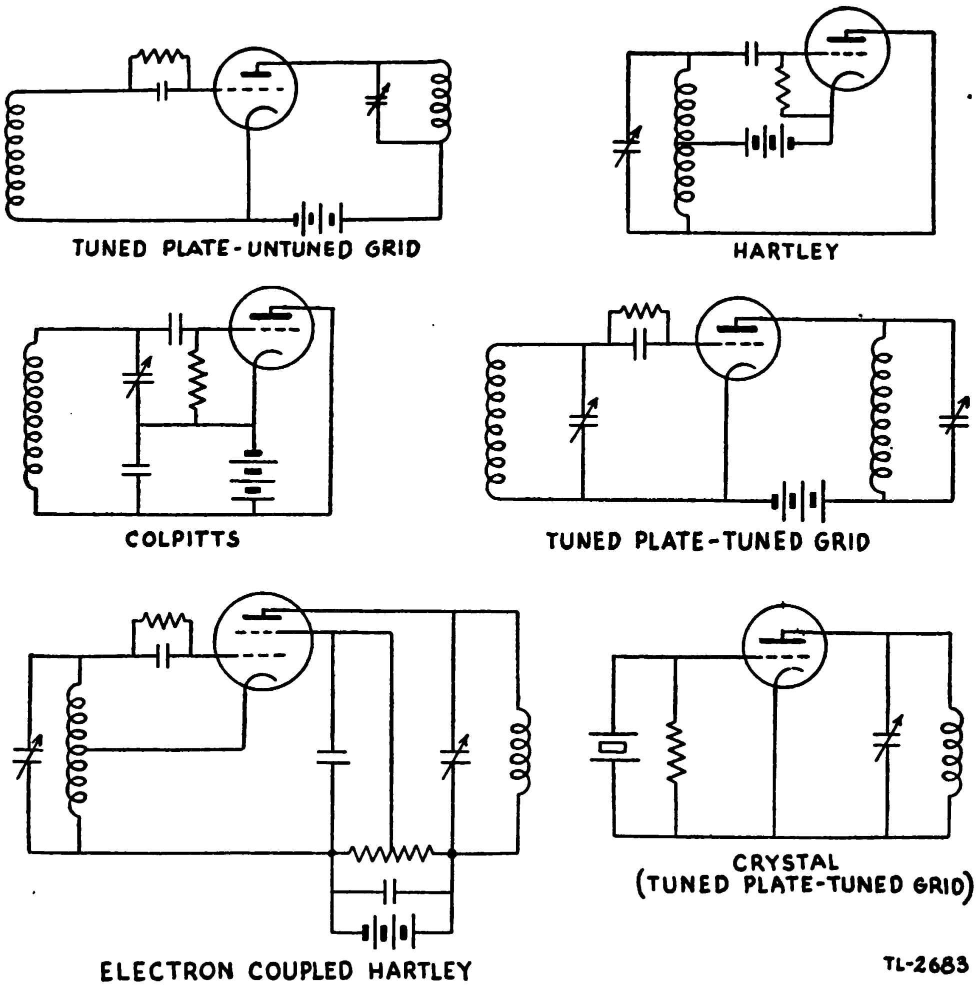


FIGURE 83.—Basic oscillator circuits.

By properly adjusting the screen tap on the voltage divider, the frequency may be made independent of any variations in the plate supply.

c. The crystal oscillator provides a remarkably steady frequency output. The oscillator proper is a crystal of quartz, which exhibits the property of developing an electrical potential across its faces when mechanically strained, and vice versa, expanding or contracting on the application of a potential. At the natural period of the mechanical vibrations of the crystal the two actions may be made mutually self-sustaining by feeding back a sufficient portion of the amplified potential to replenish the energy which is dissipated during each cycle as heat. The equivalent electrical circuit of the crystal, shown in figure 84, has a very high Q and a very high L to C ratio. C_1 in figure 84 represents the capacitance which exists between the mounting electrodes. L, C, and R represent the electrical equivalents associated with the vibrational characteristics of the crystal. At frequencies above that which corresponds to series resonance in LCR, LCR behaves as an inductance. This inductance and C_1 form a parallel tuned circuit, the antiresonant frequency of which is the frequency of the sustained oscillations. Since C is in general very much smaller than C_1, the series resonant frequency and the antiresonant frequency of the crystal lie very close to each other.

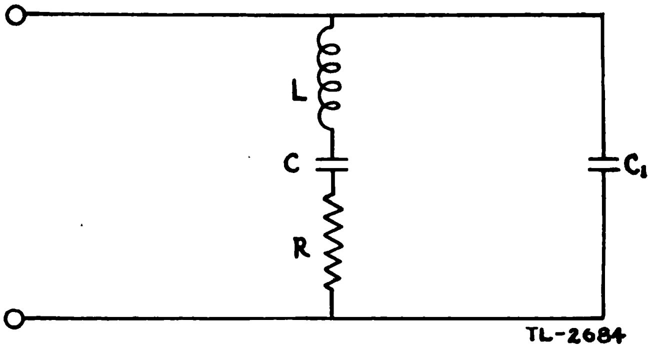


FIGURE 84.—Equivalent electrical circuit of oscillating crystal.

48. Oscillators for very high frequencies.—*a.* Resonant circuits for very high frequency oscillators sometimes take the form of short wires joining cathode and plate, with the necessary capacitance being furnished by that existing between electrodes within the tube itself. In other instances a pair of parallel wires (transmission line), short-circuited at the far end, is employed as a resonant circuit. A quarter-wave-length line (par. 85*c*) exhibits the properties of a high Q parallel resonant circuit.

b. At the ultrahigh frequencies, 50 megacycles and above, mechanical problems are encountered in the reduced sizes of the tube and circuit elements, while electrical difficulties arise in the form of frequency instability and decreased efficiency. Several forms of electron oscillator have been developed tc replace the conventional vacuum tube at the ultrahigh frequencies.

SECTION VII

CONTINUOUS WAVE TRANSMITTERS

49. Oscillator-amplifier transmitter.—*a.* A simple oscillator-amplifier combination for transmitting is shown in figure 85. The r. f. choke RFC_1 and the capacitor C_1 act as a filter to by pass radio frequency current around the oscillator plate supply. Because of the low r. f. impedance of C_1 there is no appreciable r. f. voltage drop across this capacitor, and the lower end of the oscillating tank circuit is practically at ground potential as regards r. f. voltage. Capacitor C_3 blocks the oscillator d. c. plate voltage from the grid of the amplifier, while at the same time offering a low impedance path for radio frequency current. The r. f. choke, RFC_3, in series with the amplifier bias battery, is necessary to maintain a high impressed r. f. voltage on the amplifier grid. Capacitor C_2 and r. f. choke coil RFC_2 serve to direct r. f. currents around the amplifier plate supply.

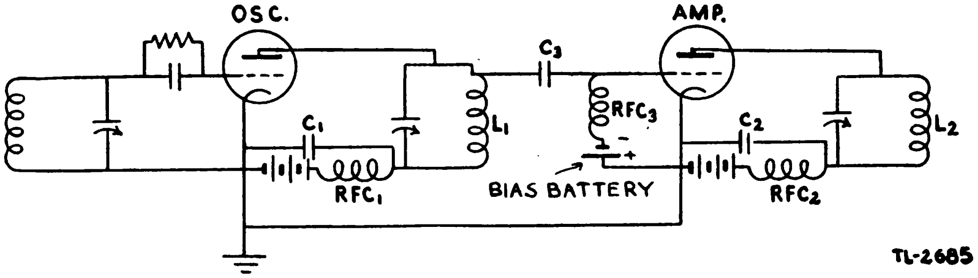
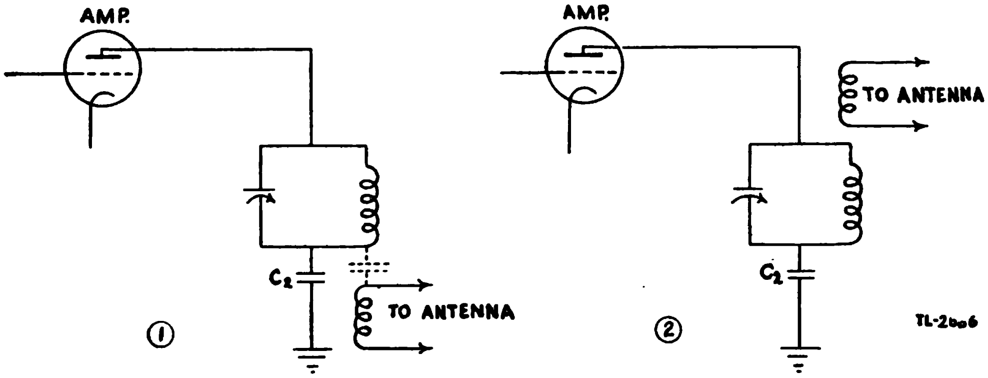


FIGURE 85.—Oscillator-amplifier transmitter.

b. If the amplifier is to be coupled into an antenna, the arrangement of figure 86① is preferable to that of figure 86②. In either case energy can be coupled through the inherent capacitance existing between the two coils. Such energy transfer must include some harmonic component because of the low impedance offered to high frequencies by this capacitance. However, in ① the electric field across the inherent capacitance (indicated by dotted lines) is negligible, since the lower end of the amplifier tank coil is approximately at ground potential by virtue of C_2. As a consequence the coupling in ① is almost entirely magnetic, and harmonic transfer is held to a minimum; whereas in ② the coupling has a greater capacitive component, hence a greater harmonic transfer.

50. Neutralization.—*a.* The radio frequency plate and grid circuits of the amplifier of figure 85 form a tuned plate-tuned grid oscillator; and unless some action is taken to prevent it, the amplifier will self-oscillate. One function of the amplifier is to isolate the oscillator from the ultimate load, the radiating system, in the interest of stability. An oscillating amplifier fails to serve this end. Only when the amplifier operates as a nonoscillating amplifier is the frequency relatively independent of any variations of its plate load impedance.



① Correct method. ③ Incorrect method.

FIGURE 86.—Coupling amplifier tank coil to antenna.

b. A favorite technique for suppressing oscillation within an amplifier consists of neutralization, that is, the introduction of a feedback voltage from the plate to the grid circuit which is equal in magnitude and opposite in phase to that which occurs as a result of the plate-to-grid capacitance within the tube. Figure 87 shows such a neutralizing arrangement adapted to the amplifier of figure 85. In figure 87, the amplifier tube interelectrode capacitance is indicated by dotted lines. Neutralization is accomplished by operating the oscillator normally and removing the plate potential to the amplifier stage. C_N is adjusted until a minimum reading is obtained on an r. f. milliammeter coupled to the tank coil, L_2, of the amplifier stage. Other r. f. indicators such as neon tubes held in the field of the tank coil will indicate neutralization at minimum glow.

Under these circumstances, C_N and the tube capacitance are such that potential variations coupled through them from the grid circuit into the plate tank circuit are equal and opposite. Then with the d. c. plate voltage applied to the amplifier, feedback from the plate circuit into the grid circuit through the tube capacitance is exactly counterbalanced by that through C_N; and the amplifier acts in a simple nonoscillatory manner, reproducing in its output circuit only those effects impressed on its input circuit from the oscillator stage ahead.

c. Cross neutralization of a push-pull amplifier is accomplished by joining the plate of the number 1 tube with the grid of the number 2 tube through a neutralizing capacitor, and the plate of the number 2 tube with the grid of the number 1 tube through another neutralizing capacitor (see fig. 88①). The r. f. voltage across each neutralizing capacitor counteracts the r. f. voltage across the interelectrode capacitance of the tube to whose grid it is connected. Another method of amplifier neutralization known as the Rice system is shown in figure 88②. This arrangement is similar to that of figure 87 except that the Rice system utilizes a split input circuit in place of a split output circuit.

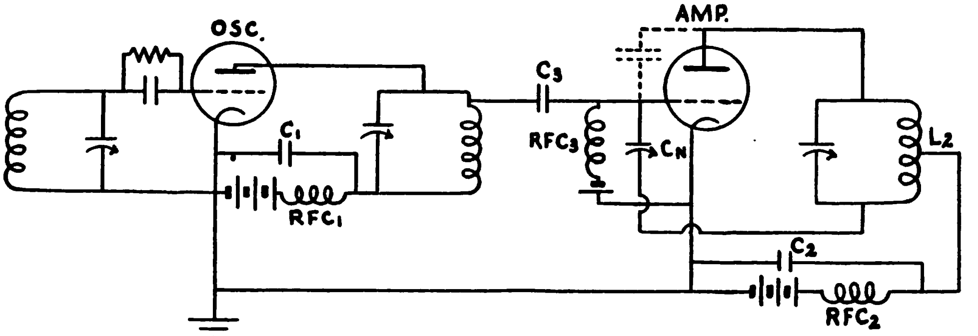
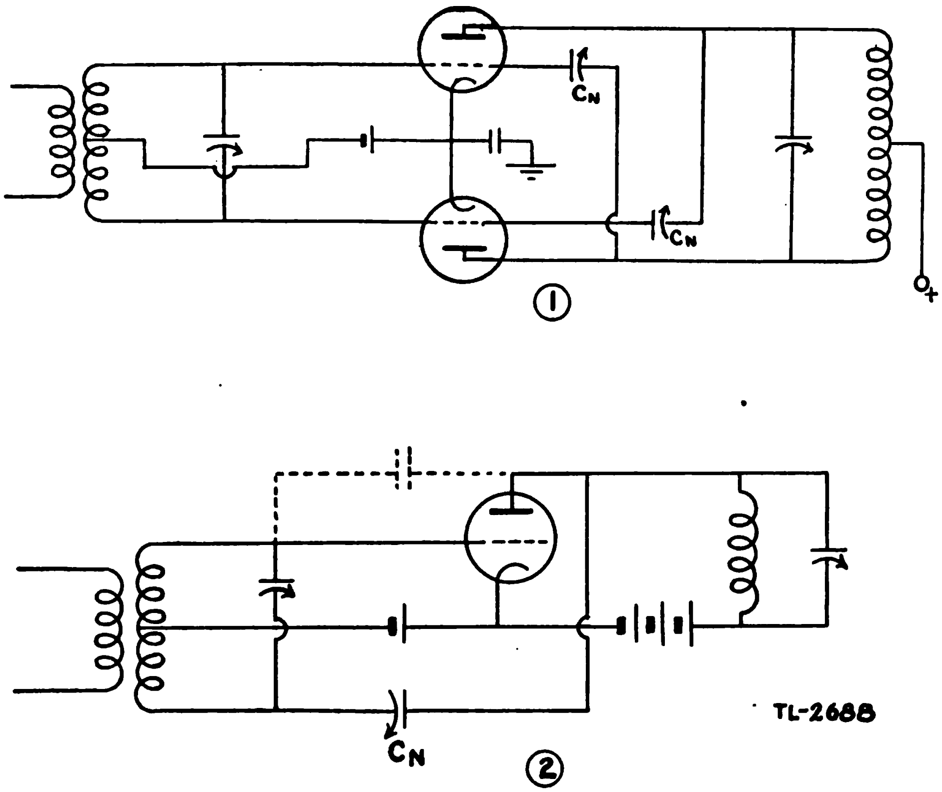


FIGURE 87.—Transmitter with neutralized amplifier.

d. Tetrodes and pentodes eliminate the problem of neutralization of the interelectrode capacitance of the tube. However, other considerations frequently preclude their use as power amplifiers in transmitters. They are more expensive than triodes, and they require additional screen power to operate. The higher power sensitivity of tetrodes and pentodes means that less driving power is required, but at the same time increased difficulties are encountered with these tubes due to stray coupling effects between output and input circuits. These undesired input effects increase in importance as the normal input signal magnitudes are decreased.

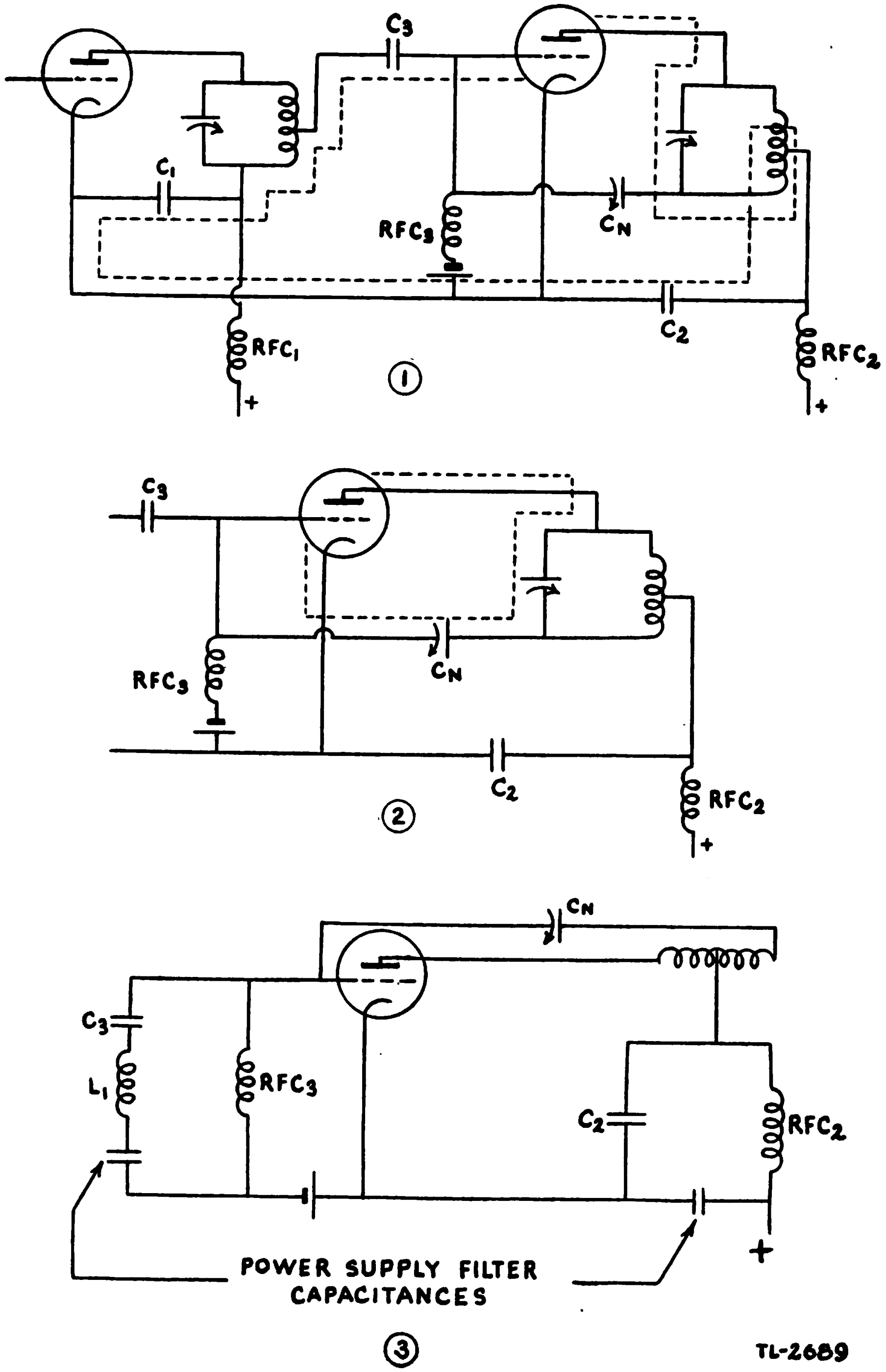
51. Parasitic oscillations.—Circuit conditions in an oscillator or amplifier may be such that secondary oscillations occur at frequencies other than that desired. Such oscillations are appropriately termed parasitic oscillations. The energy required to maintain parasitic oscillations is wasted so far as useful output is concerned. A circuit afflicted with parasitics has low efficiency and frequently operates erratically. Figure 89 shows some of the incidental circuits which may give rise to parasitics in the transmitter of figure 87. The dotted lines of figure 89① outline a high frequency circuit, and those of ② outline an ultrahigh frequency circuit. That part of the transmitter which constitutes a possible low frequency parasitic circuit is sketched in ③. Parasitic oscillations may be suppressed by placing resistors or r. f. chokes at appropriate positions in the circuits, or by slightly modifying the existing values of circuit elements; and by using care in the physical arrangement and wiring of parts.



① Push-pull stage neutralization.
② Rice system of neutralization.

FIGURE 88.—Neutralization circuits.

52. Keying systems.—*a.* A good keying system should prevent completely the radiation of energy from the antenna when the key is

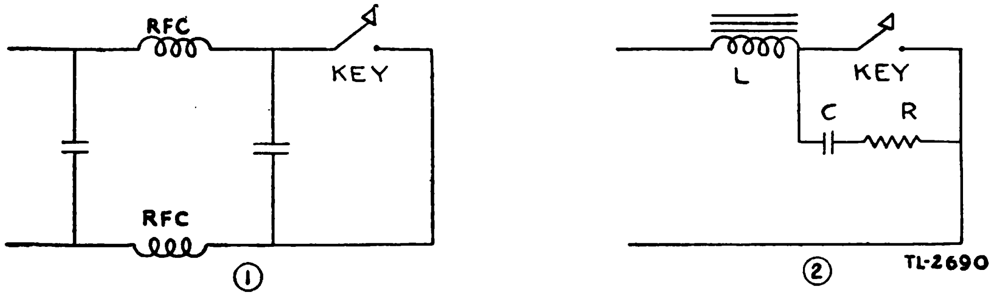


① High frequency.
② Ultrahigh frequency.
③ Low frequency.

FIGURE 89.—Parasitic oscillatory circuits in transmitter of figure 87.

open, and it should cause full power output when the key is closed. It should perform these operations without causing keying transients, or clicks, which cause interference with other stations.

b. For various reasons some energy may get through to the antenna during keying spaces. The effect is then as though the dots and dashes were simply louder portions of a continuous carrier. The backwave, or signal heard during the keying spaces, may appear almost as loud as the keyed signal; under these conditions the keying is hard to read. A pronounced backwave often results when the amplifier stage feeding the antenna is keyed. It may be present because of incomplete neutralization of the final stage, allowing some energy to get to the antenna through the grid-to-plate capacitance of the tube, or because of magnetic pickup between the antenna coupling coils and one of the low power stages. Such a condition can often be remedied by proper neutralization, or by rearranging the tank circuits to eliminate unwanted coupling, or by shielding.



① R. f. filter to absorb transients.
② Lag circuit to prevent transients.

FIGURE 90.—Key filters.

c. When a transmitter is keyed in such a manner that the power is applied and removed suddenly, an abnormally high current surges back and forth momentarily at the time of opening and closing the key. During these brief periods the transmitter is shock excited. A mechanical example of shock excitation is the tapping of a bell with a hammer to produce vibrations in the bell. Shock excited oscillations, either mechanical or electrical, are usually highly damped and of a broad band of frequencies. The radiation accompanying shock excited oscillations in a transmitter can be detected in receivers tuned to frequencies which are widely different from that on which the main transmitting is being performed. Since duration of the shock excited oscillation is short, the result is a click in the affected receiver at the beginning and ending of each code character. A key filter such as shown in figure 90① may be employed to absorb these transient oscillations, or the transients may be prevented by using a lag circuit as in figure 90②. The inductor or "choke" *L* in the lag circuit delays the rise of keying current and so prevents transients at the start of each character, while the capacitor *C* absorbs the current which would flow with the collapse of the magnetic field of the choke on the opening of the key. The resistor *R* is necessary only if the key opens and closes high potentials. Under these circumstances and with no resistor, the capacitor would attain a charge during open key periods, and a spark would occur at the key causing the contacts to stick due to development of heat. With the resistor in the circuit the energy of the charged capacitor is dissipated in it rather than across the key contacts. Also, the resistor serves to reduce the rate of change of current in charging and discharging the capacitor, which in turn reduces the shock effect on the transmitter circuit.

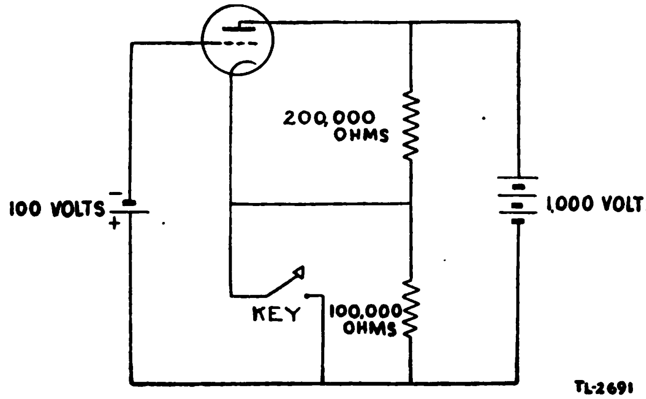


FIGURE 91.—Blocked-grid keying of amplifier.

d. The grid circuit of an amplifier is generally chosen for keying because of the relatively small currents therein. Figure 91 illustrates blocked-grid keying. With the key up, two-thirds of 1,000 volts, or 667 volts, is across the 200,000 ohm resistor; that is, 667 volts is applied to the plate; and one-third of 1,000 volts, or 333 volts, is across the 100,000 ohm resistor, so that 333+100=433 volts negative bias is applied to the grid. No plate current can flow under these conditions. With the key down and short-circuiting the 100,000-ohm resistor, the full 1,000-volt plate supply potential appears across plate to cathode, while the grid bias is reduced to 100 volts, under which conditions the amplifier operates normally.

53. Frequency doublers.—Self-excited oscillators for transmitters offer the advantage of flexibility of adjustment to various frequencies. Crystal controlled transmitters, on the other hand, operate only on fixed frequencies as determined by the crystals available.

Crystal controlled transmitters are widely used, however, because of their excellent stability. Oscillating crystals designed for very high frequencies are quite thin and fragile, and low radio-frequency crystals are generally employed in conjunction with frequency doublers. A frequency doubler is an amplifier which is so constructed and operated as to yield an output current which is of twice the frequency of the input voltage. An ordinary distorting amplifier with its plate circuit tuned to the second harmonic of the input frequency is often employed as a doubler. More efficient doubling, without employing tube distortion characteristics, is obtained from a double ended push-push amplifier. The two tubes in a push-push amplifier have their grids connected in push-pull and their plates connected in parallel as in figure 92.

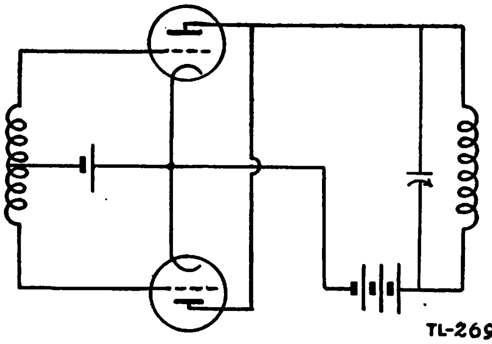
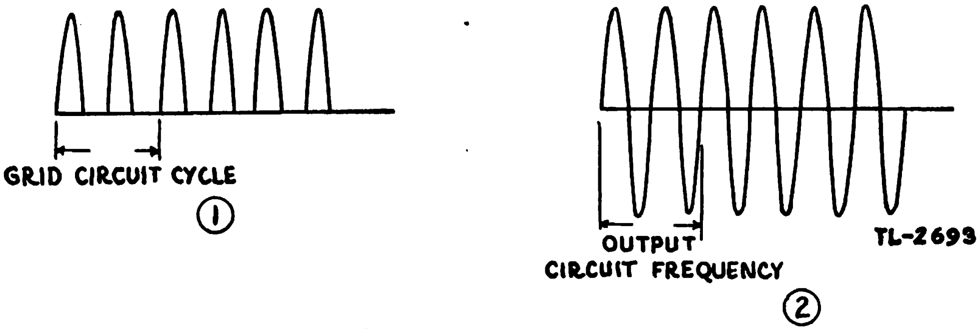


FIGURE 92.—Push-push amplifier.

Thus the tubes work alternately, and the output circuit receives two impulses in the same direction for each r. f. cycle at the grid circuit, giving all second harmonic or double frequency output in the plate circuit. Figure 93① shows plate current pulses of a push-push amplifier with tubes operated class C. The missing half cycles are supplied by the tank circuit to produce a continuous second harmonic output as in figure 93②.



① Plate current pulses.
② Output current for push-push amplifier with tubes operated class C.

FIGURE 93.

Section VIII

MODULATED TRANSMITTERS

54. Amplitude modulation.—Modulation is the variation of a radio wave at audio frequencies. Frequency modulation, variation of the frequency of the radiated wave, is discussed in section XII. Amplitude modulation, variation of the amplitude of the radiated signal, is accomplished by introducing both an audio frequency signal, say of 500 cycles, and a radio frequency signal, say of 1,000,000 cycles, into a nonlinear amplifier. The resultant sum and difference frequencies, 1,000,500 and 999,500, which convey the intelligence, are known as the side bands. The 1,000,000 cycle component is known as the carrier. Figure 94 illustrates a modulated wave as a sum of carrier and two side band frequencies. For simplicity of illustration the frequencies chosen in the figure are very low; however, the effects are similar to those in a modulated radio wave. An actual telephone transmitter side band consists of not one single frequency but contains as many frequencies as are present in the modulating signal, so that for reasonably good quality voice operation, side bands

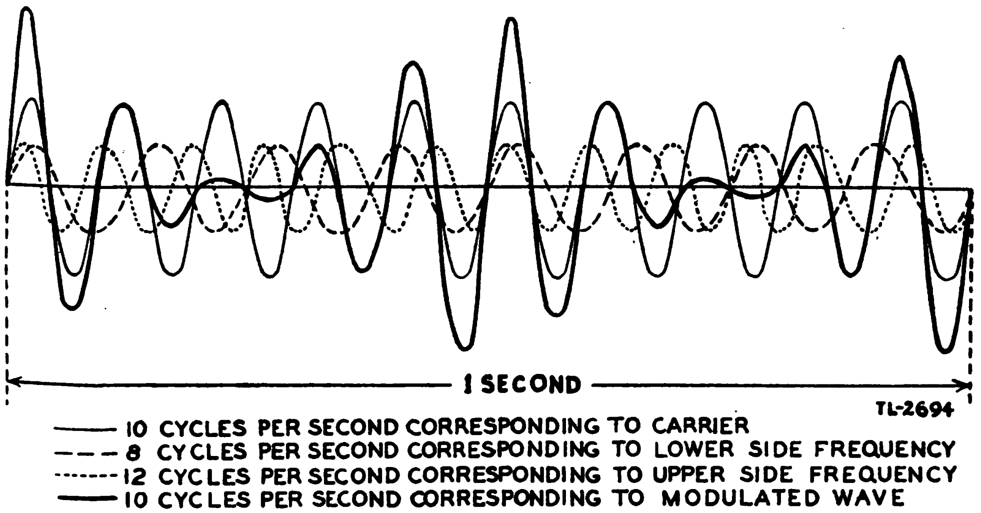


FIGURE 94.—Modulated wave showing "carrier" and "side bands."

occupy at least 3,000 cycles of the frequency spectrum either side of the carrier. Broadcast stations require side bands up to 10,000 cycles wide to convey musical programs properly. Those tuned circuits, both in transmitters and receivers, which accommodate modulated r. f. currents must be sufficiently broad to give good response to all the side band components.

55. Degree of modulation.—The degree of modulation is expressed by the percentage of the maximum amplitude deviation from the normal value of the r. f. carrier. If the positive peak r. f. current reaches twice the normal value carrier current, the negative peaks being zero, the wave is said to be modulated 100 percent (fig. 95). The effect of a modulated wave as measured by receiver response is proportional to the degree of modulation. A 10-watt carrier modulated 100 percent is about as effective as a 40-watt carrier modulated 50 percent.

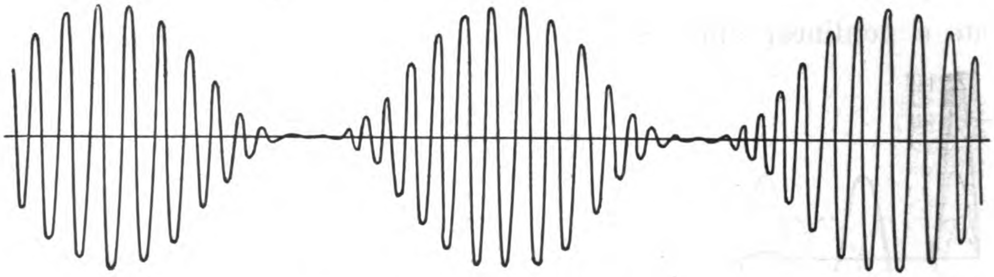


FIGURE 95.—100 percent modulation.

56. Power relations in modulated transmitter.—The amount of power required to modulate a transmitter depends on the percentage and type of modulation. To modulate a carrier 100 percent with a single sine wave of audio frequency requires an audio power equal to one-half of the r. f. carrier power. This is because with 100 percent modulation the amplitude of each side band is one-half the amplitude of the carrier. Power is proportional to current squared; thus each side band carrying one-half the current of the carrier requires one-fourth the power. However, the power required under modulation is one and one-half times the normal unmodulated power. With voice modulation the greater portion of the audio frequency components will not modulate the carrier 100 percent, so that the power increase for voice modulation is considerably less than for single tone modulation. Since the power is increased during modulation, the reading of an antenna ammeter rises when the transmitter is modulated. One of the operating tests of a modulated transmitter is to whistle into the microphone and watch for an increase in the antenna current. For 100 percent modulation with a single sine wave the antenna current increases approximately 22 percent.

57. Modulation methods.—Various methods of modulating a transmitter are in use. The audio frequency modulating voltage can be applied to the plate of one of the transmitter amplifiers to cause the output to vary in accordance with the audio frequency. This is known as plate modulation. Application of the audio frequency voltage to the control grid is referred to as grid, or as grid bias, modulation. A pentode power amplifier can be modulated by applying the audio frequency to the suppressor grid. This is known as suppressor modulation. The screen grid can also be modulated in a tetrode. Cathode modulation, in which the audio voltage is applied in the cathode circuit, is a combination of plate and grid modulation.

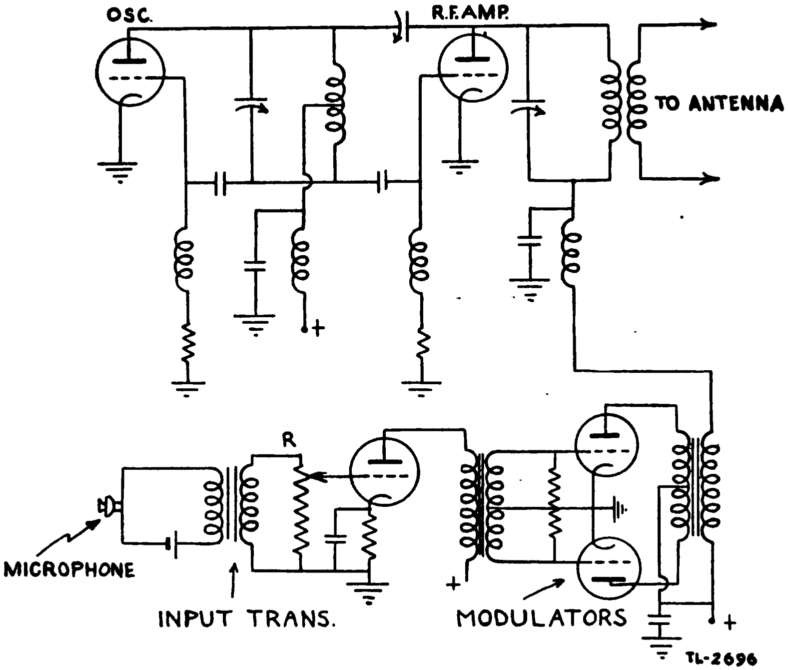


FIGURE 96.—Radiotelephone transmitter.

58. Radiotelephone transmitter.—Figure 96 shows the basic circuits of a complete radiotelephone transmitter. Sound waves impinging on the diaphragm of the microphone alternately compress and release the carbon granules of the microphone button, thereby varying the resistance of the microphone circuit and giving rise to a voice frequency pulsating current in the input transformer primary. The potentiometer *R* across the secondary of this transformer is a volume control to regulate the amplitude of the modulating signal. The grid-to-cathode resistance of the modulator tubes varies with the intensity of the signal, and resistors are connected across the inputs of these tubes to keep the net load impedance on the first speech amplifier tube nearly constant. These shunting resistors are much lower than the grid-to-cathode resistances, so that changes in the grid-to-cathode resistances have only a slight over-all effect on the load to the preceding circuit. The modulator output varies the plate voltage applied to the amplifier stage of the transmitter to produce corresponding variations in the radiated energy (fig. 97). The input speech amplifier stage can be converted into an audio frequency oscillator by providing a switch which, when closed, will couple enough of the plate circuit energy through a capacitor back to the grid circuit to cause sustained oscillations to take place. In this way a combination continuous wave, tone, and voice transmitter results.

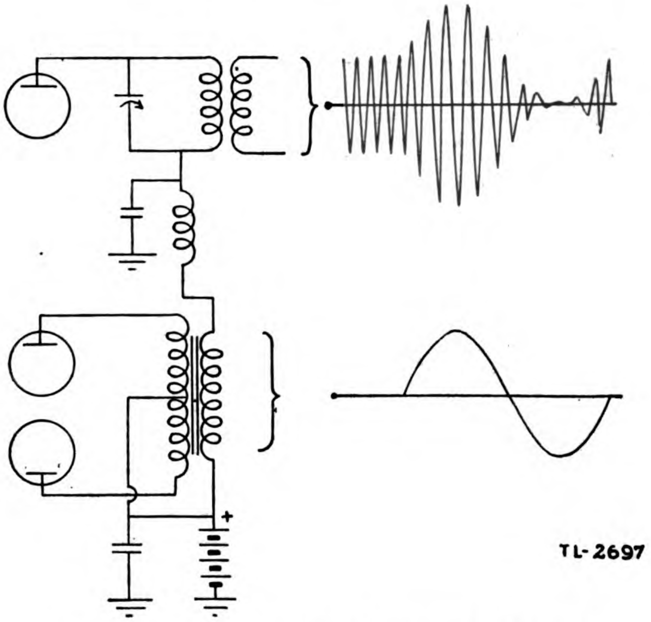


FIGURE 97.—Production of a modulated wave.

59. High and low level modulation.—When the final r. f. stage of a transmitter is modulated, the modulation is described as high level, since the modulation takes place at the highest power level in the system. If the modulation takes place in an intermediate stage with a higher power amplifier or several such stages following, it is called low level. In low level modulation, amplifiers which are used to increase the power output from the modulated stage are operated as linear amplifiers, that is, in such a manner that their a. c. output potentials faithfully reproduce the applied grid potentials. These amplifiers are operated class B, and include r. f. load resistors similar to those across the inputs of the modulators of figure 96 to prevent such distortion as might otherwise accompany the change of load impedance to the preceding stage with changes in the amplitude of the modulated signal.

60. Reduction of normal carrier power for phone operation.—A modulated amplifier must handle peak currents which are twice the normal unmodulated magnitude. This means that during modulation an amplifier must be capable of handling up to four times the power it dissipates under steady intervals of unmodulated carrier output. For this reason in a transmitter which is designed for both continuous wave and phone service, the modulated amplifier stages are always reduced in carrier power output for phone operation.

SECTION IX

VACUUM TUBE DETECTORS

61. Detection.—The conversion of r. f. energy in a receiver into audible sound frequencies to convey intelligence is accomplished by a process called detection or demodulation.

62. C. w. detection.—For the reception of continuous wave (c. w.) signals, the output of a local oscillator, say 1,001,000 cycles, is combined with the incoming signal, say 1,000,000 cycles, and applied to a class B amplifier. The local oscillator is usually the amplifier itself, in which case the amplifier is called a heterodyne detector (fig. 98). The output of the detector contains current of the sum frequency, 2,001,000 cycles, and of the difference frequency, 1,000 cycles. The former, the r. f. component, serves no useful purpose and is bypassed to ground. The latter, the a. f. component, actuates the earphones or loudspeaker, usually through an audio amplifier.

63. Phone detection.—For phone or tone reception a separate oscillator is not necessary, since the side bands differ from the carrier by the wanted voice frequencies. Here a simple diode rectifier, as in figure 99①, is adequate. An analysis of the equivalent circuit of figure 99② shows that the load resistance should be large (in comparison with the plate-to-cathode resistance) in order to develop a large a. f. output voltage across it. In practice the load resistance is generally made from 20 to 100 times the internal resistance of the tube. Diode rectifier action is shown in figure 46.

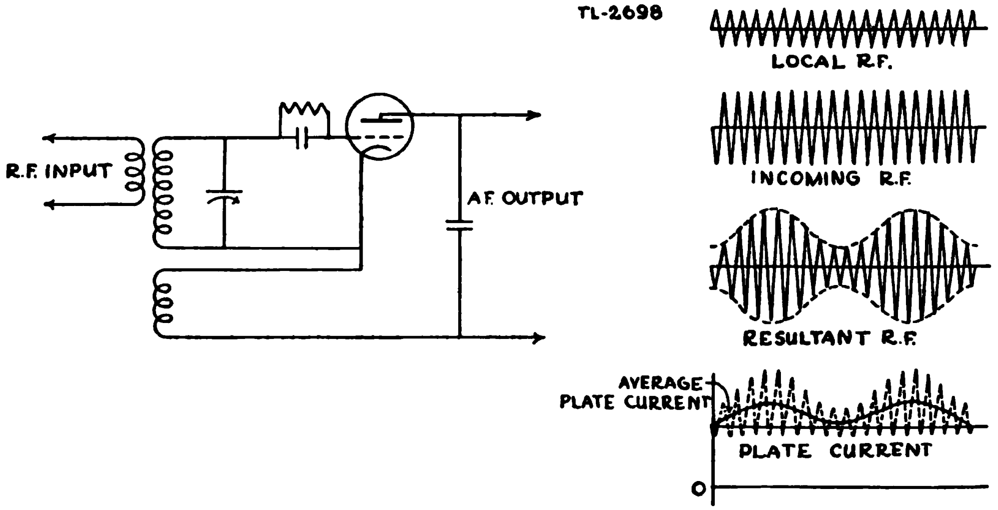
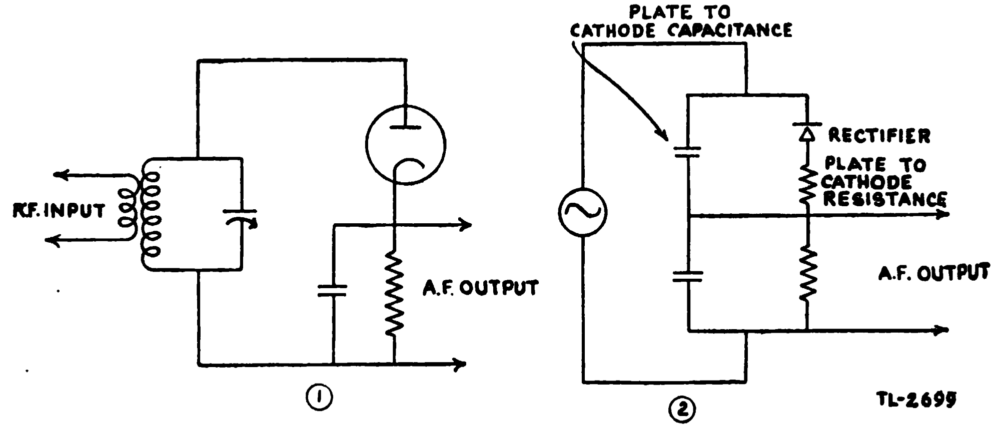


FIGURE 98.—Basic heterodyne detector circuit, and (right) how the local and incoming r. f. signals combine. The local, incoming, and resultant r. f. currents are actually alternating in nature, but the plate current of the detector tube remains direct current which is changed at the average rate, as the lowermost curve shows, to produce an audio frequency signal. For this reason, the "average plate current" curve is shown above the plate current zero line.

64. Plate and grid detection.

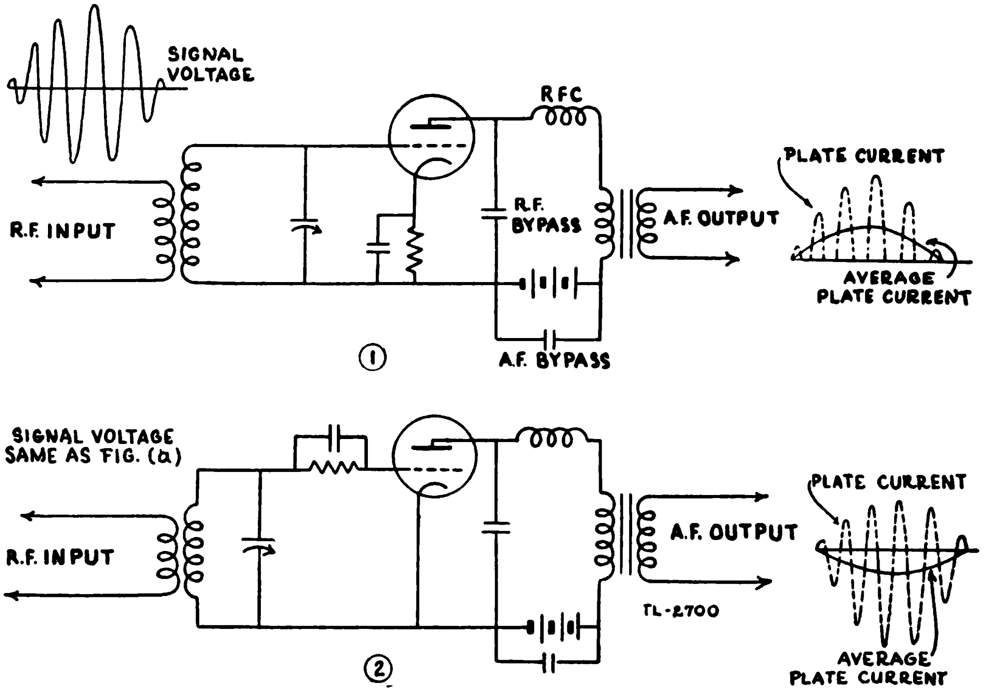
—A single tube combining both amplification and detection is sometimes employed to obtain increased output at the sacrifice of quality. In the circuit of figure 100① the tube operates at the heel of the i_p–e_p characteristic, as determined by the grid bias and by the plate potential, and amplification occurs before demodulation. The process is referred to as plate detection. In



① Diode detector. ② Equivalent circuit.

FIGURE 99.

the circuit of figure 100② the tube operates at the heel of the i_g–e_g characteristic, as determined by the grid leak bias and by the plate potential, and demodulation occurs principally first (in the grid circuit) with amplification following. This process is called grid leak, or simply grid detection.



① Plate detector.
② Grid detector.

FIGURE 100.

65. Comparison of detection methods.—Both diode and grid leak detectors draw current from the tuned circuit, thereby lowering both the selectivity and the gain of the tuned circuit. A properly designed diode detector gives less distortion than either of the other types; and usually the plate detector gives less distortion than the grid leak type. Grid leak detection was formerly used extensively for the detection of weak signals, but the development of improved radio frequency amplifiers has made the grid leak detector almost obsolete. The d. c. component produced in the diode detector is frequently used for effecting automatic volume control.

SECTION X

RECEIVERS

66. Tuned r. f. receiver.—*a.* Figure 101 shows the schematic circuit of a tuned radio frequency (t. r. f.) receiver. This receiver has one stage of tuned radio frequency amplification, a plate detector, and one stage of audio frequency amplification. The two resonant circuits are tuned by a ganged variable capacitor which has all rotor plates connected to the same shaft so that both circuits can be adjusted with a single dial. Small trimmer capacitors connected in parallel with the main capacitors compensate for inequalities in circuit constants. These trimmers are usually screw driver or socket wrench controlled from the rear or bottom of the receiver chassis.

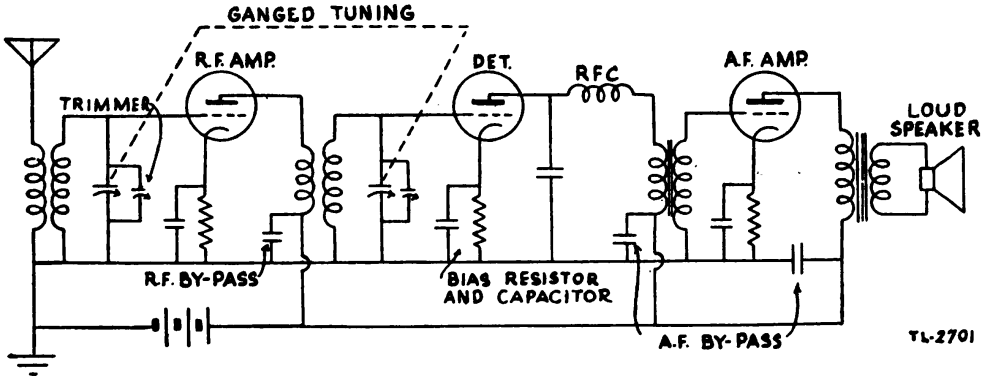


FIGURE 101.—Tuned r. f. receiver.

b. The trimmer adjustment should be made at the high frequency end of the band, that is, with the main capacitor plates out of mesh. If this adjustment were attempted at the low frequency end of the band with the capacitor plates in mesh, it would take a large change in the trimmer capacitance to cause any noticeable change in the total capacitance. On the other hand, with the tuning capacitors out of mesh and presenting only a small capacitance, a minute change in the trimmer capacitance represents an appreciable change in the total capacitance, and it is possible in this way to get a critical adjustment.

c. To compensate for slight inequalities of the two tuning capacitor sections, the end plates are sometimes slit in such a way that just a portion of these plates can be bent slightly. This provides a means of alining the two circuits at various settings of the tuning capacitors so that the circuits track over the entire band.

67. Volume control.—*a.* Volume controls can be inserted in almost any circuit. Some receivers employ volume controls in more than one circuit. A popular method of volume control is the use of a variable resistor in a cathode return circuit to regulate the bias on a variable μ tube. Automatic volume control, abbreviated a. v. c., may be had by taking the bias for one or more r. f. variable μ tubes partly from the rectified input signal. In this way the amplification given to a particular tube can be decreased in accordance with the strength of the signal to provide a fairly uniform response at the expense of a certain amount of sensitivity. Automatic volume control is particularly desirable for receivers in mobile craft wherein the signal strength changes as the vehicle is maneuvered. Figure 102 shows a detector diode with an a. v. c. circuit.

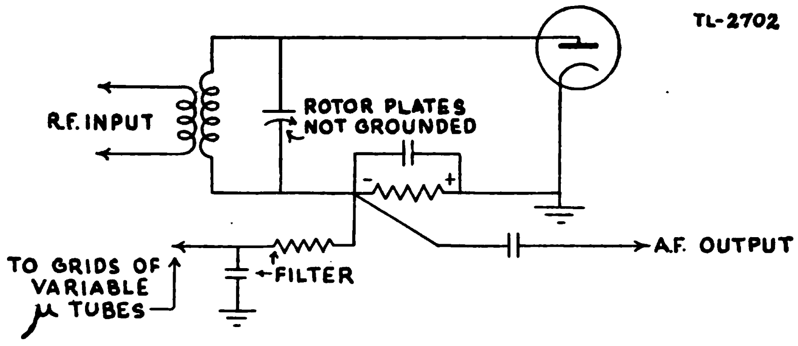


FIGURE 102.—Automatic volume control circuit.

b. The variable μ tube is designed to operate with a minimum bias of about 3 volts. This minimum bias is usually provided by a cathode resistor, and the a. v. c. bias is in series with it. A disadvantage of ordinary a. v. c. is that with it even the weakest signal reduces the amplification slightly. An adaptation which avoids this is shown in figure 103 and is referred to as delayed automatic volume control (d. a. v. c.). In this particular circuit the a. v. c. diode is separate from the detector diode, and both are housed in the same vacuum tube along with a pentode amplifier. The tube is called a duplex-diode pentode. Part of the energy which is fed to the plate of the detector diode is coupled to the a. v. c. diode section by the small capacitor *C*. By means of a cathode biasing resistor *R* the plate of the a. v. c. diode is maintained at a negative voltage which keeps it from rectifying and producing the a. v. c. voltage until the peak voltage coupled to it through *C* counterbalances this diode's negative voltage. For very weak signals, which do not produce enough voltage on the plate of the a. v. c. diode to overcome the existing negative potential, no a. v. c. voltage is developed, and thus the sensitivity of the receiver remains the same as if a. v. c. were not being used. On the other hand, when normal strength signals are being received, which do not need the set's maximum sensitivity, enough voltage will be coupled to the a. v. c. diode to overcome the small negative plate potential and produce an a. v. c. voltage drop across resistor R_1. This voltage has the a. f. and r. f.

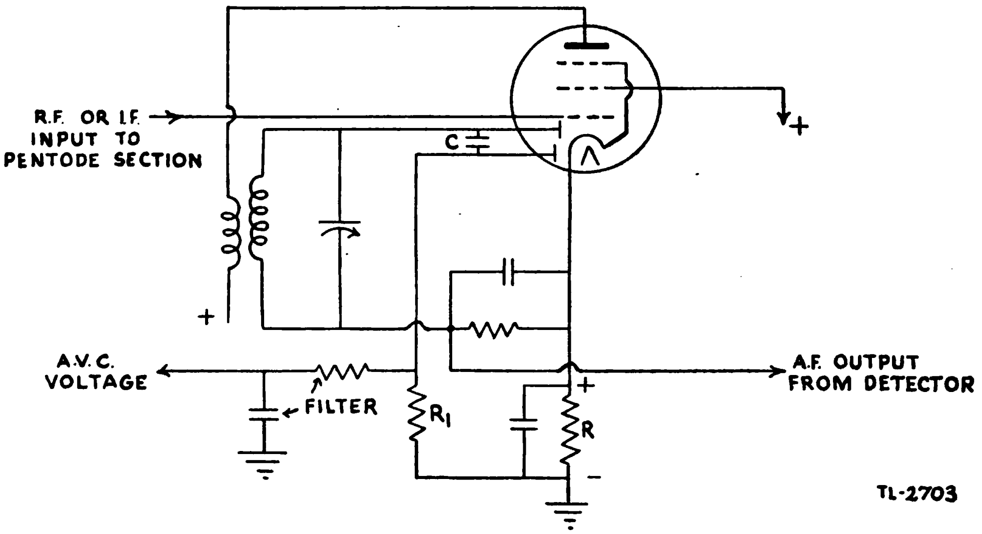


FIGURE 103.—Delayed automatic volume control.

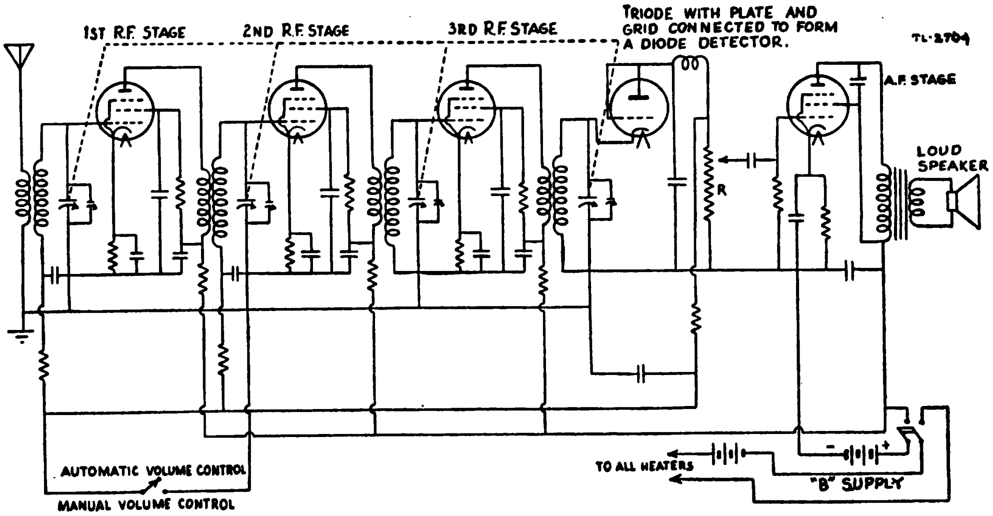


FIGURE 104.—T. r. f. receiver with automatic volume control.

components filtered from it and is applied to the grids of the variable μ tubes just as in the case of the ordinary a. v. c.

68. Circuit of tuned r. f. receiver.—Figure 104 shows the complete circuit of a tuned radio frequency (t. r. f.) receiver employing three r. f. pentode stages with automatic volume control on the first two stages only. A switch is provided for short-circuiting the a. v. c. when it is desired to use the manual control (detector output potentiometer *R*) exclusively. Figures 105 through 109 reproduce the same receiver wiring diagram with various circuits emphasized to facilitate study.

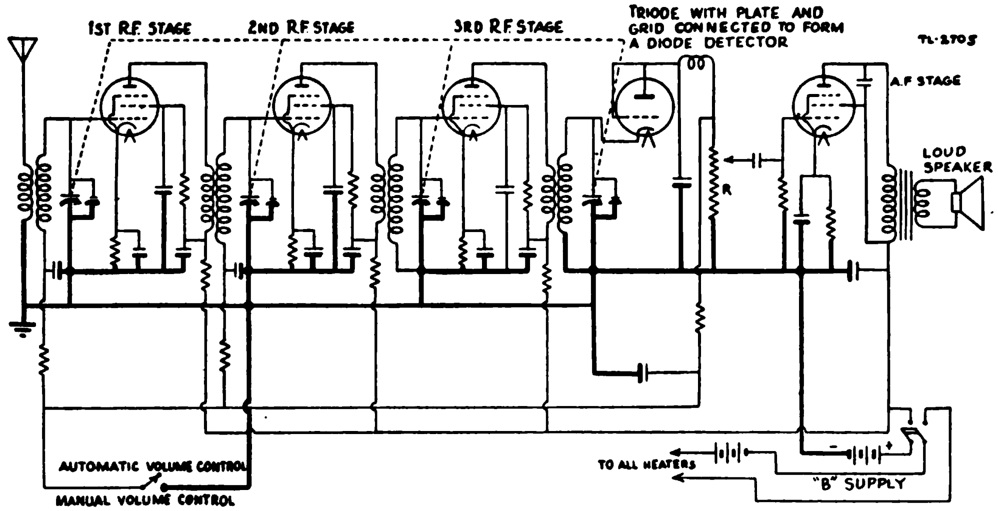


FIGURE 105.—T. r. f. receiver. Ground potential elements denoted by heavy lines.

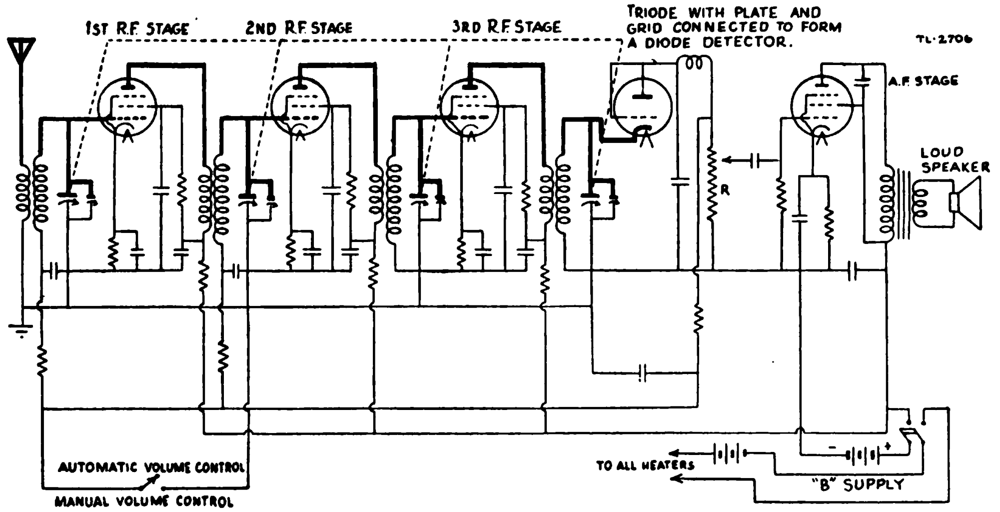


FIGURE 106.—T. r. f. receiver. Elements at high r. f. potential denoted by heavy lines.

69. Superheterodyne receiver.—*a.* The superheterodyne has replaced almost all other types of general purpose receivers at the present time. Figure 110 shows the scheme of a superheterodyne receiver by means of a block diagram. The two novel features of a superheterodyne receiver are the mixer stage and the intermediate frequency (i. f.) amplifiers. The mixer stage is often referred to as the first detector. In reality it is a heterodyne detector which, in conjunction with an appropriately tuned local oscillator, converts the r. f. input signal to a lower frequency, still r. f., which for identification is called the intermediate frequency. The second de-

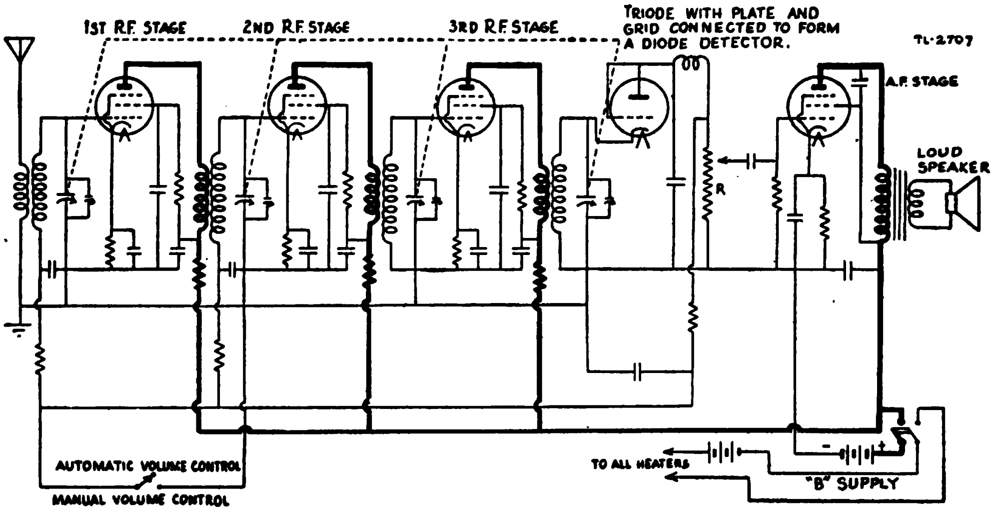


FIGURE 107.—T. r. f. receiver. D. c. plate supply shown by heavy lines.

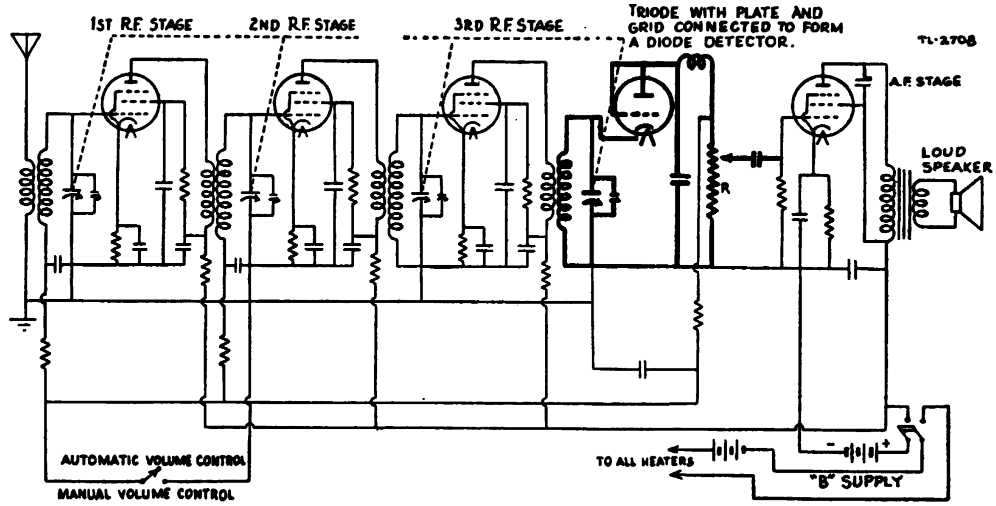


FIGURE 108.—T. r. f. receiver. Detector circuit shown in heavy lines.

tector, or demodulator, converts this intermediate frequency energy to audio frequency.

b. The mixer may be operated as a plate detector with the exception that instead of filtering the r. f. from the output, here a band pass filter is used which eliminates all frequencies except the intermediate band which is desired. This band pass filter is actually a transformer with both primary and secondary tuned. The coupling is such as to produce a resonance curve which is flat topped to accommodate a narrow band of frequencies in the manner of the curve of figure 29②. The fixed intermediate frequency permits simplicity of design to concentrate on optimum selectivity and amplification at this one particular frequency. At the relatively low intermediate frequencies employed, of the order of 500 or 1,000 kilocycles (kc.), stray capacitances are not especially troublesome, and standard pentode tubes give good voltage gain. Tuning the plate circuits allows

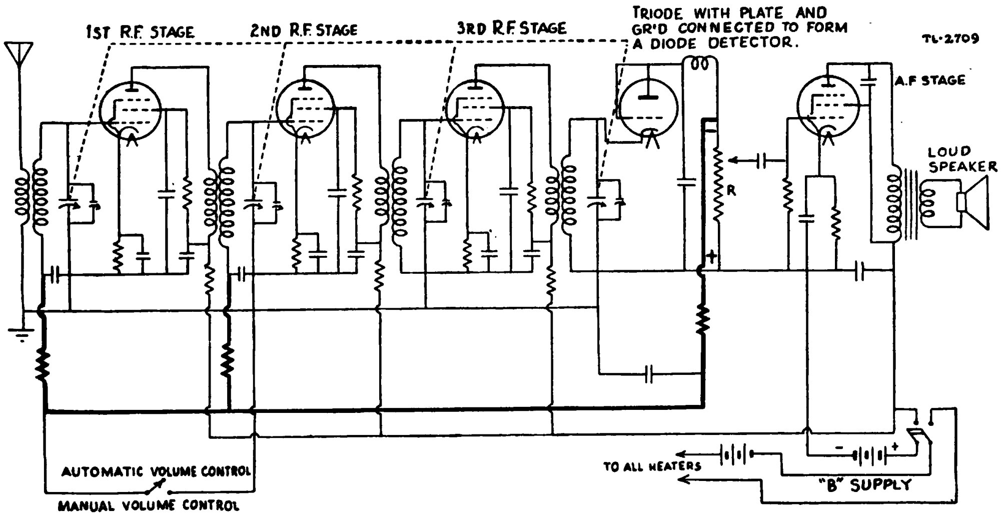


FIGURE 109.—T. r. f. receiver. A. v. c. circuit shown in heavy lines.

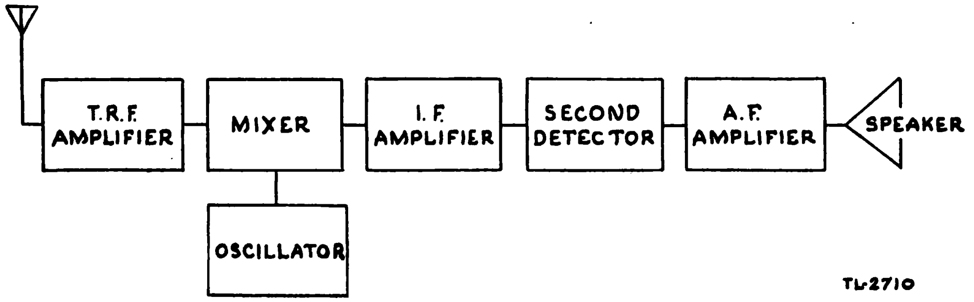


FIGURE 110.—Scheme of superheterodyne receiver.

the i. f. amplifier tubes to work into high impedance plate loads, another factor contributing to high gain.

c. The local oscillator circuit capacitor is ganged to the tuning capacitors in such a manner as to generate oscillations of a frequency which differs from the signal frequency by an amount equal to the fixed intermediate frequency. Suppose, for example, that the desired incoming signal has a frequency of 1500 kc. and that the i. f. amplifier is tuned to 465 kc. Then if the local oscillator is adjusted to 1965 kc., the mixer stage will yield (among other frequencies, which are rejected by the tuned circuits) 1965−1500=465 kc. Incidentally, a 465 kc. output of the mixer stage also results if a 2430 kc. incoming signal is present at the same time: 2430−1965=465 kc. In such a case 2430 kc. is referred to as an image frequency, since it is an image in the frequency spectrum, so to speak, of the 1500 kc. frequency about the 1965 kc. oscillator frequency (fig. 111). The tuned circuits ahead of the mixer stage are tuned to the desired frequency, 1500 in this case, so that the preselector amplifies the desired signal much more than it does the image signal. The ratio of desired signal to image signal at the mixer input is known as the image ratio and in a good superheterodyne receiver may be around 1,000.

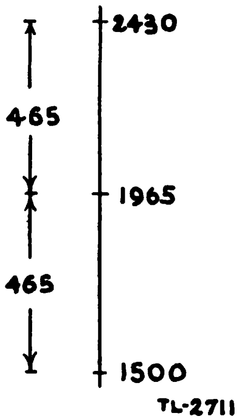


FIGURE 111.—Illustrating image frequency.

70. Pentagrid mixer.—The plate detector mixer has the disadvantage of effectively coupling a load back through the interelectrode capacitance into the input circuit, so that tuning the input circuit affects the frequency of oscillations. A pentagrid (five-grid) mixer tube connected as in figure 112 isolates the oscillator and mixer circuits. The signal and mixer grids are screened by the two adjacent grids. The fifth grid is a suppressor.

71. Converter.—A single tube performing the functions of both oscillator and mixer is known as a converter. Figure 113 shows the connections to a pentagrid converter. The grid nearest the cathode forms the control grid, and the next grid, the plate of a triode oscillator. The first grid is called the oscillator grid and the second, the anode grid. The signal is applied to the fourth grid, the third and fifth grids forming electrostatic screens. The oscillator "plate" current, which is flowing in pulses, causes electrons to shoot through the openings in the anode grid in spurts at the oscillator frequency. The effective plate current is similar to that for the pentagrid mixer, in which two grids modulate a continuously emitted space charge. Pentagrid converters offer the advantage of simplicity of tubes and of wiring. However, at higher than broadcast frequencies, that is, for most communication frequencies, their usefulness is limited by interaction which occurs between the oscillator and signal sections. A detailed circuit of the pentagrid converter is shown in figure 114.

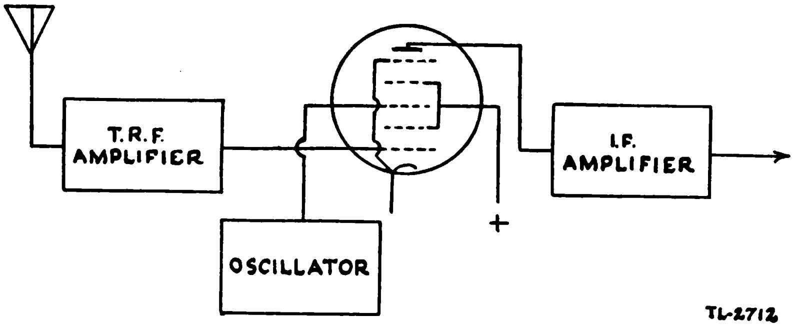


FIGURE 112.—Pentagrid mixer.

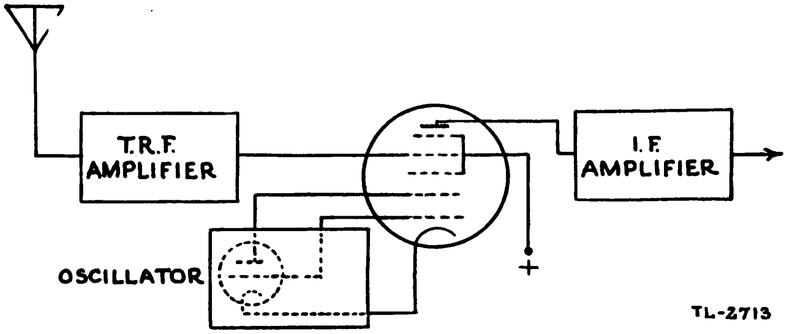


FIGURE 113.—Pentagrid converter.

72. Circuit of superheterodyne receiver.—Figure 115 shows the circuit of a six-tube superheterodyne receiver. This receiver has one stage of t. r. f. preselection, a local triode oscillator, a mixer, two stages of i. f. amplification, a diode detector with delayed a. v. c., and a power pentode output stage. A beat frequency oscillator is included for c. w. reception. Particular individual circuits of the receiver are emphasized in figures 116 to 119.

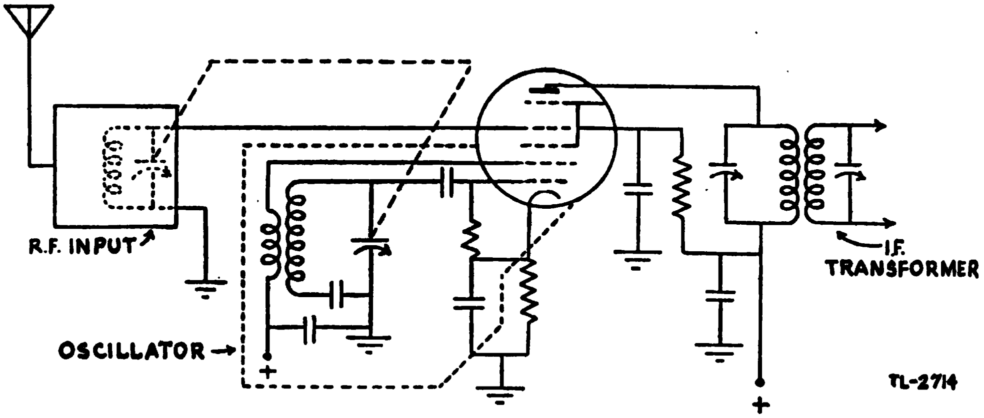


FIGURE 114.—Pentagrid converter circuit.

73. Crystal filter.—*a.* The characteristics of the quartz crystal make it particularly suitable for use in an i. f. stage of a superheterodyne receiver. The crystal serves two functions, namely, to increase the over-all selectivity of the i. f. amplifier and to permit the rejection of an interfering signal which is very close to the desired signal in frequency. These selectivity and rejectivity features are due to the fact that as the frequency of the exciting voltage is varied, the crystal behaves as a series resonant circuit at one frequency,

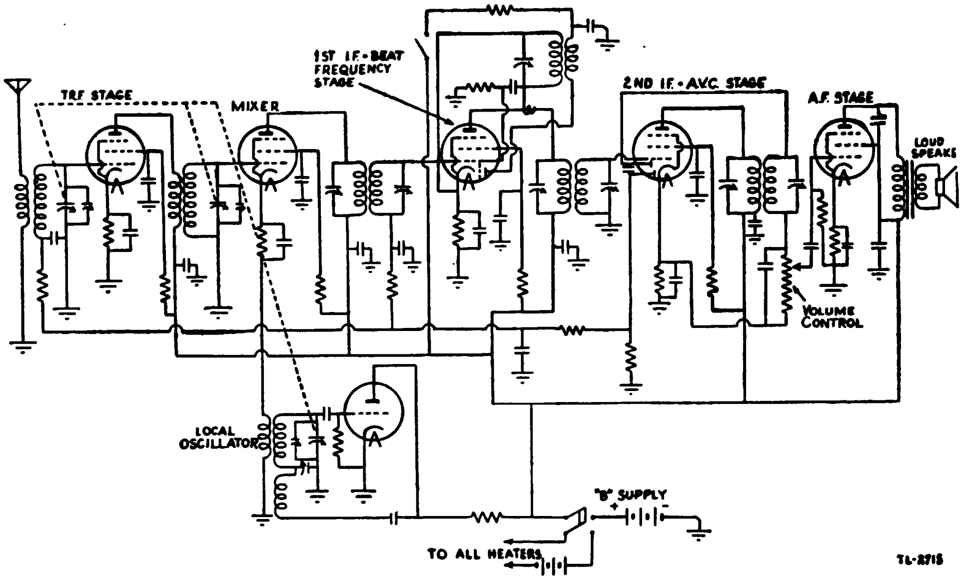


FIGURE 115.—Superheterodyne receiver.

f_r, and as a parallel antiresonant circuit at another frequency, f_a; f_a is very slightly (usually less than one part in a thousand) higher than f_r. A typical crystal circuit in an i. f. stage is shown in figure 120①.

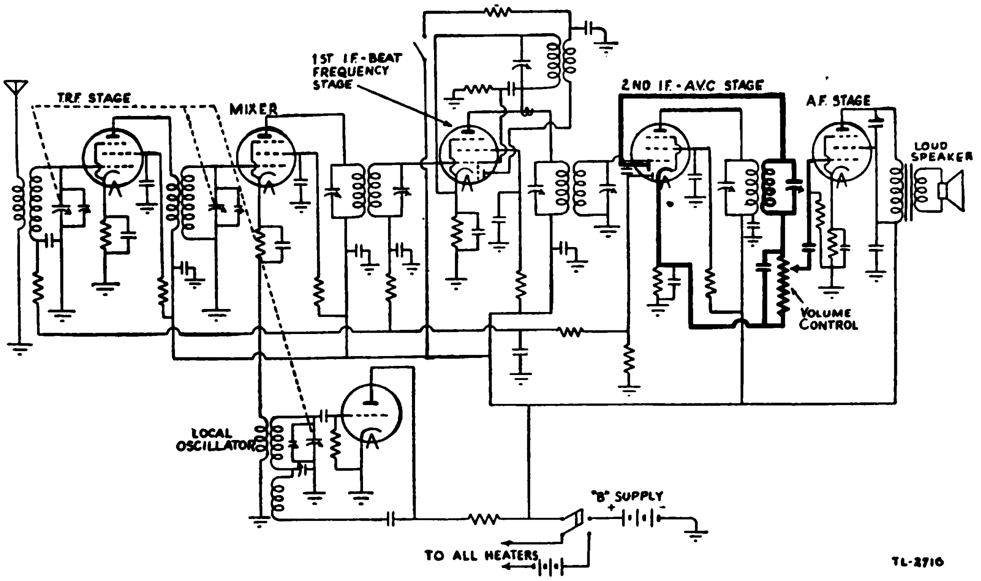


FIGURE 116.—Superheterodyne receiver. Second detector circuit shown in heavy lines.

b. At the series resonant frequency the crystal acts as a pure resistance, the magnitude of which is very small compared with the load impedance. As a consequence, at this frequency the voltage across

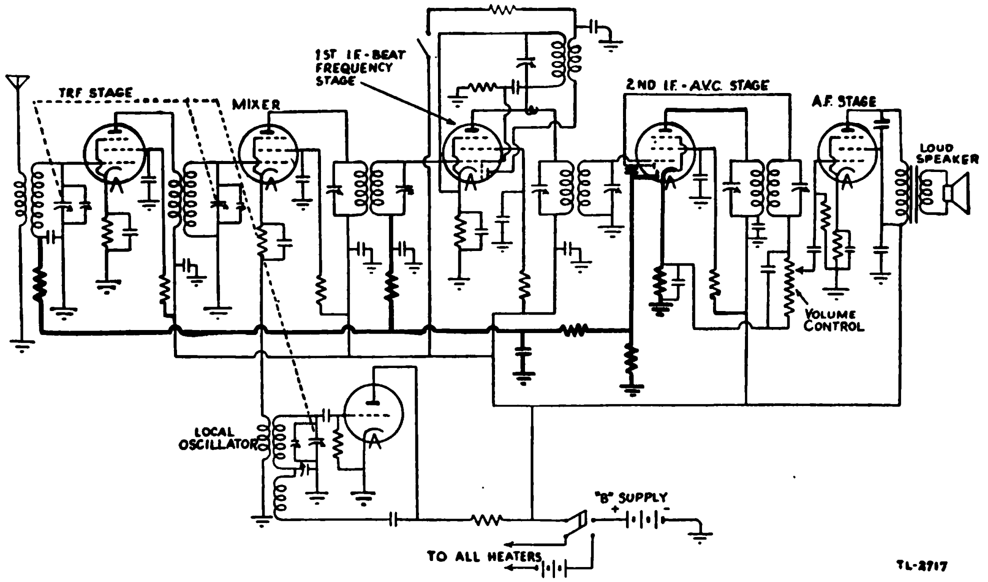


FIGURE 117.—Superheterodyne receiver. D. a. v. c. circuit shown in heavy lines.

the filter output (fig. 120②) is very nearly equal to that across L_1, that is, the output voltage is approximately one half the impressed voltage across the secondary coil L_1L_2. At all frequencies sufficiently remote from the crystal's resonant frequencies, the crystal presents a capacitative reactance due to the capacitor formed by the holder plates and the quartz dielectric. This reactance is relatively high as

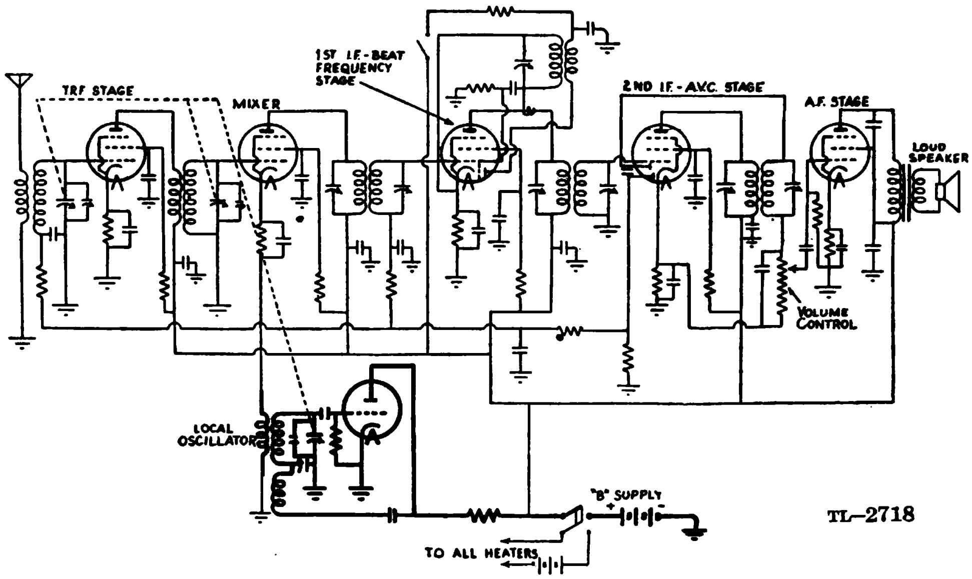


FIGURE 118.—Superheterodyne receiver. Local oscillator shown in heavy lines.

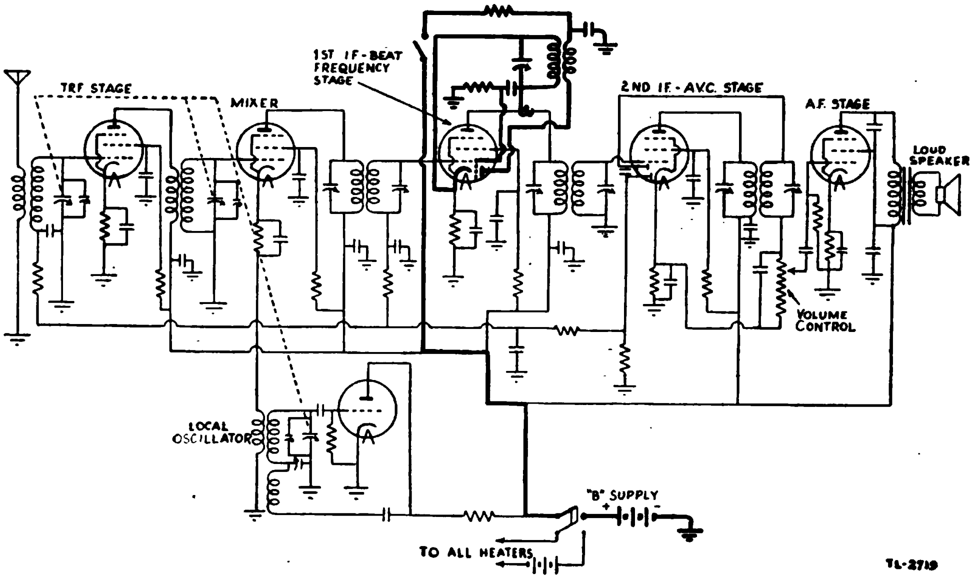
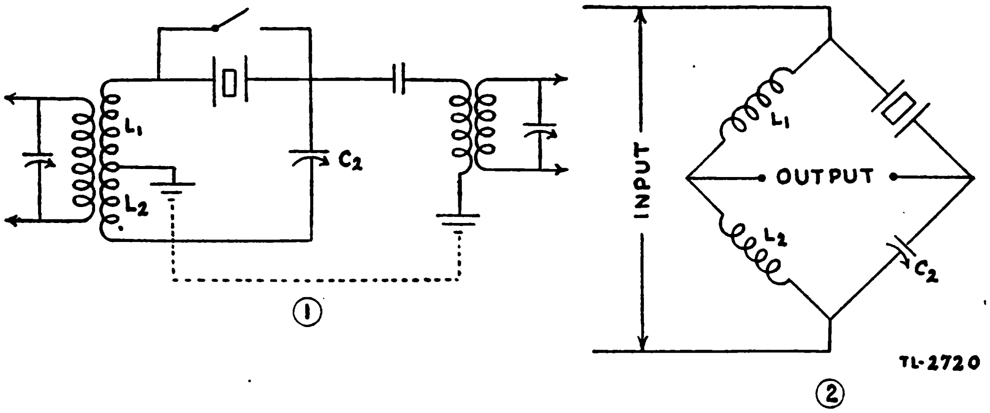


FIGURE 119.—Superheterodyne receiver. Beat frequency oscillator for c. w. reception shown in heavy lines.

compared with the load impedance, so the voltage developed across the load impedance is very small.

c. A signal which is so separated in frequency from the desired signal as to cause an audible note in the receiver can be rejected by use of the phasing capacitor C_2. To accomplish this, the local oscillator must be tuned, by adjusting the main receiver dial if necessary, so as to bring the undesired (i. f.) signal on the high frequency side of the desired (i. f.) signal. Just above f_a, the crystal, while still oscillating, presents a small net capacitive reactance. The magnitude of this reactance depends on the frequency of the exciting signal. If the capacitance of the phasing capacitor, C_2, is made equal to that of the crystal at the frequency of the interfering signal, the net output at this frequency will be negligible, since the equal capacitances together with the equal inductances, L_1 and L_2, form a balanced bridge circuit. If desired, C_2 may be set equal to the capacitance of the crystal holder, and then rejection is effective over all frequencies for which the crystal does not oscillate.



① In i. f. stage. ② Segregated to show bridge form.

FIGURE 120.—Crystal filter.

74. Multiband receivers.—Communication receivers often use one ganged set of tuning capacitors with several sets of r. f. coils to fit the particular operating bands. Alining capacitors (trimmers) are included with each set of coils so that once they are adjusted, all the circuits will tune properly with a single dial on the front panel. Some sets use plug-in coils; others have the coils permanently incorporated in the receiver with a multicontact gang switch to connect the various coils as desired. In the multiband superheterodyne receivers the only coils which need be changed are the preselector, mixer, and oscillator coils. Sometimes, when a superheterodyne is to cover an extremely wide range of frequencies, two sets of i. f. amplifier coils are provided corresponding to two intermediate frequencies, one for the high ranges and one for the low ranges.

SECTION XI

POWER SUPPLIES

75. General.—Cathode power supply is furnished by batteries or by hand driven dynamotors in portable field radio sets; semiportable and mobile sets generally use storage batteries for filament heating purposes. In permanent ground installations filaments are heated from the standard a. c. lighting circuit through a step-down transformer. Grid bias for voltage amplifiers is customarily taken from the plate supply by some means of self-bias, while for large power tubes separate rectifier-filter systems or d. c. generators are frequently employed. Plate supply in lightweight field "transceivers" is by batteries. Dynamotors driven by storage batteries or by hand are favored for plate power in portable and mobile sets, while many semiportable transmitters carry gasoline engine driven generator equipment. Permanent installations ordinarily use some sort of rectifier-filter system plate supply.

76. Vacuum tube rectifiers.—Vacuum tube rectifiers for plate supply are of two general types, high vacuum and mercury vapor. The former offers the advantage of ruggedness, the latter, high efficiency. In both types the tube contains two elements, a cathode and a plate, and both operate on the principle of current flow only during intervals of positive plate potential. In the mercury-vapor tube ionization of the mercury vapor occurs at a potential of about 15 volts. The positive mercury ions, drifting to the cathode, neutralize the negative space charge surrounding the cathode and permit electrons to proceed to the plate under conditions of very low plate-to-cathode potentials. The result is that the tube carries large current with about only a 15-volt drop in potential necessary for ionization occurring across the tube itself. However, this type of rectifier is critical of operation. Positive ions fall into the cathode at a damaging rate if the voltage across the tube becomes excessive for even short intervals. For this reason the cathode must be brought to full operating temperature before the anode voltage is applied, and temporary overloads must be carefully avoided.

77. Rectifier-filter system.—A typical full wave rectifier with filter system for a receiver or small transmitter is shown in figure 121. Each plate-filament circuit of the tube acts as a half wave rectifier delivering current during alternate half cycles when its plate is positive. The filter input voltage has a wave shape as shown in figure 37. The filter of figure 121 is known as a capacitor input filter. The input capacitance is somewhat dangerous in that it causes high charging current surges when the power is applied. On the other hand, a small input capacitance reduces the effectiveness of the filter action. A choke input filter, as in figure 36, gives a lower output voltage, but it limits possible current surges and it provides good regulation; that is, it tends to maintain the output voltage constant regardless of the load current. A bleeder resistor across the filter output assists the regulation in that it presents a constant load, and any change in the current drawn by the equipment causes a reduced percentage variation in the total load. A potentiometer voltage-divider and bleeder resistor may be one and the same unit.

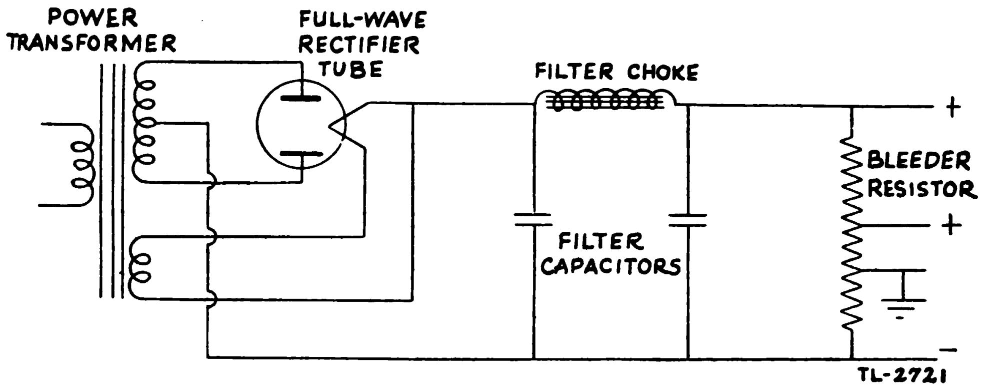
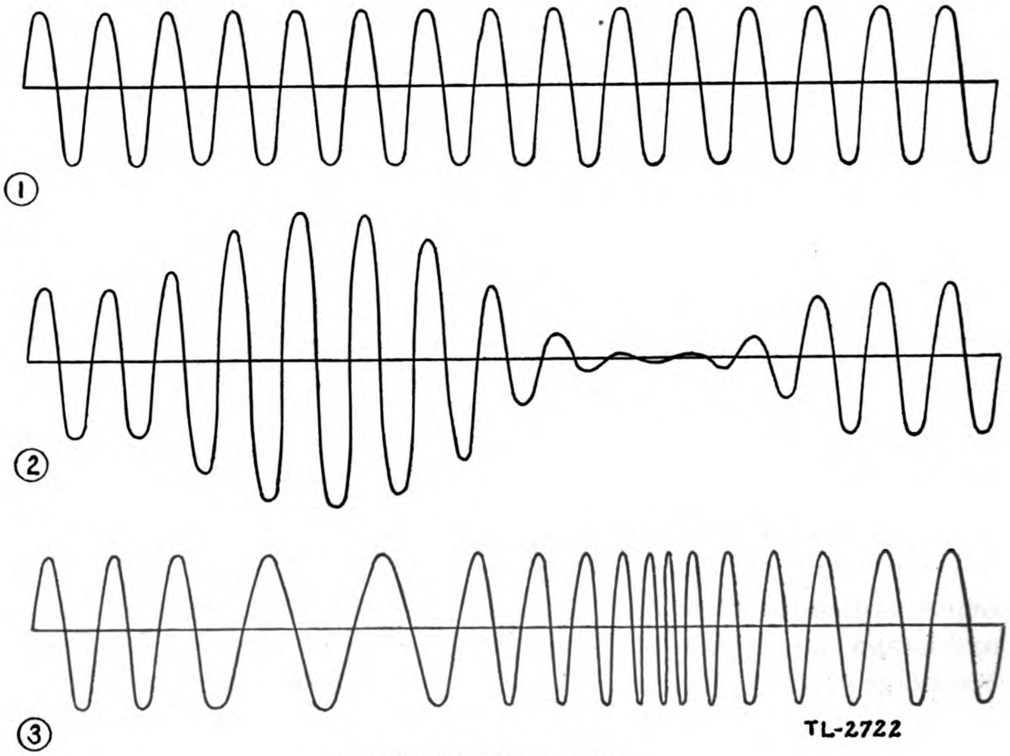


FIGURE 121.—Power supply for receiver or for small transmitter.

SECTION XII

FREQUENCY MODULATION

78. General.—Frequency modulation is the process of varying the frequency of a radio frequency wave at an audio frequency rate, without varying its amplitude. The essential difference between frequency modulation (f. m.) and amplitude modulation (a. m.) is shown in figure 122. In this figure, ① represents an unmodulated r. f. carrier; ② shows the result of amplitude modulating the carrier; and ③ shows the result of frequency modulating the carrier. In ② during the modulation period the amplitude rises and falls in accordance with an impressed audio frequency signal. In ③ during the modulation period the frequency increases and decreases in accordance with the audio signal, but the amplitude remains constant.



① Unmodulated r. f. wave.
② Amplitude modulated wave.
③ Frequency modulated wave.

FIGURE 122.—Amplitude and frequency modulation.

79. Simple modulator and demodulator.—*a.* A simple form of frequency modulator is that of a condenser microphone shunting an oscillatory circuit, as in figure 123. The diaphragm in the condenser microphone (see par. 103) forms one plate of a capacitor. Sound waves striking the microphone compress and release the diaphragm to vary the capacitance at the voice frequency. Since the microphone capacitance is in parallel with the oscillatory circuit capacitance, the effect is that of changing the frequency of the r. f. oscillations at the voice frequency rate.

b. Any parallel resonant circuit, such as those in the r. f. stages of an ordinary a. m. receiver, will act as a frequency modulation detector if the operation is such that the unmodulated carrier is tuned in on one side, rather than at the center, of the response curve, as shown in figure 124. The effect of such "detuned" operation is that, as the frequency swings above and below the normal unmodulated carrier frequency, the resulting output varies in amplitude accordingly. This amplitude modulated signal is rectified in the ordinary manner in the detector circuit.

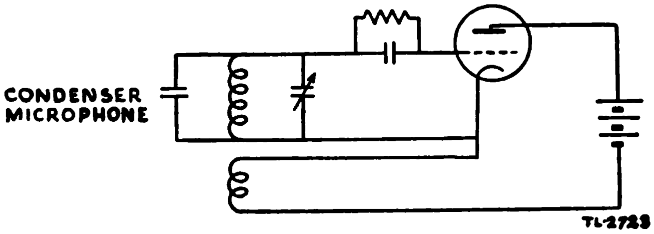


FIGURE 123.—Simple frequency modulation scheme.

80. Wide swing frequency modulation.—Frequency modulation presents an appreciable signal-to-noise ratio improvement over amplitude modulation provided the frequency swing with modulation is several times as much as the highest audio frequency transmitted. A 25-kilocycle swing to each side of the unmodulated carrier frequency is common in communication work; 75-kilocycle swings are usual in broadcast service. To obtain a wide frequency swing with modulation, the oscillator frequency is usually made much lower than the desired carrier frequency, and frequency doublers are employed to multiply the original modulated frequency. If the oscillator output has a normal frequency of 10 megacycles and is modu-

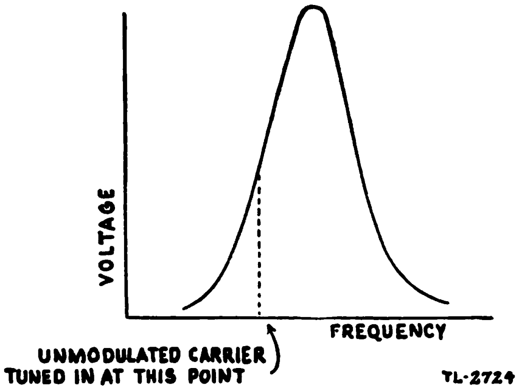


FIGURE 124.—Parallel resonant circuit as a frequency detector.

lated to produce a maximum swing of 10 kilocycles, then doubling twice results in a 40-megacycle carrier with a 40-kilocycle swing.

81. Practical frequency modulator.—Both the simple modulator and the simple demodulator described in paragraph 79 are relatively inefficient. A practical frequency modulator is shown in figure 125. Modulation is accomplished by variation of the effective reactance of the oscillatory circuit at an audio frequency rate as controlled by the microphone sound impulses. C_2 is a d. c. blocking capacitor. C_1, R_1, and R_2 form a grid bias arrangement for the control grid of the modulator. R_2 is a very high resistance of the order of a megohm. The essential elements of the circuit are the small capacitance C across the modulator control grid and the high resistance R, which is in series with C across the oscillator tank circuit. The current through R–C is very nearly in phase with the voltage across R–C (fig. 126), which voltage is that across the oscillatory circuit, and the voltage across C is practically 90° behind the voltage across the oscillatory circuit. The r. f. voltage across C (from the oscillatory circuit) is impressed on the control grid of the modulator. Audio voltages from the microphone circuit are impressed on the second grid of the modulator. The resulting audio frequency modulated r. f. plate current responses are in phase with the control grid potential, therefore 90° behind the voltage across the oscillatory circuit. The radio frequency choke in the plate circuit of the modulator offers a large re-

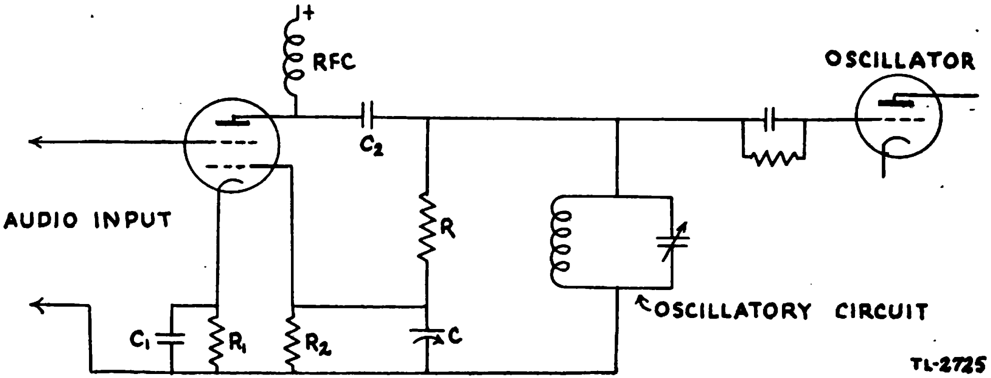


FIGURE 125.—Frequency modulator circuit.

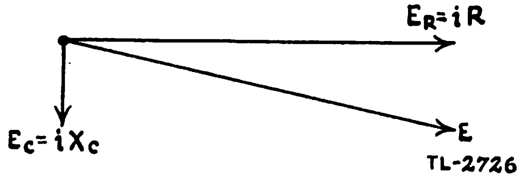


FIGURE 126.—Voltage relations in R–C circuit of figure 125 (R very much greater than X_C).

actance to the r. f. component of the plate current, so that this r. f. component flows through the tuned circuit of the oscillator. The total lagging current due to the voltage across the oscillatory circuit is greater than it would have been if it were not for the modulator circuit. The same effect could have been produced by connecting an inductor in parallel with the oscillatory circuit. Thus the modulator acts as an inductance. As sound waves strike the microphone, the potential of the second modulator grid is varied, and in turn, the modulator plate current. This varies the effective inductance of the oscillatory circuit, which then varies the frequency of the oscillations.

82. Frequency modulation reception.—*a.* A block diagram of a practical f. m. superheterodyne receiver is shown in figure 127. It will be seen that a receiver for f. m. differs from one for a. m. in two main aspects, the limiter and the frequency discriminator. A further essential difference is the width of the band to which the i. f. amplifier is tuned. For an a. m. receiver it is necessary only that the i. f. amplifier pass a range of frequencies 30 kc. wide at the most, corresponding to the separation between the two extreme side band frequencies. In an f. m. receiver the i. f. amplifier must accept a band from 50 to 150 kc. in over-all width depending upon the maximum frequency swing employed in the transmitter. The limiter serves to remove any amplitude modulation of the signal, and the frequency discriminator extracts the audio frequency signal to feed it into an ordinary audio amplifier. The limiter stage of an f. m. receiver is shown in figure 128. The actual circuit is that of an ordinary i. f. stage, but the operating conditions are quite different. The resistor $R1$ broadens the band pass characteristics of the i. f. transformer $T1$. The d. c. voltages applied to the limiter tube are very small, about 15 volts on the plate and 10 volts on the screen. Consequently, even a rather weak signal arriving on the grid saturates the tube, and the maximum possible plate current is reached when the instantaneous voltage on the grid is considerably below the maxi-

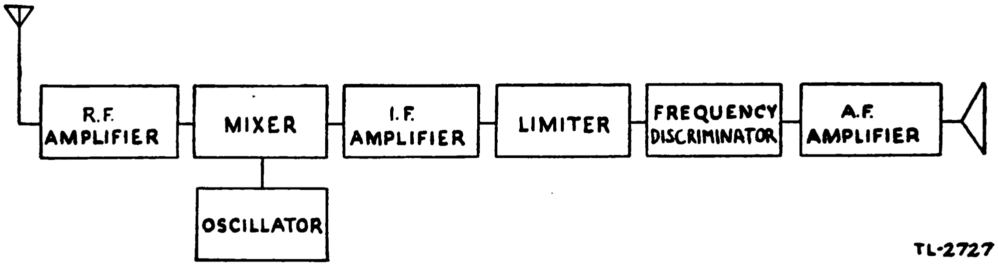


FIGURE 127.—Block diagram of f. m. receiver.

mum value of the signal voltage. The result is that as long as the signal is above a certain minimum strength, all traces of amplitude modulation are removed by the limiter action, as shown in figures 129 and 130. Since the original transmission contained no intentional amplitude modulation, any amplitude modulation present in the signal as received is the result of extraneous effects, including static and man-made noise; these unwanted components are removed by the limiter.

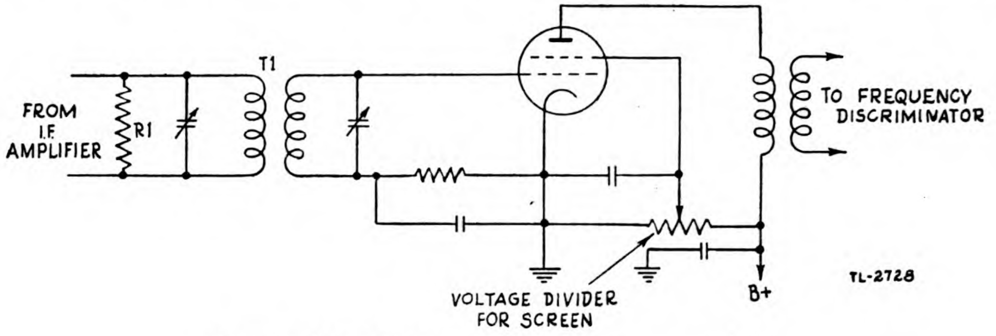


FIGURE 128.—Limiter circuit of an f. m. receiver.

b. Figure 131 shows the actual combination of the limiter stage and the frequency discriminator stage of a typical f. m. receiver. The discriminator is the equivalent of the second detector of an ordinary superheterodyne, and performs the similar function of demodulating the carrier. (See sec. XI.) The i. f. transformer *T*2 has a center-tapped secondary, *S*1–*S*2, feeding the plates of a double diode rectifier. The cathodes of the latter terminate at the ends of a center-tapped resistor *R*2, one end of which is grounded. The direct current return path of the rectifier circuit, between the center tap of *S*1–*S*2 and the

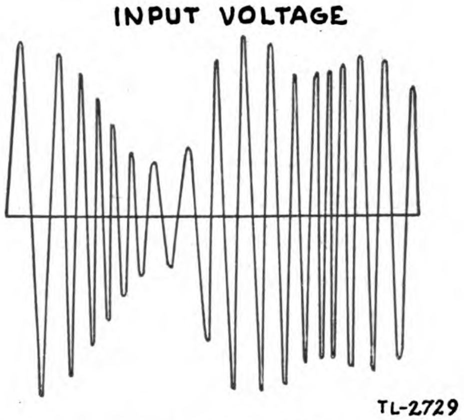


FIGURE 129.—Input signal to limiter tube, containing both a. m. noise and the desired f. m. signal.

center tap of *R*2, is completed through the inductor *L*. This coil has another function, to be explained later.

(1) The operation of the discriminator circuit in recovering the audio modulation from the f. m. signal depends on three factors. First, the center tap of *S*1–*S*2 causes a division of the signal voltage across the tuned circuit *S*1–*S*2–*C*2, this voltage being induced by the primary *P* in the usual electromagnetic fashion. The second factor is that the signal voltage across *P* is also impressed across inductor *L* because of the direct connection afforded by the coupling capacitor *C*1. Note that the coil *L* is common to both halves of the secondary of *T*2 with respect to the signal voltages applied to the two sections of the double diode. This means that two voltages are impressed on each diode: the magnetically induced voltage in the secondary circuit and the voltage which appears across inductor *L*. The third and controlling factor in the operation of the discriminator is the complex phase relationships between these voltages. These are determined by the relation between the incoming signal frequencies and the resonant frequency of the secondary circuit *S*1–*S*2–*C*2. (See sec. II.)

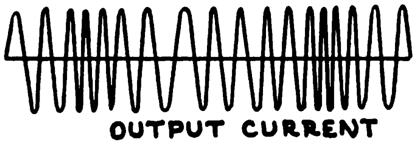


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FIGURE 130.—Output of the limiter tube. The a. m. impulses have been chopped off.

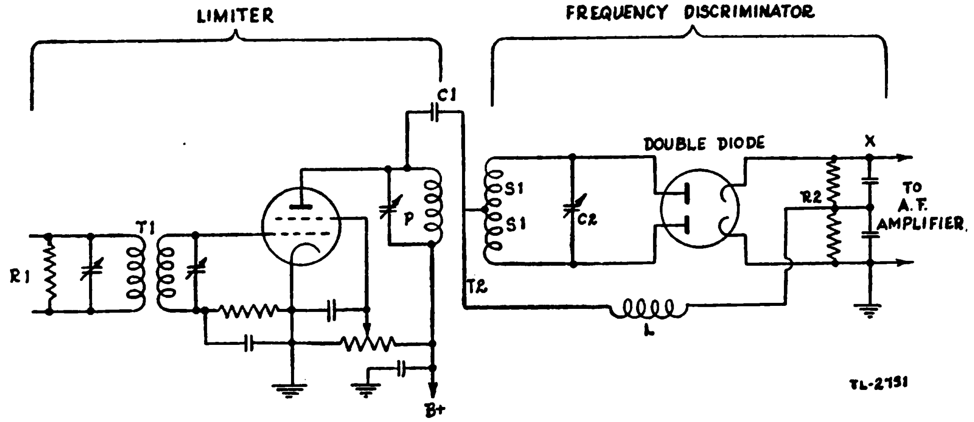


FIGURE 131.—Limiter-discriminator section of f. m. receiver.

(2) Suppose the incoming f. m. signal is not modulated; that is, the microphone at the transmitter is idle and the transmitted signal is a steady one of the carrier frequency. Although the mixer action

of a superheterodyne changes the carrier frequency to a lower one, this retains the characteristics of the original carrier, and we can therefore say that the discriminator is being fed an unmodulated signal of one frequency. When the secondary circuit $S1$–$S2$–$C2$ is tuned exactly to this frequency, it shows only a resistive effect to the incoming signal, and the phase relations between the two voltages on each diode are such that no audio frequency variations appear across the output resistor $R2$. In other words, no sound is heard from the receiver.

(3) Suppose now that the microphone at the transmitter is actuated by voice or music. The frequency of the carrier swings accordingly. In the receiver, the secondary tuned circuit $S1$–$S2$–$C2$ is not resonant to the higher and lower frequencies represented by the modulation. At frequencies above resonance, the circuit presents an inductive effect; below resonance, a capacitive effect. The phase relations between the voltages impressed on the diodes shift in such a manner as to unbalance the diode outputs. This unbalance occurs at the audio frequency rate at which the frequency of the incoming signal is changing with modulation. The alternating voltages that develop between point X and ground have the same wave shape as the original audio modulating voltage at the transmitter, so the audio amplifier and its associated loud speaker or earphones reproduce an audible sound corresponding to that impressed on the transmitting microphone.

83. General consideration in frequency modulation.—*a.* Frequency modulation transmitting apparatus, in general, is relatively simple; very little power, almost none, is required to accomplish modulation. Receiving equipment, on the other hand, is somewhat more complicated than in the amplitude-modulated system. Receivers for frequency modulation are essentially superheterodynes of advance design. Special consideration is given the limiter and discriminator portions of the circuits.

b. Frequency modulation is necessarily restricted to very high frequency channels, above 40 megacycles, in order to accommodate any reasonable number of operating stations each requiring an over-all spread of from 50 to 150 kilocycles. At these high radio frequencies radio waves behave somewhat like light waves, so that the service area of a transmitter is approximately confined to the "line of sight" range of its antenna. Incidentally, static is generally lower at these high frequencies than it is at the lower communication frequencies.

c. A disadvantage of frequency modulation from a tactical standpoint is the fact that of two stations operating on closely adjacent frequencies, a receiving station normally hears only the stronger one, signals from the weaker station being entirely inaudible in the background of the stronger one. This particular characteristic is probably a very satisfactory one for broadcast (entertainment) service. However, in the event that the inaudible signal is actually the desired one, a receiving operator has no indication of the presence or absence of the weaker station. For military communication this may be a handicap in some situations. With amplitude modulation the receiving operator experiences at least a heterodyne whistle or an unintelligible background jumble, sufficient response to give positive indication of the presence of a weak operating station, so that the receiving operator can proceed accordingly.

84. Facsimile.—*a.* Facsimile involves the transmission of any intelligence which can be recorded on paper, as, for example, letters, photographs, sketches, and maps. Facsimile differs from television in that facsimile transmits only still subjects such as pictures and printed pages, whereas television deals with living scenes. The problems of the former are much simpler than those of the latter. In fact, perhaps the principal problem of any facsimile scheme is that of obtaining a transmitting medium capable of high fidelity reproduction of audio frequency currents. Just such a medium is provided by a frequency modulation radio system.

b. The facsimile transmitter employs a light and lens arrangement which is such as to illuminate a small spot, about $\frac{1}{100}$ inch in diameter, of the copy being transmitted. Reflected light from the surface of the paper carrying the copy is focused on a photoelectric cell, which responds with a current which is in proportion to the light. The magnitude of this current controls the amplitude of an audio oscillator, which in turn modulates a radio transmitter. A mechanical arrangement shifts the light spot across the paper from side to side, the intensity of the reflected light varying with the degree of the blackness of the copy and modulating the transmitter accordingly. At the end of each line of the paper scanned, the spot is shifted down by one diameter, and a new line is scanned until the complete copy has been exposed.

c. The facsimile receiving system contains a rectifier which operates from the output of an ordinary receiver. The output of the rectifier presents a varying d. c. potential, one side of which is applied to a $\frac{1}{100}$ inch diameter steel stylus. The other side of this potential is applied to a metal drum on which is wrapped a specially treated recording paper. The stylus makes contact with the paper, and the passage of current through the paper causes a chemical coating to be removed, thereby exposing a black spot, the density of which is related to the magnitude of the current flowing. By the use of a small motor rotating at a predetermined speed, the speed being fixed in accordance with the transmitter scanning rate, the recording stylus is moved across the paper exactly in step with the scanning light of the transmitter.

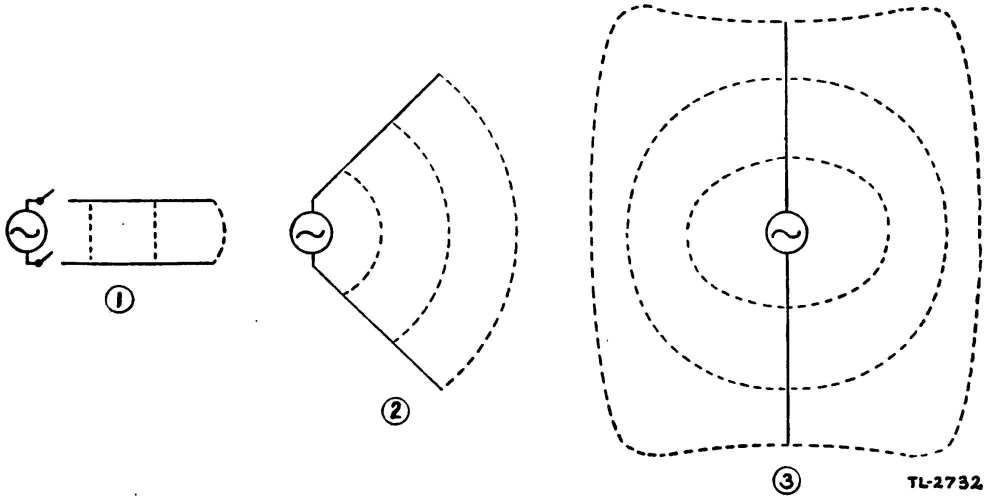
d. In the transmitter each time the scanning device shifts the light spot to the next line an extremely short low-tone impulse is transmitted. In the receiver as the end of a line is reached, the stylus is shifted to the next line and held there by a stop, and the output of the rectifier is transferred from the stylus to an electromagnet. The next impulse actuates the electromagnet, which releases the stop and permits the recording to continue on the new line in synchronization with the transmitted subject.

SECTION XIII

ANTENNAS

85. Radiation.—*a.* Two types of electromagnetic field are present about any conductor carrying an alternating current. One is the familiar induction (or magnetic) field, which gives rise to transformer action and to choke coil effects. The induction field falls off rapidly a short distance from the conductor, so that its effects are purely local. The second type of field accompanying an alternating current is a radiation field, which moves off into space. This radiation field may be properly modulated at its source and then intercepted and demodulated by a receiver to convey intelligence from one point in space to another. Some radiant energy is released from conductors carrying currents at the usual 25- and 60-cycle power frequencies; however, the amount is exceedingly small. Highest efficiency radiation is achieved at the higher frequencies, that is, at frequencies normally classified as radio frequencies, 50,000 cycles and above. This accounts for the use of these high frequencies in radio communication.

b. The commonly employed resonant radiating system is essentially a two-wire open-ended transmission line (fig. 132). Energy which flows along the line from the generator is not delivered instantaneously to the far end on the closing of the switch but proceeds along the line at a finite rate, which rate depends on the frequency of the generated voltage and on the inherent capacitance and inductance per unit length of the line. For a sine wave generated voltage, sine wave currents and voltages occur at each point along the line with a phase displacement from the original which is dependent on the distance from the generator. Electrical reflections of the voltage and current waves occur at the far end of the line, so that if the length of the line and the frequency of the generator are in the proper relation, the reflected waves reinforce the advancing waves always exactly in phase to produce large amplitude standing waves of current and voltage along the line. This is the condition of resonance under which the radiated energy is a maximum.



① Parallel wire transmission line.
② Partly opened-out transmission line.
③ Dipole.

FIGURE 132.—Resonant radiating systems.

c. If the velocity of propagation of waves along the parallel wire transmission system is v feet per second, and if the generator frequency is f cycles per second, then the voltage variations at a point which is at a distance $\lambda=\frac{v}{f}$ feet from the generator are just one cycle behind those of the generator. Similarly, at a distance $2\lambda=\frac{2v}{f}$ feet from the generator the voltage variations are exactly two cycles behind those of the generator. The distance λ (Greek letter, "lambda") is the *wave length* of the radiated wave, that is, it is the distance between two points in the wave which differ in phase by one complete cycle. The condition of resonance is obtained when the over-all length of the radiating system is an integral number of half or quarter wave lengths depending on the particular type of radiating system.

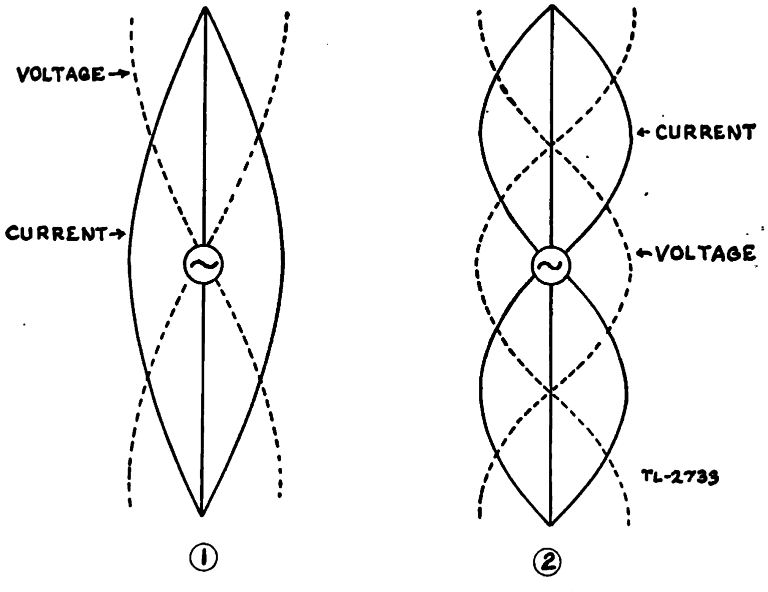
d. (1) It is now the universal practice to designate radio waves in terms of frequency, which is expressed as so many cycles, kilocycles or megacycles. Formerly, waves were designated in terms of wave length, the unit being the meter. Wave length figures are convenient in discussions of antenna systems, as the wave length gives some idea of the actual physical dimensions of the wires. For instance, a "half-wave" antenna for 50-meter transmission is 25 meters (a little more than 25 yards) long.

(2) It is well to remember that an inverse relationship exists between frequency and wave length; high frequencies correspond to short waves, and low frequencies to long waves. The following simple formulas show how one is converted to the other.

$$\text{Frequency (in cycles)} = \frac{300{,}000{,}000}{\text{Wave length (in meters)}}$$

or

$$\text{Wave length (in meters)} = \frac{300{,}000{,}000}{\text{Frequency (in cycles)}}$$



① Fundamental frequency. ② Second harmonic.

FIGURE 133.—Standing waves of current in Hertz antenna. Voltage distribution in dotted lines.

86. Antenna systems.—*a.* The parallel wire antenna confines the moving electric field to one direction and hinders the propagation of waves from progressing generally in all directions. More nearly uniform radiation in all directions is secured as the transmission line is altered in stages from ① to ③ of figure 132. In ① the radiation field is small in extent and is confined mainly to the end, while in ③ the complete electric field forms a part of the radiation. The disposition of ③ is referred to as an electric dipole or as a Hertz antenna. The standing wave resonance distribution of the current in such an antenna at the fundamental frequency (lowest frequency at which the antenna can resonate) is shown in figure 133①, maximum at the center and minimum at the ends. The wave length of the corresponding radiated wave is twice the length of the antenna. Current distribution in the same antenna excited at twice the fundamental frequency (second harmonic) is shown in figure 133②. The wave length of the corresponding radiation is equal to the length of the antenna. The voltage distribution in the dipole is shown by dotted lines in figure 133.

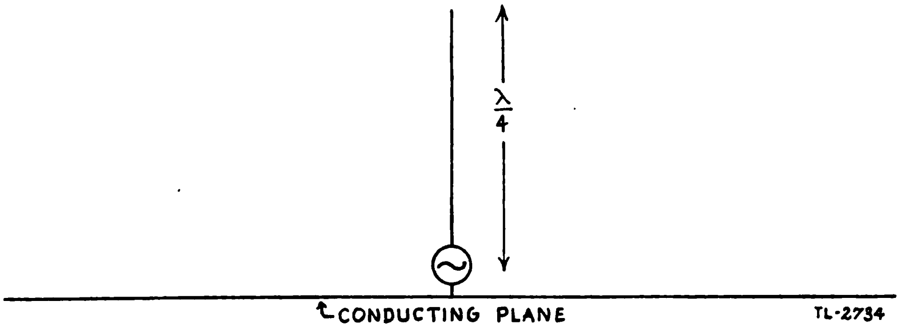
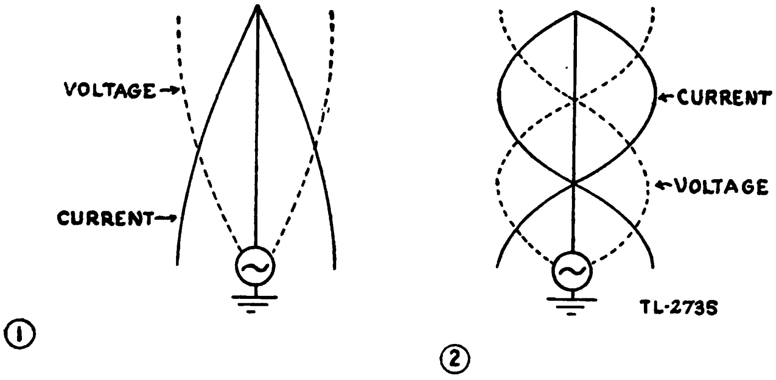


FIGURE 134.—Lower half of Hertz antenna replaced by extensive conducting plane.



① Fundamental frequency. ② Third harmonic.

FIGURE 135.—Current distribution in Marconi antenna.

b. If the lower half of the antenna is replaced by an extensive conducting plane (fig. 134), no disturbance is caused in the propagated waves from the upper half. A practical form of such a radiating system is the so-called Marconi antenna in which the lower terminal of the generator is connected to ground and the earth's surface serves as the extended conducting plane. Current and voltage distributions in such an antenna at the fundamental and third harmonic frequencies are as shown in figure 135. The wave length of the radiation at the fundamental frequency is four times the length of the antenna, and at the third harmonic it is four-thirds the length of the antenna. In the grounded Marconi antenna the voltage is necessarily a minimum at the ground, so that the antenna resonates only when excited at odd harmonic frequencies.

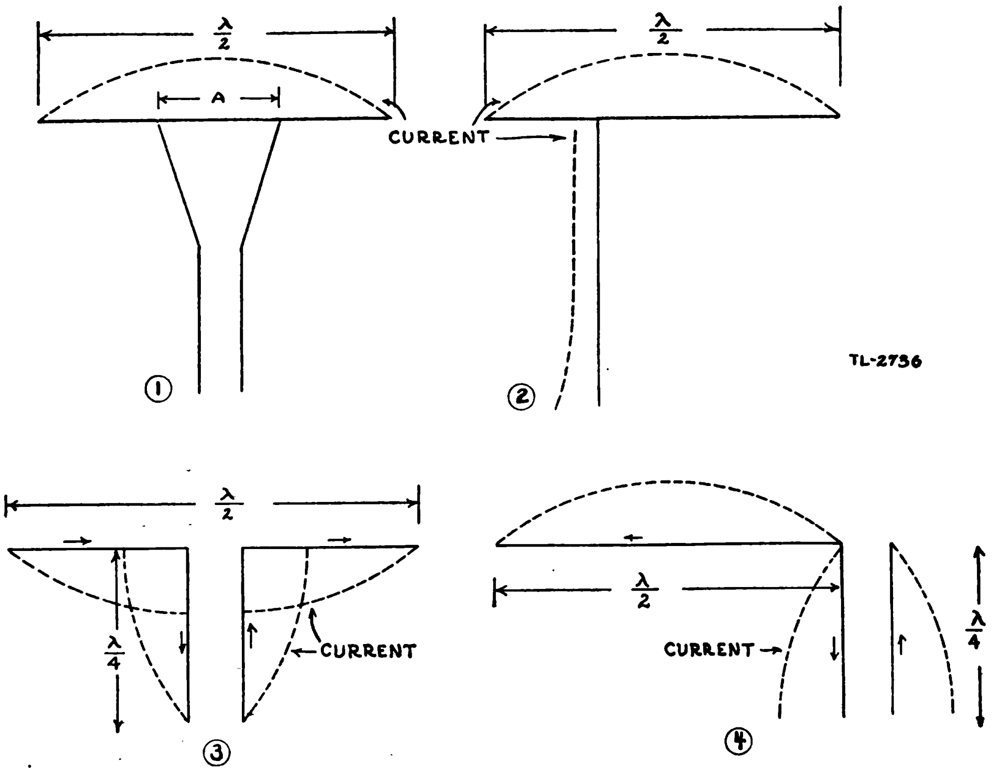
87. Feeder systems.—*a*. Standing waves could not arise in a parallel wire transmission line which is infinite in length, because the advancing waves should never reach the far end to produce the necessary reflected waves. As a consequence, since a resonant condition would not be attainable in an infinite line, the radiated energy in such a line would be negligible. Electrically, the condition of an infinite line can be obtained by terminating a finite line in the impedance which a corresponding infinite line can be calculated to present, namely,

$$Z_o=\sqrt{\frac{L}{C}}$$

where L and C are the inductance and capacitance per unit length of the line, respectively. Z_o is called the characteristic impedance of the line. A transmission line terminated in its characteristic impedance is useful as a feeder system for transferring radio frequency energy without radiative losses from a transmitter to an antenna in case the two are necessarily separated by some distance.

b. Because the effective voltage and current vary along an antenna (figs. 133 and 135), the impedance of an antenna varies according to the positions of the connections used to couple it to the power source. A number of methods are possible for properly coupling a nonresonant line to an antenna. Two of them are shown in figure 136 ① and ②. In the arrangement of figure 136① the appropriate impedance match is secured by varying the spacing, A, between the feeder connections. The single-wire line of figure 136② is a modification of the two-wire line in which the ground supplies a return circuit through the antenna to ground capacitance. The proper adjustment of a nonresonant transmission line can be determined by checking for the absence of current maxima or voltage maxima along the line with an inductively coupled flashlight bulb or with a neon bulb in contact with the wire, respectively.

c. If the transmission line is not terminated in its characteristic impedance, resonance effects result. A resonant transmission line, as illustrated in figure 136③ and ④, may be regarded as a portion of the antenna which is folded back on itself so that the radiation from one half cancels the out-of-phase radiation from the other half. The line of figure 136③ is fed from the transmitter at a point of low current and high voltage. Such a feed system is commonly connected to the transmitter across the capacitor of a parallel tuned circuit. The line of figure 136④ is fed from the transmitter at a point of high current and low voltage, and is normally connected in series with a series resonant circuit. Resonant transmission lines are less efficient than nonresonant lines; however, they are easier to adjust, and they are suitable for use over a wider range of frequencies than are nonresonant lines. Resonant lines are satisfactory if the transmitter is located only a short distance from the antenna.

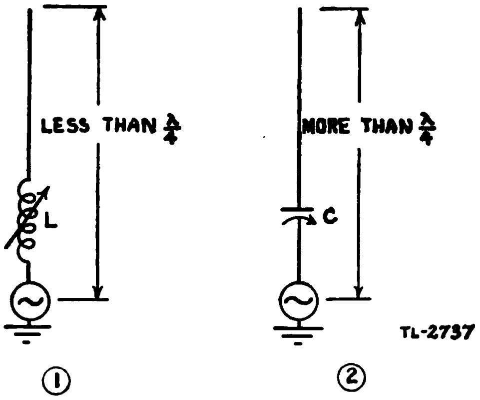


① and ② Nonresonant transmission lines.
③ and ④ Resonant transmission lines.

FIGURE 136.—Feeder systems.

88. Loading.—*a.* Often one antenna system is used to transmit signals of various frequencies. In most instances it is impractical to vary the physical length of the antenna to resonate accordingly as the excitation frequency is changed. However, the electrical length may be changed by loading, that is, by lumped-impedance tuning.

If the antenna is too short for the wave length being used, it is resonant at a higher frequency than that at which it is being excited. Therefore, it offers a capacitive reactance at the excitation frequency. This capacitive reactance can be counterbalanced by introducing a lumped-inductive reactance as shown in figure 137①. Similarly, if the antenna is too long, it offers an inductive reactance, which can be corrected by introducing a lumped capacitive reactance as in figure 137②.



① To compensate for too short an antenna.
② To compensate for too long an antenna.
FIGURE 137.—Loading.

b. Figure 138 shows a typical antenna tuning unit. In ① the transmitter feeds the antenna system at a point of high voltage; in ② the transmitter feeds the antenna system at a point of high current. The arrangements of ③ and ④ provide antenna loading for use with a short antenna, for example, with a short mast antenna of the buggy whip variety as is conveniently mounted on moving vehicles.

89. Propagation of radio waves.—*a.* The radiation from an antenna is conveniently regarded in two parts, that which travels along the surface of the earth, called the ground wave, and that which is propagated at an angle above the horizontal, called the sky wave. The ground wave suffers energy losses because of earth currents which it induces and because of dielectric effects. The attenuation associated with dielectric losses increases with the frequency, so that the ground wave of high frequency transmitters is effective over only relatively short distances. If the ground wave of a 1-megacycle radiation is effective over about 50 miles, the ground wave of a 10-megacycle radiation from a transmitter of comparable power may be essentially confined to within a 10-mile radius.

b. The sky wave passes into the ionosphere, an ionized layer of the earth's atmosphere, at a height of about 70 miles above the surface of the earth. The depth of the layer, its degree of ionization, and its effective height above the earth's surface vary with the seasons, solar radiation, and sunspot activity. The radiant energy of a sky wave is partly transmitted through the ionosphere, partly absorbed in it, and partly reflected back to earth. The angle of reflection depends on the frequency and on the angle of approach of the incident radiation. The reflected sky wave is in part reflected back on striking the surface of the earth and continues on its path from earth to ionosphere and back until it is completely absorbed. A picture of the attenuated ground wave and of the refracted and reflected sky waves from a transmitter is shown in figure 139. Those components of the sky wave which proceed upward at angles with the vertical which are less than the critical angle (fig. 139) are partly absorbed by the ionosphere and partly transmitted through it, but they are in no part reflected back to the earth. The critical angle is related to the frequency of the radiation, increasing as the frequency increases, so that sky waves of ultrahigh frequency are not returned to the earth at all, and communication on these frequencies is almost entirely by means of the ground wave alone.

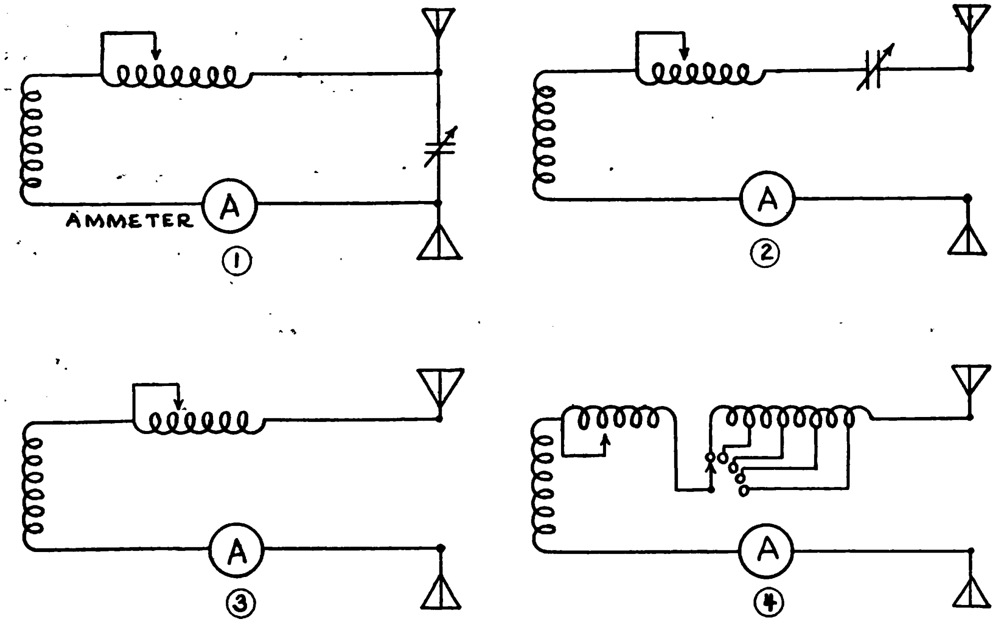


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FIGURE 138.—Antenna tuning unit of radio transmitter BC-191-A.

c. There is a portion of the earth's surface, as shown in figure 139, which is reached by neither ground wave nor sky wave. The distance from the transmitter to the point where the first sky wave returns to the earth is called the skip distance. Skip distances of several hundred miles are common on the higher frequencies.

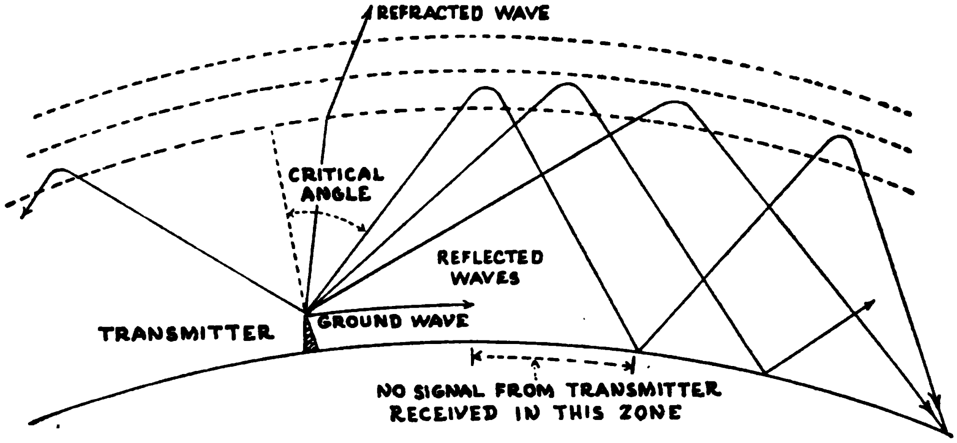


FIGURE 139.—Ground and sky waves from transmitter.

90. Fading.—Fading, random rising and falling of the intensity of a received signal, is attributed to the interaction of different components of the same radiation, which by virtue of having traveled different paths from the transmitter, arrive at the receiver in different phase relations. The condition of the ionosphere is continually changing, so that at one instant the several components of the received wave may be in complete reinforcement to present a very strong signal, and at a later instant the phase relations may be such that the combined effect is very weak.

SECTION XIV

MAJOR COMPONENT PARTS OF RADIO CIRCUITS

91. General.—*a.* In general the theory applicable to electrical communication circuits is the same as that applied to power circuits;

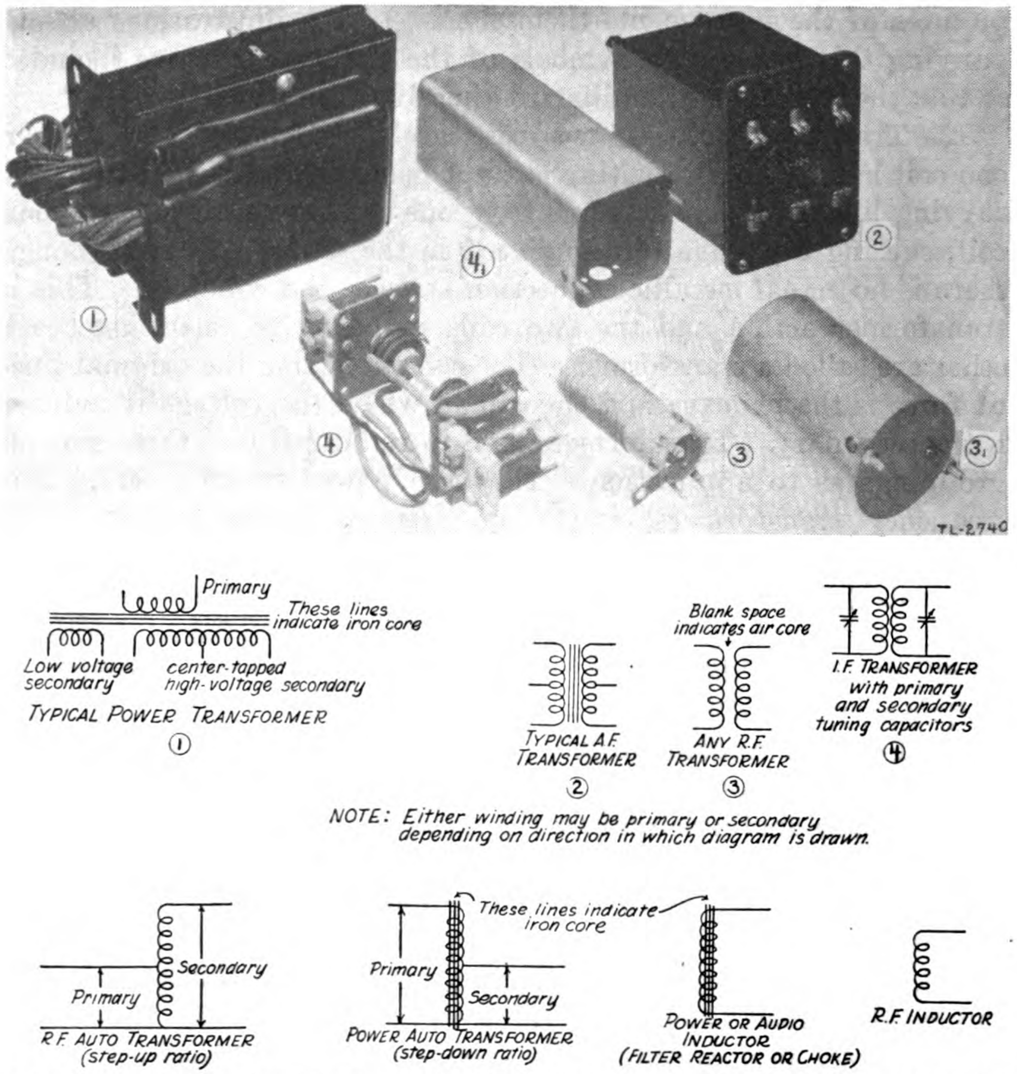
however, the components used in communication circuits differ widely in design from those of power circuits.

b. Certain convenient "symbols" are universally used in radio diagrams to represent these component parts. In effect they are shorthand pictures of the instruments themselves. In the illustrations accompanying this section, the symbols of the various parts are included so that the student can familiarize himself with them.

92. Transformers.—If two coils are placed near to each other, one coil having an alternating current generator connected to it, the varying lines of magnetic force from one coil cut through the second coil, causing a voltage to be induced in the second coil even though there is no actual metallic connection between the windings. This is transformer action and the two coils in inductive relation to each other are called a transformer. The coil producing the original lines of force is the primary and the coil in which the voltage is induced is the secondary. Transformers used in radio fall into three general groupings as to application. They are power transformers, audio frequency transformers, and radio frequency transformers. The power and audio frequency transformers have cores of magnetic materials (usually some form of iron). The radio frequency transformers are generally of air core design; however, very small magnetic cores (usually powdered iron) are used in some intermediate frequency transformers.

93. Power transformers.—Power transformers in general transfer power from one circuit, at a certain frequency, voltage, and impedance to another circuit at the same frequency, but at a different voltage and impedance. Power transformers used in radio receivers and transmitters transform the source voltage, usually 110–120 volts, 60 cycles, to either higher or lower voltages. When the voltage is raised, for example in plate circuit application, the transformer employed is called a step-up transformer; when the voltage is reduced, for example, in filament circuit application, the transformer employed is called a step-down transformer. Power transformers having both step-up and step-down windings on the same core are widely used in radio receiver and transmitter construction. Figure 140① shows a typical power transformer.

94. Audio frequency transformers.—Audio frequency transformers are used to transfer voltages of wide audio frequency range rather than voltages of a single frequency as in the case of a power transformer. A transformer suitable for transforming voltages in the audio frequency range from one circuit to another must have certain design features not found in a power transformer. A perfect transformer should transform without loss or phase change as a result of modifying the magnitude of the load impedance. To accomplish this the transformer would need to have unity coupling,



① Multiwinding power transformer. Flexible leads from the various windings are brought out through holes in the bottom of the case.

② Audio amplifying transformer. This particular one is of the push-pull output type, with tapped primary and secondary.

③ Radio frequency transformer. This fits inside the round aluminum shield can (③$_1$).

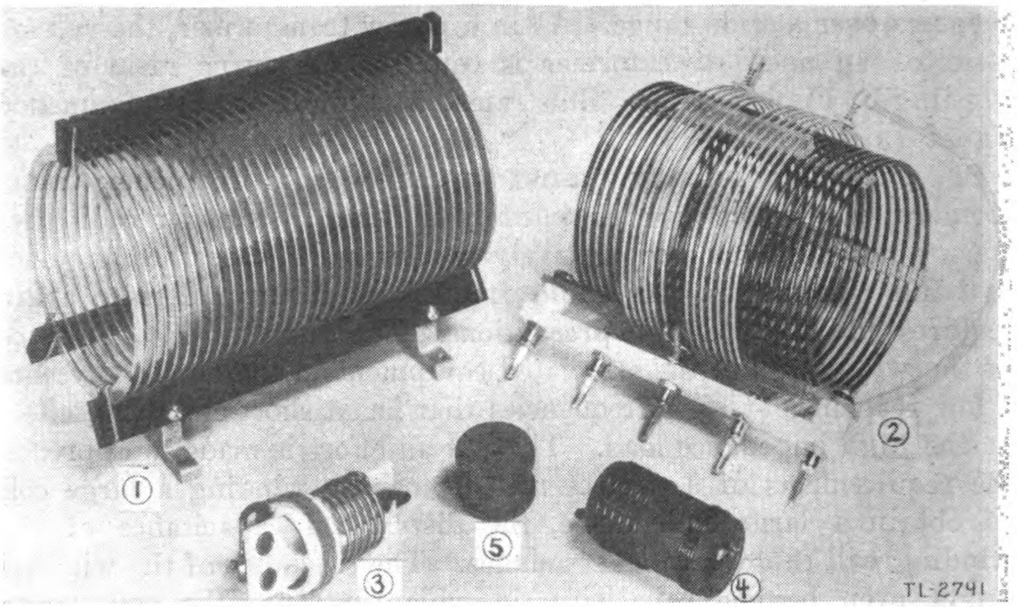
④ Intermediate frequency, with attached midget variable air capacitors for tuning the primary and the secondary. This assembly fits inside the square aluminum shield can (④$_1$).

FIGURE 140.—Typical transformers used in radio circuits.

infinite inductance and no resistance in its primary and secondary windings, yet have a finite ratio of winding inductance. A good audio frequency transformer can only approximate these conditions by having the resistance of its windings small and the inductance of its windings large compared to the circuit with which they are connected, and by having high permeability cores with windings so placed that the flux linkage is a maximum. The frequency response of a transformer is limited at the low frequencies by the inductance of its windings and at the high frequencies by the distributed capacitance of its windings. The core dimensions are determined by the flux required. An audio transformer must be able to carry a limited amount of direct current in its primary winding without causing magnetic saturation of the core. By a suitable compromise of inductance and distributed capacitance, a transformer winding can be designed that will have practically a uniform response to audio frequencies over a wide range. As in a power transformer, the voltage ratio of an audio transformer is equal to the turns ratio of the windings. Figure 140② illustrates a typical audio frequency transformer.

95. Radio frequency transformers.—Radio frequency transformers in receivers and transmitters are used to transfer radio frequency voltages of a comparatively narrow band; therefore, they act as band pass filters. At radio frequencies the transformer again requires additional design precautions. The distributed capacitance of the windings and the associated equipment in the circuit presents a low reactance at high frequencies that has a short-circuiting effect on the high impedance load. Thus, if an effort is made to approach the requirements of a perfect transformer by winding a large coil to obtain a large inductance, the distributed capacitance of the winding will cause parallel resonance. The reactance of the winding might even become capacitive, in which instance the coil would actually act as a capacitor. At radio frequencies, only a comparatively narrow band of frequencies needs uniform amplification, hence the capacitive reactance present can be used in combination with the self-inductance of the windings to obtain resonance and impedances comparable with the R_p of the associated tube. Resonance provides a band pass filter action which passes the wanted frequencies and rejects unwanted frequencies. In practice either one or both of the windings are tuned by variable capacitors of the proper capacitance range to allow tuning across a certain frequency range, for example, 550 to 1500 kc. in the case of a broadcast receiver. The coupling between windings in a radio frequency transformer is rather critical. Loose coupling will cause insufficient voltage transfer and a loss of wanted frequencies; tight or overcoupling will broaden the response or resonance curve and allow unwanted frequencies to pass. The induced voltage in the secondary at optimum coupling is seldom much higher than the primary voltage; however, there is a resonant rise in voltage in the secondary due to the Q of the resonant circuit. The presence of iron cores at radio frequencies gives rise to eddy current and hysteresis losses that practically preclude their use except in the case of intermediate frequency transformers. Figure 140③ shows a typical radio frequency transformer and ④ shows a typical intermediate frequency transformer.

96. Autotransformers.—It is possible to obtain transformer action with only a single coil if a connection is made somewhere along the winding between the extreme ends. If a step-up voltage effect is desired, the winding between the tap and one end is considered the primary and the entire winding acts as the secondary. If a step-down effect is desired, the entire winding is considered the primary and the section between the tap and one end acts as the secondary. Such transformers are known as "autotransformers" and are used in both power and radio frequency applications.

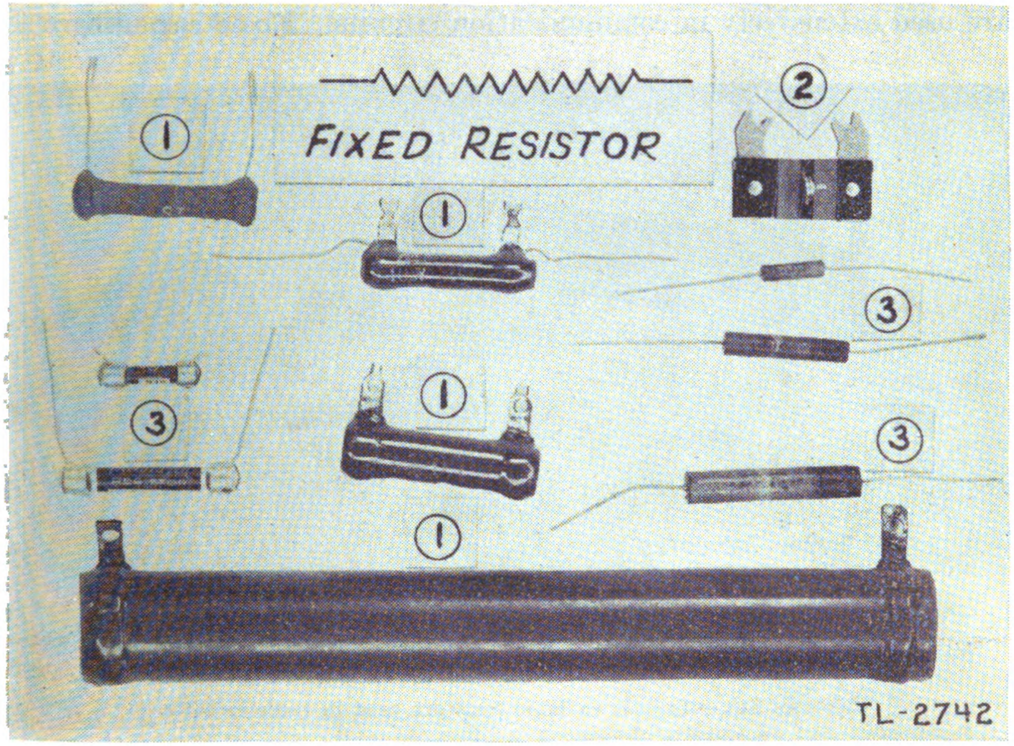


① Single-winding "tank" inductor, used in high power transmitters.
② Plug-in type r. f. transformer used in medium power transmitters.
③ and ④ Small r. f. transformers used in ultrahigh frequency receivers and transmitters.
⑤ Small r. f. inductor or "choke coil" used in receivers and low-power transmitters.

FIGURE 141.—Typical r. f. inductors and transformers.

97. Inductors.—An inductor is any single-winding coil. If it has many turns of wire on an iron core, its inductance and therefore its impedance are high, and it is used mainly as part of low frequency filter systems, especially in a. c. power supplies for receivers and transmitters. Iron core inductors, sometimes called "chokes," resemble power and amplifying transformers in appearance (fig. 140① and ②).

a. Inductors consisting of small air-core spools of wire have a high impedance to radio frequency currents, and are therefore used as chokes in r. f. circuits (fig. 141⑤).



Those in group ① use resistance wire wound on ceramic tubes, with the wire itself covered by a protective coating of heavy enamel. The single resistor ② is also of the wire-wound type, but with a center tap and without covering for the wire. Those in group ③ use a thin layer of metallized carbon on an insulating form, or consist of a solid carbon stick of small cross section.

FIGURE 142.—Typical fixed resistors employed in radio sets.

b. Inductors consisting of a few large turns of heavy wire are used as part of the *LC* "tank" circuits of transmitters. Since they are subjected to high voltages and must carry considerable r. f. current, their insulation must be very good (fig. 141①).

98. Fixed resistors.—Fixed resistors used in radio circuits are of many types and sizes. They range in resistance from a fraction of an ohm to several megohms. Resistors are rated in ohmic value and also according to the power which they can safely dissipate in the form of heat. Figure 142 illustrates typical fixed resistors of various values of resistance and wattage.

99. Variable resistors.—In many instances variable resistors are desirable for obtaining control of current flow in a circuit. There are many types of variable resistors used in radio circuits. Further classified as to application, they fall under the general headings of rheostats, potentiometers, voltage dividers, etc. Figure 143 illustrates these types of variable resistors.

100. Fixed capacitors.—*a*. Both fixed and variable capacitors are used extensively in communication circuits. Fixed capacitors are of various types and sizes and, in general, are classified in terms of the dielectric used, as mica capacitors, paper capacitors, oil filled capacitors, etc. The electrolytic capacitor uses as a dielectric a thin film of oxide and gas which is formed chemically when voltage is applied to the unit. One of the conductors is usually aluminum foil and the other the electrolyte. Like batteries, electrolytic capacitors are manufactured both in the wet and dry types. Due to the extremely thin film of dielectric, very large values of capacitance without excessive physical size can be obtained. These capacitors have high leakage and low internal resistance as compared to other types and are useful only in pulsating d. c. circuits. Attention must be given to the proper polarity of these capacitors when they are connected in a circuit. Due to these operational limitations electrolytic units are used almost exclusively in power filter circuits.

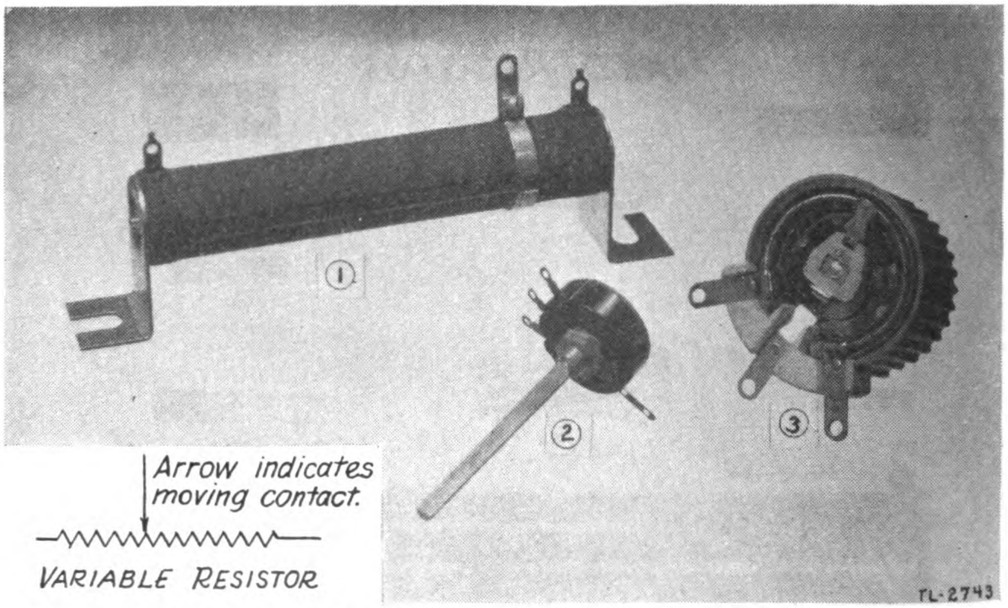
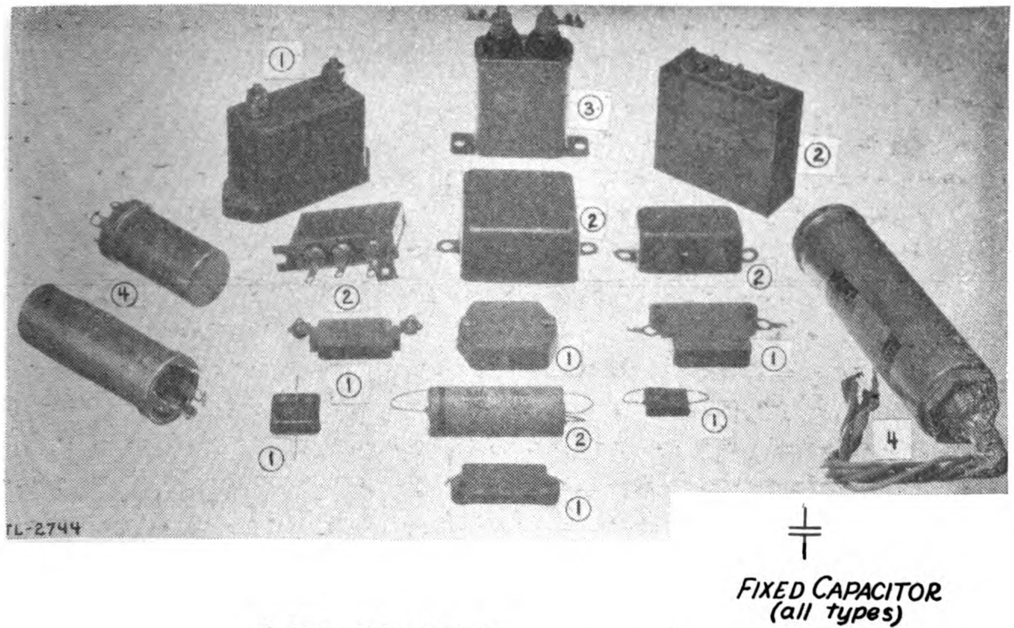


FIGURE 143.—Typical variable resistors used in radio circuits.

b. Mica capacitors have low leakage and high voltage ratings but are limited in capacitance by cost factors to about 0.05 microfarad.

Paper capacitors consist of tinfoil and paper rolled together and impregnated with wax to exclude moisture. Capacitors of this type vary approximately in capacitance values from $1/10$ to 2 microfarads. Where large capacitance and high voltage rating are required, oil filled capacitors are used. The actual dielectric material is oil-treated paper, and the whole container is also filled with oil to keep the assembly protected. Figure 144 shows a group of fixed capacitors of various types.

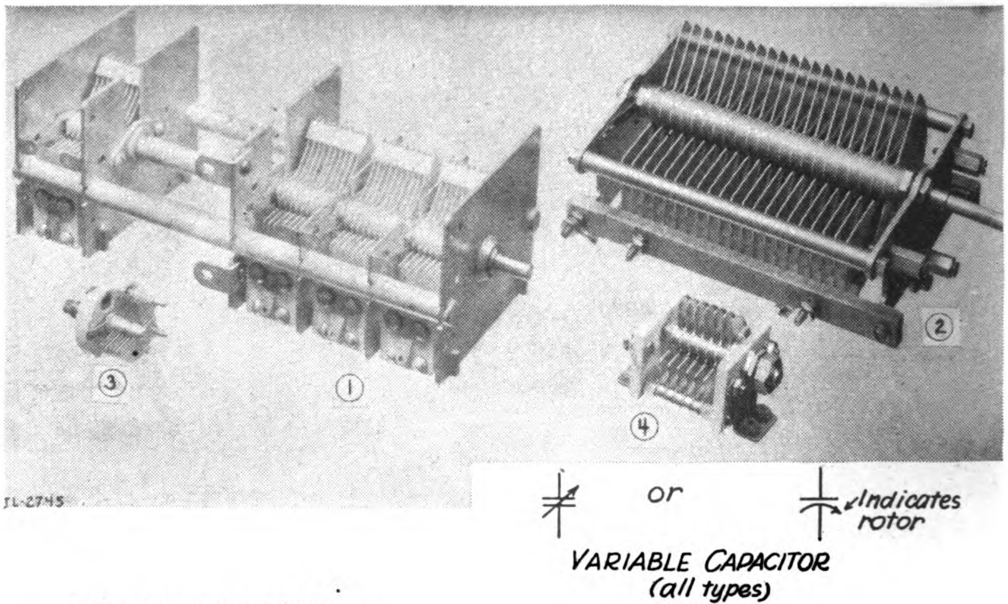


① Mica dielectric type.
② Paper dielectric, wax impregnated.
③ Paper dielectric, oil impregnated.
④ Electrolytic.

FIGURE 144.—Typical fixed capacitors.

101. Variable capacitors.—Most variable capacitors used in communication circuits are of the air dielectric type. In general, they consist of two sets of metal plates insulated from each other and so arranged that one set of plates can be moved in relation to the other set. The stationary plates are called the stator; the movable plates, the rotor. The capacitance range of variable air capacitors is from a few micromicrofarads to several hundred. Figure 145 shows a typical group.

102. Piezoelectric crystals.—Certain crystals, of which quartz is the principal one encountered in radio, exhibit a phenomena called the piezoelectric effect. Prepared sections cut from such a crystal will, when subjected to an electric field, be placed under stress and slightly deformed. If the crystal section is placed under such mechanical stress, it will develop a difference of potential between its faces. Such a crystal section has a natural frequency of mechanical vibration determined by its position in the original crystal. A crystal section for use in radio is ground to a thickness which will produce a desired frequency, and is mounted in a holder with its faces in contact with metal electrodes. An example of its use is control of frequency in a vacuum tube oscillator circuit. Some of the tuned circuit voltage is fed back to the crystal, causing it to vibrate and produce a varying potential between its electrodes. This is in turn amplified and impressed on the tuned circuit. Optimum output is obtained by tuning the circuit to the crystal's natural frequency, which is highly stable. The use of crystals in filter circuits has been explained in paragraph 73. Figure 146 illustrates some typical crystals and holders.



① Four-gang receiving type.
② Single unit, with wide plate spacing, used in high-power transmitters.
③ Midget "trimmer" or "padder" type.
④ Midget type, with wide plate spacing, used in high frequency transmitters.

FIGURE 145.—Typical variable capacitors.

103. Microphones.—A microphone is a device for converting acoustical energy into electrical energy. The various types of microphones are named in accordance with the methods used to produce this conversion. Thus, there are carbon, condenser, dynamic, velocity, and crystal microphones. Carbon microphones use the variation of resistance between carbon granules, due to acoustical or sound pressure on a diaphragm, to vary an electrical current at sound frequencies. Condenser microphones operate on the principle of acoustical energy causing variation in the spacing between two plates; the resulting variation of electrostatic capacitance causes a

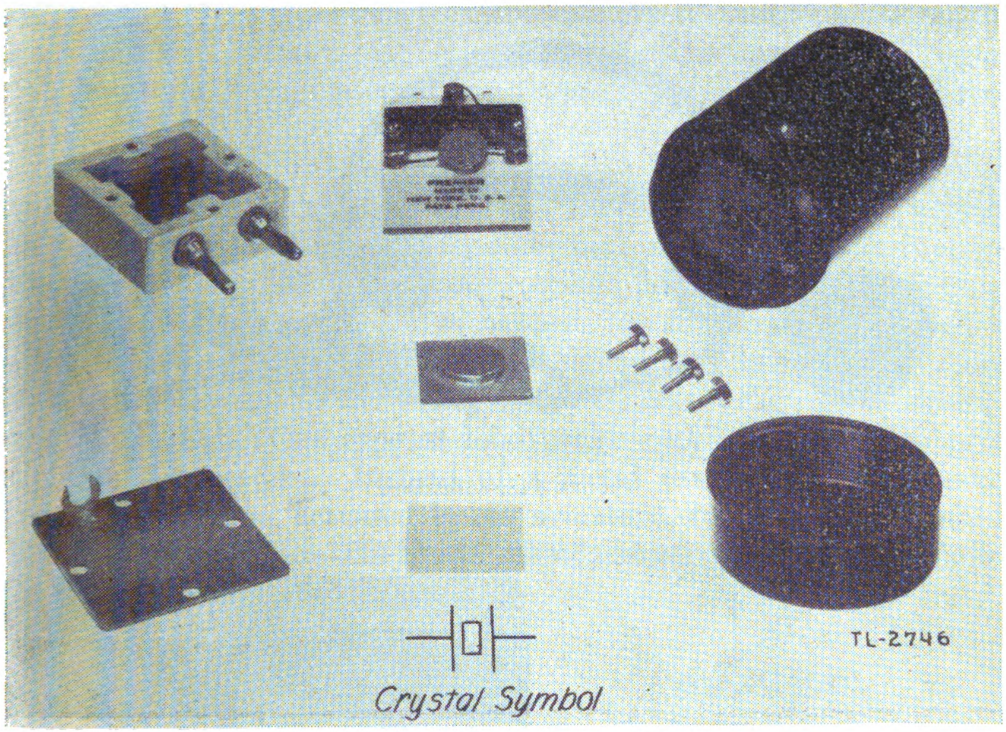


FIGURE 146.—Typical crystals and holders.

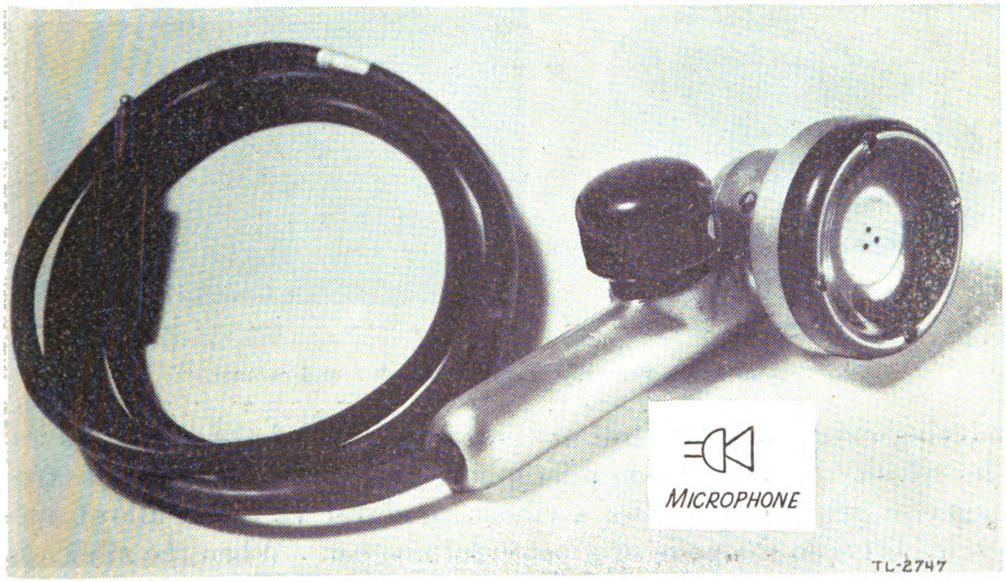


FIGURE 147.—Carbon microphone, T-17.

variation at sound frequencies in a high d. c. potential applied between the plates. A dynamic microphone uses a low-impedance coil mechanically coupled to a diaphragm. The sound waves move the diaphragm and coil, the movement of the coil in a magnetic field inducing currents in the coil at the frequencies of the sound waves. The velocity type or ribbon microphone also operates on the electromagnetic principle but uses a ribbon of dural (a metal alloy) suspended between the poles of a powerful magnet. When the ribbon is vibrated by acoustical energy, it cuts the lines of force and a current,

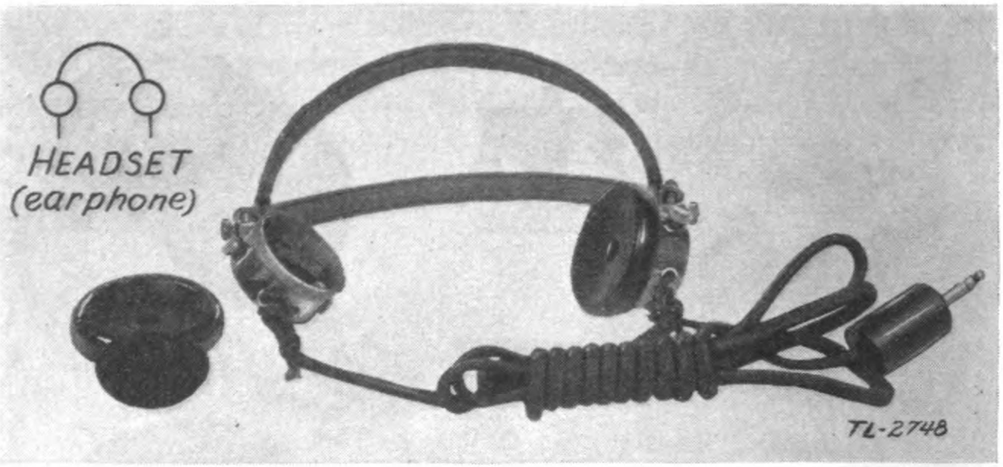


FIGURE 148.—Headset.

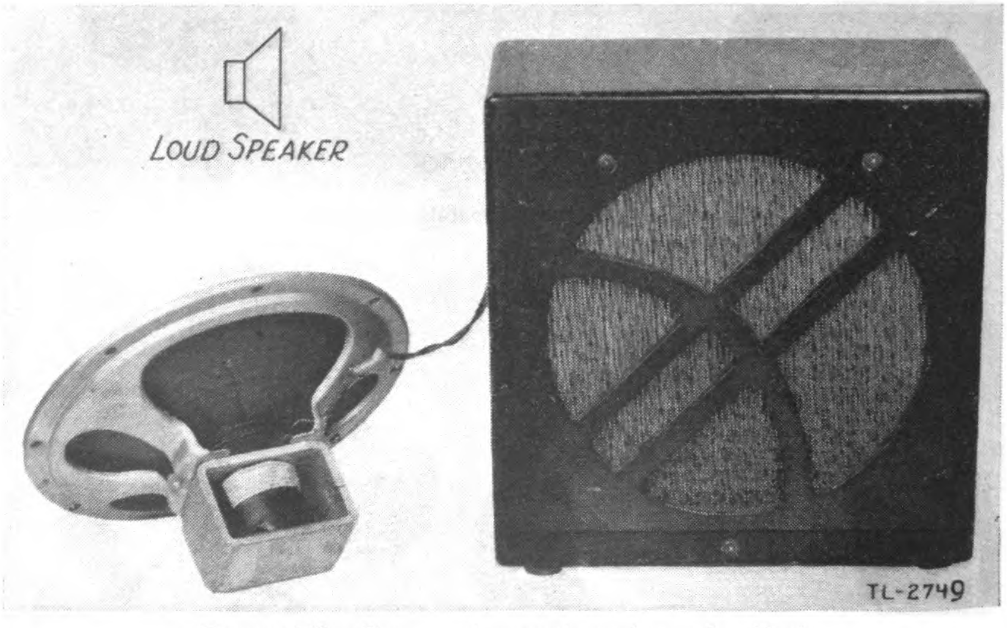
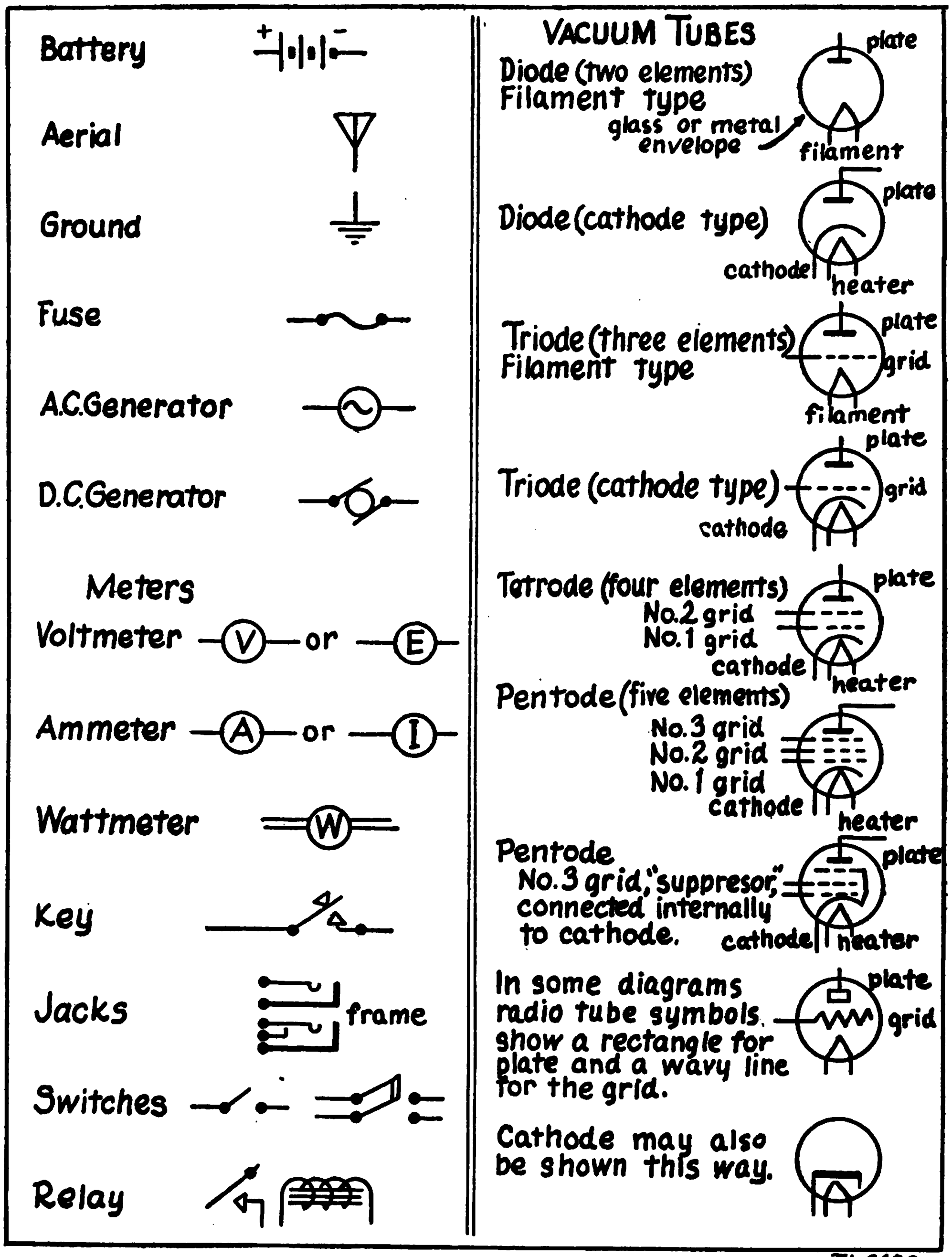


FIGURE 149.—Permanent magnet speaker and cabinet.

which varies in accordance with the sound waves, is induced in the ribbon. One type of crystal microphone has a Rochelle salt crystal fastened to a diaphragm. Sound waves move the diaphragm and cause the crystal to vibrate, thus producing an alternating voltage between the crystal electrodes at the frequencies of the sound waves. All of the types mentioned except the crystal microphone require some source of current, magnetic field, or polarizing voltage. Figure 147 shows an Army microphone (type T-17) which is the carbon type.

104. Headsets and loudspeakers.—A headset or a loudspeaker is a device for converting electrical energy into acoustical energy. In general, the headset or loudspeaker performs the opposite function of a microphone. When varying currents flow through the windings on the permanent magnet of a headset, the diaphragm is caused to vibrate in accordance with these currents and produces audible sound waves proportional to the variations of current. Figure 148 shows a typical headset. One type of loudspeaker works on the same principle as the headset. Instead of a metal diaphragm, the speaker uses a paper cone, actuated by an armature, for setting up audible sound waves. Figure 149 shows a loudspeaker of this type removed from its cabinet.



TL-3139

FIGURE 150.—Additional symbols used in radio diagrams.

APPENDIX I

ABBREVIATIONS

The use of certain abbreviations to represent radio words, terms, and expressions, in diagrams and written matter, has become standard. It is well to understand how they are derived and used.

As a general rule, a basic word is abbreviated merely by putting a period after its first letter. Thus w. represents watts and h. represents henrys. If the basic word takes on a prefix to indicate a larger or a smaller unit, the initial letter of the prefix is combined with the initial letter of the word. Thus kilowatt becomes kw. when it is preceded by a number; that is, 10 kw. to mean ten kilowatts. All abbreviations are both singular and plural; the plural form does not take a final s.

The Greek letter μ (pronounced *mū*) stands for micro, meaning one millionth part. It may precede any basic unit of measure. Thus the farad, the measure of capacitance, which is too large for practical purposes, invariably is cut down to the microfarad, one millionth part of a farad. For very small capacitances, the unit micromicrofarad is used. The corresponding abbreviations are μf and $\mu\mu$f.

The letter m as a prefix means one thousandth part. (By itself or as the last letter of an abbreviation it means meter, the unit of length in the metric system.) Milliampere, a thousandth of one ampere, is abbreviated as ma. Small radio frequency inductors (choke coils) usually have values of a few millihenrys, the abbreviation for this unit being mh.

The capital letter M (to be distinguished carefully from the small letter m) is sometimes used for mega, meaning one million. It applies particularly to the term megacycles, one million cycles. Because it is so readily confused with m for milli, it should be avoided, and the word megacycles should be spelled out in full wherever possible.

The Greek letter μ is also used as a general symbol—not as an abbreviation—for the amplification factor of vacuum tubes and for the permeability of magnetic materials. Since it is employed alone in these connections, it is not likely to be mistaken for the prefix μ meaning one millionth.

The student who reads books and current magazines will quickly notice certain very confusing irregularities in the use of the prefix letters μ and m. In many cases m is employed instead of μ to indicate one millionth, and in the same text it is also used to mean one thousandth. The abbreviation mf. (also frequently given as mfd.) correctly means millifarad, but capacitors having values in millifarads would be enormous. (The largest capacitors used in radio work are about 50 microfarads.) Actually, the "mf." is intended to mean μf., microfarads, and it is fairly safe to assume that this is the case. However, when the letter m is used before a. for ampere or v. for volts, the abbreviations are quite likely to mean milliampere or microampere, or millivolt or microvolt, respectively, unless the circuit conditions, the nature of the apparatus, etc., give some indication of what unit is intended. To avoid this trouble, publications of certain engineering societies use no abbreviations at all, but spell out all words and terms. This is a safe and sensible practice, but it is often desirable or even necessary to employ the shortened forms, and the following list is therefore given as a matter of information and reference. The abbreviations are grouped according to their common usage, rather than alphabetically.

Abbreviation	*Meaning*
a	ampere
μa	microampere (one-millionth of an ampere)
ma	milliampere (one-thousandth of an ampere)
v	volt
μv	microvolt (one-millionth of a volt)
mv	millivolt (one-thousandth of a volt)
kv	kilovolt (one thousand volts)
kva	kilovolt-ampere
w	watt
μw	microwatt (one-millionth of a watt)
mw	milliwatt (one-thousandth of a watt)
kw	kilowatt (one thousand watts)
ohm	Not abbreviated. Spell out in full or use the Greek letter omega (Ω).

Abbreviation	*Meaning*
Greek letter omega Ω (capital) ω (small letter)	The Greek letter omega is the equivalent of the letter o, so it is frequently used in diagrams to indicate resistance values in ohms. The capital omega should always be used because the small letter looks like an ordinary w and can easily be confused with w for watt.
MΩ	megohm (mega plus ohm), meaning one million ohms.
c	cycle
kc	kilocycle (one thousand cycles)
mc	megacycle (one million cycles)
f	farad
μf	microfarad (one-millionth of a farad)
μμf	micromicrofarad
h	henry
μh	microhenry (one-millionth of a henry)
mh	millihenry (one-thousandth of a henry)
m	meter (measure of length)
cm	centimeter (one-hundredth of a meter)
mm	millimeter (one-thousandth of a meter)
L, C, R	These are used as symbols rather than as abbreviations for inductance (L), capacitance (C), and resistance (R), in formulas and diagrams. Thus, the inductors in a circuit usually are marked L1, L2, L3, etc.; the capacitors C1, C2, C3, etc.; and the resistors R1, R2, R3, etc.

Abbreviation	*Meaning*
I or i E or e	Similarly used as symbols to represent current (I or i) and voltage (E or e). Thus, I_p, used in discussions of tube characteristics, means plate current; E_g means grid voltage.
K or k	Used alone near tube symbols, represents the cathode connections.
H or h	Used alone near tube symbols, represents the filament or heater connections.
G or g	grid
P or p	plate
c. w.	continuous wave (refers to keyed, unmodulated radiotelegraph signals)
i. c. w.	interrupted continuous wave (keyed "tone" radiotelegraph signals)
r. f.	radio frequency
t. r. f.	tuned radio frequency
a. f.	audio frequency
i. f.	intermediate frequency
r. f. t.	radio frequency transformer
a. f. t.	audio frequency transformer
i. f. t.	intermediate frequency transformer
d. c.	direct current
a. c.	alternating current. ("D. c. current" and "a. c. current" are incorrect usage)
h. f.	high frequency
u. h. f.	ultra high frequency
b. f.	beat frequency
b. f. o.	beat frequency oscillator
a. m.	amplitude modulation
f. m.	frequency modulation
a. v. c.	automatic volume control
d. a. v. c.	delayed automatic volume control

Abbreviation	*Meaning*	
a. v. e.	automatic volume expander	
ant	antenna	
gnd	ground	
xtal	crystal	
c. r.	cathode ray	
SW	switch	
s. p. s. t.	single pole single throw (refers to switches)	
d. p. d. t.	double pole double throw	
d. p. s. t. (etc.)	double pole single throw	
d. c. c.	double cotton covered (refers to wire insulation)	
s. s. c.	single silk covered	
s. c. c. (etc.)	single cotton covered	
c. p. s.	cycles per second	
r. p. m.	revolutions per minute	
hp	horsepower	
r. m. s.	root mean square	
"mike"	microphone	
"A"	Refers to power supplies to the filament ("A"), plate ("B"), and grid ("C") circuits of radio tubes. Originally meant to designate batteries (storage or dry type) but now used in a general sense.	
"B"		
"C"		
e. c. o.	electron coupled oscillator	
v. t. v. m.	vacuum-tube voltmeter	
WVP, WAR (etc.)	Call signs of radio stations are all capitals, without periods.	
C	Centigrade	Temperature scales. When not otherwise indicated, readings in degrees are assumed to be on the Fahrenheit scale.
F	Fahrenheit	

APPENDIX II

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TM 1-455, "Electrical Fundamentals." This is an Army publication.

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"Receiving Tube Manual."

"Transmitting Tube Manual," both published by RCA Manufacturing Company, Inc., Camden, N. J.

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(For explanation of symbols, see FM 21–6.)

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