

CHAPTER IX.—THE RADIO-TELEGRAPHIC TRANSMITTER

THE VALVE OSCILLATOR

Conversion of mechanical energy into oscillations

1. In this chapter it is proposed to deal with the production of oscillatory currents by means of the thermionic valve. By this is meant the conversion of electrical energy, which is supplied by a source of electromotive force, such as a primary battery or a direct current generator, into energy which is still electrical, but which takes the form of oscillations in a circuit possessing inductance and capacitance. In considering the production of continuous electrical oscillations, two useful analogues may be given. First, we have the production of a continuous sound wave by the violin. The sound is a longitudinal vibration of the air which is set in motion by the vibrating violin string. Suppose the frequency to be emitted is 256 cycles per second, corresponding on the scientific scale to the note "middle C"; it is quite impossible for the performer directly to supply to the string the energy required to cause it to vibrate with undamped amplitude at this rate. To put it crudely, he cannot shake the string continuously at such a high frequency, while merely plucking it and allowing it to vibrate freely will set up a damped vibration, which is not the aim of the performer. The violinist therefore supplies the energy not directly to the string, but to the bow, which is composed of horse hair and is covered with resin. This forms an adhesive surface which repeatedly grips and releases the string as it is moved over the latter, and the continuous supply of energy imparted to the bow is converted into energy in the form of oscillation in the string and the surrounding air. Second, take an ordinary carbon microphone and a telephone receiver and connect them in series with a suitable battery. If the microphone and receiver are placed near each other, it may be found that the telephone receiver commences to howl, apparently spontaneously. If the reader has never performed this experiment, he is advised to do so; if a service "hand press" microphone is used, the type of receiver used for land-line telephone will be found better than a wireless telephone receiver for this purpose, and a six-volt battery will probably be sufficient to cause the effect.

2. This emission of sound by the telephone takes place because sooner or later, some slight noise will occur in the vicinity of the microphone. This noise is a sound wave and consists of successive states of compression and rarefaction in the surrounding atmosphere. These variations of pressure, impinging upon the diaphragm of the microphone, cause variations of resistance of the carbon granule pack, and consequently a variation of current in the electrical circuit. This variation of current flowing round the coils of the telephone receiver produces a movement of the diaphragm, and consequently an emission of sound. This sound travels through the air to the microphone causing a further change in its resistance and a repetition of the foregoing cycle of events will occur, *ad infinitum*. In this instance energy is drained continuously from the battery, and is partly converted into mechanical oscillation of the telephone diaphragm.

The triode oscillator

3. The phenomena associated with the discharge of a condenser in a circuit possessing inductance and resistance is discussed in Chapter VII, and it is there stated that the discharge

will be of an oscillatory nature if the resistance of the circuit is less than $2\sqrt{\frac{L}{C}}$. The quantity of

electricity stored in the condenser at the end of each successive half-cycle becomes progressively less until all the original energy has been dissipated, and the oscillation so produced is referred to as a damped oscillation. An undamped electrical oscillation will be produced only if arrangements are made to introduce into the circuit, at regular intervals, an amount of energy equal to that dissipated in the interval, and this may be accomplished by means of the triode valve. Fig. 1 shows what is probably the simplest arrangement for the purpose; in this diagram the

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circuit to be maintained in oscillation consists of a condenser having a capacitance of C farads, an inductance of L henries and a resistance of R ohms which may be supposed to represent the whole of the causes of energy dissipation, while T is a triode valve with its usual sources of H.T. and L.T. supply. The coil L_1 , shown in dotted line, is called the reaction coil, and performs a most important function, but in a preliminary study of the action of the valve, we may consider this coil to be omitted, the grid and filament being directly connected. On closing the switch S an anode current will be established owing to the electric field set up between filament and anode by the H.T. voltage, and this current will flow through the inductance L . The latter must offer opposition to the growth of the current in the form of a counter-E.M.F. the effect of which is to set up a P.D. between the plates of the condenser C , and a resulting displacement current in the dielectric. The anode current tends to a steady value, and the counter-E.M.F. of the inductance becomes smaller and smaller, as the voltage of the condenser rises, and very shortly after the switch is closed, the charge gained by the condenser causes its P.D. to rise above the counter-E.M.F. of the inductance. The condenser will then commence to discharge through the conductive path, setting up a damped oscillation of the nature described in Chapter VII, and upon its cessation,

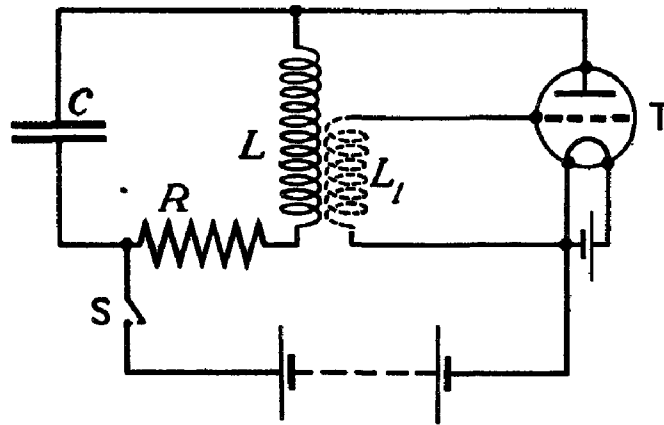


FIG. 1, CHAP. IX.—Simple C.W. oscillator.

the anode current will remain at a constant value. Since there is then no counter-E.M.F. in the inductance no further oscillation will take place. Under the above conditions, the triode merely acts as a series resistance of a few thousand ohms and tends to damp out rather than to maintain the oscillation.

4. Let us consider this oscillation more closely, and suppose that the initial voltage to which the condenser is charged is 100 volts, while the persistency of the ensuing oscillation is 81 per cent. The latter statement implies that if no further energy is imparted to the oscillatory circuit, the amplitude of the condenser P.D. at its second peak will be 90 volts, the polarity of the condenser being reversed. In order to maintain an undamped oscillation an additional charge must be introduced into the condenser during every cycle of oscillation, the magnitude of which will be sufficient to raise the condenser P.D. to its original value despite the wastage of energy which occurs. This energy may be introduced by causing a variation of anode current of such a nature that the resulting counter-E.M.F. is in phase with the counter-E.M.F. caused by the condenser discharge, and the variation of anode current can be achieved by variation of the grid-filament potential. It is for this purpose that the reaction coil L_1 is fitted. The changing flux set up by the oscillatory current through the coil L links with the reaction coil, setting up in it an E.M.F. and therefore a P.D. between grid and filament of the valve, which varies in the same manner as the magnetic flux. The variation of grid-filament potential in turn causes the anode current to vary at the frequency at which the circuit L, C, R , is oscillating; provided that the connections to the coil L_1 are correctly made, the changes of anode current are so timed, or phased, as to augment the charge which is flowing into the condenser at any instant, and the valve will then tend to maintain the circuit in oscillation. Oscillations will however only be maintained if the mutual inductance between the coils L and L_1 exceeds a certain value which depends upon the constants of the

valve as well as upon those of the oscillatory circuit. It has already been stated (Chapter VIII) that if the grid-filament voltage of the triode varies in a sinusoidal manner, i.e. if $v_g = \mathcal{V}_g \sin \omega t$ the valve may be considered to act as a generator having an E.M.F. equal to μv_g or $\mu \mathcal{V}_g \sin \omega t$ volts and an internal resistance of r_a ohms. The equivalent circuit is therefore that of fig. 2 in which the equivalent generator is shown to be supplying the tuned anode circuit L, C, R . As the grid-filament voltage is actually derived from the oscillatory circuit by mutual induction between the anode circuit inductance and the reaction coil, the tuned anode circuit must be in parallel resonance with the supply frequency, and will therefore offer an effective or dynamic resistance of $\frac{\omega^2 L^2}{R}$ or $\frac{L}{CR}$ ohms.

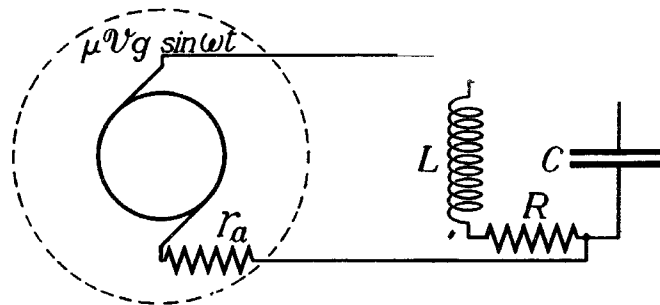


FIG. 2, CHAP. IX.—Equivalent circuit of fig. 1.

Coupling conditions for maintenance of oscillations

5. The building up of an oscillation may now be considered more closely. Assuming that the initial rise of current will cause some feeble oscillation in the circuit L, C, R , let the oscillatory current through the inductance be $i_L = \mathcal{I}_L \sin \omega t$ superimposed upon the steady current, I_a . In this discussion it is only necessary to consider the oscillatory current, and the steady component will therefore be ignored. Remembering that i_L is sinusoidal in form, it may be helpful to omit the factor “ $\sin \omega t$ ” for the present, and to confine the investigation to amplitudes only. The sequence of events following the initial rise of current may now be enumerated quantitatively:—

(i) The oscillatory current through the inductance L will have a peak value \mathcal{I}_L by hypothesis. This current produces an oscillatory flux, which linking with the coil produces by Faraday’s law, an E.M.F.

$$\mathcal{V}_g = \omega M \mathcal{I}_L$$

(ii) This E.M.F. is applied between grid and filament of the valve; the effective voltage in the anode circuit is $\mu \mathcal{V}_g$ and

$$\mu \mathcal{V}_g = \omega M \mu \mathcal{I}_L$$

(iii) The resulting anode current change is of the same form as \mathcal{V}_g that is, sinusoidal, and has the value \mathcal{I}_a where $\mathcal{I}_a = \frac{\mu \mathcal{V}_g}{Z}$; since $Z = r_a + \frac{L}{CR}$

$$\mathcal{I}_a = \frac{\omega M \mu \mathcal{I}_L}{r_a + \frac{L}{CR}}$$

(iv) This oscillatory current acts as a supply current to the reactor circuit L, C, R and will produce in it an oscillatory current \mathcal{I}'_L . The relation between supply current \mathcal{I}_s and oscillatory (or circulating) current \mathcal{I}_o in a reactor is given in Chapter V by the equation

$$\mathcal{I}_o = \frac{\omega L}{R} \mathcal{I}_s$$

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In this particular case \mathcal{I}_o is the new oscillatory current \mathcal{I}'_L and the supply current is \mathcal{I}_a .

$$\therefore \mathcal{I}'_L = \frac{\omega L}{R} \mathcal{I}_a$$

or

$$\mathcal{I}'_L = \frac{\omega L}{R} \times \frac{\omega M \mu \mathcal{I}_L}{r_a + \frac{L}{CR}}$$

from which it will be seen that the second impulse of oscillatory current \mathcal{I}'_L will be equal to the first one, \mathcal{I}_L , if

$$\frac{\omega^2 LM \mu}{R r_a + \frac{L}{C}} = 1.$$

By the relation $\omega^2 = \frac{1}{LC}$ this may be written as

$$\frac{\mu M}{CR r_a + L} = 1.$$

6. If μM is greater than $CR r_a + L$ the second impulse will be greater than the initial one, and as M may be either positive or negative its sign will decide whether the tendency of the

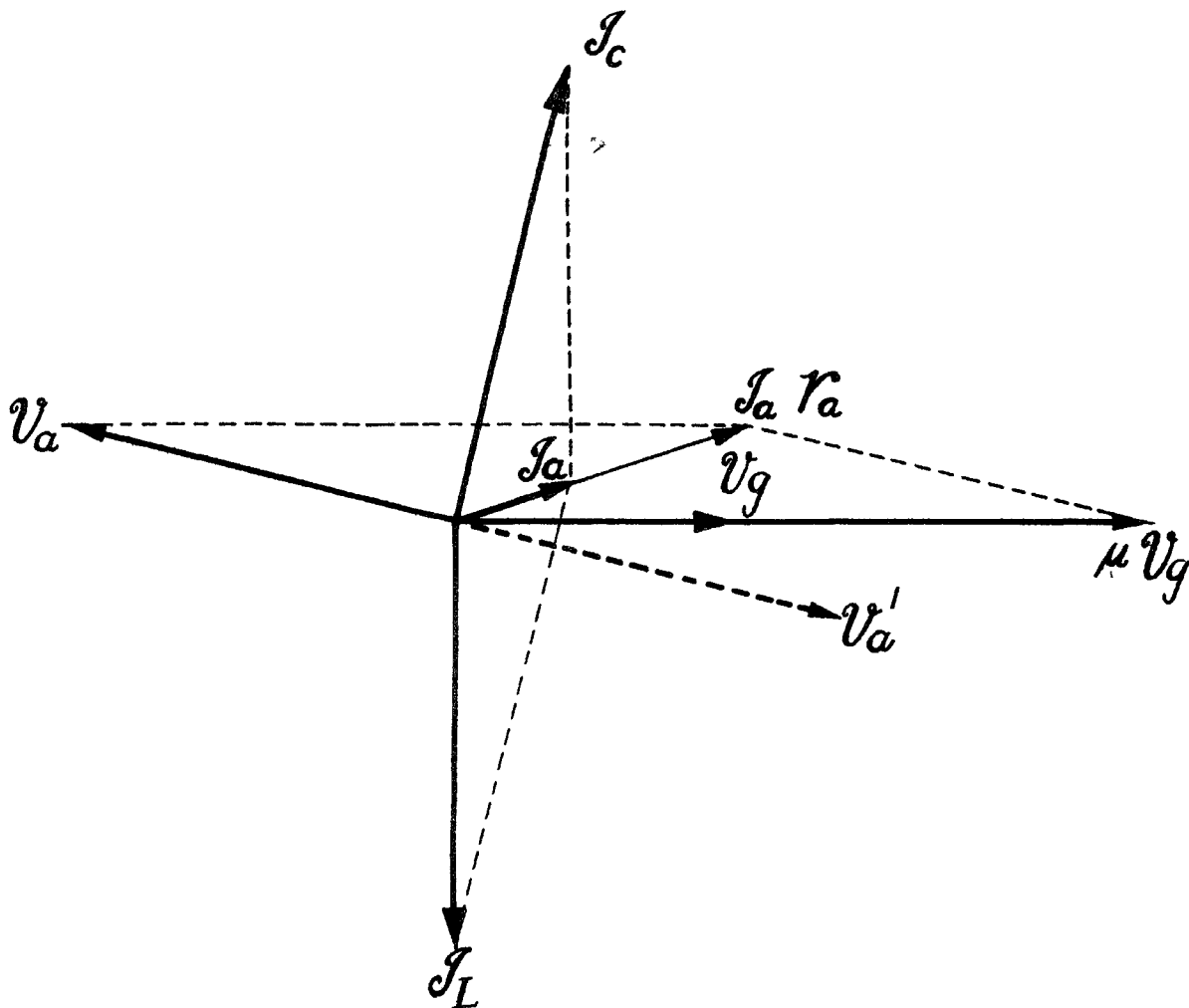


FIG. 3, CHAP. IX.—Vector diagram showing phase relations for maintenance of oscillations.

induced grid-filament voltage v_g is to maintain or suppress the oscillation. Oscillation will only be maintained if the grid-filament voltage leads upon the current in the inductance by an angle approaching 90° , as shown in the vector diagram, fig. 3. Here the datum vector is \mathcal{I}_L . Reverting to the use of instantaneous values, since $i_L = \mathcal{I}_L \sin \omega t$ and $\frac{di_L}{dt} = \omega \mathcal{I}_L \cos \omega t$ (Chapter V),

$$\begin{aligned} v_g &= -M \frac{di_L}{dt} \\ &= -M \omega \mathcal{I}_L \cos \omega t. \end{aligned}$$

Therefore v_g lags on i_L by 90° if M is positive, and for the correct phasing conditions M must be negative in sign.

The anode-filament P.D. is shown by the vector \mathcal{V}'_a equal and opposite to the vector \mathcal{V}''_a which is the oscillatory P.D. across the tuned anode circuit. Since

$$\mathcal{V}'_a = R i_L + L \frac{di_L}{dt}$$

and

$$i_L = \mathcal{I}_L \sin \omega t$$

$$\mathcal{V}'_a = R \mathcal{I}_L \sin \omega t + \omega L \mathcal{I}_L \cos \omega t$$

$$= \sqrt{R^2 + \omega^2 L^2} \mathcal{I}_L \sin \left(\omega t + \tan^{-1} \frac{\omega L}{R} \right).$$

That is, \mathcal{V}'_a leads on \mathcal{I}_L by an angle $\tan^{-1} \frac{\omega L}{R}$ which is nearly 90° because in practice ωL is much larger than R . The anode-filament P.D. \mathcal{V}''_a is equal and opposite to this, and is therefore practically 180° out of phase with the grid-filament voltage \mathcal{V}''_g .

The current \mathcal{I}_c through the capacitive branch of the tuned circuit leads on the P.D. \mathcal{V}'_a by 90° , and the oscillatory component of the anode current, \mathcal{I}_a , is the vector sum of \mathcal{I}_L and \mathcal{I}_c . It is very nearly in phase with the grid-filament voltage \mathcal{V}''_g .

Final amplitude reached by the oscillation

7. In the simple circuit shown in fig. 1 the condition for any oscillation once started to increase in amplitude, is that μM must be greater than $CR r_a$. Now although μ , r_a and g_m are commonly referred to as the "constants" of a triode, the ratios which they represent are only constant over the portion of the characteristic curve which is approximately straight. As the anode current decreases, reaching the curved foot of the characteristic, the mutual conductance decreases and the anode A.C. resistance increases. The result of this opposite tendency is that the amplification factor usually remains fairly constant over a very wide range, although the anode A.C. resistance becomes greater for small values of anode current. It may therefore be assumed that in the relation $\mu M > CR r_a + L$ which must be satisfied if the oscillation is to increase in amplitude, all quantities are constant except r_a . If the mutual inductance M is very little greater than that required to make the two sides of the expression equal, the oscillation will increase in amplitude until the variations of anode current extend to a portion of the characteristic over which the average value of r_a is such that $CR r_a + L$ becomes equal to μM , and the oscillation is maintained at this amplitude.

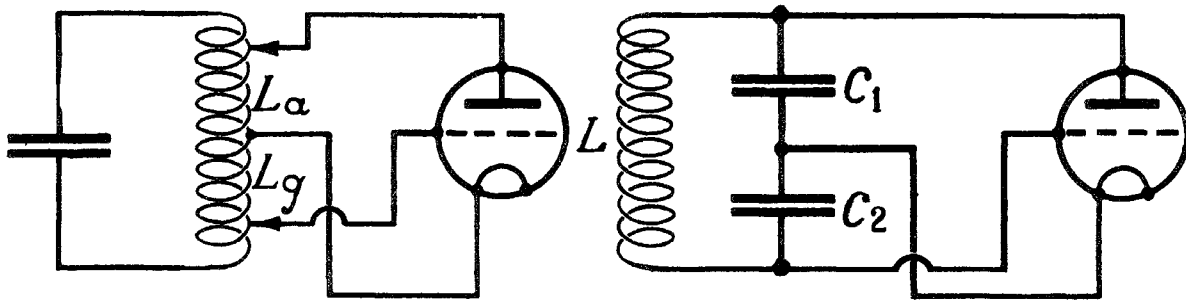
Valve oscillator circuits

8. Although it is necessary for some form of coupling to exist between the grid and anode circuits in order to maintain the anode current in oscillation it is not necessary that this coupling shall be due to mutual induction. Any form of inductive or capacitive coupling can be utilised provided the connections are so made that the correct phase relationship is obtained between grid and anode oscillatory voltages. Three common arrangements are shown in fig. 4 in which the method of supplying the H.T. voltage to the anode has been disregarded for the sake of simplicity.

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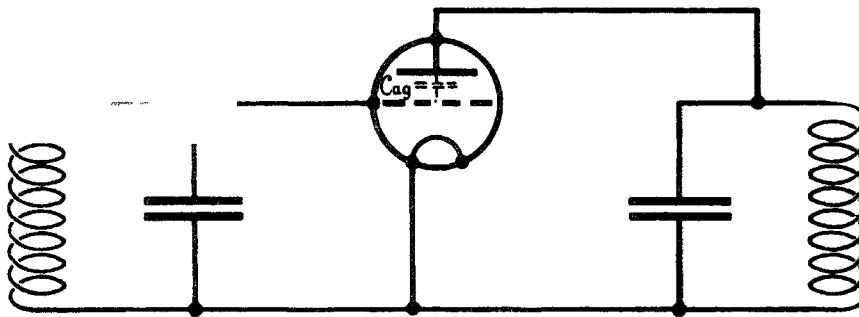
The Hartley oscillator.—The scheme of connections shown in fig. 4a makes use of combined mutual and auto-inductive coupling and is called the Hartley circuit. This is frequently used for oscillators operating upon the higher radio frequencies of the order of from 3 to 30 megacycles per second, interchangeable coils being of course necessary to cover the whole band. Its practical advantage lies in the ease with which sufficient coupling may be attained even with coils of only two or three turns. If the coil is wound continuously in a spiral the oscillatory anode-filament and grid-filament voltages are essentially in approximate anti-phase because the filament is connected to some point between the grid and anode, and the current in the winding L_a lags by 90 degrees on the grid-filament voltage.

The Colpitts oscillator.—In this circuit, fig. 4b, the oscillation is maintained by auto-capacitive coupling. This circuit is used in some service transmitters particularly for the lower frequencies,



(a) Hartley circuit

(b) Colpitts circuit



(c) Tuned anode - Tuned grid circuit

FIG. 4, CHAP. IX.—Valve oscillator circuits.

i.e. of the order of 200 k.c/s. The oscillatory circuit itself consists of the inductance L and the two condensers C_1 and C_2 in series. Suppose that on switching on some slight oscillation takes place in the circuit L, C_1, C_2 . The oscillatory current in the capacitive branch sets up a corresponding P.D. between the plates of the condenser C_2 and as these are connected between grid and filament this voltage causes a further change of anode current, which is so phased as to reinforce the original oscillation. The condensers C_1 and C_2 together form what is to all intents and purposes a potentiometer, a portion of the anode-filament P.D. being tapped off to supply the grid excitation, and the circuit is inherently self-oscillatory provided that the ratio $\frac{C_2}{C_1}$ does not exceed the amplification factor of the valve. In a practical transmitter the capacitance C_1 is usually that of the aerial, while C_2 has a fixed value depending upon the type of valve and the type of aerial it is required to use. The transmitter may then be made to cover a wide frequency

range by using interchangeable tuning inductances only. A transmitter using mutual inductive coupling for the same frequency range would require two sets of interchangeable coils and a larger number of connecting plugs and sockets, which tend to cause a loss of efficiency and power output owing to dirt and corrosion.

The tuned-anode/tuned-grid circuit.—This is shown in fig. 4c. Anode and grid circuits possess both inductance and capacitance and are brought into resonance or very nearly into resonance with each other. In such circumstances the inherent inter-electrode capacitance between grid and anode (and the connecting leads thereto) is sufficient to transfer energy from one circuit to the other, the resulting grid-filament P.D. causing a variation of anode current of such a phase as to maintain the anode circuit in oscillation. This circuit is most suitable for high frequency transmission of the order of 3 to 15 megacycles per second. To cover such a wide frequency band several sets of coils are required, generally in pairs, although sometimes a single grid coil may cover the range of two anode coils. The anode circuit capacitance may, of course, be that of the aerial.

Series and shunt feed

9. In the oscillator circuit given in fig. 1 the H.T. supply is connected between one end of the tuning inductance and to the filament. The tuning coil then carries both the oscillatory current and the steady anode current of the valve, and the arrangement is known as the series feed system. An alternative method of feeding is the parallel feed system, fig. 5, in which the

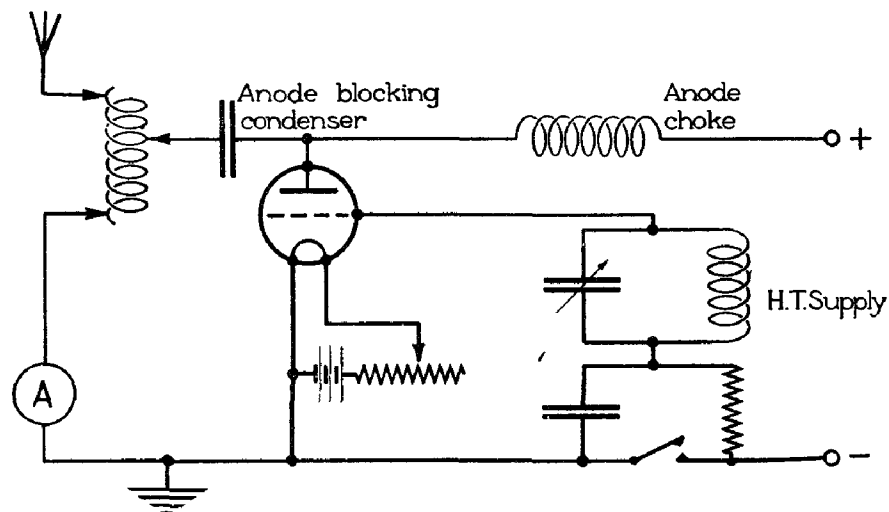


FIG. 5, CHAP. IX.—Parallel feed to valve oscillator.

H.T. supply is fed through a choking coil, the inductance of which is large compared to the inductance of the tuning coil. The H.T. supply via this anode choke, as it is termed, is connected directly to anode and filament of the valve, and the tuning inductance is normally also connected between the same points, but a condenser called the anode blocking condenser is interposed in order that the H.T. supply shall not be short-circuited by the tuning inductance. There is no essential difference in the action of series and parallel feed systems, but the latter has the advantage that the aerial tuning inductance is insulated from the source of H.T. supply. The anode choke must be designed with great care in order to ensure that its natural frequency does not fall within the frequency band to be covered by the transmitter. If this does occur, heavy circulating currents may flow in the coil and cause a breakdown, or alternatively the damping losses may be so great that the valve fails to maintain the oscillation. Interchangeable anode chokes for different frequency bands form a possible solution but only at the expense of an increase in cost, space, weight and rapidity of frequency changing.

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Evolution of a C.W. transmitter

10. The circuits shown in figs. 1 and 4 are generally referred to as C.W. oscillators to distinguish them from actual transmitting circuits in which many additions to the simple oscillator circuits are generally fitted. The circuit of a typical transmitter in which many of these refinements have been incorporated is given in fig. 6, in which the devices enumerated in the following sub-paragraphs are indicated by the corresponding arabic numeral.

(i) The oscillations are generated either in an "aerial circuit" tuned to the desired frequency, which is called direct aerial excitation, or are caused to set up oscillations in it by additional apparatus. The latter methods of aerial excitation are now becoming universal, and are dealt with later. For the present attention will be confined to the direct form of aerial excitation, and the oscillations will be considered to be generated in the aerial circuit, which is an open oscillator and consequently a good radiator.

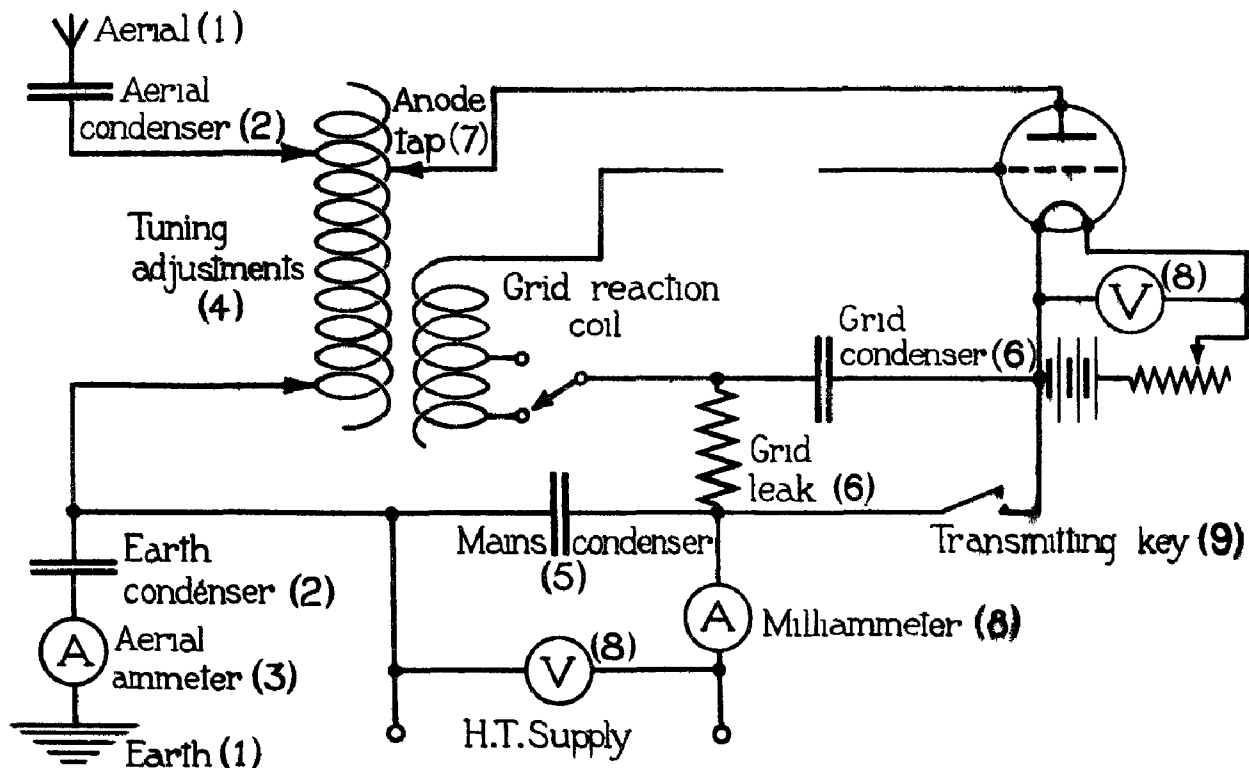


FIG. 6, CHAP. IX.—C.W. transmitter, direct aerial excitation.

(ii) With the method of H.T. supply shown in fig. 1, if the upper and lower plates of the condenser *C* are replaced by an aerial and earth connection respectively, a possible source of failure and danger to personnel is introduced, for both the aerial wire and the earth connection are now at a high steady potential with respect to the filament of the valve. A person standing on the earth and touching the filament battery, for example, would "short-circuit" the source of H.T. supply. To avoid this, large condensers are placed in series with the aerial and earth connections, the order of capacitance being $\cdot 01 \mu F$. Such large condensers cause practically no decrease in the total effective capacitance of the aerial-earth system.

(iii) An aerial ammeter is provided in order to show when oscillations are being produced, and to indicate the magnitude of the oscillatory current. Operators frequently under-estimate the importance of the aerial ammeter; it must always be remembered that if a transmitter is switched on and the key pressed, the existence of a fault in the oscillatory circuit is generally indicated by the absence of "reading" on this meter. If oscillations do not commence when

power is supplied to the valve, serious heating of the latter may occur. Especially in conditions where the valve is out of sight of the operator as in some aircraft sets, the aerial ammeter must be regarded as an essential part of the equipment and not as a refinement which could be dispensed with.

(iv) Means are provided for variation of frequency of the generated oscillations. This is usually achieved by varying the amount of inductance in the aerial circuit, the exact method depending upon the requirements of the particular transmitter.

(v) A mains condenser is provided and is connected across the terminals of the source of H.T. supply ; its value should be large and its insulation resistance high. The function of this condenser is to confine the oscillatory variations of anode current to the transmitter itself. If the H.T. source is a D.C. generator, its armature windings will be of high impedance, and will seriously reduce if not entirely prevent the variation of anode current which is necessary to maintain the oscillation. The condenser forms a low impedance path in parallel with the generator windings, allowing these variations to reach the full value permitted by the valve characteristic and dynamic resistance of the oscillatory circuit.

(vi) Suitable arrangements are made for the provision of a considerable grid bias voltage. The necessity for this will be considered later.

(vii) The anode of the valve is connected to some suitable point on the aerial tuning inductance, which is called the anode tapping point. This requirement also will be dealt with in due course.

(viii) For the purpose of adjusting the power supplies to the transmitter, suitable ammeters and voltmeters are provided. If weight and space permit, these are (a) a voltmeter showing the voltage applied to the filament. (b) a milliammeter showing the average anode current. (c) a voltmeter showing the voltage of the H.T. supply.

(ix) Means must be provided for interrupting the wave by a morse key for telegraphic transmission. The method of "keying" the transmitter usually adopted in aircraft sets using direct aerial excitation is to interrupt both the negative H.T. lead and the grid circuit. For high power or high-speed (automatic) transmission the "keying" arrangements may be more complicated e.g. as in figs. 29 and 42.

Production of I.C.W. waves

11. The radiation produced by a C.W. transmitter is of constant amplitude throughout the period during which the transmitting key is pressed, except for a very short period during which the oscillation is building up to its maximum amplitude, and a similar period when the key is

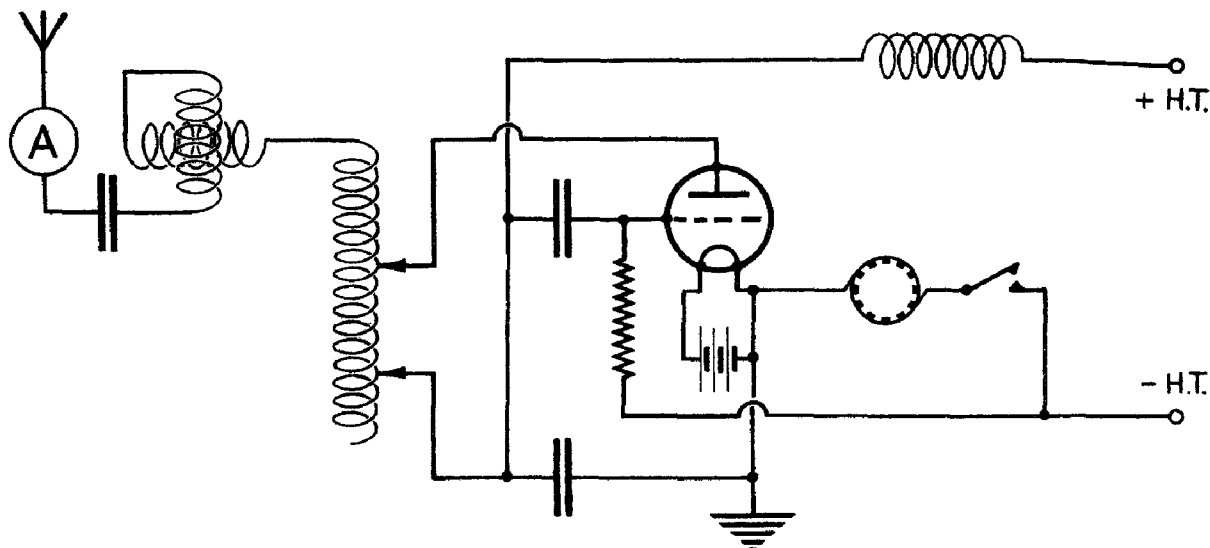


FIG. 7, CHAP. IX.—I.C.W. transmitter.

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raised, for the aerial will then continue to oscillate with rapidly diminishing amplitude until the energy stored at the moment of raising the key is totally dissipated. If it is desired to radiate I.C.W. waves, the continuous wave must be interrupted at some rate which lies in the audio-frequency range, in practice from 200 to 2,000 times per second. The simplest method, which is also as efficient as any other, is to arrange a rotary interruptor in series with the transmitting key, fig. 7. A typical form of interruptor consists of a pair of brass discs which are mounted side by side upon the shaft of a motor and are in electrical connection, but insulated from the shaft. One of the discs is wholly of metal and is known as the slip ring, while the interruptor disc proper has a number of insets of insulating material (usually mica or fibre) let into its periphery. Brushes of springy phosphor bronze bear upon the edge of each disc. When the transmitting key is pressed and the discs are in rotation, the current in the key circuit is interrupted at a rate depending upon the speed of rotation and the number of conducting segments on the edge of the interruptor disc, i.e. if the speed is 2,400 r.p.m. or 40 r.p.s. and the disc has 10

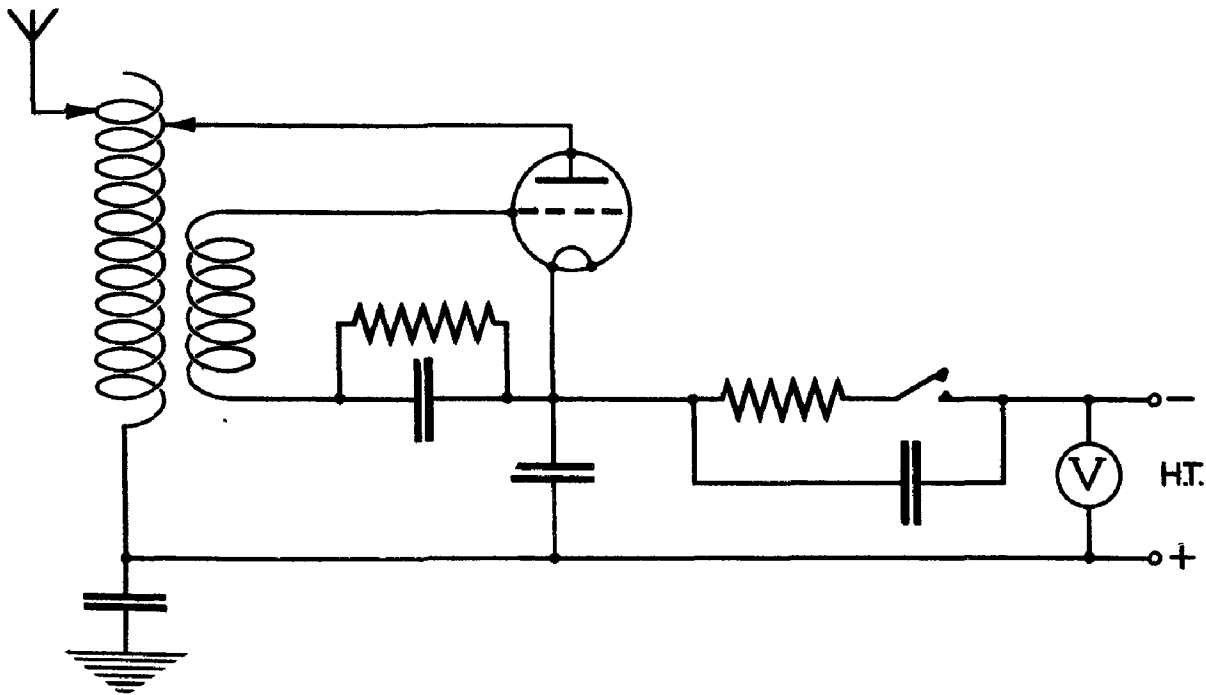


FIG. 8, CHAP. IX.—Simple key click eliminator.

conducting segments, the number of interruptions will be 400 per second, and the resulting transmission will consist of interrupted continuous waves having this group frequency. This method has the advantage that the interruptor may be mounted on the shaft of the generator supplying the anode voltage for the transmitter, which is particularly convenient in aircraft.

Key clicks

12. If a high frequency receiver is situated in the vicinity of a medium or low frequency transmitter or vice versa, it is often found that severe interference to reception is caused by the operation of the transmitter in spite of the large difference in frequency between the radiated wave and that to which the receiving aerial is tuned. This interference has been traced to two causes, (i) radiation of harmonics by the transmitter, (ii) the shock excitation of the receiving aerial. The former effect can only be eliminated by reduction of the harmonic content of the radiated wave, one possible remedy being an indirect coupling between the aerial and the oscillatory circuit of the transmitter. The latter effect, which is generally referred to as key click interference, is produced as follows. When the transmitter is "keyed" by the normal

method, the full H.T. voltage is immediately applied between the anode and filament of the transmitting valve and the resulting oscillation reaches its maximum amplitude in a very short space of time, equivalent to say 20 to 30 cycles. The field strength in the vicinity of the receiver increases in magnitude in the same way, and causes a rapidly increasing induced E.M.F. in the receiving aerial, which is set into oscillation at its natural frequency no matter how remote this may be from that of the inducing electric field. The remedy

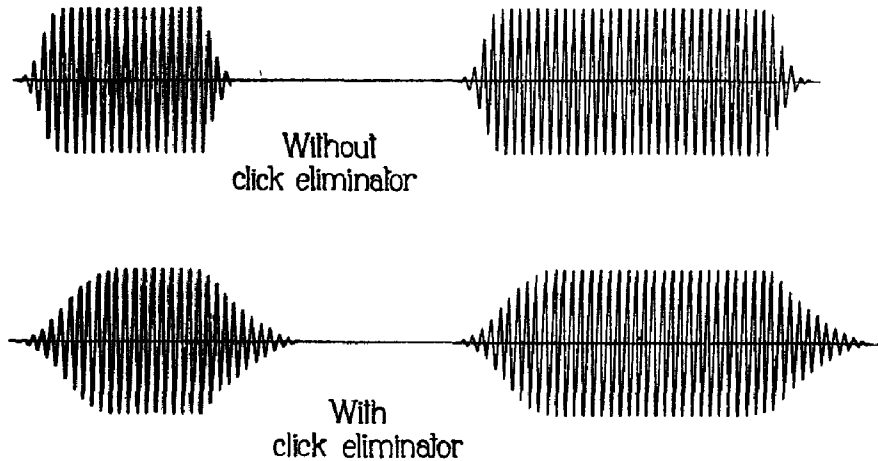


FIG. 9, CHAP. IX.—Growth and decay of oscillations.

for this state of affairs is to ensure that the oscillatory current in the transmitting aerial reaches its final amplitude very slowly, and this may be achieved by either of two methods. In the simplest form, a resistance of the order of 500 ohms is inserted in series with the H.T. supply to the generator, on the generator side of the mains condenser as shown in fig. 8. On closing the transmitting key, the voltage applied to the anode-filament path of the valve is that of the mains

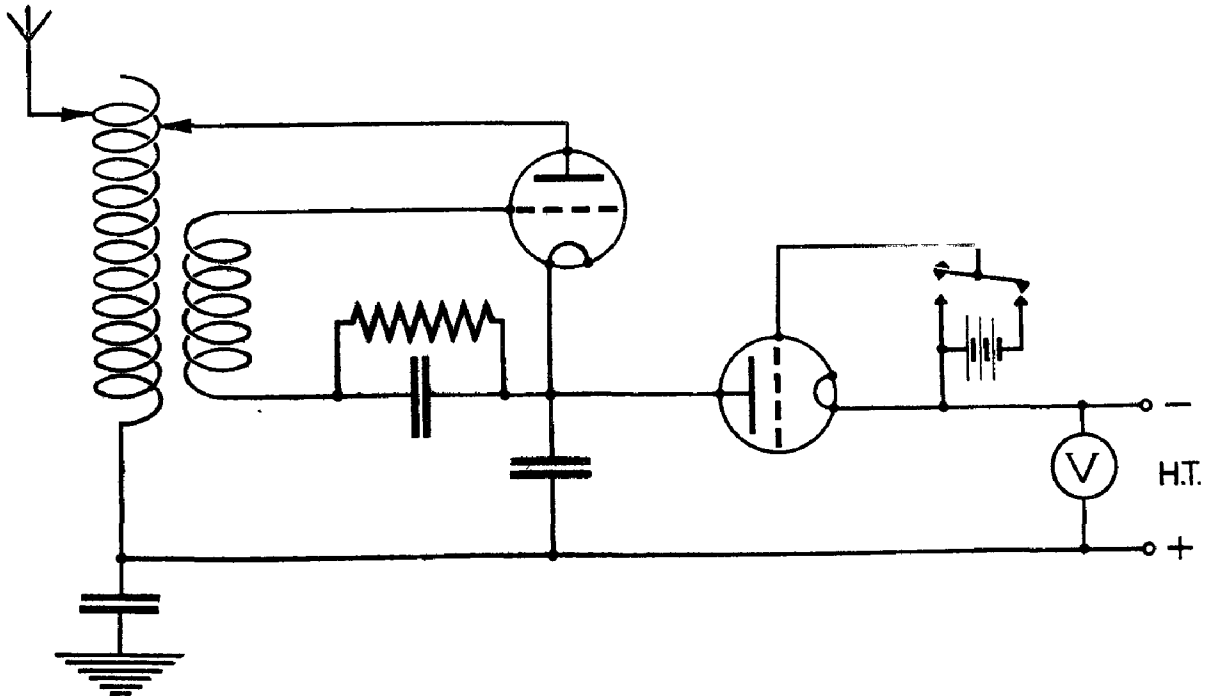


FIG. 10, CHAP. IX.—Key click eliminator for high power transmitter.

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condenser, and the latter is initially not equal to that of the H.T. supply, owing to the presence of the resistance, although it rises to this value after a certain interval as explained in Chapter I. When the transmitting key is raised, the mains condenser is charged to the supply voltage, and continues to supply the anode of the valve, the voltage gradually falling in a manner complementary to that in which it increases when the key is pressed. The amplitude of the oscillatory current in the aerial therefore increases and decreases slowly, and shock excitation of neighbouring receiving aerials is avoided. A condenser is shunted across both key and resistance to reduce sparking at the key contacts. The effect of the key click eliminator upon the rate of growth and decay of the oscillation is shown in fig. 9. It must be noted that this remedy necessitates a slight change in the location of the transmitting key, in order to ensure that the mains condenser becomes discharged at the end of each morse element.

13. A device which is more suitable for installation in high power transmitters is shown in fig. 10. Here the resistance element of the key click eliminator is the anode-filament path of an auxiliary thermionic valve, and the transmitting key is inserted in its grid circuit. When the key is raised the grid of the auxiliary valve is given a considerable negative potential with respect to the filament, and the resistance of its anode-filament path becomes infinitely large, so that no current can flow in the anode circuit of the transmitting valve. On pressing the key, the grid of the auxiliary valve is given zero potential with respect to its filament, and the resistance of its anode filament path falls to some value of the order of a thousand ohms, allowing the mains condenser to charge and oscillations to build up as in the circuit previously described. The advantage of this method is that the transmitting key is not required to break the main anode circuit, and sparking at the key is negligible; it is therefore better adapted for high power and high speed signalling than its prototype. The principal disadvantage of this device is the necessity for high insulation of the filament supply for the auxiliary valve.

Tuning a transmitter

14. This term is used in the service to signify the whole procedure of preparing a transmitter for operation on a given frequency. The exact details of course vary with different transmitters, but the following sequence of operations is usually necessary.

(i) Examine all external connections. This precaution should never be omitted unless the transmitter has been observed in operation immediately before retuning. After completing a minor repair, it is easy to omit to replace a single lead, which may fall on to another and cause a short-circuit.

(ii) Switch on the L.T. supply to the filament, and adjust the filament voltage or current to the correct value for the type of valve in use.

(iii) Switch on the H.T. supply to the transmitter, adjusting its value to not more than two thirds the maximum permissible voltage for the particular transmitter.

(iv) Having verified that H.T. and L.T. supplies are correct switch them off; switches are generally fitted in such a manner that this can be done without prejudice to the adjustments made in (iii).

(v) Adjust the aerial tapping point on the aerial tuning inductance to a value suitable for the desired frequency. With any given type of transmitter experience is the only guide to this; for this reason many service transmitters are provided with tables of approximate adjustments which should be consulted.

(vi) Set the anode tap, if separately adjustable, to a point not nearer to the tuning tap than half way between the latter point and the earth-potential end of the tuning coil.

(vii) Switch on H.T. and L.T. supply, press the transmitting key and observe (a) the aerial ammeter, (b) the anode current milliammeter; (a) should indicate that oscillatory current is flowing in the aerial circuit, (b) that anode current is flowing; care should be taken that this is not excessive. The normal anode current for the transmitter is usually given in the tables previously mentioned. In their absence it should be remembered that overheating of the valve will be avoided, even if oscillations are absent, provided that the power input to the transmitter

is less than the permissible dissipation of the valve, e.g. if the transmitter has only a single V.T. 5 B valve, rated at 250 watts, and the H.T. voltage is adjusted to 2,000 volts, an anode current not exceeding 125 milli-amperes is permissible.

(viii) If oscillations do not commence, try a change of anode tap. In transmitters with reversible connections to the grid circuit, the appropriate leads should be interchanged. When neither of these adjustments produce the desired effect, some fault probably exists and the steps to be taken are usually detailed in the appropriate Chapter of A.P.1186 (Signal Manual Part IV).

(ix) When oscillations are obtained, the key should be held down and the frequency measured with an appropriate wavemeter; adjustment of the aerial tuning inductance is then performed until the frequency is very near to that desired. There is no necessity to make this adjustment to the limit of possible accuracy, if the anode tap is separately adjustable.

(x) Adjust the anode tap until maximum output (i.e. aerial amperes) is obtained. The anode current will then usually have the minimum value. If this is not so, adjust for the greatest ratio of oscillatory to anode currents, provided that the maximum permissible anode current is not exceeded.

(xi) Readjust the aerial tuning inductance to the frequency desired, with the utmost precision to which the wavemeter can be observed.

(xii) In carrying out these operations two precautions should always be observed. First, the key should never be held down longer than necessary. The practice of locking the key while the tuning chart is consulted is liable to cause overheating of the transmitter components and the H.T. generator. Secondly, remember to switch off the H.T. supply to transmitter before touching any component other than the transmitting key. In modern H.T. transmitters the dangerous portions are usually screened in such a manner that access is impossible without interrupting the H.T. supply.

Adjustment of transmitter to desired frequency

15. This adjustment is performed with the aid of an instrument known as a wavemeter or frequency meter. Many different types of wavemeter are in use in the service, and an account of the principles involved in their design and operation will be found in Chapter XIII. For the present, the simplest form will be briefly described. This consists of a calibrated closed oscillatory circuit, incorporated with which is some device which serves to indicate the presence of an oscillatory current in the circuit. One such device is a miniature 2-volt lamp, which will glow with full

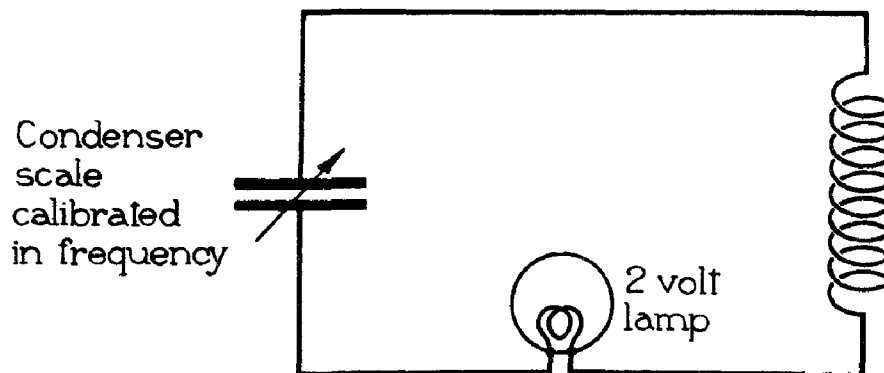


FIG. 11, CHAP. IX.—Simple wavemeter.

brilliance if a current of about 100 milliamperes is passed through it (fig. 11). When the transmitter is in operation, the wavemeter is so held that the magnetic field of the transmitting inductance links with the inductance of the wavemeter circuit, and an oscillatory E.M.F. is induced in the latter. The resulting current in this circuit will reach a maximum if the wavemeter circuit is in resonance with that of the transmitter, and this is shown by the maximum brilliancy of the lamp. The frequency to which the meter is adjusted is then read from its calibrated scale, and this is identical with the transmitter frequency.

EFFICIENCY AND OUTPUT

Oscillatory power in sinusoidal oscillator

16. In order to maintain oscillations in the simple circuit of fig. 1, a portion of the power taken from the H.T. supply must be transferred to the oscillatory circuit. A simple investigation will show how great this quantity must be. The total anode current at any instant will be $I_a + \mathcal{I}_a \sin \omega t$ while the anode-filament P.D. at the same instant will be $E_a - \mathcal{V}_a \sin \omega t$ because \mathcal{I}_a is 180° out of phase with \mathcal{V}_a . The power dissipated in the form of heat in the valve itself will be the product of the anode current and the anode voltage and is equal to $(I_a + \mathcal{I}_a \sin \omega t)(E_a - \mathcal{V}_a \sin \omega t) = P_L$.

$$P_L = I_a E_a - I_a \mathcal{V}_a \sin \omega t + \mathcal{I}_a E_a \sin \omega t - \mathcal{I}_a \mathcal{V}_a \sin^2 \omega t$$

$$= I_a E_a - I_a \mathcal{V}_a \sin \omega t + \mathcal{I}_a E_a \sin \omega t - \frac{\mathcal{I}_a \mathcal{V}_a}{2} + \frac{\mathcal{I}_a \mathcal{V}_a}{2} \cos 2 \omega t.$$

Of the above expression, only two terms have average values over a number of complete cycles, viz. $I_a E_a$ and $\frac{\mathcal{I}_a \mathcal{V}_a}{2}$. The power expended in heating the anode is therefore $I_a E_a - \frac{\mathcal{I}_a \mathcal{V}_a}{2}$. Now

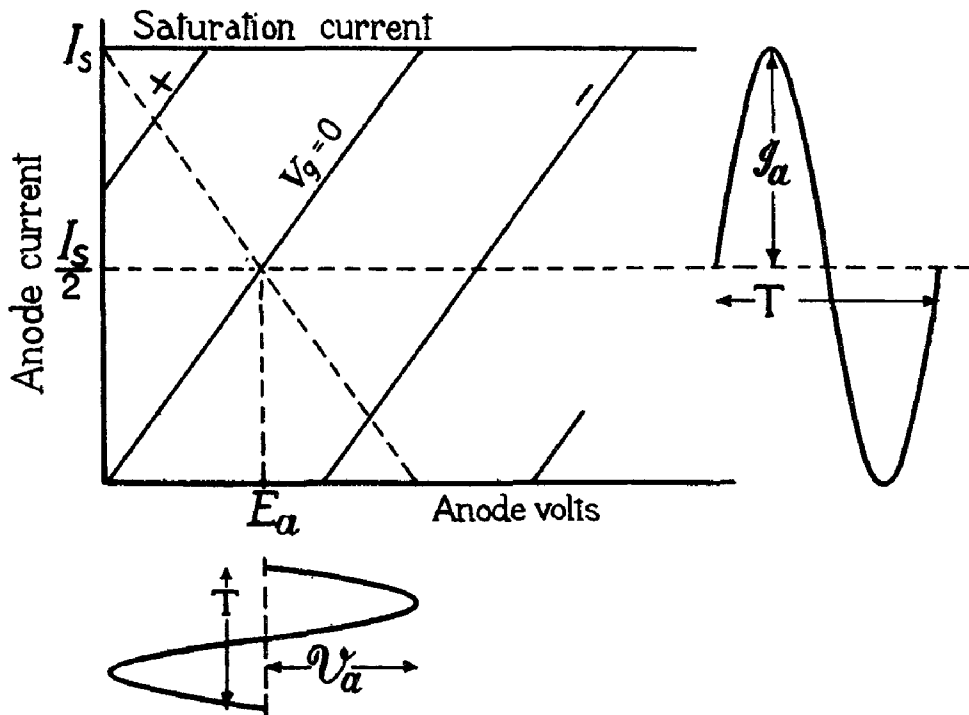


FIG. 12, CHAP. IX.—Ideal $I_a - V_a$ characteristics, showing conditions giving theoretical efficiency of 50 per cent.

$I_a E_a$ is the power supplied to the circuit by the H.T. source, and the difference between $I_a E_a$ and $I_a E_a - \frac{\mathcal{I}_a \mathcal{V}_a}{2}$, namely $\frac{\mathcal{I}_a \mathcal{V}_a}{2}$, is the power which is converted into oscillatory form. If this is to be a maximum, the amplitudes of the oscillatory current \mathcal{I}_a and oscillatory voltage \mathcal{V}_a must be as large as possible. The maximum possible variation of anode current is from zero to saturation value. Suppose that the $I_a - V_a$ characteristic curves of the valve are straight lines between zero and saturation value I_s , the zero grid volts curve passing through the origin

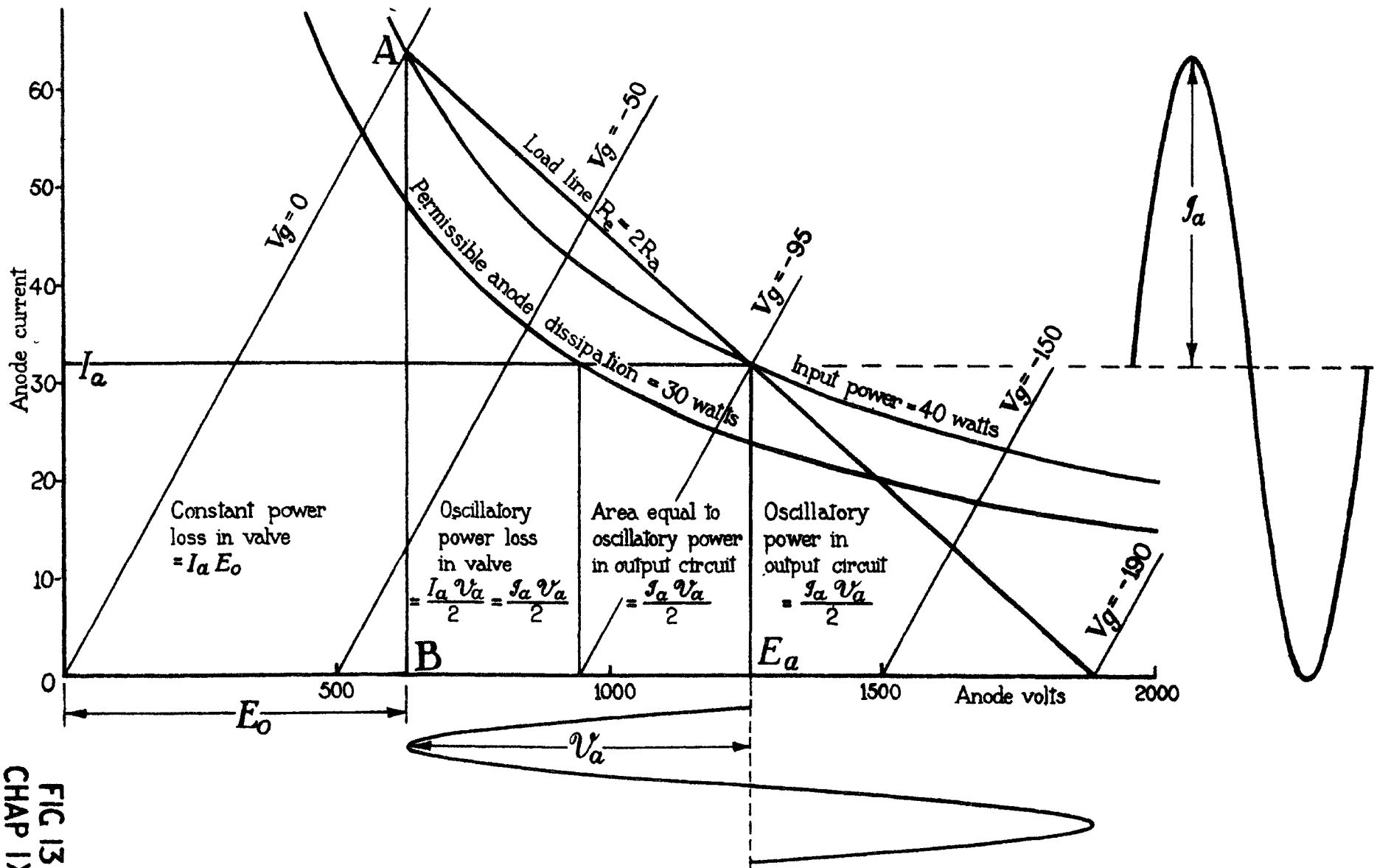


FIG 13
CHAP IX

SINUSOIDAL OPERATION WITHOUT GRID CURRENT

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(fig. 12). This assumption is frequently made for theoretical purposes and the curves are referred to as "ideal characteristics." Provided that the mean anode current is one-half the saturation value, $\frac{I_s}{2}$, the anode current can execute a variation between zero and saturation value, and \mathcal{I}_a will have the value $\frac{I_s}{2}$. The maximum variation of anode-filament P.D. is from zero to $2E_a$, which is only possible if the amplitude \mathcal{V}_a of the oscillatory component is equal to the steady voltage E_a . The maximum power output is therefore $\frac{\mathcal{V}_a \mathcal{I}_a}{2} = \frac{E_a I_s}{4}$, while the power input is $E_a I_a = \frac{E_a I_s}{2}$. The ratio of power output to power input, i.e. the efficiency of the valve as a power converter, is therefore 50 per cent. A study of fig. 12 will show that there is only one value of external or load resistance $R_e = \frac{L}{CR}$ which will allow this output and efficiency to be obtained under the given conditions. The load line must pass through two points, viz. saturation current when the anode-filament P.D. falls to zero, and one-half saturation value when the anode-filament P.D. is E_a . On drawing the load line through these points, it is obvious that its slope is equal to the slope of the valve characteristics i.e. the dynamic resistance of the load must be equal to the anode A.C. resistance of the valve.

Efficiency and output without grid current

17. It must now be made clear that the above conditions are not possible in practice. The postulation of straight-line characteristics is justifiable because a slight departure from linearity does not affect the output but only the wave-form. The serious error in the above reasoning is the assumption that the amplitude of the oscillatory component of anode-filament P.D. can be made equal to the H.T. supply voltage E_a . As maximum positive grid potential and minimum anode-filament P.D. occur practically simultaneously owing to the approximately anti-phase relationship between \mathcal{V}_a and \mathcal{V}_g (fig. 3) it is essential that the anode potential shall never fall below the most positive value of grid potential, otherwise excessive grid current will flow. The valve will then cease to generate oscillations at the frequency of the tuned circuit, although possibly a spurious or parasitic oscillation may be set up at some other frequency.

No anxiety will arise on this account if steps are taken to ensure that the grid potential can never attain any positive value. Let us therefore investigate the production of oscillations with sinusoidal variation of anode current and voltage, but with sufficient negative grid bias to ensure that no grid current will flow during any portion of the cycle. We may assume that the valve possesses ideal characteristics as before, and that the maximum power dissipation of the valve must not be exceeded; this will generally preclude the possibility of allowing the anode current to rise to saturation value. The characteristics shown in fig. 13 closely resemble those of a small transmitting valve, the permissible dissipation being 30 watts. The load line lies across the characteristics with one end terminating upon the curve $V_g = 0$, because it has been stipulated that the grid voltage variation must not extend into the region of positive grid voltage. The projection of this point upon the voltage axis, as shown by the line A B, gives the minimum allowable anode-filament P.D., which will be denoted by E_o . The H.T. supply voltage will be $E_a = E_o + \mathcal{V}_a$, the mean anode current I_a and the total variation of anode current from zero to $2I_a$. The amplitude of the oscillatory anode current, \mathcal{I}_a , will therefore be equal to the mean anode current I_a ; the output power will be $\frac{\mathcal{I}_a \mathcal{V}_a}{2}$ and the input power $I_a E_a$ or $\mathcal{I}_a (E_o + \mathcal{V}_a)$. Without further calculation therefore we may conclude that the efficiency η under these conditions is $\frac{\mathcal{I}_a \mathcal{V}_a}{2} \times \frac{1}{\mathcal{I}_a (E_o + \mathcal{V}_a)} = \frac{\mathcal{V}_a}{2 (E_o + \mathcal{V}_a)}$

(fig. 12). This assumption is frequently made for theoretical purposes and the curves are referred to as "ideal characteristics." Provided that the mean anode current is one-half the saturation value, $\frac{I_s}{2}$, the anode current can execute a variation between zero and saturation value, and \mathcal{I}_a will have the value $\frac{I_s}{2}$. The maximum variation of anode-filament P.D. is from zero to $2E_a$, which is only possible if the amplitude \mathcal{V}_a of the oscillatory component is equal to the steady voltage E_a . The maximum power output is therefore $\frac{\mathcal{V}_a \mathcal{I}_a}{2} = \frac{E_a I_s}{4}$, while the power input is $E_a I_a = \frac{E_a I_s}{2}$. The ratio of power output to power input, i.e. the efficiency of the valve as a power converter, is therefore 50 per cent. A study of fig. 12 will show that there is only one value of external or load resistance $R_e = \frac{L}{CR}$ which will allow this output and efficiency to be obtained under the given conditions. The load line must pass through two points, viz. saturation current when the anode-filament P.D. falls to zero, and one-half saturation value when the anode-filament P.D. is E_a . On drawing the load line through these points, it is obvious that its slope is equal to the slope of the valve characteristics i.e. the dynamic resistance of the load must be equal to the anode A.C. resistance of the valve.

Efficiency and output without grid current

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It can be proved that this is a maximum when $R_e = 2 r_a$ and therefore the maximum output is

$$P_o \text{ (max.)} = \frac{E_a^2}{2} \times \frac{2 r_a}{16 r_a^2} = \frac{E_a^2}{16 r_a}.$$

The grid bias for this output will be

$$\frac{E_a}{\mu} \times \frac{3 r_a}{4 r_a} = \frac{3}{4} \frac{E_a}{\mu}$$

and the efficiency

$$\frac{R_e}{2(2r_a + R_e)} = \frac{2 r_a}{2(2r_a + 2r_a)} = \frac{1}{4} \text{ or 25 per cent.}$$

Advantage of high efficiency

19. Summarising the above, it may be stated that in a triode oscillator in which the anode current executes sinusoidal variations and grid current is allowed to flow during a large portion of every cycle, the efficiency may approach 50 per cent., while if grid current is totally avoided the efficiency cannot exceed 25 per cent. Under the latter conditions the maximum power output is only one-third of that expended in heating the valve, which is consequently much larger and more expensive than would be required if a higher efficiency were achieved. For example, in a low-power ground station, an output of 200 watts may be required, and if the transmitter operates at an efficiency of only 20 per cent. the input power must be 800 watts, of which 600 watts are dissipated in the valve itself. If, however, an efficiency of 80 per cent. can be achieved the input power is only 250 watts of which 200 watts are utilised and 50 watts dissipated by the valve. The economy resulting from the use of smaller and less expensive components is of far greater importance than the actual saving in electrical energy, particularly in sets designed for use in aircraft. When operating under sinusoidal conditions, the energy is supplied to the oscillatory circuit continuously, at the exact rate at which it is converted into oscillatory power. This mode of supply is not essential, for an oscillation will be maintained at a constant amplitude if the necessary amount of energy is supplied in bulk during a short interval during each period. The action is analogous to that of a child's swing which is maintained in oscillation by giving correctly timed pushes at a certain point during each oscillation, and when an electric circuit is supplied with energy in this way it is said to undergo "impulse excitation."

20. (i) High efficiency of power conversion is achieved by maintaining the grid potential at a value so negative that anode current flows during only a portion of each cycle instead of during the whole cycle as in sinusoidal operation, for less energy is then dissipated as heat at the anode. The variation of anode current during a single cycle of grid voltage, under three different conditions of grid bias, is shown in fig. 14, (a), (b) and (c). At (a) the mean negative grid potential is such

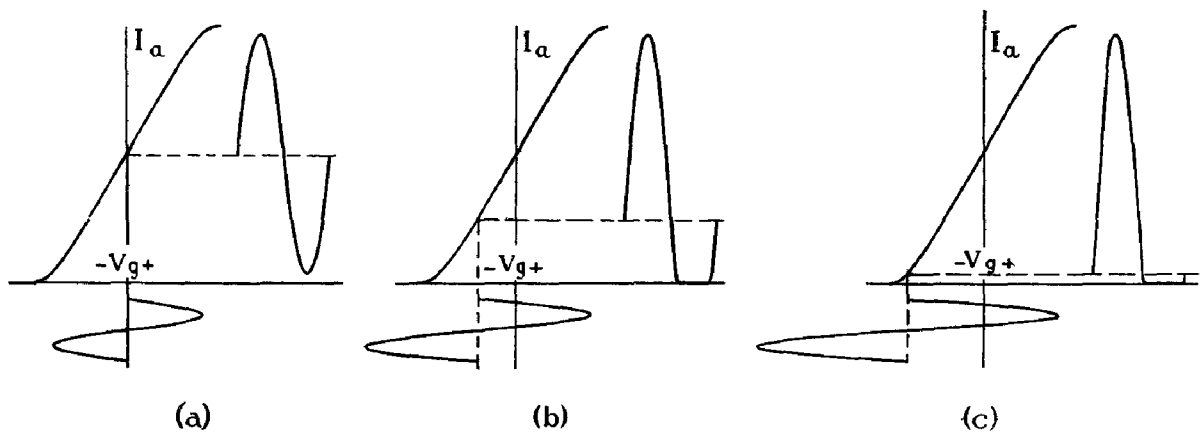


FIG. 14, CHAP. IX.—Reduction of mean anode current by negative grid bias.

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that the mean anode current is one-half the saturation value, while the amplitude of oscillatory grid voltage is just sufficient to cause a variation of anode current between saturation value and zero. This is the condition under which, on the assumption that the anode-filament P.D. may be allowed to fall to zero at the instant when the oscillatory P.D. across the tuned circuit is a maximum, a theoretical efficiency of 50 per cent. is attainable. At (b) the grid has been given a negative bias but no corresponding increase in anode voltage, and although the variation of grid filament potential is still sinusoidal, the corresponding changes of anode current do not obey the simple sine law. The average anode current is not one-half the saturation value, but rather less than this, and the input power is correspondingly reduced. The total change of anode current, however, is the same as in the previous instance, i.e. from its mean value to saturation, then falling to zero and finally returning to its mean value, in the course of one cycle of oscillatory grid voltage, and consequently the power transferred to the oscillatory circuit is the same in each case, and the latter mode of operation results in the same output with a reduced input power, that is, higher efficiency of power conversion.

(ii) At (c) the grid has been given such a large negative bias that an appreciable anode current flows only during the positive half-cycle of grid voltage, and the corresponding change of anode current takes the form of a half sine wave, approximately. Under this operating condition the input power is still further reduced, while the power converted into oscillation is practically the same as before, hence the efficiency is higher than under the conditions shown in fig. 14b. It will be shown that under the operating conditions of fig. 14c a theoretical efficiency of 78.5 per cent. is obtained. It must always be borne in mind that as the negative bias is increased it is necessary to increase the peak value of oscillatory grid voltage in order that the maximum possible variation of anode current may be obtained, otherwise the power output will fall off as the efficiency is increased. The total excursion of grid voltage is obviously equal to twice its peak value, and this is generally referred to as the "grid swing." It will be seen in fig. 14 that the operating condition at (c) requires twice the grid swing called for by the mode of operation shown at (a), but this increase in oscillatory grid voltage is easily attained by increasing the coupling between the anode and grid circuits. As the peak anode current must at least approach saturation value, it is essential that the grid voltage shall be allowed to assume positive values during a portion of the cycle, otherwise the output will be low. It would seem that this necessity could be avoided by increasing the anode supply voltage and so ensuring that saturation current occurs at the instant at which the grid voltage is zero, but with most transmitting valves this would entail the employment of an excessively high anode voltage. In general it may be said that maximum output can only be obtained by allowing the valve to pass grid current during some portion of the oscillatory cycle.

Efficiency of oscillator biased to "cut off" point

21. The efficiency and output power under conditions corresponding to fig. 14c are approximately determined as follows:—It is assumed that the I_a-V_a curves have the ideal form shown in fig. 15, and in the preliminary stage we may suppose it is permissible to allow the anode filament P.D. to fall to zero at the instant of peak oscillatory voltage across the output circuit. Let A B be the load line for an effective external load R_e and O B the steady anode supply voltage E_a which is equal to the peak value \mathcal{V}_a of the oscillatory voltage across the load. The peak value of anode current is $O A = I_p$. The negative grid bias is just sufficient to ensure that anode current flows only on positive half-cycles of grid-filament voltage, and the anode current therefore takes the form of impulses of semi-sinusoidal form as previously explained. The analysis of such a wave-form shows that it consists of a fundamental component \mathcal{I}_a the amplitude of which is one half the peak value, or $\frac{I_p}{2}$, together with a series of even harmonics. Only the fundamental will set up an appreciable oscillatory voltage across the anode circuit because it is tuned to the fundamental frequency, and this voltage wave-form is practically sinusoidal in spite of the presence of harmonics in the current wave. The mean value of the anode current over a complete cycle is $\frac{I_p}{\pi}$, and the input power is $\frac{E_a I_p}{\pi}$. The output power will be equal to the product of the

R.M.S. current and voltage across the tuned circuit. The R.M.S. current is $\frac{I_p}{\sqrt{2}} = \frac{I_p}{2\sqrt{2}}$, and the R.M.S. voltage is $\frac{V_a}{\sqrt{2}}$; the output is thus equal to $\frac{E_a I_p}{4}$ and the efficiency is

$$\eta = \frac{\frac{E_a I_p}{4}}{\frac{E_a I_p}{\pi}} \times 100 = \frac{\pi}{4} \times 100 = 78.54 \text{ per cent.}$$

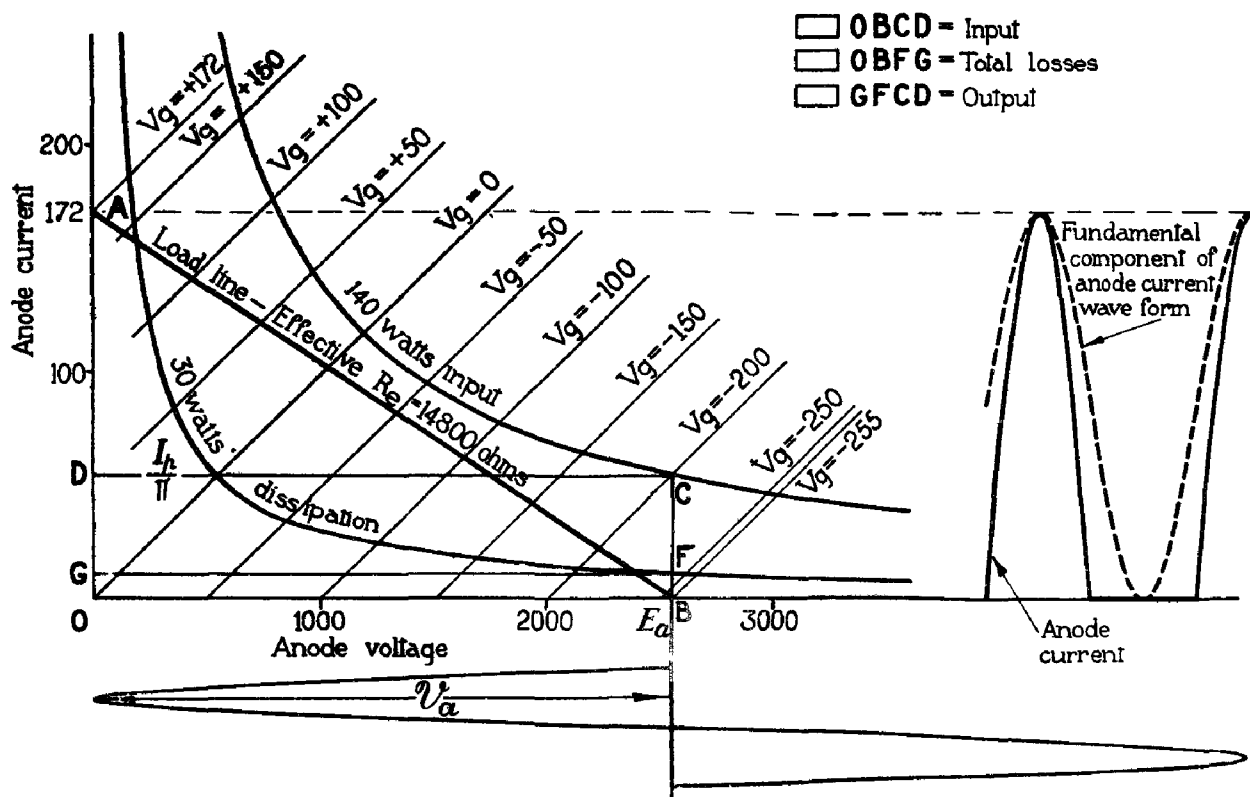


FIG. 15, CHAP. IX.—Theoretical efficiency and output with impulse excitation.

If the output is to be the greatest possible without exceeding the permissible power dissipation of the valve, the effective dynamic resistance of the load is also fixed. The actual dynamic resistance R_d is obviously equal to $\frac{V_a}{I_p} = \frac{2E_a}{I_p}$ but its effective value R_e is only $\frac{E_a}{I_p}$ because so far as the valve is concerned current only flows during alternate half-cycles. The anode dissipation is equal to the difference between input and output power and must be caused by the mean steady current and the D.C. resistance of the valve. However, with the ideal characteristics postulated, this is identical with the anode A.C. resistance. Algebraically, then,

$$\frac{E_a I_p}{\pi} - \frac{E_a I_p}{4} = \left(\frac{I_p}{\pi}\right)^2 r_a.$$

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Dividing throughout by I_p^2

$$\frac{E_a}{\pi I_p} - \frac{E_a}{4I_p} = \frac{r_a}{\pi^2}$$

As $\frac{E_a}{I_p} = R_e$,

$$R_e \left(\frac{1}{\pi} - \frac{1}{4} \right) = \frac{r_a}{\pi^2}$$

$$R_e = \frac{4}{\pi} \frac{r_a}{4-\pi}$$

$$= 1.48r_a.$$

It must be borne in mind that the dynamic resistance of the load is twice this, or $2.96r_a$. In fig. 15 the "virtual load line" A B is drawn with a slope corresponding to $1.48r_a$.

The peak value of the anode current is dependent solely upon the permissible anode dissipation P_L and the resistance of the valve.

$$P_L = \left(\frac{I_p}{\pi} \right)^2 r_a$$

$$I_p = \pi \sqrt{\frac{P_L}{r_a}}$$

while the peak oscillatory voltage \mathcal{V}_a and the supply voltage E_a are obtainable by the relations

$$\mathcal{V}_a = \mathcal{I}_a R_d$$

$$E_a = I_p R_e.$$

Example 1.—The $I_a - V_a$ curves of fig. 15, are those of the V.T.1A valve; $P_L = 30$ watts, $r_a = 10,000$ ohms, $\mu = 10$. The optimum (virtual) load is 1.48×10^4 ohms and the peak anode current = $\pi \sqrt{\frac{30}{10^4}}$ amperes or 172 milliamperes.

$$E_a = .172 \times 1.48 \times 10^4 = 2,550 \text{ volts.}$$

$$\text{Input} = \frac{E_a I_p}{\pi} = 140 \text{ watts.}$$

$$\text{Output} = \frac{E_a I_p}{4} = 110 \text{ watts.}$$

$$\text{Anode dissipation} = 140 - 110 = 30 \text{ watts.}$$

These are the conditions shown in fig. 15. The input grid-filament voltage may be calculated as follows. The peak anode current is that which would be obtained in an equivalent circuit consisting of a generator of $\mu \mathcal{V}_g$ volts having an internal resistance r_a and a load resistance R_e . Hence

$$I_p = \frac{\mu \mathcal{V}_g}{r_a + R_e}$$

$$= \frac{\mu \mathcal{V}_g}{2.48r_a}$$

As

$$I_p = \pi \sqrt{\frac{P_L}{r_a}}$$

$$\pi \sqrt{\frac{P_L}{r_a}} = \frac{\mu \mathcal{V}_g}{2.48r_a}$$

or

$$\mathcal{V}_g = \frac{2.48\pi}{\mu} \sqrt{P_L r_a}.$$

In the chosen example,

$$\begin{aligned} \mathcal{V}_g^{\circ} &= \frac{2 \cdot 48\pi}{10} \sqrt{30 \times 10^4} \\ &= 426 \text{ volts.} \end{aligned}$$

In fig. 15 the grid bias is -255 volts, while at the anode current peak the grid voltage reaches $+172$ volts, and the amplitude of the grid-filament oscillatory voltage must be $172 + 255 = 427$ volts. The slight divergence between graphical and calculated values is of no practical significance.

22. It is necessary in practice to stipulate that the anode-filament P.D. shall not fall below a certain value, say E_o volts. The supply voltage must then be $E_a = E_o + \mathcal{V}_a^{\circ}$ and the power input $\frac{(E_o + \mathcal{V}_a^{\circ}) I_p}{\pi}$ watts. The total losses will be increased because an amount of power $\frac{E_o I_p}{\pi}$ will be dissipated in addition to the quantity $\left(\frac{I_p}{\pi}\right)^2 r_a$.

Hence
$$\frac{r_a}{\pi^2} I_p^2 + \frac{E_o}{\pi} I_p = P_L$$

or
$$\frac{r_a}{\pi^2} I_p^2 + \frac{E_o}{\pi} I_p - P_L = 0.$$

Solving this as a quadratic equation we find

$$I_p = -\frac{E_o \pi}{2r_a} + \sqrt{\left(\frac{E_o \pi}{2r_a}\right)^2 + \frac{P_L \pi^2}{r_a}}.$$

The positive sign only is inserted before the radical because I_p must be a positive quantity. The power balance sheet now becomes

$$\text{Input} = (\mathcal{V}_a^{\circ} + E_o) \frac{I_p}{\pi}$$

$$\text{Output} = \frac{\mathcal{V}_a^{\circ} I_p}{4}$$

$$\text{Losses} = \left(\frac{I_p}{\pi}\right)^2 r_a + \frac{E_o I_p}{\pi}$$

$$\text{Input} - \text{Losses} = \frac{\mathcal{V}_a^{\circ} I_p}{\pi} + \frac{E_o I_p}{\pi} - \frac{I_p^2 r_a}{\pi^2} - \frac{E_o I_p}{\pi}$$

$$\text{Output} = \frac{\mathcal{V}_a^{\circ} I_p}{\pi} - \frac{I_p^2 r_a}{\pi^2}$$

$$\text{Hence} \quad \frac{\mathcal{V}_a^{\circ} I_p}{\pi} - \frac{\mathcal{V}_a^{\circ} I_p}{4} = \frac{I_p^2 r_a}{\pi^2}$$

which signifies that the optimum virtual load resistance is independent of E_o , and is in fact $1 \cdot 48 r_a$ as before. Thus if it is necessary to limit the minimum anode-filament P.D. to about 250 volts (say 80π or $251 \cdot 3$ volts)

$$\begin{aligned} I_p &= -\frac{80\pi^2}{2 \times 10^4} + \sqrt{\left(\frac{80\pi^2}{2 \times 10^4}\right)^2 + \frac{30\pi^2}{10^4}} \\ &= 134 \text{ milliamperes.} \end{aligned}$$

$$\mathcal{V}_a^{\circ} = I_p R_c = 0 \cdot 134 \times 14,800 = 1,985 \text{ volts.}$$

$$E_a = \mathcal{V}_a^{\circ} + E_o = 1,985 + 251 \cdot 3 \doteq 2,236 \text{ volts.}$$

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$$\text{Input power} = \frac{E_a I_p}{\pi} = \frac{2,236 \times .134}{\pi} = 95.4 \text{ watts}$$

$$\text{Output power} = \frac{\gamma_a I_p}{4} = \frac{1,985 \times .134}{4} = 66.5 \text{ watts}$$

$$\text{Total losses} = 95.4 - 66.5 = 28.9 \text{ watts}$$

$$\text{Efficiency} = \frac{\text{output}}{\text{input}} \times 100 = \frac{66.5}{95.4} = 69.7 \text{ per cent.}$$

The required grid-filament input voltage is found as before and is 332 volts, while the grid bias is $\frac{E_a}{\mu}$ or -223.6 volts. Hence the grid will now swing positive up to 110 volts as shown in fig. 16.

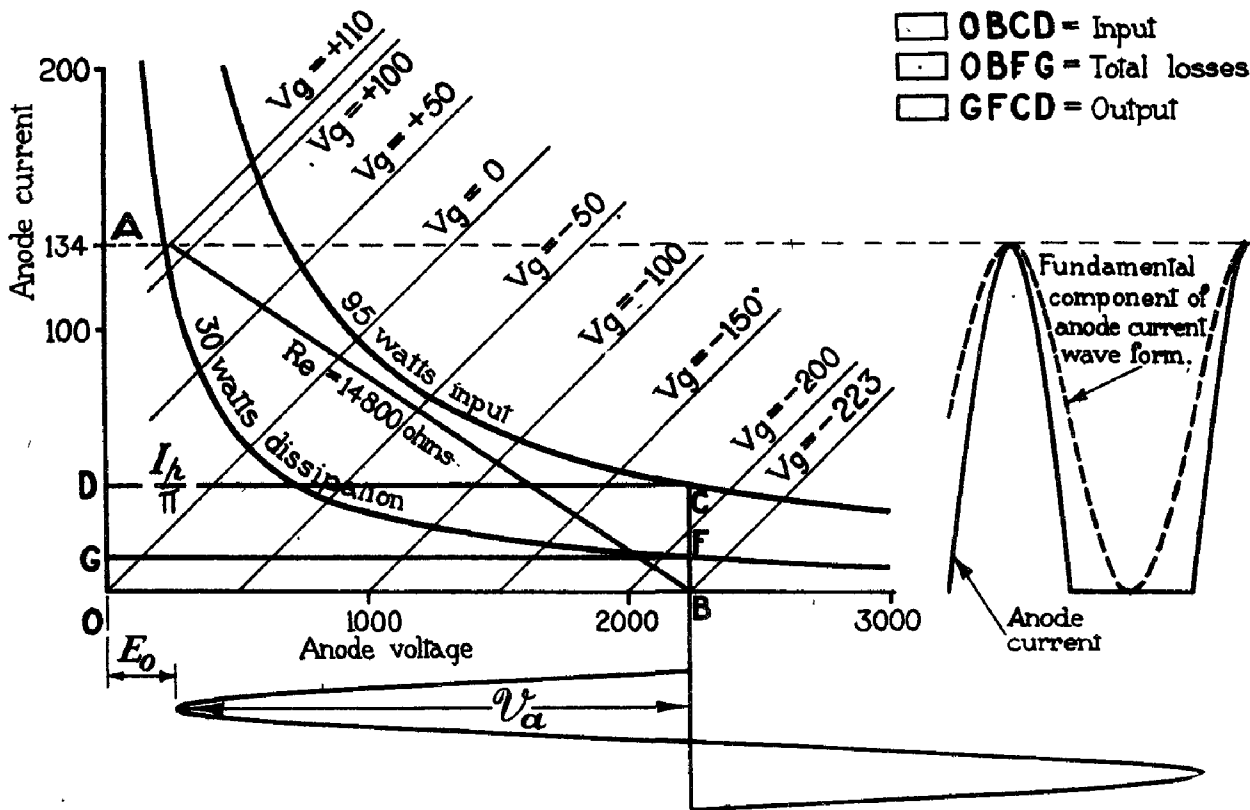


FIG. 16, CHAP. IX.—Efficiency and output with impulse excitation.

It may here be observed that in many instances the emission available from the filament may be less than that required to give both maximum efficiency and output. If the emission of the valve in the previous examples is only 100 milliamperes, and the available H.T. voltage 1,000 volts, the maximum input power under semi-sinusoidal conditions will be 31.8 watts, and at 70 per cent. efficiency the output will be about 22 watts, hence the power dissipated in the valve will only be about 10 watts instead of 30. Again, if the valve has ample emission but the H.T. voltage is limited owing to questions of safety or insulation of various components (the latter factor being of importance when space is limited as in aircraft transmitters) the optimum load impedance for maximum output will often be less than the anode A.C. resistance of the valve.

Production of harmonics

23. The increased efficiency of power conversion obtainable by impulse excitation is accompanied by the production of harmonic variation of anode current, that is to say, the non-sinusoidal variation of anode current is really the sum of a number of sinusoidal variations and a mean steady current. These harmonic variations of anode current produce oscillatory currents of corresponding frequency in the oscillatory circuit, but the proportion of harmonic to fundamental oscillatory current is less than the corresponding proportion in the anode current, because the anode circuit is tuned to the fundamental frequency but not to the frequency of the harmonic. When direct aerial excitation is employed, the proportion of second harmonic to fundamental aerial currents is given by the following formula.

Let I_1 be the component of anode current at fundamental frequency,

I_2 the component of anode current at second harmonic frequency,

χ the magnification of the aerial circuit,

\mathcal{I}_1 the component of aerial current at fundamental frequency,

\mathcal{I}_2 the component of aerial current at second harmonic frequency,

then
$$\frac{\mathcal{I}_2}{\mathcal{I}_1} = \frac{I_2}{I_1} \times \frac{4}{3\chi}$$

Although impulse excitation gives higher efficiency than sinusoidal operation, the power converted into oscillations at harmonic frequencies is wasted so far as the distant receiver is concerned, although this radiation can and does cause interference with receivers in the neighbourhood of the transmitter. In order to avoid this interference, some form of indirect coupling between aerial and oscillatory circuits may be adopted. In such instances it is preferable to couple the aerial to the inductive branch of the oscillatory circuit rather than to the capacitive branch, for the harmonic currents are always greater in the latter path than in the former.

Methods of obtaining grid bias in transmitter

24. The grid bias may be provided by a battery or by a motor generator, the latter method being rarely adopted. Battery bias is sometimes used in low power C.W. transmitters and in the amplifier stages of frequency-controlled transmitters. Frequently, however, the bias is obtained by allowing grid current to flow during a portion of the cycle. In series with the grid reaction coil is placed a condenser, in parallel with which is a resistance of the order of 10,000 ohms. The action of this condenser may be best studied by first considering the resistance to be absent, and assuming oscillation to commence. On completing the filament circuit, but with the anode circuit open, the grid may possibly collect a few electrons if it possesses some slight positive potential with respect to the filament, but even so, in a very short time its potential must become equal to that of the filament and it will be assumed that this is the case when the anode circuit is completed. The production of oscillations is accompanied by variation of grid potential as previously described, and whenever the grid is positive with respect to the filament, it acts as a collecting as well as a controlling electrode. The electrons collected by the grid will charge the grid condenser, negatively on the plate connected to the grid, and a corresponding positive charge will be developed on the plates connected to the filament. The grid thus acquires a potential negative to the filament which becomes progressively greater in each succeeding cycle and the anode current is correspondingly reduced. With sufficient coupling between grid and anode circuits, the grid becomes so negative that the anode current is reduced to zero. The oscillation then dies away and does not recommence, because the grid condenser retains its charge and prevents the re-establishment of anode current.

25. Now consider the action with a "grid leak" of large resistance connected in parallel with the condenser. When oscillations commence, the grid collects electrons on every positive half-cycle of grid voltage, but these electrons can now leak away to an extent depending upon the resistance of the leak. With a suitable value of the latter the grid potential gradually becomes more negative, just as before, but eventually reaches some value at which the number of electrons collected by the grid during the portion of the cycle in which grid current is flowing is just equal

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to the number which escape from the grid through the resistance during the whole cycle. The grid potential then remains practically constant at this value, which can be adjusted to any desired amount by choice of capacitance of grid condenser, resistance of leak, and coupling between grid and anode circuits. It is found that satisfactory operation can be obtained in nearly all transmitters if the capacitance of the grid condenser is from $\cdot 0001$ to $\cdot 002 \mu F$ (the higher values being used for low frequency transmitters) and the leak resistance from 10,000 to 50,000 ohms. The condenser and leak method of obtaining grid bias possesses an important advantage over all other methods, for with this device oscillations always commence with zero grid bias, and the initial anode current variations occur on the steepest portion of the valve characteristic, resulting in a rapid growth in the amplitude of the oscillation. As already stated, by correct choice of value of grid condenser and leak resistance, the grid bias will increase in value as the amplitude of oscillation increases. If some permanent form of grid bias is employed, such as a battery, the mean grid voltage is the same over the period during which the amplitude of oscillation is growing as when the final amplitude is reached, and consequently the initial changes of anode current occur near the curved foot of the characteristic where the slope is small. Under such conditions considerable time is taken for the oscillation to reach maximum amplitude, and too great a value of negative bias may prevent the inception of oscillations.

Intermittent oscillations

26. When the grid bias is derived by the condenser and leak method, it is sometimes found that the oscillations are periodically interrupted, either at an audible rate or possibly several thousand times per second. Intermittent oscillation occurs when the coupling between the anode and grid circuits is much greater than is necessary for the bare maintenance of oscillations, and the time constant $C_g R_g$ of the condenser and leak combination is so large that the charge on the grid condenser cannot leak away with sufficient rapidity. Oscillations start as usual about an operating point situated upon the linear portion of the V_a-V_g characteristic, but the operating point moves downward and to the left into the region where the dynamic mutual conductance is low, and the amplitude of the oscillation starts to decrease. With the correct value of grid leak and degree of coupling, the decrease of amplitude is followed almost instantaneously by a change of bias, stabilising the amplitude of the oscillation at this value as already stated. Under the conditions now in question, however, the decrease of amplitude is not immediately followed by a decrease of negative bias owing to the slow rate of discharge of the grid condenser, and consequently the amplitude of the next oscillation is still further reduced, the effect being cumulative. When the oscillation has died out, the grid condenser still continues to discharge, slowly, through the leak, and the oscillations recommence when the operating point has reached a location on the I_a-V_g characteristic at which the conditions are again favourable. This phenomenon is occasionally utilised in the design of low power oscillators from which a Type A2 (Tonic Train) emission is desired; such oscillators are often referred to as "squeggers." Its occurrence in a C.W. transmitter indicates a breakdown of the grid condenser or grid leak resistance, calling for immediate attention.

Function of the anode tapping point

27. As the output circuit is in effect a rejector circuit in series with the valve, the latter being considered to act as an A.C. generator of voltage μV_g at the resonant frequency of the output circuit, it seems at first sight that the scheme of connections shown in fig. 1 would be perfectly satisfactory for all purposes. Unfortunately, however, the maximum oscillatory power is rarely developed under these circumstances for the following reasons. The value of the product LC in the oscillatory circuit is fixed by the frequency which the transmitter is to radiate, because

$$f = \frac{1}{2\pi\sqrt{LC}}$$
 Taking L and C independently, the capacitance is usually that of the aerial alone,

its value depending upon the design of the aerial and therefore upon the circumstances in which the transmitter is to be used, i.e. air or ground. The capacitance of the aerial being practically incapable of variation, the adjustment of frequency is generally made by varying the inductance in series with the aerial. On the other hand if maximum output power is required, we have seen

that the dynamic resistance of the oscillatory circuit must bear a definite relation to the internal resistance of the valve, e.g. for sinusoidal operation without grid current, $R_d = 2r_a$. Now as $R_d = \frac{L}{CR}$ and the resistance of the aerial circuit is also constant at any given frequency, it appears that the correct loading conditions can only be obtained by a suitable choice of the ratio $\frac{L}{C}$, but as both L itself and the product LC are already fixed by other considerations, it is usually impossible to vary this ratio. The desired effect can be achieved however, by connecting the valve to the output circuit in the manner shown in fig. 17a. Here the circuit consists of two parallel branches, one containing an inductance L only, the other containing an inductance l and a condenser C in series. The circuit must of course possess an inherent resistance R , which may be considered as "lumped" at any point in the circuit, its exact location being immaterial because it is so small that its effect on the phase of the current is negligible. The reactance of the purely inductive branch is ωL ohms, and that of the other branch is $\frac{1}{\omega C} - \omega l$ ohms. Hence,

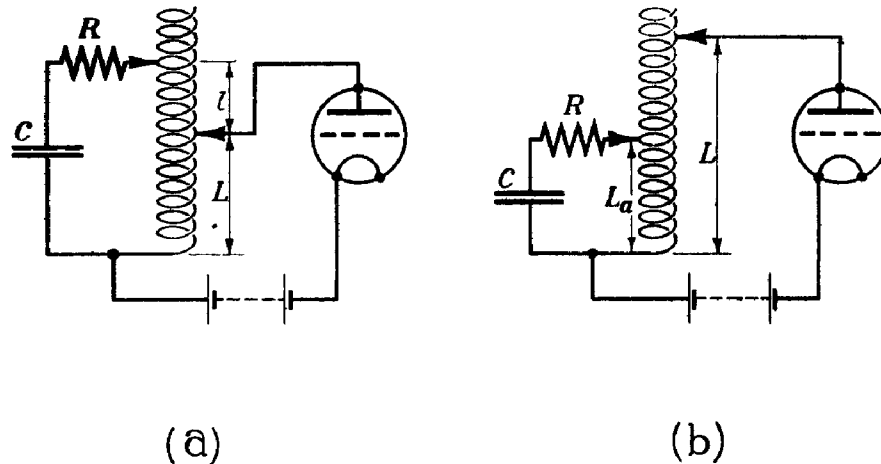


FIG. 17, CHAP. IX.—Anode tapping point.

if a voltage V is applied to the circuit

$$I_L = \frac{V}{\omega L} \text{ lagging on } V \text{ by } 90^\circ,$$

$$I_C = \frac{V}{\omega C - \frac{1}{\omega l}} \text{ leading on } V \text{ by } 90^\circ,$$

the effect of the resistance being neglected.

The supply current I_a is equal to the arithmetical difference of these or

$$I_a = V \left(\frac{1}{\omega L} - \frac{1}{\omega C - \omega l} \right).$$

The supply current will be zero if $\frac{1}{\omega L} = \frac{1}{\omega C - \omega l}$ or $\omega L = \frac{1}{\omega C} - \omega l$, that is if $\omega^2 = \frac{1}{(L + l)C}$.

It will be noted therefore that in a rejector circuit of total inductance $L + l$ and capacitance C the resonant frequency is not changed by altering the position of the two points to which the supply voltage is connected. The circulating current I_L or I_C for a given supply voltage is however

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greater in the circuit of fig. 17a than in the original rejector circuit, for in the latter the current in the inductive branch for example, would be $\frac{V}{\omega(L+l)}$ instead of $\frac{V}{\omega L}$ as in the present condition.

28. The power P expended in the oscillatory circuit depends upon the resistance, and is equal to $I_L^2 R$ watts. Since $I_L = \frac{V}{\omega L}$,

$$P = \frac{V^2}{(\omega L)^2} R = \frac{V^2 CR (L+l)}{L^2} \text{ watts}$$

because $\omega^2 = \frac{1}{(L+l)C}$. An alternative expression for the power expended is $\frac{V^2}{R_d}$ where R_d is the dynamic resistance of the parallel circuit, and equating these

$$\begin{aligned} \frac{V^2}{R_d} &= \frac{V^2 CR (L+l)}{L^2} \\ R_d &= \frac{L^2}{(L+l)CR} \\ &= \left(\frac{L}{L+l}\right)^2 \frac{L+l}{CR} \text{ ohms.} \end{aligned}$$

Now $\frac{L+l}{CR}$ is the dynamic resistance of the tuned circuit when connected in the anode circuit with no anode tap, and when the latter device is fitted, the dynamic resistance may be either larger or smaller than this. The physical explanation is as follows. The aerial tuning inductance may be considered to act as an air-core auto-transformer, and in Chapter VI it is shown that if the resistance of the secondary circuit of a transformer is R_2 ohms, the equivalent resistance transferred to the primary circuit is $\frac{R_2}{T^2}$ ohms, T being the transformation ratio. The effective

transformation ratio in the present instance is $\frac{L+l}{L}$, and as the value of L may be varied by means of the anode tap without affecting the value of $L+l$, the effective resistance transferred to the anode circuit may also be varied. This effect is easily illustrated by numerical examples.

Example 2.—A valve of $r_a = 10,000$ ohms has an anode circuit consisting of an inductance of $2,000 \mu H$, and a capacitance of $.001 \mu F$ in parallel, the total resistance of the oscillatory circuit being 50 ohms. The conditions of operation require that R_d shall be $2r_a$. What portion of the total inductance should be included in the anode circuit?

The dynamic resistance of the anode circuit without anode tap is $\frac{2,000}{.001 \times 50}$ or 40,000 ohms, and for maximum output this must be reduced to 20,000 ohms.

$$\frac{40,000}{20,000} = \left(\frac{L+l}{L}\right)^2$$

$$\frac{L+l}{L} = \sqrt{2}$$

$$L = .707 (L+l)$$

i.e. the anode tapping point should be adjusted so that .707 of the aerial tuning inductance is included in the anode circuit. At high frequencies, it may be necessary to use a step-down auto-transformer in order to secure correct loading conditions, as in the following example.

Example 3.—If the valve and circuit remain as above, except that the value of aerial inductance required for tuning purposes is $200 \mu H$, what is the position of the anode tap for maximum output?

Instead of denoting the tuning inductance by $L+l$ it will be preferable to denote it by a single symbol, L_a .

The dynamic resistance of the oscillatory circuit is now $\frac{L_a}{CR} = \frac{200}{.001 \times 50} = 4,000$ ohms.

$$\left(\frac{L_a}{L}\right)^2 = \frac{4,000}{20,000}$$

$$L = \sqrt{5} L_a \\ = 2.24 L_a.$$

This signifies that 2.24 times as much inductance must be included in the anode circuit as is required in the oscillatory circuit, and the arrangement used is shown in fig. 17b. This condition only arises in practice in the high frequency band.

29. When the anode tap has been adjusted for maximum output the external and internal impedances R_d and r_a are said to be matched, and it must be clearly understood that by matching, equality of internal and external impedance is not necessarily implied. In practical transmitters two methods of adjusting the anode tap may be met with. In large transmitters designed for use on the ground, the aerial capacitance at one station may differ considerably from that at another, and as space and weight are not of primary importance the design of the transmitting inductance may be sufficiently flexible to allow the desired frequency range to be covered with any aerial system likely to be adopted. In such circumstances the anode tap is independently adjustable, its optimum position being found by trial and error. In aircraft, however, the aerial design for use with a given type of transmitter is standardised, and it is generally possible to design the transmitter in such a manner that the operation of changing the value of tuning inductance automatically adjusts the anode tap to its optimum value. The advantage of this is the saving of time which might otherwise be spent in an endeavour to achieve a slight improvement in output power.

The pulse coil

30. In certain transmitters operating upon the high frequency band, the tuning inductance consists only of a variometer. Owing to the necessity for relative movement of its coils it is not desirable to arrange an anode tapping point directly upon the variometer windings. The matching of internal and external impedances is then achieved by the addition of what is called a pulse coil, the arrangement being shown in fig. 18a and 18b. It will be seen that the pulse coil is in effect an auto-transformer which may be used either as a step-up, step-down or unity transformation ratio device by judicious selection of the tapping points, and matching can be achieved over a wide frequency range. The inductance of the pulse coil should be of the order of ten times the maximum inductance of the variometer winding.

31. In designing a transmitter, the power output required may be taken as the starting point, and together with the efficiency of power conversion, a figure for which may be assumed

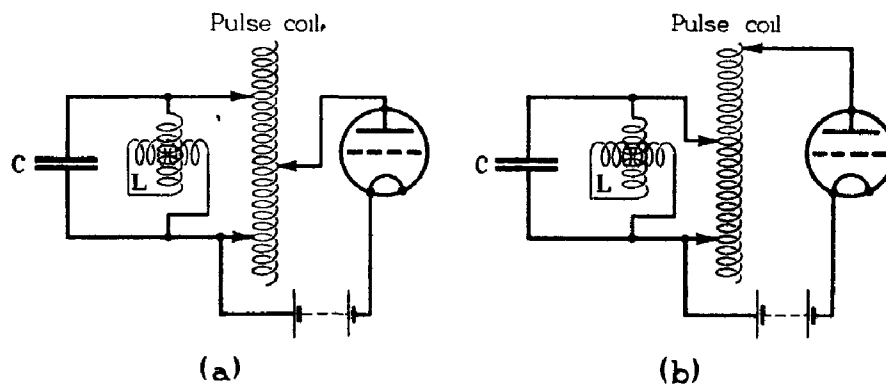


FIG. 18, CHAP. IX.—Use of pulse coil.

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from experience of similar designs, the rating of the valve is obtained ; for example if the required output is 100 watts and an efficiency of 66 per cent. is considered feasible, 100 watts will be two-thirds of the input power, hence the latter must be 150 watts, and the valve is required to dissipate one-third of the input, or 50 watts. The ratings of both the H.T. generator and the valve are now known, and the remainder of the circuit is built up round these fundamental components. As it is impossible to provide an indefinite range of valves of various ratings, it is often necessary to use two or more valves in order to obtain the desired output, the valves being connected in series, in parallel, or in push-pull. The first method offers practical difficulties which prevent its adoption, but the two latter methods are in general use.

Valves in parallel

32. Valves are said to be in parallel when the corresponding electrodes are interconnected, the filaments being connected in parallel and fed from a common L.T. source, the anodes connected to a common terminal and thence to the anode tap, while the grids also are connected to a common terminal and thence to the reaction coil or tuned grid circuit as the case may be. If, in case of emergency, an attempt is made to increase the output of an existing transmitter by connecting valves in parallel, it is important to observe that the valves must be as nearly identical as possible, otherwise there is a possibility that one or more may act merely as shunt resistances across the others, absorbing power instead of supplying it to the oscillatory circuit. This is not likely to happen unless valves of very different characteristics, e.g. a V.T. 25 and a V.T. 13C are so connected, but the permissible variation decreases as the number of valves is increased. As the anode A.C. resistance of two similar valves in parallel is only one-half the resistance of a single valve, the optimum external resistance will be lower, and the amount of inductance included between the anode tap and the low potential end of the anode inductance must also decrease. This requirement places a limit on the number of valves which may be operated in parallel, for a point is reached at which the inductance included in the anode circuit becomes so small that the phasing conditions necessary to maintain oscillation are no longer preserved. If two valves are perfectly matched, and are working into the correct load resistance, the power output should be double that obtainable from a single valve under the same operating conditions. The circulating current in the oscillatory circuit will therefore be increased in the ratio $1 : \sqrt{2}$.

Valves in push-pull

33. The scheme of connections given in fig. 19 is called push-pull connection. The name is perhaps unfortunate because it tends to cause the reader to expect an explanation of its operation in terms which interpret the idea of pushing and pulling too literally. Generally, valves may

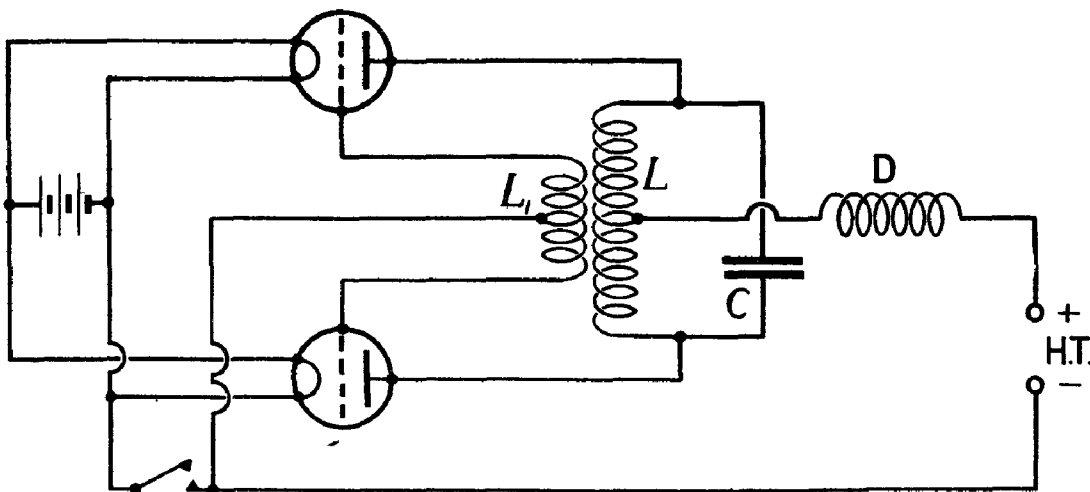


FIG. 19, CHAP. IX.—Simple push-pull oscillator.

be said to be in push-pull when one half of the total grid-filament voltage is applied to each valve of a pair, the output voltages being combined in such a manner that the total is double that of a single valve. The manner in which an oscillation may be maintained, when once established in the output circuit, is as follows :—

(i) Consider the cycle to commence at the instant at which the whole of the oscillatory energy is stored in the anode circuit inductance, and the circulating current is a maximum. At this moment the electron flow through the inductance is in the direction B to A as shown by the arrow in fig. 20a, and the induced E.M.F. in the reaction coil L_1 is zero because the connections are so arranged that the relative phases of current and voltage are as shown in fig. 3, i.e., the grid-filament voltage is 90° ahead of the current in the anode circuit inductance. The anode currents in both valves are of equal magnitude as indicated by the length of the arrows. It should be noted that the arrows indicate the direction of the electron flow in all cases. During the time the current is flowing in the inductance a certain amount of energy is dissipated in the

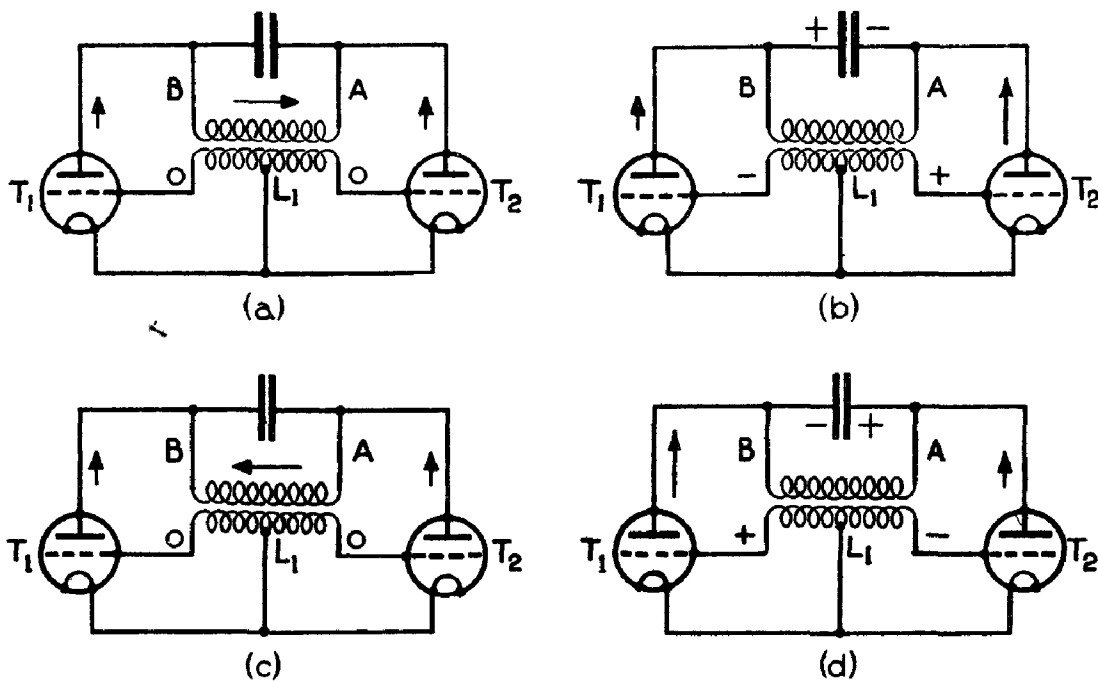


FIG. 20, CHAP. IX.—Action of push-pull oscillator.

form of heat and electro-magnetic radiation and it is convenient to consider that a certain number of the electrons which collectively comprise the oscillatory current are brought to rest in giving up this energy.

(ii) A quarter of a cycle later the energy is all stored in the condenser which is charged with the polarity shown in fig. 20b. The current in the inductance has by this time fallen to zero but the induced E.M.F. in the reaction coil is at its maximum value, the grid of the valve T_2 being positive with respect to the filament and that of the valve T_1 being negative. The anode current of T_2 is therefore increasing and a supply of electrons is introduced into the right-hand side of the condenser in addition to those carried by the circulating current previously mentioned. These electrons serve to replace those brought to rest by the conversion of the kinetic energy into various forms of wastage. The valve T_1 also assists in the re-charging of the condenser, for the reduction of its anode current implies that fewer electrons are arriving at the left-hand side of the condenser than when normal anode current is flowing.

(iii) The condenser will now commence to discharge through the inductance, electrons flowing through the coil from A to B, fig. 20c. At the instant when this current reaches its

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maximum the grid-filament voltage of both valves is zero and anode currents normal. The whole of the energy is then stored in the inductance, the condenser voltage being zero. The current now continues to flow, charging the condenser negatively on the left-hand side; as the condenser voltage rises the current falls and is zero at the instant when the condenser charge is a maximum. The grid-filament voltage of the valve T_1 reaches its maximum positive value at this instant while that of T_2 is at its maximum negative value. The anode current of T_1 therefore increases so introducing a negative charge in the left-hand side of the condenser, which replaces those electrons which have given up their kinetic energy. The condenser then discharges once more, the conditions at the end of the next quarter of a cycle being those of fig. 20a, and the foregoing cycle is then repeated.

34. The manner in which the inception of the oscillation takes place is not obvious at first sight. In fig. 19, if the positive anode supply is connected to the electrical centre of the inductance L the two halves of the circuit are perfectly symmetrical. With valves of exactly similar characteristics, the closing of the circuit will cause equal rates of increase of anode current through both valves simultaneously and it would appear that two equal and opposite counter-E.M.F.'s are developed in the inductance, the resulting condenser charge being zero. It must be emphasized that it is not possible to achieve this exact symmetry. Even if momentarily obtained, the condition would not persist, e.g. even a minute change in the magnetic field of the earth will not affect both halves of the circuit at the same instant and to the same degree and therefore will cause some slight counter-E.M.F. to be set up, which must introduce a charge into the condenser C . The slightest asymmetry in the circuit will cause a larger counter-E.M.F. in one half of the inductance than in the other, and a resulting condenser charge, when the circuits are first completed, and once energy is stored an oscillation will occur (provided the damping is sufficiently low); the foregoing action shows that once established it will be at least maintained, and will increase in amplitude until limited by characteristic curvature if the mutual inductance between the coils L and L_1 exceeds the critical value. The impossibility of achieving exact similarity in both halves of the circuit is shown by the practical necessity for the anode choke (D, fig. 19). If absolute symmetry were attainable, this choke could be omitted, for the electrical centre of the inductance L is at the same oscillatory potential as the filament. The choke is inserted because it is practically impossible to find the exact electrical centre, and its inclusion ensures that the actual point at which the H.T. supply is fed is not thereby brought to filament potential also.

35. The advantages claimed for the push-pull type of circuit are:—

(i) The greater frequency band which may be covered by a given inductance and condenser when these components constitute either the grid (input) or anode (output) circuit of the valve. The anode-filament capacitances of the two valves are in series across the tuning condenser C in fig. 19, and the total effective capacitance in parallel with C is only one-half of that which would exist if a single valve were employed. In the same way, the grid-filament capacitances are in series across the reaction coil and the total effective capacitance of this circuit is also less than with a single valve. This effect does not appear to be of great importance in circuits in which a tuning condenser is used, for as a rule the inter-electrode capacitance will form only a very small portion of the total.

(ii) The circuit is symmetrical, and consequently variations of capacitance with respect to earth have a smaller effect upon the frequency than in circuits such as the Hartley or Colpitts.

(iii) The harmonic variations of anode current produced by impulse excitation are considerably reduced. This appears to be the most important advantage of the push-pull circuit and will be further considered.

36. The arrangement of valves in push-pull is such that the half-cycles of grid voltage which cause the grid of one valve to become positive with respect to the filament, have the opposite effect upon the grid of the other valve. If it is desired to show the effect of grid voltage upon both valves, the characteristic curves must be combined as shown in fig. 21 if operation takes place without grid bias, and as shown in fig. 22 if grid bias is applied. In transmitters using

impulse excitation, the latter condition is applicable and it will be assumed that the operating point is near the curved "foot" of the curve, the grid voltage swing and resulting change of anode current being as shown. It will be observed that the anode current change is far from sinusoidal, and on the right-hand side of the figure the anode current has been analysed into its principal component frequencies, i.e. the fundamental and second harmonic. It will be observed that the fundamental components, if added, result in a first harmonic which has double the

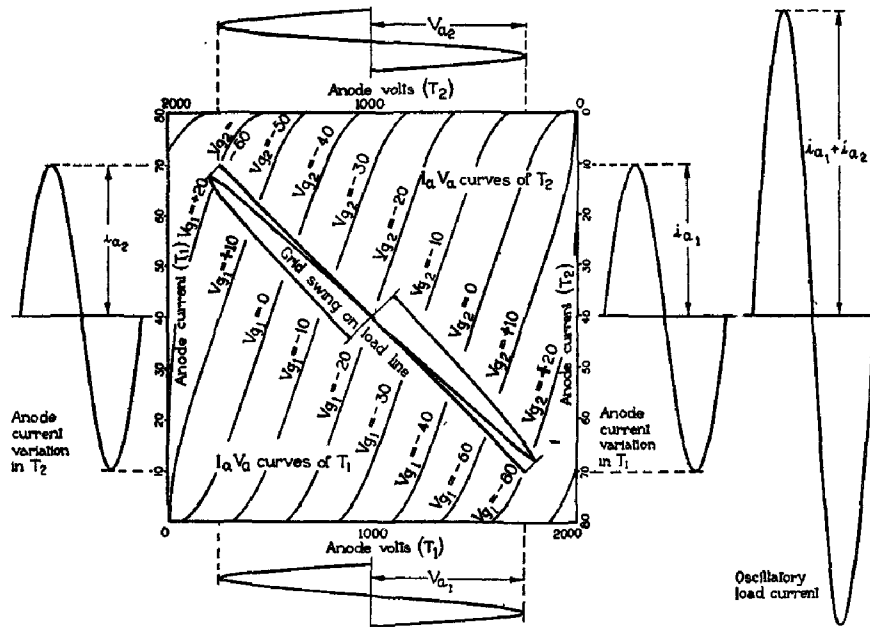


FIG. 21, CHAP. IX.—Combined characteristics of valves in push-pull without negative bias.

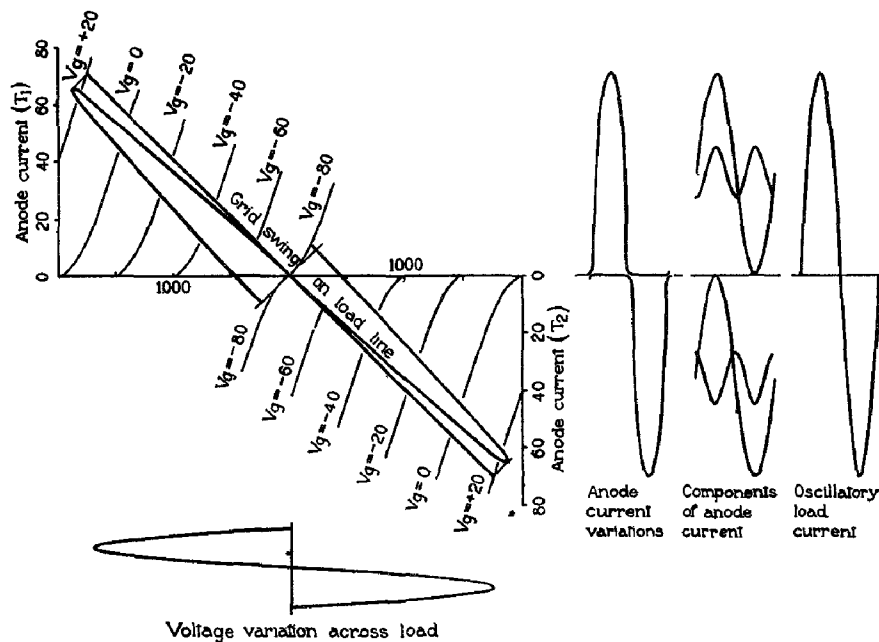


FIG. 22, CHAP. IX.—Combined characteristics of valves in push-pull, biased to foot of characteristic.

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amplitude of either of the individual amplitudes, while the addition of the two second harmonic variations results in zero current. In other words, the fundamental variations of current in the oscillatory circuit are in phase with each other, while the second harmonics are in antiphase, and cancel each other. If the characteristic curves of the two valves in push-pull were identical, this cancellation of even harmonics would be complete, and therefore the system would combine the efficiency of impulse excitation with the purity of wave-form associated with operation upon the linear portion of the characteristic. Unfortunately, however, it is rarely that two valves can be so equally matched as to give more than a slight reduction of second harmonic, at any rate under service conditions. In general, it may be said that if space and weight permit the employment of two valves, it is preferable to utilise them as an oscillator and power amplifier, in the manner presently described, rather than in push-pull. The amplifier itself may however be of the push-pull type for the reasons enumerated in paragraph 35 (i) and (ii).

POWER SUPPLIES

L.T. supply to transmitter

37. In low power transmitters a secondary battery is frequently utilised to supply the necessary heating current for the valve filaments. Provided the cells are in good condition the filament current is maintained at a very steady value, and this results in an approach to stability in the values of anode A.C. resistance and grid-filament conductance of the transmitting valve or valves. The employment of battery supply for L.T. purposes is therefore conducive to a high degree of frequency constancy. Mobile transmitters e.g. in aircraft, preferably utilise battery supply for this reason, although in some instances it may be found desirable to employ a "dual purpose" generator, that is one in which two separate armatures are mounted on a common shaft, the rotor being driven through a constant speed clutch by a windmill in the slip stream. One armature then supplies say 5 amperes at 10 volts for filament heating, while the other supplies the small anode current, e.g. up to 100 milliamperes, at 2,000 volts. A machine of this kind is also a feasible method of supply to a semi-portable transmitter, the drive being supplied by a petrol motor. High power ground station transmitters may be fitted with motor generators for filament supply, owing to the reduction of maintenance compared with batteries, while at stations in which an alternating supply is available, this may be used to supply the filament circuits, through suitable step-down transformers. This generally results in a slight variation in the amplitude of the emitted radiation and a spreading of its frequency over a rather wider band than with a battery supply, but the effect is not harmful, at any rate in C.W. or I.C.W. transmission.

H.T. supply to transmitter

38. Low power transmitters may utilise a battery of inert or secondary cells, provided the total power input does not exceed a few watts, but for higher powers, either direct or alternating current generators must be employed. The direct current generator is only suitable for voltages up to about 4,000 volts, difficulties with commutation and effective insulation between armature windings and core being experienced with higher voltages. For this reason, alternating current generators are almost universally employed for high power transmitters, the necessary conversion into direct current being performed by a rectifying system. The term rectification is used to denote the conversion of an alternating into a direct current, and the commutator fitted to a D.C. generator is merely a particular form of mechanical rectifier. In the sense in which it is usually employed, however, rectification means the achievement of this conversion without aid of rotating machinery, and the term will be used with this signification in the subsequent paragraphs. A rectifier, then, may be defined as any conducting body or substance which does not obey Ohm's law, and the thermionic valve fulfils this condition as has already been shown. When the input voltage is large and a large power output is required the most suitable form of valve for rectifying purposes is the diode.

Half-wave rectifying system

39. The simplest form of rectifying circuit is that known as the half-wave rectifying system, and is shown in fig. 23. In this diagram the power supply is derived from an alternator, although in practice the ordinary commercial supply mains may be used. The supply voltage is usually from 200 to 250 volts, and is raised to say 3,000 volts by a step-up transformer. The filament of the rectifying diode may be heated by a suitable battery, but it is more convenient to utilise the A.C. supply for this purpose, and the diagram shows an L.T. transformer having a step-down of about 10 to 1, giving a filament supply at about 20 to 25 volts. An ammeter and rheostat are fitted in order that the filament current may be adjusted to the value shown on the label of the valve. So far as power supply is concerned, the transmitter may be represented by a resistance R which is connected in parallel with a condenser C called the reservoir condenser. The action of the system may be explained by first assuming that the load resistance is absent. The filament being heated to its correct temperature, an anode current will be established only when the anode is at a positive potential with respect to the filament. On closing the switch S an alternating current flows in the primary winding of the transformer and an alternating E.M.F. is

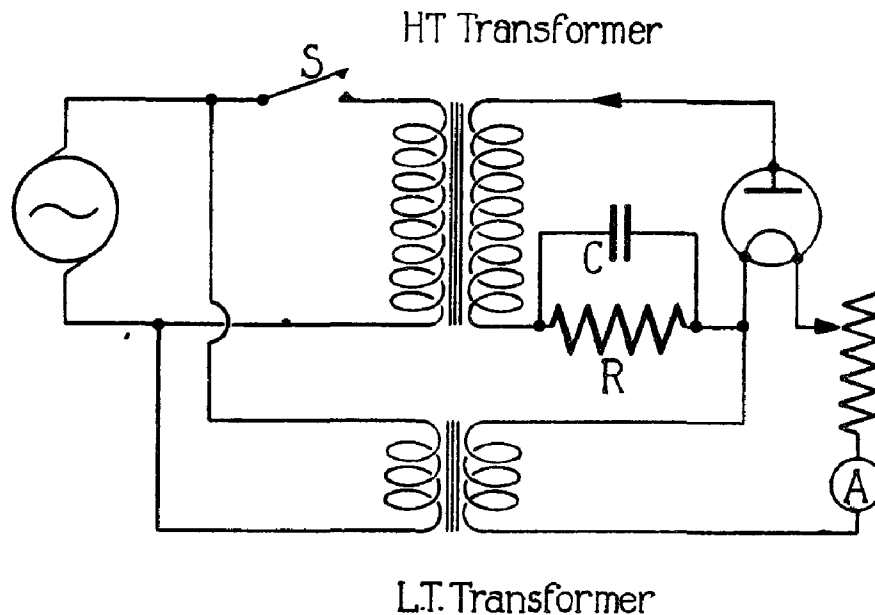


FIG. 23, CHAP. IX.—Half-wave rectifying circuit.

developed in the secondary winding. During those half-cycles in which the anode is positive an electron current will flow through the valve and the secondary winding of the transformer, charging the reservoir condenser negatively on the left-hand plate. A corresponding displacement current is set up in the dielectric and causes a repulsion of electrons from the right-hand plate which therefore acquires a positive charge. No such current will be established during those half-cycles in which the anode is negative with respect to the filament. After a few cycles, the P.D. between the plates of the condenser will be equal to the peak secondary voltage of the transformer, and no further action will take place. This charging process is shown graphically in fig. 24.

40. If the rectifier is assumed to possess an ideal characteristic, i.e. infinite resistance for negative values of applied voltage and a constant finite resistance for positive values, an idea of the charging process during the first half-cycle can be obtained by assuming that the peak current is equal to that which would be caused by the peak voltage, less that which would be caused by

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a steady voltage equal to the counter-E.M.F. of the condenser at the end of the half-cycle. If \mathcal{I}_1 is the peak value of the current, \mathcal{E} the peak value of the applied voltage and V_1 the counter-E.M.F. of the condenser at the end of the first half cycle,

$$\mathcal{I}_1 = \frac{\mathcal{E} - V_1}{r_a}.$$

The average value of this current will be $I_1 = \frac{\mathcal{I}_1}{K}$, K being equal to π if the current wave is semi-sinusoidal, hence

$$I_1 = \frac{\mathcal{E}}{K r_a} - \frac{V_1}{K r_a}.$$

The charge Q_1 introduced into the condenser by this average current flowing for one half-cycle is $I_1 \times \frac{T}{2}$ or $\frac{I_1}{2f}$.

$$\therefore Q_1 = \frac{\mathcal{E}}{2K f r_a} - \frac{V_1}{2K f r_a}$$

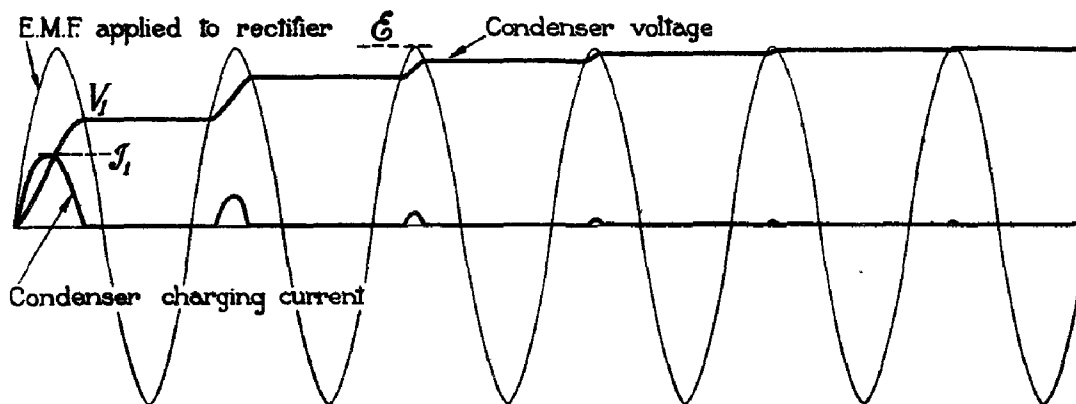


FIG. 24, CHAP. IX.—Charge of reservoir condenser under no load conditions (half-wave rectifier).

and V_1 , the voltage to which the condenser is charged, is $\frac{Q_1}{C}$, hence

$$V_1 = \frac{\mathcal{E}}{2K f r_a C} - \frac{V_1}{2K f r_a C}$$

$$V_1 \left(1 + \frac{1}{2K f r_a C} \right) = \frac{\mathcal{E}}{2K f r_a C}$$

and

$$V_1 = \frac{\mathcal{E}}{1 + 2K f r_a C}.$$

As an example, take $K = \pi$, $f = 50$ cycles per second, $C = 1\mu F$, $r_a = 2,000$ ohms, $\mathcal{E} = 2,000$ volts. Then

$$V_1 = \frac{2,000}{1 + 2\pi \times 50 \times 2 \times 10^3 \times 1 \times 10^{-6}}$$

$$= \frac{2,000}{1.628} = 1,230 \text{ volts.}$$

During the next positive half-cycle of transformer secondary voltage, anode current will not start to flow until the transformer voltage exceeds 1,230 volts, so that in effect only 2,000—1,230 or 770 volts are available to produce a further charge in the condenser. If this further charge produces an additional counter-E.M.F. of $\frac{770}{1.628}$ volts, and so on during succeeding cycles, the rate at which the condenser P.D. will grow will be shown as below. In this table $\mathcal{V}_1, \mathcal{V}_2, \mathcal{V}_3$, etc., represent the differences between the applied peak E.M.F. and the condenser P.D., the latter quantity for each half-cycle being denoted by V_1, V_2, V_3 , etc.

$$\begin{aligned} \mathcal{E} &= 2,000 \\ V_1 &= \frac{2,000}{1.628} = .615 \times 2,000 = 1,230 \\ \mathcal{V}_1 &= 2,000 - 1,230 \\ &= 770 \\ V_2 &= .615 \times 770 + 1,230 = 472 + 1,230 = 1,702 \\ \mathcal{V}_2 &= 2,000 - 1,702 \\ &= 298 \\ V_3 &= .615 \times 298 + 1,702 = 184 + 1,702 = 1,886 \\ \mathcal{V}_3 &= 2,000 - 1,886 \\ &= 114 \\ V_4 &= .615 \times 114 + 1,886 = 70 + 1,886 = 1,956 \\ \mathcal{V}_4 &= 2,000 - 1,956 \\ &= 44 \\ V_5 &= .615 \times 44 + 1,956 = 27 + 1,956 = 1,983 \\ \mathcal{V}_5 &= 2,000 - 1,983 \\ &= 17 \\ V_6 &= .615 \times 17 + 1,983 = 10.4 + 1,983 = 1,993.4 \end{aligned}$$

After six cycles the condenser will be charged to a voltage practically equal to the applied peak voltage, and no further action will take place. Though admittedly an approximation, this argument traces out clearly the successive stages by which an applied voltage of sinusoidal form results in the development of a steady P.D. between the condenser terminals. The curve shown in fig. 24 to which reference has already been made, is actually plotted from the data calculated above.

41. Now consider the load resistance to be connected as shown in fig. 23. During the first positive half-cycle the diode will allow an electron current to flow as in the case just discussed, and of this a portion will flow through the resistance and a portion will charge the condenser with the same polarity as before. By the end of the half-cycle the condenser P.D. will reach some finite value V_1 (fig. 25). During the next half-cycle the anode is negative, no anode current will flow, and the condenser will receive no charge. The condenser P.D. will now tend to maintain the current through the resistance R, and will therefore fall, say to V_2 . During the second positive half-cycle an anode current will not be established until the transformer secondary voltage is equal to the condenser P.D., V_2 ; at this instant the reservoir condenser will commence to charge once more, eventually reaching some P.D., V_3 , greater than V_2 , but when the secondary voltage falls below the condenser P.D. no further charge will be introduced. Meanwhile the current through the load resistance has been maintained, and in fact slightly increased, by the combined effects of the transformer voltage and condenser P.D. During the remaining portion of the positive half-cycle and the succeeding negative half-cycle, the condenser receives no charge, but

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continues to maintain the load current, and the P.D. across the load falls slightly, i.e. from V_3 to V_4 . After a few cycles the energy received by the condenser during the positive half-cycles will be exactly equal to that dissipated in the load resistance during the whole cycle, and the condenser R.D. will be maintained at an average value V_0 , about which it fluctuates slightly as shown in the diagram.

The slight variation in the voltage at the load terminals is called the voltage ripple, and is obviously an undesirable phenomenon. It is convenient to regard it as a small alternating voltage superimposed upon the average condenser voltage V_0 , the fundamental frequency of this ripple voltage being equal to that of the A.C. supply, although higher harmonics are also present.

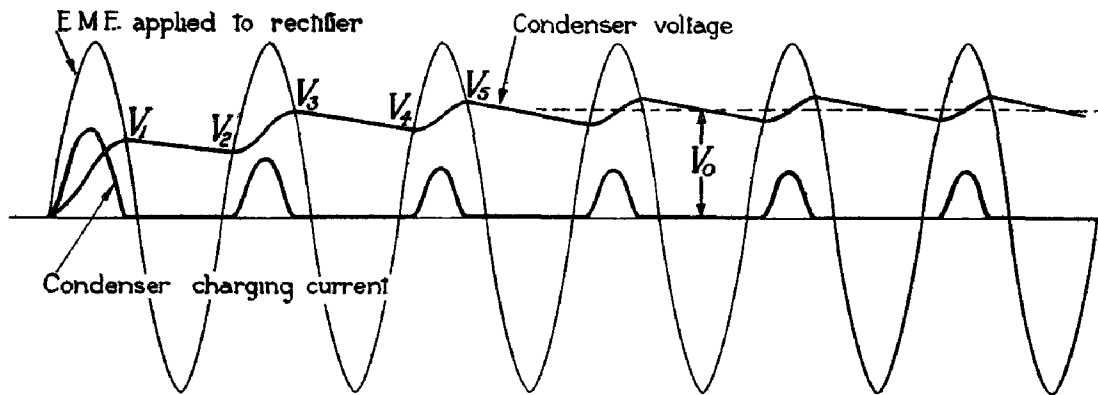


FIG. 25, CHAP. IX.—Charge of reservoir condenser under working conditions (full-wave rectifier).

The effect of the ripple is to modulate the anode current supply to the transmitter, and the resulting radiation is not truly a continuous wave. The percentage variation of the condenser P.D. is, by fig. 25, $\frac{V_5 - V_4}{V_0} \times 100$. This percentage is inversely proportional to the load resistance, the capacitance of the reservoir condenser, and the ripple frequency. For a given transmitter, fixing the value of the load resistance, therefore, the ripple is less with a high frequency supply voltage than with a low, and it would appear that the reservoir condenser should also be as large as practicable. It must however be observed that the larger the capacitance, the greater is the number of cycles taken to charge the condenser to its final mean value V_0 , and if the capacitance is larger than one or two microfarads the quality of the transmission may become "chirpy", while when signalling at extreme ranges the shorts may possess insufficient power to give an audible response. The supply frequency is usually fixed by considerations other than those of signalling, e.g. in this country all commercial supply mains will eventually be standardised at 50 cycles per second. It is possible to reduce the percentage of ripple by the use of a full-wave rectifying system.

Full-wave rectifying system

42. (i) In the full-wave rectifying system both half-cycles of the transformer voltage are utilised in charging the reservoir condenser. A typical arrangement is shown in fig. 26. Two separate diodes U_1 , U_2 are connected in such a way that they share a common filament supply, but the anode of each valve is connected to one end of the secondary winding of the transformer. The latter carries a tapping at the electrical centre and the reservoir condenser is connected between this point and a point in the rectifier filament circuit, the load resistance being connected in parallel with the reservoir condenser as in the half-wave system. The action of the circuit follows from the previous discussion, and may be outlined as follows. When the switch S is closed, suppose the upper end X of the secondary winding to become positive with respect to

the filaments, and the opposite end Y correspondingly negative. As the voltage rises an electron current is established in the valve U_1 but not in the valve U_2 and electrons flow into the condenser at the plate A which thereby acquires a negative charge, the plate B becoming positive. At the end of the first half-cycle the condenser is charged to the voltage V_1 (fig. 27). During the next half-cycle, the anode of the valve U_2 is positive to the filament, and the electron current through it again charges the reservoir condenser, with the same polarity as before. At the end of one cycle, therefore, the condenser has received two charges instead of only one as in half-

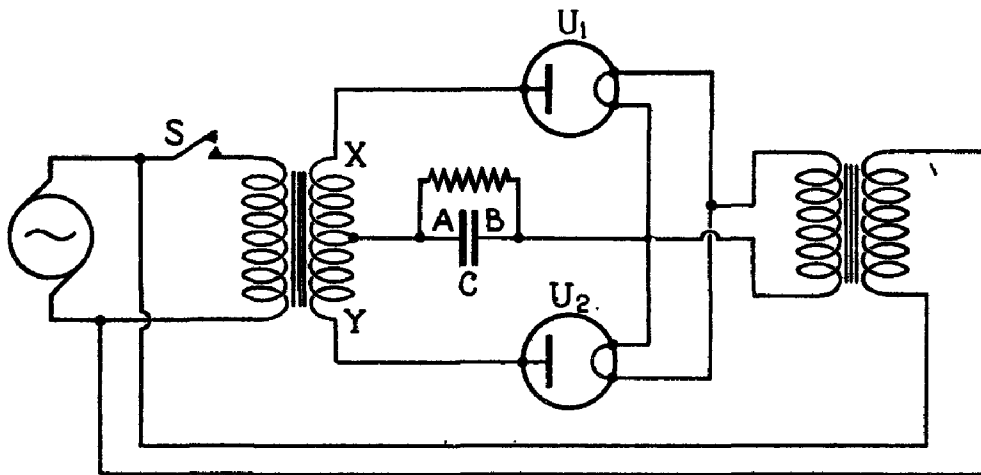


FIG. 26, CHAP. IX.—Full-wave rectifying circuit.

wave rectification. So far as charging is concerned, the method of connecting the diodes has the effect of making both half-cycles of positive sign, and in fig. 27 the negative half-cycles have been inverted to show this effect. The condenser P.D. tends to maintain a current in the load resistance, and in the intervals when the condenser is not actually receiving a charge its terminal P.D. falls; thus the condenser P.D. will increase during successive cycles as shown by the line V_1, V_2, V_3 , etc. During the first few half-cycles, the condenser voltage gradually reaches a state of equilibrium in which the charge given up in order to maintain the load current is just

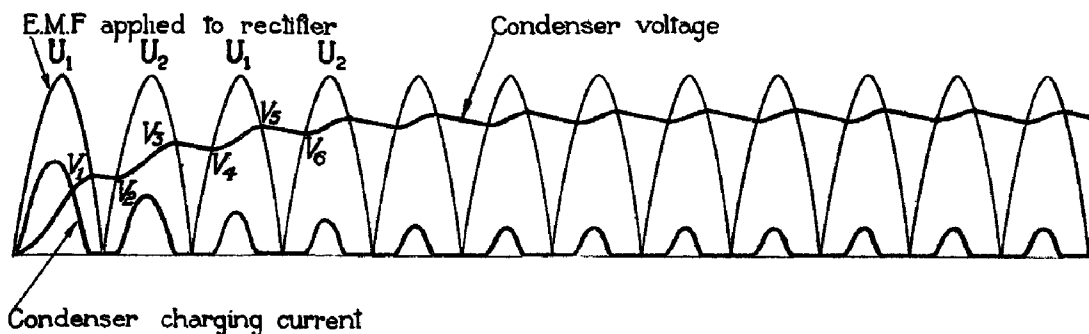


FIG. 27, CHAP. IX.—Charge of reservoir condenser under working conditions (full-wave rectifier).

balanced by the charge received from the rectifying valves. A slight voltage ripple is found to exist, its fundamental frequency being twice the supply frequency. For a given transmitter and reservoir condenser, the percentage ripple in the full-wave system is one-half that of the half-wave system.

(ii) In practice, the wave-form of the transformer secondary voltage is rarely if ever sinusoidal, for even if the wave-form of the alternating supply has this desirable characteristic, the wave-form of the secondary E.M.F. is distorted owing to the presence of a unidirectional current in the

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secondary winding during certain portions of the cycle, this current being of course that which charges the reservoir condenser. In the half-wave circuit, this current flows always in the same direction through the whole secondary winding, and consequently there is a steady magnetising component of current and a constant flux in the core, upon which the alternating flux is superimposed. The result of this is to increase the time during which anode current flows, and to reduce the peak value of the anode current. The current and voltage waves of an actual half-wave rectifier are shown in fig. 28a, for a circuit having a comparatively large reservoir condenser. These may be compared with corresponding curves for a full-wave rectifier, fig. 28b, which indicate the greater approach to constant load current given by the latter system.

Keying arrangements and safety devices

43. (i) In the service, two types of diode are in general use in rectifying systems for H.T. supply to transmitters. The first is the hard or vacuum type, for example the valve, rectifying V.U.7.A. These are diodes which are exhausted to the highest degree possible, the filament being of hairpin form and the anode consisting of a nickel cylinder. The anode A.C. resistance of the valve V.U.7.A. is of the order of 1,000 ohms. Their rather high internal resistance is a disadvantage of the vacuum type, causing the P.D. at the terminals of the reservoir condenser to fluctuate violently with changes of load, such as would be caused by "keying" the C.W.

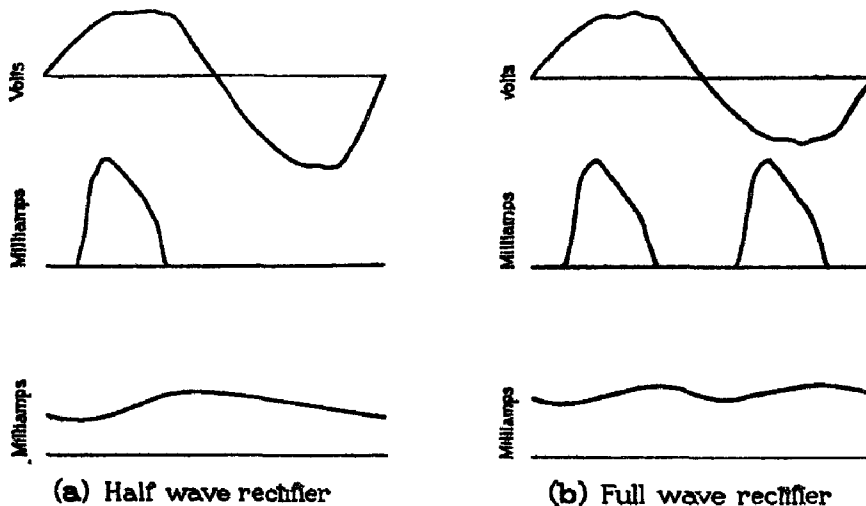


FIG. 28, CHAP. IX.—Secondary E.M.F., charging current, and load current of practical half-wave and full-wave rectifiers.

transmitter. For this reason it is desirable to arrange the keying device in such a manner that it interrupts not only the H.T. supply from the reservoir condenser, but also the primary circuit of the transformer. If this is not done, the condenser P.D. rises to the peak voltage of the transformer winding, in the case of the half-wave rectifier, or to one-half this value with the full-wave rectifier every time the load is entirely removed, and on pressing the key an excessive current may flow in the anode circuits of the transmitter. This is not likely to cause damage, although it may possibly throw undue strain on certain portions of the insulation, nevertheless the excessive voltage is undesirable because it must result in variation of the valve circuit constants and therefore in frequency variation.

(ii) A common method of keying a transmitter supplied by a vacuum-diode rectifying system is shown in fig. 29. The circuits are interrupted in three places, viz., (a) the primary winding of the transformer, (b) the H.T. negative and grid circuits, (c) the H.T. positive supply to the anode of the transmitting valve. This is performed by an electro-magnetic relay key which is operated by a solenoid. The morse key itself is placed in series with the solenoid together with a suitable source of direct current. This diagram also shows two safety devices which are often

incorporated in ground station transmitters. The transmitter is usually mounted in metal panels which totally enclose all those parts which are at dangerously high potential, doors being provided to allow access for adjustment, replacement of valves, etc. Safety switches are then fitted in such a manner that when any door is open the power supply to the transmitter is automatically interrupted. It must be firmly realised that the mere interruption of the power supply does not render all portions of the circuit safe to handle, for the reservoir condenser remains charged to its normal voltage under these conditions. An additional switch is therefore fitted by which the reservoir condenser can be completely discharged. This may be arranged for hand or automatic operation, and is marked "transmit" and "safe" in fig. 29. It can be seen that when the switch is at "safe" the reservoir condenser is short-circuited.

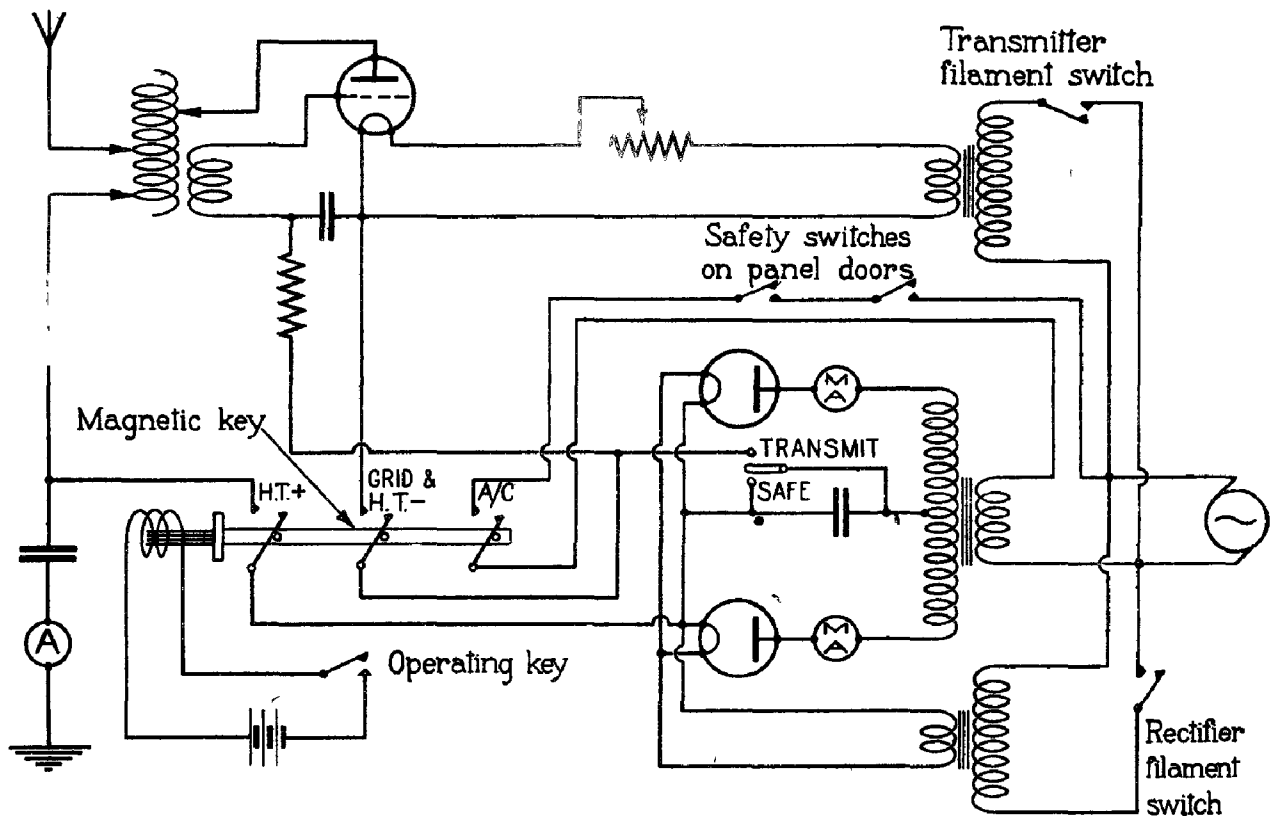


FIG. 29, CHAP. IX.—C.W. transmitter with full-wave rectifying system, showing method of keying and safety arrangements.

(iii) The door switches need not operate directly in the H.T. transformer primary circuit. In modern practice the latter frequently contains an electromagnetic switch similar in principle to the magnetic key, and the door switches are then arranged to break the D.C. supply to the solenoid. This D.C. supply may obviously be obtained from the same source as that from which the magnetic key bobbin is energised, which may be a secondary battery, or may be derived from the A.C. mains through a metal rectifier. The action of this device depends upon the rectification which takes place at a contact between pure copper and a thin film of cuprous oxide. The resistance of such a contact is much higher when the applied E.M.F. is in one direction than in the other, but does not approach infinity as in the vacuum diode. The oxide film will withstand a P.D. of a few volts only, and the practical rectifier consists of a pile of copper discs, oxidised on one side only, which are separated by lead washers and clamped together. Four such units are generally used, the method of connection being known as the full-wave bridge circuit, fig. 30. No reservoir condenser is used as a rule because the existence of an appreciable ripple is not

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detrimental to their operation as a means of D.C. supply to the magnetic keys and switches above mentioned. Provided that a metal rectifier is not overloaded its life is very much longer than that of a diode rectifier.

The hot cathode mercury vapour diode

44. This rectifier has grown in favour during the past few years for H.T. supply purposes where a moderately high voltage is required. The valve consists of a glass bulb containing an oxide-coated filament and a tungsten anode, and is invariably air-cooled even in the largest sizes. It is easily distinguished by its construction from the vacuum type. The latter is to all intents and purposes merely a transmitting valve with the grid structure omitted, the design of both diodes and triodes of high vacuum being based upon the same considerations. The gas-filled

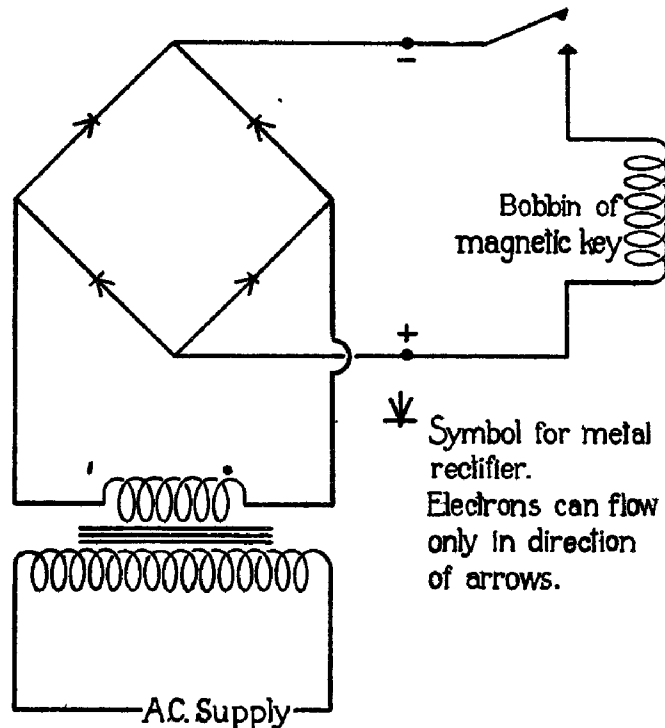


FIG. 30, CHAP. IX.—Full-wave rectifier (bridge circuit) for auxiliary D.C. supplies.

diode is characterised by large inter-electrode spacing compared to the dimensions of the electrodes, the anode in particular being much smaller than the anode of a vacuum diode of equal dissipation. These reduced dimensions are rendered possible by the low power losses in the valve and its consequent high efficiency as a rectifier.

In manufacture the valve is first thoroughly exhausted and a small quantity of liquid mercury is then introduced into the envelope. A proportion of this mercury is vapourised and a state of equilibrium is reached at which the pressure of the mercury vapour is sufficient to prevent further vaporisation, the gas pressure being then of the order of $\cdot 00001$ to $\cdot 00003$ millimetres. The feature of this diode by which it chiefly differs from the high vacuum type is that an anode-filament P.D. of only 15 to 20 volts is sufficient to cause an anode current corresponding to the full electron emission. When the anode is positive with respect to the filament, electrons emitted from the latter encounter mercury vapour molecules, and if the anode-filament P.D. exceeds 10·4 volts the velocity attained by the electrons will be sufficient to cause ionisation

as a result of the collisions. Owing to the small amount of gas present, this ionisation does not lead to any great increase in the anode current, but the positive ions which are formed move so slowly towards the filament compared with the velocity of the electrons in the contrary direction that the negative space charge caused by the latter is practically neutralised, and the anode draws electrons from the filament at the rate at which they are emitted. The anode voltage required to produce the full saturation current is only slightly greater than the potential necessary to cause ionisation, and as the latter is 10·4 volts the full emission is obtainable with an anode filament P.D. of only 15 to 20 volts. Provided however that the anode-filament P.D. does not exceed 22 volts, the mercury vapour ions move so slowly, owing to their comparatively large mass, that no damage is caused to the filament coating by the arrival of positive ions. The important constants of this type of valve are (a) the maximum allowable peak anode current, and (b) the maximum permissible inverse anode voltage, that is the maximum voltage by which the anode may become negative to the filament. The peak anode current is determined by the design of the filament and is not affected by the presence of gas, while the maximum permissible inverse voltage is that which is just insufficient to cause a spark to pass between anode and filament, and is less than the voltage which would cause this effect in vacua. For this reason, the inverse voltage effect is of little importance in high vacuum rectifying valves designed for power supply to transmitters, and was not mentioned in this connection.

45. (i) Owing to the effects of the presence of gas, the mercury vapour diode must be operated under somewhat rigid conditions compared with the high vacuum type. The working temperature must be maintained within certain limits, because the temperature of the valve determines the amount of mercury which will exist in the form of vapour, i.e. if the temperature is too low, more mercury will exist in liquid form and less as vapour, and this will result in a decrease in the number of positive ions formed by collision between electrons and gas molecules. Sufficient anode current can then only be obtained by raising the anode voltage, which will have the effect of producing increased ionisation, but if this increase causes the anode-filament P.D. to exceed 22 volts, the velocity with which the positive ions will impinge upon the cathode will be sufficient to cause disintegration of the latter. On the other hand, an excessive temperature will enable sparking to take place inside the envelope at a lower inverse voltage than normal. A further precaution is necessary, in that an excessive anode current, even if only allowed to persist for a fraction of a second, may cause permanent damage to the valve, for the increased current is accompanied by an increased IR drop in the valve itself and this may exceed the 22 volts above mentioned as the maximum safe anode-filament P.D. The filament must always be brought to full operating temperature before the anode voltage is applied, otherwise during the time taken by the filament to reach the temperature of normal emission, the IR drop in the valve will exceed the safe limit and the filament will suffer heavy damage. For this reason the invariable practice is to fit a device which prevents the application of the anode voltage until some twenty to thirty seconds after the filament circuit has been completed. This apparatus is generally termed the time delay relay, and may be operated by various means. In one type the action is dependent upon the flexure of a bi-metallic strip when heated by a local current, while in another, a coiled spring operates through an escapement similar to that of a clock, the H.T. supply to the anode of the valve being completed only when the specified time has elapsed after the closure of the filament circuit.

(ii) The filament is invariably oxide-coated because it must be designed to function with low terminal voltage, about five volts being the maximum. It is apparent that the P.D. between the ends of the filament must be considerably less than the anode-filament P.D. and the latter rarely exceeds 15 volts. To illustrate this point, assume that the filament P.D. is 8 volts and that the peak voltage of the anode is allowed to rise 15 volts above the most positive part of the filament, then the P.D. between the negative end of the filament and the anode will be 23 volts, and is above the value at which positive ion bombardment of the filament causes disintegration of the latter. This can only be avoided by reducing the anode-filament P.D. to less than 14 volts, a value which is insufficient to obtain full emission from the positive end of the filament. The rule adopted is that the peak value of P.D. between the ends of the filament, plus the peak anode-filament P.D., shall not exceed 22 volts.

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46. The chief advantages of this type of rectifier are, first its high efficiency, and second its excellent voltage regulation compared with the high vacuum type. The latter feature leads to its adoption for H.T. supply to radio transmitters because it signifies that the voltage variations caused by "keying" the transmitter are comparatively small and do not lead to appreciable frequency variation. The low value of permissible inverse voltage renders it unsuitable for use in normal half-wave or full-wave circuits, and its most usual method of connection is shown in fig. 31 which is called the voltage-doubling circuit. Two similar gas-filled diodes are used, each requiring its own separately-insulated filament supply; it is usual to utilise small step-down transformers for this purpose. One end of the H.T. transformer secondary is connected to one anode and one filament of the valves, while the filament and anode respectively of these valves are connected to the outer terminals of two condensers in series, the centre point being led to the opposite end of the transformer secondary. The action of this circuit is as follows:— Assuming that the first half-cycle of primary current causes the upper end of the H.T. secondary to become positive, an electron current will be established in the valve U_1 , which on reaching the anode will pass through the transformer secondary, charging the plate A of the condenser C_1 negatively, a corresponding repulsion of electrons from the plate B completing the circuit

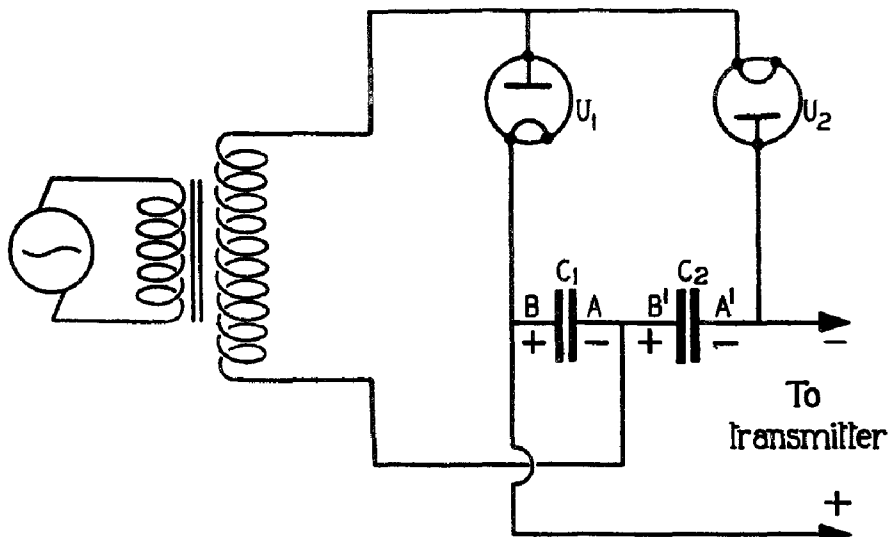


FIG. 31, Chap. IX.—Voltage doubling rectifier circuit for gas-filled diodes.

electron current. During this half-cycle, the valve U_2 is completely inoperative. On the succeeding half-cycle the lower end of the H.T. secondary winding becomes positive, and an electron current is established through the valve U_2 charging the plate A^1 negatively and repelling electrons from the plate B^1 leaving it positively charged. The electron current then flows through the transformer secondary to the filament of U_2 . At the end of one complete cycle, therefore, the condensers C_1 and C_2 are both charged, the P.D. between the terminals of each being within a few volts of the peak secondary voltage. The load, i.e. the H.T. circuit of the transmitter, is connected across the outer terminals of the two condensers and is therefore supplied at a voltage which is the sum of the two condenser voltages, or practically double the peak secondary voltage of the transformer, hence the term voltage-doubling circuit.

Let us now consider the inverse voltage to which the valve is subjected. Let the P.D. applied to the load be V_0 and the peak secondary voltage \mathcal{E} . Then when the valve U_1 is in operation U_2 is subjected to a peak voltage which is the sum of \mathcal{E} and $\frac{1}{2}V_0$ and as each condenser charges to a voltage practically equal to \mathcal{E} the inverse voltage is very nearly equal to V_0 . This may be compared with the inverse voltage to which the valves are subjected in the full-wave rectifying system. Here the P.D. across the load is also V_0 and is nearly equal to the half-secondary voltage, \mathcal{E} . The valve which is not passing an electron current has a peak inverse

voltage which is equal to the half-secondary voltage plus the P.D. across the reservoir condenser or $\frac{e}{2} + V_0$ which is greater than $2V_0$. For a given value of V_0 therefore, the voltage doubling circuit is preferable to the full-wave system if gas-filled valves are to be employed.

FREQUENCY CONTROL

Frequency variation

47. (i) The development of the valve transmitter in the forms already described was such a great advance upon previous methods of generating high-frequency oscillations that these have been almost entirely supplanted. Its introduction led to an enormous increase in the number of radio transmitting stations throughout the world, and with the growth of radio communication a new problem arose, i.e. the question of interference at the receiver by stations other than those with which communication is required. Much can be done to minimise this interference by careful design and operation of the receiver, and this aspect of the subject will be taken up in later chapters, but for the present it must be realised that full advantage of the selectivity of any receiver can only be obtained if certain requirements are fulfilled by the transmitter. These are (a) the frequency of the wave emitted must remain as nearly constant as possible during the whole course of any transmission or series of transmissions, otherwise the receiving operator must keep his apparatus in a process of continual re-adjustment, which calls for a high degree of skill and leads to the necessity for repetitions, etc., even with a capable operator. (b) When for a given frequency a certain set of adjustments have been found and standardised, this frequency shall be emitted whenever the particular adjustments are resorted to, even if a considerable time has elapsed since the original calibration took place. If this condition is not satisfied it is fruitless to make precise frequency allocations according to power and geographical distribution of stations with a view to the reduction of interference.

(ii) The closeness of frequency allocation depends upon the nature of the wave emitted. Every transmitter radiates, not a single frequency, but a band of frequencies, although this may appear to be at variance with the preceding text. It is quite true to say that a C.W. oscillator may emit a single frequency, but intelligence can only be transmitted by breaking up the transmission in some way, e.g. by telegraphic key in the case of the C.W. transmitter. The mere fact that the wave is interrupted causes additional frequencies to be introduced; these are in the immediate neighbourhood of the nominal frequency and must not be confused with the harmonics previously mentioned. The C.W. transmitter operating upon a given frequency radiates power in a band of frequencies covering about 250 cycles above and below the nominal frequency, while the total band occupied by an I.C.W. transmitter may be as much as 10 k.c/s.

48. In transmitters using direct aerial excitation, the principal cause of frequency variation is the change of aerial capacitance which occurs whenever the aerial system moves with reference to its counterpoise or earth system, and in many instances this effect completely masks all other causes. It was therefore the first point to be attacked, the remedy being to use some form of indirect coupling between the actual valve output circuit (which then becomes a closed oscillator) and the aerial circuit itself. Any form of inductive or capacitive coupling may be employed, the choice being made chiefly from the aspect of ease of manipulation, although certain forms are better than others from the point of view of freedom from harmonic radiation. In order to obtain maximum transfer of energy to the aerial circuit, both the coupled circuits must be tuned to the same frequency, or at any rate very nearly so. An increase in the degree of coupling beyond the critical value at which the resonance curve ceases to preserve a single peak will not result in an increase in aerial current, but if this coupling is exceeded a curious effect may occur. The oscillatory circuits as a whole have two resonant frequencies and the valve tends to maintain oscillations at that frequency for which its effective load resistance is least. As the two frequencies are close together and the effective resistance at either frequency is not much different from the resistance at the other, any small alteration in effective resistance may cause a sudden change

low power oscillation is then caused to supply grid excitation to a power amplifier, consisting of one or more stages of radio-frequency amplification. The output power of this amplifier is delivered to the aerial circuit, the frequency of the radiation being that of the original low power or master oscillator; under correct operating conditions, the tuned circuits incorporated in the power amplifier have no influence upon the radiated frequency.

A circuit showing the essential features of a master-oscillator-controlled transmitter is given in fig. 32, in which the apparatus shown inside the dotted rectangle forms the master-oscillator. The latter thus consists of a triode valve T_1 , so arranged that oscillations are generated in the anode circuit, the particular form of oscillator in this instance being the Colpitts circuit. The oscillatory flux about the anode inductance L links with the coupling coil L_2 and induces in it an E.M.F. of the generated frequency, which is applied between grid and filament of the power amplifier valve T_2 . The resulting changes of anode current cause oscillatory power to be generated in the aerial circuit at the frequency of the master-oscillator. For maximum output from the power amplifier, its anode circuit must be tuned to the frequency which it is desired to amplify, i.e. the aerial circuit and the closed circuit of the master-oscillator must be adjusted to the same frequency.

Self-oscillation in power amplifier

50. Referring to fig. 32, let us suppose that the oscillator valve T_1 is removed, but the circuit otherwise remains the same. Every component has some slight capacitance to every other, and to earth, while it is possible that many of the connecting leads will have some slight mutual induction with others, no matter how carefully they are spaced. Under certain conditions, the aerial circuit of the power amplifier may be resonant with the grid circuit consisting of the coupling coil L_2 and the stray capacitance across its ends. Now these two resonant circuits are coupled together by the inter-electrode (anode-grid) capacitance of the amplifier valve, and will therefore act as a tuned-anode/tuned-grid oscillator. Hence we find that at this particular frequency the power amplifier itself acts as a transmitter and the master-oscillator is redundant so far as the production of aerial oscillations are concerned. The frequency emitted however is now subject to all the causes of variation already discussed, and the possibility of the transmitter operating in this way, even if the oscillator valve is returned to its normal position, is obviously undesirable.

Neutralisation of power amplifier

51. The steps necessary to remove all risk of the power amplifier valve acting as an oscillation generator are easily seen. Since the oscillations are produced owing to the existence of coupling between the anode and grid circuits, either this coupling must be destroyed, or a coupling of equal magnitude and opposite sign introduced between the two circuits. A possible solution is as follows. Since for oscillation to be maintained by magnetic coupling, the sign of the mutual inductance between anode and grid coils must be negative, the tendency to oscillation owing to the anode-grid capacitance coupling may be annulled by a certain amount of positive mutual inductance between anode and grid coils, as shown in fig. 33a. The principal disadvantage of this solution is the practical one of designing the mutual inductive coupling in such a way that it will be sufficiently great at the lowest frequencies, and yet be capable of extremely fine adjustment so as to counterbalance exactly the capacitance coupling.

A simple modification of this method is found very effective in practice. Instead of coupling the output and input (i.e. anode and grid) circuits together, an additional coil is loosely coupled by mutual induction to the anode coil, and is connected between grid and filament, a very small variable condenser being interposed, as in fig. 33b. The power amplifier valve thus virtually possesses two input circuits, one from the master oscillator, and the other coupled to its own output. The sign of the mutual induction in the latter coupling is such as to oppose the maintenance of oscillations, and the actual voltage applied between grid and filament by this coil is controlled by varying the capacitance of the small variable condenser. By this means any tendency to self-oscillation can be completely neutralised, and the method is eminently suitable for use in aircraft transmitters, being robust and easily adjusted.

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Master-oscillator-controlled transmitters for aircraft

52. The essential features of this type of transmitter can now be summarised. The primary necessity is that the frequency of the oscillator itself shall be as constant as possible, bearing in mind the conditions under which the transmitter is to operate. A ground station, operating upon a fixed frequency, can be maintained within about .01 per cent. of that allotted. This high standard is only possible if with the aid of numerous subsidiary devices, mention of which will be made in due course. At the other extreme is the aircraft transmitter in which space and weight are primary considerations in design, while robustness and freedom from breakdown are of equal importance once the instrument is accepted for service use. Again, a given aircraft may be employed in many different duties at various times, thus necessitating radio operation over an extremely broad frequency spectrum, and the transmitter must be capable of operation over the whole service range of frequencies, otherwise it must be changed when necessary to suit the particular operation upon which the aircraft is to be engaged. Considerations of space, weight and time involved in change of apparatus all indicate that the ideal aircraft transmitter should cover any frequency upon which the aircraft may operate, and it is unreasonable to expect a

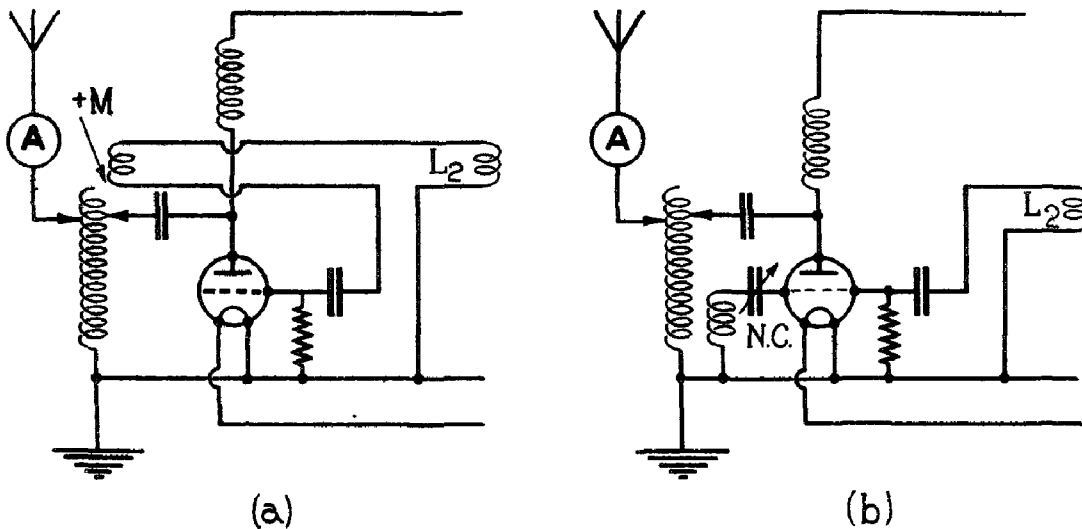


FIG. 33, CHAP. IX.—Theoretical and practical forms of neutralisation of amplifier circuit.

frequency constancy even approaching that achieved under the ideal conditions of single frequency operation on the ground. In aircraft transmitters therefore, the master-oscillator system must be designed to give the highest constancy obtainable without the aid of subsidiary devices such as temperature control, and every effort is made to make the master-oscillator itself a constant frequency source.

Constancy of frequency of master-oscillator

53. In a previous paragraph it was pointed out that the frequency generated by the master oscillator would depend, even in the simplest instances, upon the effective resistance of the tuned circuit and upon the anode A.C. resistance of the oscillator valve, as well as upon the effective inductance and capacitance, including in the latter the effects due to mutual inductance and stray capacitance. Now the effective resistance of the tuned circuit is not actually lumped in the circuit at one point, but depends upon a number of power-dissipating factors, such as the power transferred to the grid circuit of the power amplifier, eddy currents in neighbouring metals, dielectric losses in surrounding insulating material, and losses due to the flow of grid current. Ignoring for the present the variations in effective inductance and capacitance, consider the anode A.C. resistance and grid A.C. resistance, which are denoted by r_a and r_g respectively. These are to some extent dependent upon each other, and upon the amplitude of the generated oscillations,

thus, for a fixed value of grid bias, an increase of amplitude leads to increased grid current, and the slope of the $I_g - V_g$ curve increases rapidly for positive values of grid voltage. Hence the increase of amplitude is accomplished by an increase of grid A.C. conductance, or a decrease of grid A.C. resistance. On the other hand, provided saturation value of anode current is not attained, this increase of amplitude will affect r_a very little. Now consider the conditions when grid bias is obtained by the condenser and leak method. The greater the amplitude, the more negative the bias, and the mean anode current decreases, the working point finally reached being near the curved portion at the foot of the $I_a - V_g$ curve, hence the anode A.C. resistance of the valve increases with amplitude of oscillation. As the final value of bias taken up by the grid is that at which a small steady grid current flows, the grid A.C. resistance corresponds to this value in any case and is not greatly affected by the amplitude. The final amplitude of oscillation corresponds to some particular values of r_g and r_a such that the power generated by the oscillator valve is exactly equal to the total power dissipated in the oscillator, including all the circuit losses, which are expressed by the effective resistance R . Efforts to design a constant frequency oscillator are therefore in the direction of minimising the variations in r_a and r_g , or by arranging the circuit in such a manner that the frequency generated is independent of these resistances. The first step is to arrange that the supply voltages are maintained as constant as possible, and this problem presents more difficulty than is apparent on the surface, particularly in aircraft. For L.T. supply a battery is preferable to an air-driven generator, and baretters may be inserted in series with the filaments. The baretter consists of a resistance of iron wire or some alloy, which is enclosed in a bulb which is filled with hydrogen. The resistance of the element is not constant, but depends upon the current flowing, i.e. the iron has a large positive temperature coefficient. The use of such a baretter thus tends to maintain the current at a constant value, but its utility is limited by the fact that it is not instantaneous in action.

54. In aircraft, the most convenient method of obtaining H.T. supply for a complete master-oscillator-controlled transmitter is by the employment of a generator, capable of supplying up to about 2,000 volts. The regulation of this generator is of considerable importance, for the load upon it is constantly varying during every cycle of oscillation, because the value of the anode A.C. resistance of the valve is not constant during the whole of the cycle. The frequency variation due to this can be reduced by supplying the anode circuit of the master-oscillator through a swamping resistance, of a value equal to or slightly greater than the valve A.C. resistance. The presence of this resistance (R_1 in fig. 32) necessitates an H.T. voltage about double the working anode-filament voltage of the oscillator valve, but this is not a serious matter as the power-handling capacity of this valve is much less than that of the amplifier valve, and a higher value of H.T. voltage would be required for the latter in any circumstances. The oscillator circuit must be designed with the highest magnification practicable, and in order to achieve this the total effective resistance of the oscillatory circuit must be as low as possible. As the power supplied to the amplifier circuit represents a portion of the effective resistance of the oscillatory circuit, this power must also be small. Next, the effective r_a must be as high as possible, so that variations of this quantity make little change in the ratio $\frac{R}{r_a}$. This is attained by operating with considerable grid bias obtained by the leaky condenser method, which enables a large value of r_g to be maintained simultaneously, and thus tends to give higher circuit magnification. From this point of view a high-resistance grid leak is indicated.

Methods of obtaining frequency constancy by designing circuits in which the frequency generated is independent of r_a and r_g have been little used in this country, although they have found some favour in America. They depend upon the use of phase-shifting circuits between the valve and the oscillatory circuit, and the additional complexity renders them unsuitable for use in transmitters subject to frequent alteration of operating frequency.

Tuning a master-oscillator-controlled transmitter

55. The general principles outlined in paras. 14 and 15 apply to the tuning of all installations, but where a master-oscillator is fitted it is not possible to couple the wavemeter to the oscillatory circuit and so adjust the latter to the desired frequency, owing to the nearly perfect screening

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which is essential for satisfactory operation. As a rule, therefore, the oscillatory circuit is approximately calibrated, at any rate at a few points, and the procedure of tuning may be outlined as follows:—The master-oscillator is set to the desired frequency as nearly as possible by interpolation between the points of calibration, and is switched on, the capacitance of the neutralising condenser for the amplifier valve being first set to zero. Switching arrangements usually provide that for tuning, reduced power is applied to the oscillator valve, while the amplifier valve is completely inoperative. Owing to the un-neutralised anode-grid capacitance of this valve, however, a small oscillatory voltage will be developed in the aerial circuit, and the resulting current may be observed by means of a suitable low-reading thermo-ammeter. The aerial circuit is now brought into resonance with the master-oscillator by adjusting the aerial tuning inductance until the aerial current reaches a maximum value. Before applying full power to the transmitter, the anode-grid capacitance of the amplifier valve must be neutralised, by adjustment of the neutralising condenser, until the aerial current is reduced to zero, and when this operation has been performed, the low-reading thermo-ammeter is switched out of the aerial circuit and a meter of full current-carrying capacity substituted. By means of suitable switches, the amplifier valve is rendered operative, and up to about two-thirds of the maximum power input supplied to the transmitter, the frequency radiated by the aerial circuit being then measured in the usual manner. A slight re-adjustment of the oscillator frequency may be made without the necessity for a repetition of the neutralising procedure, but if the frequency differs considerably from that anticipated, it is necessary to switch off, re-set the master-oscillator to a slightly higher or lower frequency, and repeat the neutralisation. In all cases, when dealing with service transmitters, the tuning instructions given in A.P. 1186, Signal Manual, Part IV, should be strictly adhered to. In order that an aircraft transmitter may be set up to the desired frequency on the ground, it is necessary to simulate the effect of the aircraft aerial system by a suitable circuit in order that the aerial tuning inductance may be adjusted to an approximately correct value, and the neutralisation correctly performed. The apparatus used for this purpose is known as an artificial aerial, and may consist of a fixed inductance of a few microhenries, a variable condenser, and a series resistance having a value approximately equal to the radiation resistance of the aerial system to be used. The capacitance may be of the order of from $\cdot 00002 \mu F$, simulating that of a fixed aerial for use in the 10 to 20 M.c/s band, to about $\cdot 0003 \mu F$, representing the capacitance of a trailing aerial of about 250 feet. Instructions relating to each particular design of artificial aerial will be found in the tuning instructions referred to above.

Frequency control of master-oscillator

56. Reference has already been made to the possibility of attaining an enhanced degree of frequency constancy in the master-oscillator itself by means of auxiliary apparatus, in circumstances which permit the increase of space and weight and the additional complexity entailed. These measures may be divided into two classes, first, thermostatic control of the temperature of the master-oscillator and its associated circuits. Second, the employment of some form of electro-mechanical oscillator having a high degree of frequency constancy as a control for the electrical frequency. Thermostatic control entails the location of the whole of the master oscillator, including the valve itself, in a compartment which is automatically maintained at a temperature slightly higher than would be reached by the apparatus in the absence of temperature control. This compartment is heated by an electric radiator, and the amount of current flowing in the heating circuit is controlled by an instrument called a thermostat. The most sensitive thermostat is the toluene type, the principle of which is as follows. A vessel having a large surface area contains a quantity of liquid toluene, which has the property of expanding considerably when subjected to only a slight increase of temperature, that is, its coefficient of expansion is very high. A glass U-tube connected to this vessel contains a quantity of mercury and in one vertical member the mercury level rises and falls with the variation in the volume of toluene, and therefore with the temperature. A platinum wire is fused through the tube well below the normal mercury level, and a similar wire at a point just above the normal level. When the mercury rises to the level of the latter wire, the two are bridged conductively and complete the operating circuit of a relay, the local contacts of which then break the electric supply

to the radiator. The temperature of the compartment falls until the contraction of the toluene allows the mercury level to fall clear of the upper wire, and when this occurs the relay contacts close, again completing the circuit through the radiator. By careful design a toluene thermostat can be made to maintain the temperature of the compartment constant to within $\cdot 01^{\circ}$ C., and by special construction it is claimed that a constancy within $\cdot 001^{\circ}$ C. has been achieved. A simpler form of thermostat is also in use, in which the variation of temperature causes flexure of a bi-metallic strip, the latter carrying a contact which opens or closes the heating circuit. This device is not so sensitive as the toluene thermostat but is comparatively simple and robust and occupies little space.

Three forms of electro-mechanical oscillator are used for frequency control, viz.

- (i) the electrically driven tuning fork,
- (ii) the piezo-electric crystal.
- (iii) the magneto-striction oscillator.

Only a brief outline of the principles of the first two can be given here. The third method is only rarely adopted.

Tuning fork control

57. The tuning fork has long been recognised as a standard of frequency, forks for the tuning of musical instruments being generally designed to vibrate at a frequency corresponding to the note A next above middle C (440 cycles per second). Provided the temperature is constant and the amplitude of vibration low, the tuning fork maintains its nominal frequency with extreme accuracy. For frequency control, it is usual to employ a fork having a frequency lying between one and two k.c/s. This is very much lower than the frequency of transmission and it is necessary to have recourse to considerable amplification, the frequency being doubled or trebled at each stage.

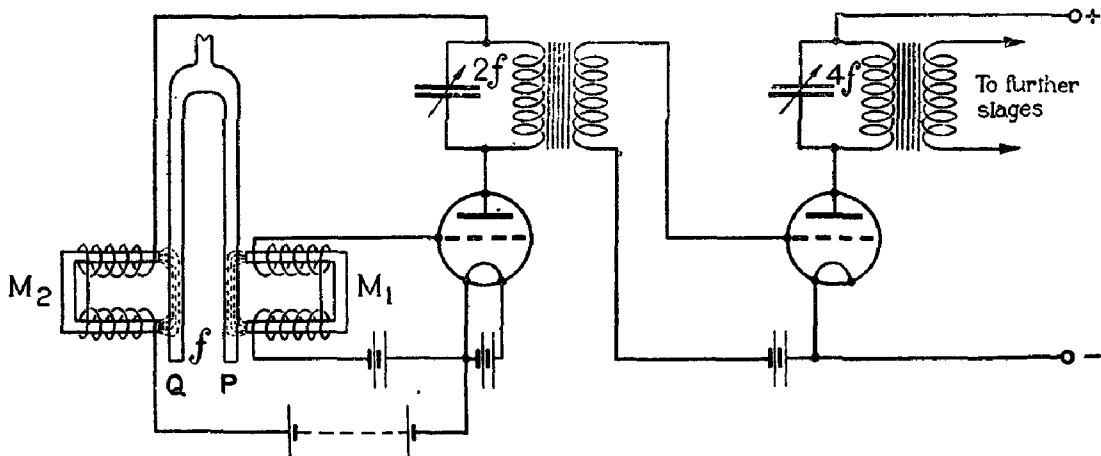


FIG. 34, CHAP. IX.—Frequency control by tuning fork.

The number of such stages is reduced by the employment of a high initial frequency, but unfortunately it is difficult to ensure satisfactory maintenance by electrical means at frequencies higher than about 2 k.c/s. The fork is maintained in vibration at its natural frequency by the arrangement shown in fig. 34. Near the base of each prong is mounted an electromagnet, the coils of which are wound upon soft iron pole pieces which are extensions of the poles of a permanent magnet as in the telephone receiver; in practice a pair of telephone receivers suitably modified may actually be utilised for the purpose. The coils of one magnet are connected in the anode circuit of a triode valve, and the coils of the magnet operating upon the other prong are connected between grid and filament, suitable grid bias being arranged. The fork is analogous to an electrical circuit having very small damping, and therefore very little power losses. This equivalent circuit may be considered to be electromagnetically coupled to both grid and anode

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circuits, and once set in oscillation can be maintained in this state by the conversion of a small amount of electrical energy into mechanical energy during each cycle of oscillation. Vibration can be initiated by a slight tap on the base of the fork, and the subsequent action is somewhat as follows. At a given instant suppose both the prongs P and Q are moving outwards, then the reluctance of each magnetic circuit is decreased and the flux through each coil increases with a consequent induced E.M.F. in each coil. The E.M.F. induced in the coil M_1 is applied between grid and filament of the valve causing a change of anode current, and if this variation causes an increase in the flux density of the magnet M_2 , the prong Q will be attracted more strongly than by the normal flux. As the prongs reach the limit of their outward excursion the induced E.M.F. in the coil M_1 falls to zero, and when owing to their elasticity the prongs move inward, the increase of reluctance in the air gap between M_1 and P results in the production of a further induced E.M.F. which is applied between grid and filament of the valve. The consequent change of anode current in turn causes a reduction of the pull of M_2 upon its prong, and the latter therefore moves inward to a greater distance than would otherwise be the case. In this way the fork is maintained in vibration, and adjustment of the frequency within small limits can be achieved by loading the ends of the prongs with metal washers. The mean grid potential is maintained at such a value that the anode current changes are unsymmetrical, and a circuit tuned to the second harmonic of the fork frequency is included in the anode circuit of the valve. The second harmonic frequency is selected by this circuit for magnification, and this frequency is further amplified with a similar frequency doubling process at each stage until the desired frequency is reached, after which power amplification is employed in order to supply the aerial with the necessary power. If the frequency of the fork is 1 k.c/s for example, eight frequency doubling stages will give an output at 256 k.c/s. It is obvious that this method of operation in conjunction with thermostatic control of the temperature of the fork itself will give a high degree of constancy, probably being superior to all other methods, but it suffers from the following limitations, (i) its use is limited to certain exact multiples of the tuning fork frequency, i.e. those obtainable by frequency multiplication, (ii) the large amount of auxiliary apparatus can only be justified in stations of comparatively large power. Certain B.B.C. broadcasting stations are controlled in this manner.

Crystal control

58. Crystal control is suitable for use in the higher frequency bands, i.e. above about 1,000 k.c/s at which tuning fork control would become impracticable owing to the large number of frequency-multiplication stages which would become necessary. Certain crystalline substances, notably quartz, tourmaline and rochelle salt, possess the property to which the name piezo-electric (from the Greek piezo, to press) is given. The phenomena associated with this property are briefly as follows. When a suitable plate of the material is subjected to mechanical stress, electric polarity is developed upon opposite faces of the plate. A reversal of the nature of the stress, for example a change from tension to compression, causes a reversal of the electric polarity. Conversely, if a difference of electric potential exists between two opposite faces, mechanical strain or deformation of the crystal occurs, and the sense of this strain is reversed by a reversal of electric polarisation. The material in almost universal use for frequency control practice is quartz which is comparatively cheap and robust. Tourmaline is used in certain instances, but rochelle salt (sodium-potassium tartrate) which possesses the piezo-electric property to a much higher degree than any other substance, is rarely used, owing to its mechanical and electrical weakness. Quartz is a mineral which is found in crystalline form chiefly in Madagascar and Brazil. It is an oxide of silicon (SiO_2) and the silica used in the construction of large power transmitting valves is actually fused quartz. The natural quartz crystal, fig. 35, is of an irregular hexagonal section, opposite sides being parallel, and the ends are pointed, taking a form which is nearly pyramidal. The axis passing from end to end along the length of the crystal is called the Z or optical axis, because a section cut from the crystal perpendicular to this axis exhibits certain optical properties which need not be considered. Two other systems of axes may also be drawn, namely the three axes X_1, X_2, X_3 , passing through opposite corners of the section, which are called electrical axes, and the system consisting of the three axes Y_1, Y_2, Y_3 , which are perpendicular

to the faces of the crystal. These are called the mechanical axes. A slab cut from the crystal with flat sides perpendicular to an electrical axis, fig. 36a is called an X (or Curie) cut while a slab cut with flat sides perpendicular to a mechanical axis, fig. 36b, is called a Y (or 30°) cut. For different applications of the piezo-electric effect, either of these "cuts" may be preferable. A distinctive property of such crystal is that it possesses a well marked mechanical resonant frequency, which depends upon the density and the elasticity of the quartz. The natural frequency of a slab of quartz is found to depend upon the axes in which the cut was made, and upon the thickness, of the slab, thus an X-cut slab has its "thickness" in the X direction, and its natural frequency is found by experiment to be approximately $\frac{2.86 \times 10^8}{t}$ k.c/s. while a Y-cut slab has a natural frequency approximately equal to $\frac{1.96 \times 10^8}{t}$ k.c/s., t being the thickness in millimetres.

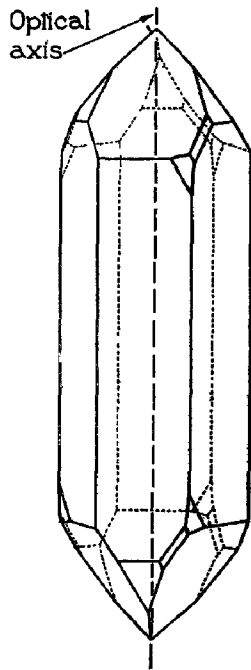


FIG. 35, CHAP. IX.
Natural quartz crystal.

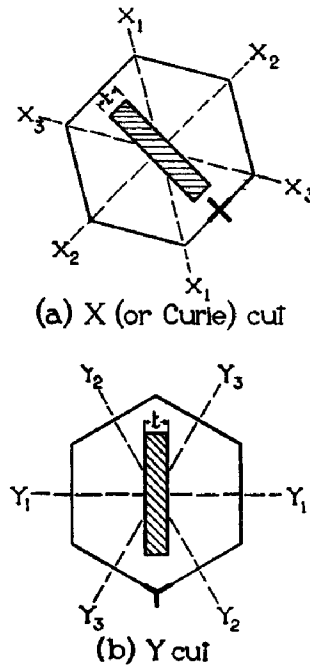


FIG. 36, CHAP. IX.—AXES of quartz crystal shewing X and Y cut plates.

59. (i) The electrical properties of a quartz crystal may be shown by mounting it between two metal plates so that it constitutes an electrical condenser of small capacitance and connecting it in parallel with the tuning condenser of a closed oscillatory circuit, which is then adjusted to a frequency near to the known or estimated natural frequency of the crystal. The closed circuit is then coupled to a calibrated valve oscillator which is capable of very fine adjustment of frequency. The potential difference between the crystal faces may be measured by a suitable radio-frequency valve voltmeter, and it will be observed that as the oscillator frequency is varied the voltmeter reading gives the resonance curve of the closed circuit, but instead of being perfectly smooth over its whole range, there is a steep and sharp voltage drop over a range of a few cycles, the optimum drop occurring at the natural frequency of the crystal, and a typical curve showing the effect is given in fig. 37. The portion of the curve marked A B C is referred to as a "crevasse," and the cause of a crevasse is the absorption of power by the quartz crystal, this power being expended in producing mechanical oscillations. In practice, owing to various causes, a crystal may have several natural frequencies spaced very closely in the spectrum, and this is obviously undesirable. Even if the quartz itself is of a suitable quality, multiple crevasses may be caused

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by lack of parallelism between the two faces of the crystal, or by minute flaws or scratches in the material. The high cost of really good quartz crystals is due to the tedious process of cutting and grinding which may prove to be wasted if the crystal cannot be so manipulated as to give one clearly defined natural frequency well separated from any subsidiary resonances which may exist. The equivalent electrical circuit of the quartz crystal in its mounting is shown in fig. 38, in which C_1 represents the capacitance of the small condenser formed by the quartz dielectric and metal electrodes while the inductance L capacitance C and resistance R represent electrical analogues of the mass, stiffness and mechanical resistance or dynamic friction. The interest of

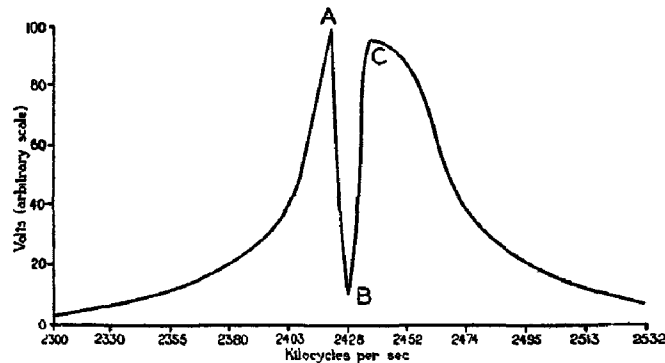


FIG. 37, CHAP. IX.—Resonance curve of quartz crystal shewing crevasse.

this method of representation lies in the values which must be allotted to the constants L , C and R , and may be exemplified by a certain crystal for which these values were accurately determined. The natural frequency of the crystal in this instance was about 44 k.c/s, the object of choosing such a low frequency crystal being to avoid errors of measurement, which is difficult at higher frequencies. The equivalent inductance was found to be 160 henries and the capacitance .08 micro-microfarad, while the equivalent resistance was 1,500 ohms. The magnification of the equivalent electrical circuit is therefore approximately 30,000, whereas in an actual electric

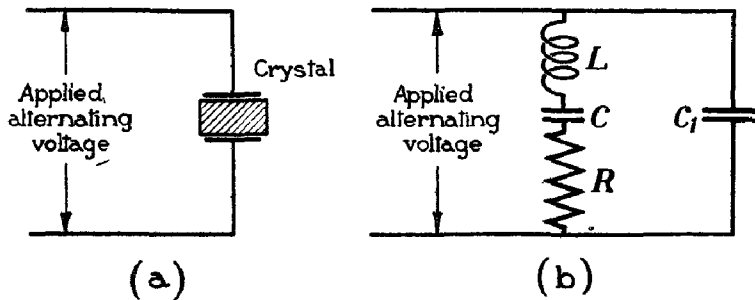


FIG. 38, CHAP. IX.—Quartz crystal under applied alternating voltage, and equivalent electrical circuit.

circuit tuned to this frequency it would be difficult to achieve a magnification of 1,000. In fig. 39 the crevasse is shown upon a very open frequency scale, and it will be observed that a forty per cent. variation of oscillatory voltage occurs within a frequency of about 2 cycles each side of the crystal frequency.

(ii) The initial selection of natural quartz crystals likely to produce suitable oscillators is performed by inspection, the method of natural formation of the crystal being a rough guide. Trial slabs cut from the crystal are then ground flat and parallel, saws fed with diamond dust being used for cutting, and carborundum of various grades for rough grinding. When the latter

stage is reached the slabs are tested for piezo-electric properties by the application of mechanical stress, the faces of the slab being placed between electrodes which are connected to an electrometer. The finished crystal usually takes the form of a disc of about 1 inch diameter or a square of approximately 1 inch side, the thickness depending upon the natural frequency required. Final

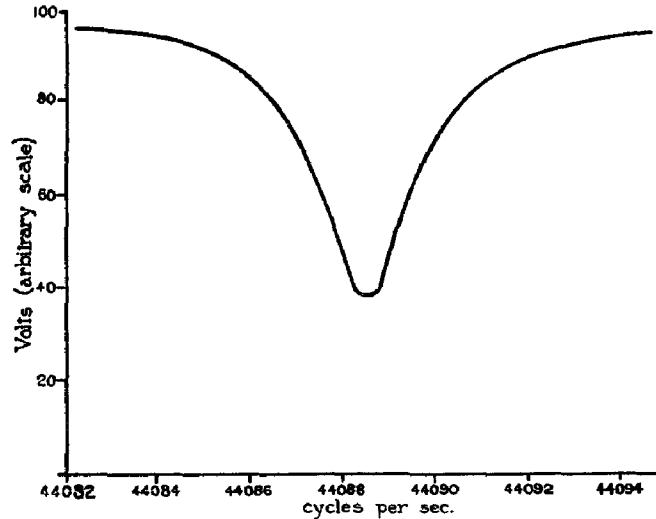


FIG. 39, CHAP. IX.—Crevasse in resonance curve of quartz crystal.

grinding to fine limits is performed upon an optically flat surface with rouge, and the frequency determined by actual trial in a suitable oscillatory circuit. It is important that the crystal should be allowed to attain its working temperature before deciding that further grinding is desirable.

Crystal mountings

60. Three types of mounting have been developed and all are used to some extent. Least frequently employed is that in which the crystal itself has a metallic electrode sputtered directly upon each face, the crystal being then mounted on its edge between light springs, or laid hori-

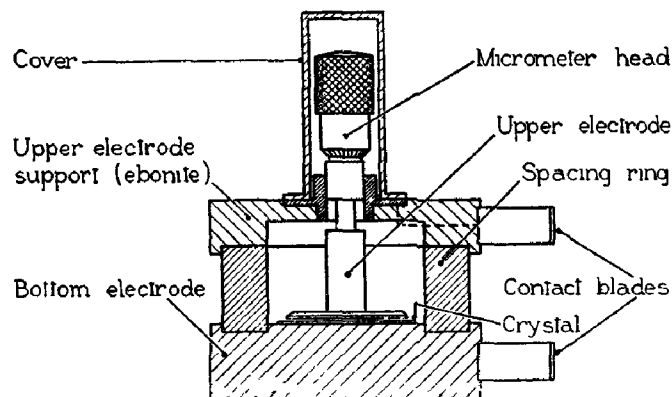


FIG. 40, CHAP. IX.—Mounting for quartz crystal.

zontally upon a conducting surface, a copper strip contact resting upon the upper metallised face of the crystal. A more common form used with unmetallised crystals is shown in fig. 40. It consists of a dust-tight case, which contains a lower electrode upon which the crystal lies in a shallow circular trough. The upper electrode is mounted upon a micrometer screw by means of

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which it can be brought as near to the crystal as may be desired, without actually touching it. The employment of an air gap is desirable for two reasons. First, the mechanical load upon the vibrating crystal is reduced, and its oscillatory properties are more easily stimulated. Second, the frequency of oscillation depends to some degree upon the mechanical damping, and by varying the air gap a variation of the frequency can be obtained, which however is only over a small range. Electrodes must be unaffected by atmospheric conditions and are therefore usually made from stainless steel.

Maintenance of oscillations

61. In order to maintain the crystal in oscillation at its natural frequency, it is necessary to supply power in a manner similar to that employed for the maintenance of any other oscillation, and a thermionic valve (triode) is generally adopted for this purpose. A suitable circuit is shown in fig. 41. The quartz crystal is inserted between the two electrodes of the mounting and the latter are connected to grid and filament of the valve, a grid leak being provided to avoid complete insulation of the grid, and to maintain the latter at the desired potential with reference to the filament. The anode circuit contains an inductance L which may have a condenser C connected in parallel as shown, but for the present this condenser may be disregarded. The existence of the grid-anode inter-electrode capacitance is of importance in the action, which is approximately as follows. Assuming that the filament is heated, on closing the switch (S) there will be an increasing electron current through the valve, and owing to the reactance of the coil L this increase of current

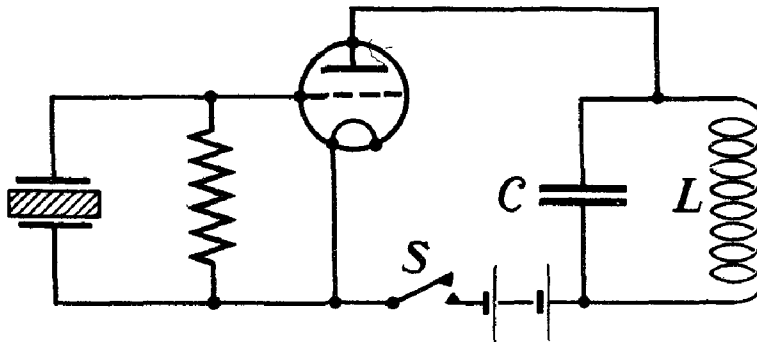
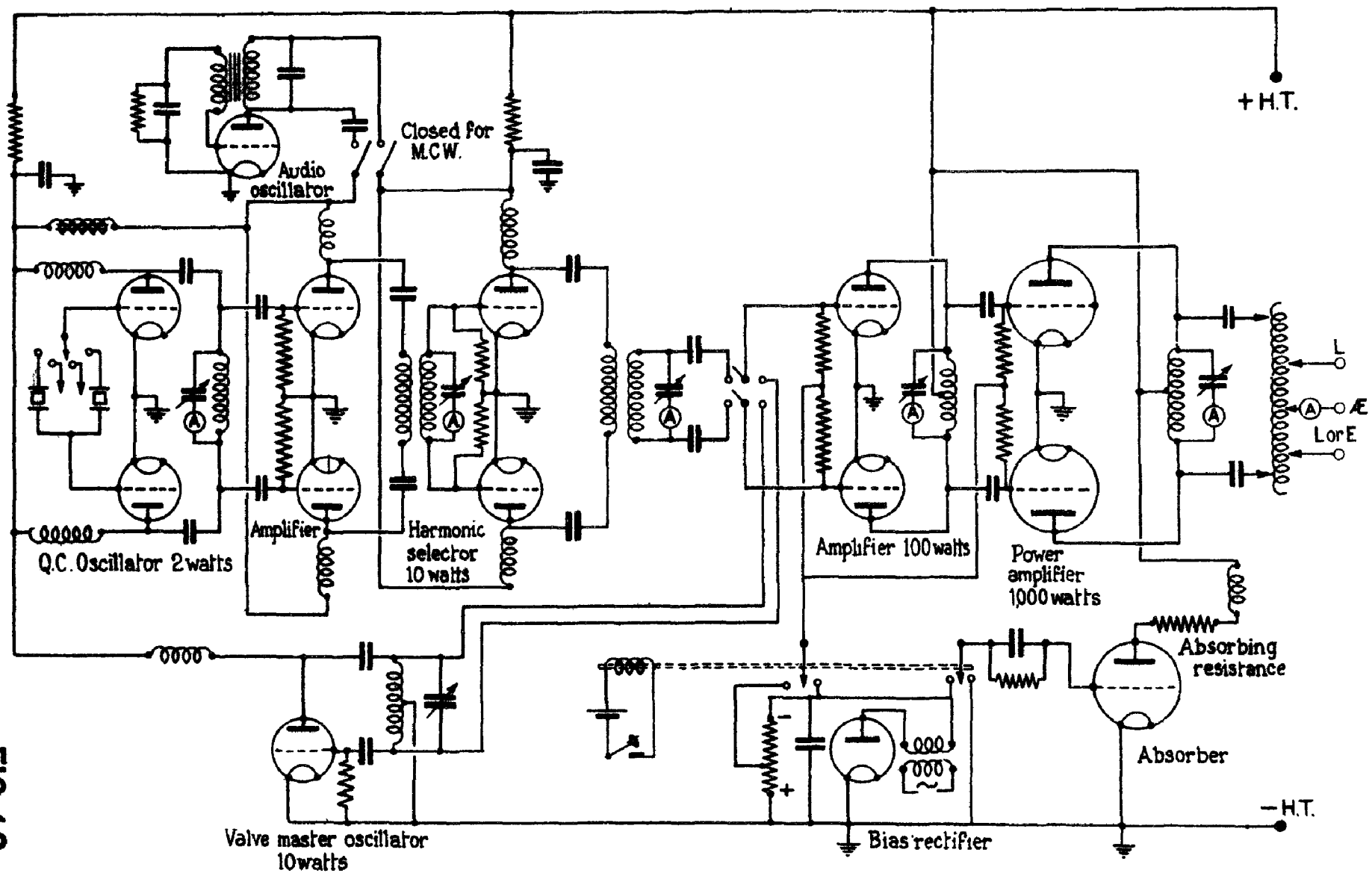


FIG. 41, CHAP. IX.—Circuit in which oscillation may be maintained by quartz crystal.

is accompanied by a fall of anode-filament potential. The grid-anode inter-electrode capacitance and the small condenser formed by the crystal and its electrode are in series between anode and filament, and therefore the fall of anode-filament potential will be accompanied by a change of potential between the electrodes, i.e. a change of P.D. between the faces of the crystal. The latter will therefore either expand or contract, and will then vibrate mechanically with lightly damped sinusoidal motion, the mode of vibration being longitudinal. As it vibrates, sinusoidal variations of P.D. are developed upon its faces, and by means of connections to the electrodes the varying P.D. is applied between grid and filament. The variations of anode current so caused must cause further changes of anode-filament P.D. and consequently, further oscillation of the crystal, the phasing of these resultant changes being such that the crystal is maintained in mechanical vibration at its natural frequency with undamped or increasing amplitude. The correct phasing conditions are fulfilled if the anode circuit reactance is positive, i.e. inductive at the frequency to which the crystal is resonant. It will be observed that the anode current is a pulsating one and may be considered to consist of a steady component and an oscillating component, the latter having the frequency of the crystal oscillation. By means of the condenser C the anode circuit may be brought nearly into resonance with this frequency, with a considerable increase in the circulating current of the circuit. This crystal controlled oscillation may be used to control the frequency of the requisite number of amplifying stages combined if necessary with frequency multiplication, so that the desired aerial output power is achieved.



TYPICAL QUARTZ CONTROLLED TRANSMITTER

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Effect of temperature variation

62. X-cut crystals have a negative temperature coefficient, the natural frequency decreasing by about 30 parts in a million per degree Centigrade. They are suitable for use in the type of mounting shown in fig. 40 and generally require a small air gap. In commercial practice they are frequently used to control the frequency of ground transmitters without temperature control, because they oscillate readily and parasitic oscillations are not so troublesome as in Y-cut crystals. Y-cut crystals have a positive temperature coefficient which may be as much as 100 parts in a million per degree Centigrade. If used in a mounting without an air gap, oscillations are more easily maintained than in the X-cut plate. For this reason Y-cut plates are often used in commercial aircraft and marine transmitters operating upon a single frequency. They are more prone to parasitic oscillation than are X-cut plates. If cut from a natural crystal at certain definite angles with respect to the X, Y and Z axes, it is possible to obtain a plate having a temperature coefficient approaching zero. The AT-cut for example, is parallel to the X axis and inclined at an angle of 35° to the Z axis. This angle has to be very accurately determined and maintained during cutting and grinding, and consequently such plates are not in common use.

High frequency transmitters

63. The general principles outlined above are applicable to transmitters up to a frequency of about 60 M.c/s. As the frequency increases beyond about 1 M.c/s, increasing care must be exercised to avoid stray coupling between components and the shunting effect of accidental capacitance. The avoidance of these effects is made more difficult by the necessity for close grouping of the various parts in order to reduce the resistance and inductance of connecting links. Condensers which function perfectly on lower frequencies may become resonant circuits or inductive reactances owing to the presence of their internal conductors. Ohmic losses in conductors may actually be increased by using tube or wire of a gauge larger than a certain optimum and in any case it is desirable that the turns of tuning coils should be spaced by an amount equal to, and preferably double, the diameter of the conductor. Interchangeable coils are a necessity if any considerable frequency range is to be covered, switch or plug variation of inductance being avoided whenever possible. Radio-frequency chokes may give rise to irregularities of operation owing to their distributed capacitance.

As the frequency becomes higher it is a matter of increasing difficulty to achieve the degree of frequency constancy demanded by the ordinary method of C.W. reception, i.e. the heterodyne method described in Chapter X. A frequency variation of 500 cycles per second will cause serious inconvenience to a receiving operator and almost certainly render many repetitions necessary. If the transmitter frequency is only 500 k.c/s. this corresponds to a stability of one part in a thousand, which is easily achieved without frequency control. At 5 M.c/s, however, it is equivalent to one part in ten thousand, which is hardly attainable without frequency control, except possibly in transmitters of very low power. At 50 M.c/s. it corresponds to one part in 100,000, which is a high standard even for a quartz-controlled transmitter with thermostatic temperature control. A partial remedy is to use I.C.W. instead of C.W., the transmitter then emitting a characteristic note. Heterodyne reception is then of course unnecessary but the frequency band occupied by any one line of communication is increased to a corresponding degree, thus giving rise to interference between adjacent channels. It is difficult to grind quartz crystals for frequencies higher than about 6 M.c/s., for the crystal is then so thin that it becomes slightly flexible and cannot be ground accurately flat and parallel. It is therefore usual in crystal-controlled transmitters of high frequency to generate a frequency of the order of 3 M.c/s, the final frequency being attained by a process of frequency multiplication in the amplifier stages. Tourmaline crystals may be used up to about 20 M.c/s, but this material is much more expensive than quartz and its utility is limited by this factor.

64. The circuit diagram of a typical quartz-controlled ground station transmitter is shown in fig. 42. The quartz-controlled master-oscillator is of the push-pull type, and any one of four crystals may be selected by means of a switch, so that four "spot frequencies" can be maintained with a high order of accuracy. A valve-controlled master-oscillator is also provided in case of a

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breakdown of any crystal, or to generate any frequency other than those provided for by the crystal control. Both the master-oscillators may be thermostatically controlled, although no arrangements to this end are given in the diagram. Following the crystal oscillator is a buffer amplifier having an oscillatory circuit magnetically coupled to its anode circuit; this supplies the excitation to the grid-filament path of the following stage. The oscillatory circuit may be tuned either to the crystal frequency, or to a harmonic, and is referred to as the harmonic selector. As the push-pull layout greatly reduces the even harmonics it is necessary to select and amplify one of the odd ones, the third being generally used. The third and fourth stages are power amplifiers, and must be neutralised, but the neutralising condensers have been omitted for simplicity. The output of the final stage is applied to an auto-transformer which serves to match the anode A.C. resistance of the valves to the actual load, the latter being of course the transmitting aerial. If directly fed from the transmitter, the aerial is connected to the terminal marked (AE) and the earth or counterpoise to the terminal marked (L or E) while if the aerial is fed through transmission lines, these are connected to the terminals (L) and (L or E).

The keying arrangements are shown only in outline, the system used being called "absorption" keying. The object of this is to keep the H.T. voltage as nearly constant as possible, by maintaining an approximately equal load on the generator at all times. The two power amplifying stages derive their negative grid bias from a diode rectifier which is fed from a single-phase A.C. supply, and the magnetic key is arranged to vary the bias. When the key is "up" the grids are biased so negatively that the anode current in both stages is reduced to zero, and when "down" a portion of the bias resistance is short-circuited, the grids become less negative, and normal anode current flows. The absorber valve has a resistance of suitable value in its anode circuit, and the power dissipated in this stage is equal to that dissipated in the power amplifier stages. When the key is "up" the absorber valve grid bias is normal, allowing appreciable anode current to flow, while when "down" the bias is so negative that the anode current is suppressed. In effect therefore, when the morse key is operated, the magnetic key transfers the generator load from the power amplifiers to the absorption valve and vice versa. The actual keying circuits are generally more complex than those shown. The anode voltage of the buffer stage can be varied at a suitable audio frequency by closing the switch marked "close for M.C.W." The transmission is then of the modulated continuous wave type.

Ultra-high-frequency oscillations

65. The method of maintaining oscillations by means of the triode which was discussed in the earlier portion of this chapter, depends upon the production of an oscillatory grid-filament P.D. by coupling the grid circuit to the anode circuit of the triode. This may be termed the "reaction" method of maintaining oscillation. If in a circuit of this type an attempt is made to produce extremely high frequency oscillations, it is found that there is a limit beyond which any given valve will fail to produce the desired effect. This failure is in part caused by the difficulty of designing an oscillatory circuit having a natural frequency higher than 100 M.c/s (corresponding to a wavelength of 3 metres) owing to the inherent inductance of connecting leads to the valve electrodes and to the existence of distributed capacitance. Careful attention to these points may result in an increase in frequency up to about 300 M.c/s ($\lambda = 1$ metre) but it is impossible to maintain oscillations at a frequency appreciably higher than this owing to a further limitation which does not depend upon the circuit constants, namely, the time taken for the emitted electrons to reach the anode of the valve. It may be said that at frequencies sufficiently high to make the mass of the electrons an appreciable factor in the determination of their motion, the reaction method fails to maintain the desired oscillation.

Electronic oscillations are defined as oscillations produced in a thermionic system by virtue of the inertia of the electron. The work of Barkhausen and Kurz is generally regarded as the foundation of this branch of the subject, their discovery of electronic oscillations resulting from certain tests on the degree of vacuum in transmitting valves. In these experiments a positive potential was applied to the grid and a negative potential to the anode, and positive ions produced by grid current would then fall into the anode, so that the magnitude of the anode current could be taken as an indication of the degree of softness of the valve. As a result, it was found that

an anode current was sometimes established in such a direction that it could only be caused by an electron flow to the anode, and not a positive ion current. When this phenomenon was produced, a simple wavemeter situated near the valve indicated the production of oscillations by the valve. Further research shewed that if the grid of a triode is maintained at a positive potential with reference to the filament, while the anode potential is maintained at zero or a slightly negative value, oscillations can be maintained in a circuit connected either between grid and anode, grid and filament, or anode and filament. These oscillations depend upon periodic motion of electrons in the inter-electrode space, and are only maintained when the natural frequency of the circuit has a certain relationship with the frequency of vibration of the electrons. One explanation advanced by these physicists to explain the results is as follows. Electrons emitted by the filament receive acceleration owing to the positive grid potential, and some of them pass through the grid, after which their acceleration becomes negative. A number of them therefore have their direction reversed, travelling back towards the grid, passing through the latter to the vicinity of the filament. Here they are repelled by the presence of other emitted electrons and attracted by the positive grid, their direction of motion again undergoing reversal. Hence a number of electrons are constantly maintained in periodic or oscillatory motion in the inter-electrode space, and this constitutes an oscillatory current of very high frequency. With certain assumptions, the wavelength can be calculated from the formula

$$\lambda = \frac{1,000}{\sqrt{V_g}} \frac{d_a V_g - d_g V_a}{V_g - V_a}$$

in which

d_a = twice the distance between anode and filament.

d_g = twice the distance between grid and filament.

V_a = anode-filament P.D.

V_g = grid-filament P.D.

One of the assumptions made in deriving this expression is that the electrodes are flat parallel planes, and the error in using this formula to calculate the wavelength obtainable with triodes of ordinary design may be as much as 25 per cent.

66. The above theory fails to account for the establishment of an electron current in the anode circuit of the valve. It has been pointed out, however, that if an alternating component of P.D. exists between grid and anode, work is done on the moving electrons during the half-cycle in which they receive acceleration toward the anode, and work is done by the electrons during the half-cycle in which they move toward the grid. Electrons reach the anode during the former half-cycle, if the steady negative potential is less than the peak value of anode grid P.D. on the positive half-cycle. The work done by the electrons determines the amount of damping which can be made good in the oscillatory circuit, resembling in this respect the overcoming of

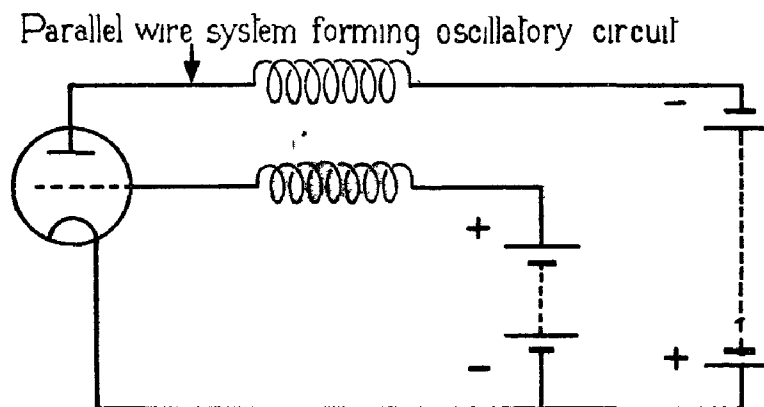


FIG. 43, CHAP. IX.—Barkhausen-Kurz oscillator.

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damping by reaction in the ordinary triode oscillator. From this point of view, the anode current represents electrons which are wasted so far as the production of oscillations is concerned, i.e. it represents a form of damping loss. Another mechanism of maintenance is possible when the anode diameter is considerably greater than the grid diameter and the anode is at filament potential. The grid-anode space may then become saturated while the grid filament space is unsaturated, and it has been suggested that successive regions of high and low electron density may be set up in the grid-anode space, these regions moving to and fro periodically in a manner resembling the compression and rarefactions constituting a sound wave. A circuit connected between grid and anode, the natural period of which is twice the time taken by an electron to pass from grid to anode, would then be maintained in oscillation. A circuit suitable for the production of B-K oscillations is shown in fig. 43, although all triodes are not adapted for use in this manner. Best results are obtained with an optimum ratio of anode diameter to grid diameter, which is about 3 : 1. A close spiral of fine wire appears to form the design of grid most conducive to the maintenance of oscillations, while the anode should be of cylindrical form. Attempts to produce the desired results with the commercial designs of valve having an anode of flattened box form with a V or N filament have so far been unsuccessful, and best results are obtained with valves in which the filament is short and straight, with the grid and anode carefully mounted concentrically with the filament. Only by such precautions can any appreciable power output be obtained. The grid becomes the electrode which is called upon to dissipate most heat, and grid failure is usually the factor which determines the life of the valve.

It has been stated that the anode electron current represents a damping loss, and it is desirable to reduce this as far as possible. This is the chief reason for applying a negative potential to the anode, although the equation given above shows that an increase in negative anode potential leads to a slight decrease of wavelength or increase of frequency. It may now be stated that this equation is based on the assumption that the period of the oscillation is approximately four times the "time of flight" of an electron, the latter term being now in common use to denote the time of transit of an electron from cathode to anode.

The magnetron

67. The generic term magnetron is applied to any type of thermionic valve in which the anode current is controlled by the presence of a magnetic field, instead of, or sometimes in addition to, the control exercised by the electric potential of the grid. The practical form of magnetron is usually a diode and only this form need be mentioned. A typical example is shown diagrammatically in fig. 44 in which the cathode is a directly heated filament, and is surrounded by a cylindrical anode, which is split along its length to reduce eddy current losses. The electrodes are mounted in a glass envelope in the usual way, but in the anode-cathode space a magnetic field of about 20 to 50 oersteds is maintained by a solenoidal winding which surrounds the bulb. The figure shows that the filament lies in the same direction as the magnetic field. The electrons

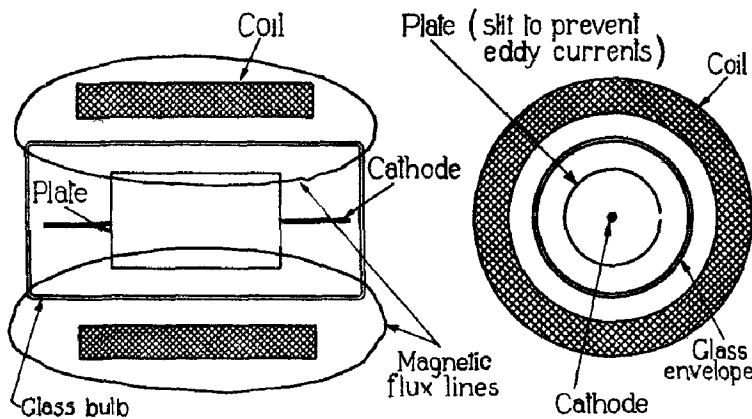


FIG. 44, CHAP. IX.—Diagrammatic representation of magnetron.

which are emitted by the filament constitute an electric current, and on several previous occasions reference has been made to the force exerted by a magnetic field upon an electric current—or upon a moving electric charge, which is the same thing. An electron which is emitted from a filament into a magnetic field will experience this force, and consequently receive acceleration, the latter being proportional to its velocity and at right angles to its direction of motion. If the magnetic field is uniform this results in the electron taking a path which is the arc of a circle. This effect is present in all valves having a co-cylindrical arrangement of directly heated filament and anode, owing to the magnetic field set up by the filament heating current, but it only becomes of importance in high-power valves carrying filament currents of the order of 50 amperes, and

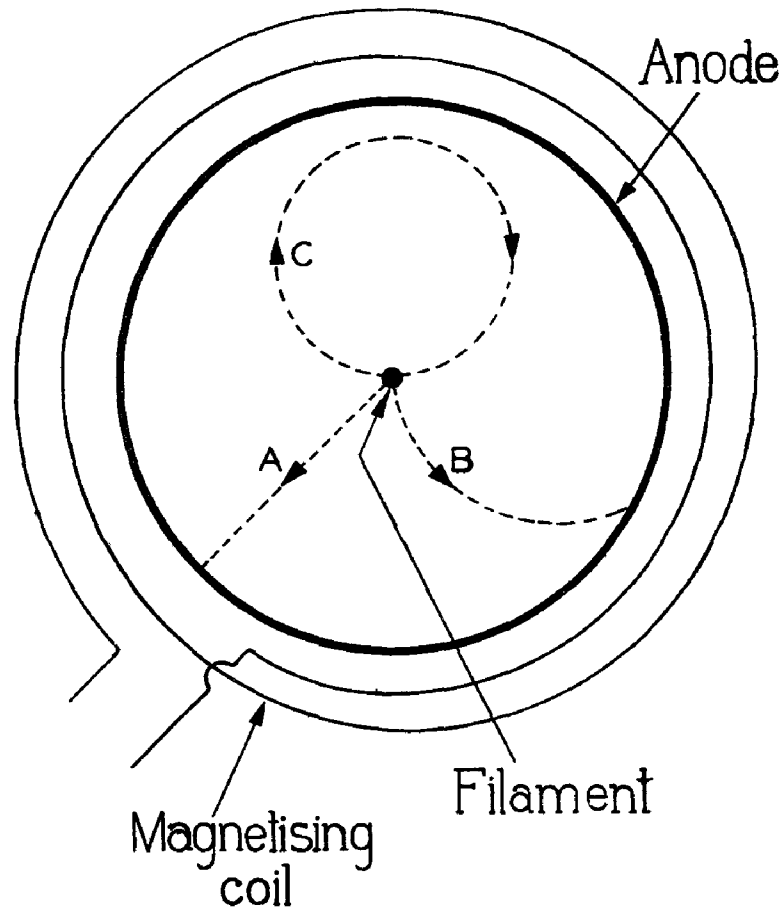


FIG. 45, CHAP. IX.—Paths of electrons with variation of magnetic field strength.

the additional magnetising coil is necessary to produce magnetron phenomena in low-power valves. The effect of the magnetic field upon the anode current is shown in fig. 45. If the magnetic field strength is negligible an electron leaving the filament will travel to the anode by the shortest path, as shown by the dotted line A. An increase in the strength of the field will cause the electron to be deflected, travelling a path somewhat as shown at B, while if the field strength exceeds a certain value the electron will travel in a closed path as shown at C, in which case the anode current will fall to zero. The magnetic field strength necessary to cause the electrons to fail to reach the anode is given by the equation

$$H = \frac{6.72\sqrt{V}}{r}$$

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where V is the anode-filament P.D. and r the radius of the anode. This "cut-off" is very critical, and a considerable variation of anode current is obtainable for slight variations of magnetic field strength. The action of a magnetron is therefore analogous with that of a triode, except that the anode current is controlled by variation of the strength of the magnetic field instead of by variation of the grid-filament potential.

68. The type of magnetron most used for the production of very high frequency oscillations is the split-anode type shewn in fig. 46. The anode consists of two half-cylinders of nickel which are insulated from each other and have separate leading-in conductors. A tuned circuit is con-

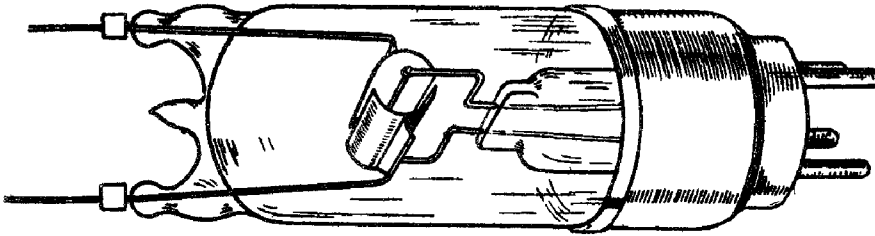


FIG. 46, CHAP. IX.—Split-anode magnetron.

nected between the two halves of the anode, the H.T. supply being arranged by means of a centre tap on the inductance, the magnetic field being produced by a solenoidal winding carrying direct current, and the field strength being adjusted to a value at which the anode current is reduced to nearly but not quite zero. The mechanism by which oscillations are produced is not entirely understood, but the magnetron is certainly capable of maintaining oscillations of the order of 5,000 M.c/s, corresponding to a wavelength of about six centimetres, and the power obtainable is much greater than with triodes producing the Barkhausen-Kurz type of oscillation. It is therefore probable that the magnetron will undergo considerable development to meet the demand for additional communication channels in the ultra-high frequency band.

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