June 6, 1933. F. H. DRAKE 1,912,891

ELECTRICAL AMPLIFIER CIRCUITS

Filed Oct. 31, 1928 2 Sheets-Sheet 1

Fig. 1.

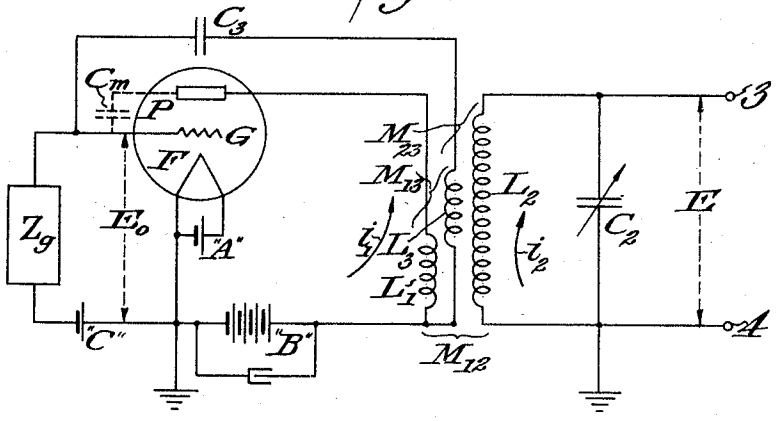
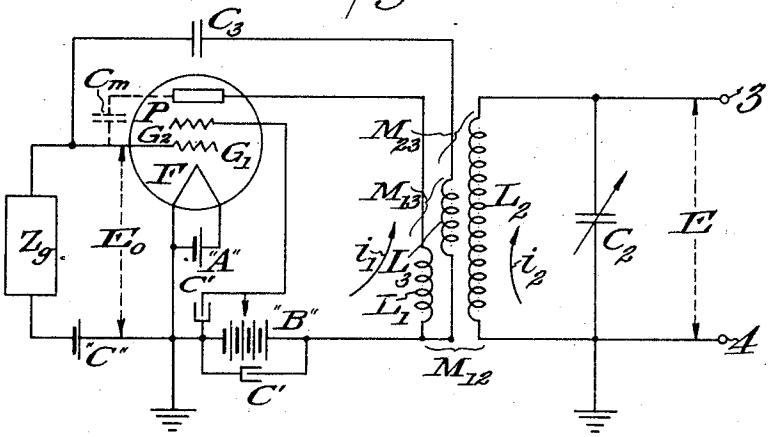


Fig. 2.



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Filed Oct. 31, 1928 2 Sheets-Sheet 2

Fig. 3.

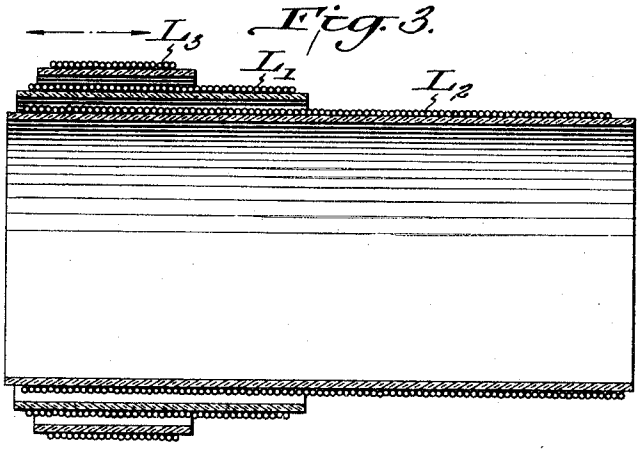
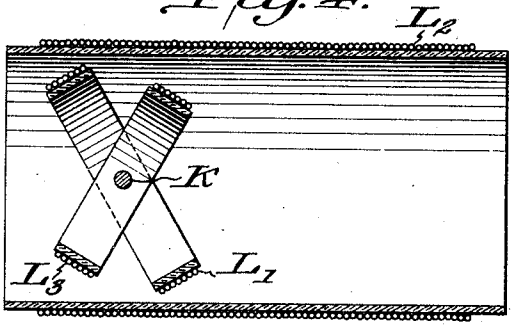


Fig. 4.



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UNITED STATES PATENT OFFICE

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ELECTRICAL AMPLIFIER CIRCUITS

Application filed October 31, 1928. Serial No. 316,207.

This invention relates to electrical circuits of the character of electrical amplifier circuits and the like and especially to such circuits of the type employing electron or vacuum tubes. Such tubes may include a closed vessel, an electron emitting-element or cathode, an electron-receiving anode or plate, and one or more elements or control means which ordinarily take the form of grids or the like. Such tubes are commonly known as "audions", "triodes", "tetrodes", and so forth. My invention relates more particularly to a neutralized electrical amplifier circuit of the foregoing type, and provides a method of and means for reducing or suppressing retroactive or regenerative currents due to coupling between output and input circuits of such an electrical amplifier. The retroaction or regeneration which it is desired to reduce or suppress may be due to capacitive coupling between these circuits, and especially to capacity between the anode and control element of the tube, this capacity being augmented by stray capacities between external connections and circuits associated with these elements, and my invention provides a novel and improved method of and means for neutralizing this capacity coupling. My invention relates also to the design, proportions, and circuit constants of an electrical amplifier circuit including a radio frequency transformer, and to such a circuit having certain electrical relations between elements thereof, these relations being of such a nature as to tend to reduce undesired or disturbing regenerative or feed-back action through the capacitive coupling above referred to. By means of my invention this regenerative or feed-back current may be reduced to smaller values than are ordinarily obtainable with the simple balance conditions and adjustments commonly employed. My invention relates also to a three-coil or three-winding transformer for use in conjunction with a tube of the above described type in an electrical amplifier circuit, and to such a transformer having a primary winding or input coil adapted for connection between the anode and cathode of a tube, a secondary winding or output coil which may be tuned by a variable condenser if desired, and a third winding or neutralizing coil electromagnetically coupled to the primary winding and connected through neutralizing capacitive impedance to the control element of the tube, the secondary winding being coupled electromagnetically to both the primary winding and the neutralizing winding, as is characteristic of the so-called "neutrodyne" circuit. In such a three-coil transformer and electrical circuit associated therewith the electromagnetic coupling between the several windings may assume a certain range of values, as will be hereinafter described; and within this range the coupling between the primary winding and the neutralizing winding may be less than substantially unity coupling, but, within the scope of my invention, may also, in certain cases, be substantially equal to unity, as will appear from the description which follows:

I am aware that electrical circuits employing transformers of the three coil type above described have hitherto been extensively employed in connection with so-called "neutrodyne" radio frequency amplifiers. My invention, however, relates to such a three coil transformer, and to an electrical circuit associated therewith, proportioned and constructed in a novel manner, and having a certain particular, novel relation or relations, among the electrical constants and circuit elements thereof, as is hereafter described and explained.

In the accompanying drawings Figure 1 is a diagrammatical representation of an electrical amplifier circuit including a tube of the three-element type and a three coil transformer associated therewith. Figure 2 illustrates a similar arrangement employing a

tube of the four-electrode or "double-grid" type. Figures 3 and 4 illustrate diagrammatically examples of certain forms of transformer with which the electrical relations according to my invention may be substantially realized.

Referring now particularly to Figure 1, the tube T is provided with anode P, control element or grid G, and cathode F. An input circuit of any desired type is illustrated diagrammatically as being connected between the grid and cathode, and has an impedance represented by Zg. The "A", "B" and "C" batteries, or equivalent socket-power or other devices, or alternating current filament supply means, may be arranged in any convenient manner. The capacity Cm, illustrated in dotted lines, represents the disturbing inter-electrode capacity which causes feed-back from the plate or output circuit to the grid or input circuit. Cm includes the inherent grid-plate capacity, together with stray external capacities which exist effectively between the grid and plate terminals of the tube and operate to augment the effective tube capacity. A three coil transformer L_1—L_2—L_3 is associated with the tube, the primary winding L_1 and "B"-potential source being connected in series between anode P and cathode F, and the secondary winding L_2 being coupled therewith and being tuned by variable condenser C_2 to form a resonant output circuit having output terminals 3 and 4. The neutralizing coil or winding, L_3, is electromagnetically coupled with the primary winding L_1 and is connected effectively at one terminal to the cathode, and at the other terminal to the grid through the neutralizing capacity C_3 to form a neutralizing circuit. The coil L_1 and L_3 are either wound in opposite directions, and connected as in Figure 1, or are wound in the same direction, with reversed connections, so that the mutual inductance between them is effectively negative. The mutual inductance between the coils L_1 and L_2 is designated as M_{12}; the mutual inductance between the coils L_2 and L_3 as M_{23}; and the mutual inductance between the coils L_1 and L_3 as M_{13}. The output voltage of the amplifier is designated as E, which is the voltage available across the tuning condenser C_2. The input voltage across the input impedance Zg between grid and cathode is designated as E_0. The alternating current plate current, i_1, flowing through the coil L_1 produces across this coil a voltage which feeds back through the capacity Cm a disturbing potential onto the grid or input terminal, G, of the tube. By virtue of the neutralizing winding L_3, electromagnetically coupled to coil L_1, and neutralizing capacity C_3, connected in series therewith, a voltage may be fed back to the grid in such a phase and amplitude as to off-set to a considerable extent the effect of the disturbing feed back through capacity Cm, as is already well understood in this art.

In developing and discussing the balance conditions for an electrical network of the type above described, I will first consider the balance relation for a two-coil system including only the coils L_1 and L_3, i. e., the coil L_2 being removed, or M_{12} and M_{23} being each equal to zero. In such a system the balance conditions are

$$(1) \quad M_{13}^2 = L_1 L_3$$

$$(2) \quad C_3 = C_m\left(\frac{L_1}{M_{13}}\right)$$

The condition of equation (1) is imposed in order that the balance shall be independent of frequency, and has the physical meaning that the coils L_1 and L_3 are coupled with unity coupling. Equation (2) gives the required value of the neutralizing capacity C_3 in terms of the capacity C_m and the ratio of the primary inductance L_1 to the mutual inductance M_{13}. In general, I have determined both theoretically and by experiment, that the condition given in equation (1) above is of far less practical importance than the condition given in equation (2). A considerable departure from the condition of equation (1) still permits an exact balance of the network for a single frequency, and a good approximation to balance over a considerable range of frequencies. If equation (1) is not satisfied, then exact balance is obtained for the frequency

$$\frac{\omega}{2\pi}$$

when

$$(2)' \quad C_3 = C_m \frac{L_1}{M_{13} + C_m L_1 L_3 \omega^2 (1 - \tau 2)}$$

where

$$\tau 2 = \frac{M_{13}^2}{L_1 L_3}$$

If $\tau = 1$, equation (2)′ reduces to equation (2) above. Furthermore a computation of the term $C_m L_1 L_3 \omega^2$ shows that in many practical cases this term is negligible compared with M_{13}, so that a balance sensibly independent of frequency may be obtained without the use of unity coupling.

Equation (2) above will hereinafter be termed the "primary balance condition", and equation (1) above will be termed the "unity coupling condition".

Turning now to the case of the three-coil transformer as shown in Figure 1, when the circuit L_2–C_2 is tuned for maximum E the current i_2 flowing in L_2–C_2 will in general be large compared with the currents flowing through L_1 and L_3. The voltages produced in coils L_1 and L_3 by i_2 are determined by the mutual inductances M_{21} and M_{23}. In order

that these voltages may not affect the grid potential, the neutralizing capacity C_3 must have the value:

$$(3) \quad C_3 = C_m\left(\frac{M_{21}}{M_{23}}\right)$$

Equation (3) is herein termed the "secondary balance condition". This is substantially a frequency-free balance for any degree of coupling in the transformers, and is the balance usually obtained in practical radio frequency amplifiers of the "Neutrodyne" type by the common method of impressing a signal on the grid and filament terminals of the cold tube and adjusting C_3 for minimum voltage across C_2.

With the foregoing discussion by way of explanation, I may now state that I have found, as a result of both theoretical and experimental investigation, that the condition for null effect upon the grid or input terminal of the tube for arbitrary currents i_1 and i_2, in the complete three-coil system illustrated in Figure 1, is the simultaneous fulfillment of both the primary and secondary balance conditions stated above: that is, the simultaneous fulfillment of the following conditions:

$$(1) \quad M_{13}^2 = L_1 L_3$$

$$(2) \quad C_3 = C_m\left(\frac{L_1}{M_{13}}\right)$$

$$(3) \quad C_3 = C_m\left(\frac{M_{21}}{M_{23}}\right)$$

The feedback or retroaction produced by a departure of C_3 from the value prescribed by equation (2) is much less serious than that produced by a similar departure from the condition of equation (3) because i_2 is usually much greater than i_1; and it has already been stated above that the feedback produced by departure from the condition of equation (1) is small compared with that produced by a similar departure from equation (2). We have therefore in practice a substantially frequency-free simultaneous balance condition giving negligible feedback to the grid or input terminal if:

$$(2) \quad C_3 = C_m\left(\frac{L_1}{M_{13}}\right)$$

$$(3) \quad C_3 = C_m\left(\frac{M_{21}}{M_{23}}\right)$$

Equations 2 and 3 may be simultaneously satisfied if, and only if:

$$(4) \quad \frac{L_1}{M_{13}} = \frac{M_{21}}{M_{23}}$$

Equation (4) above is the relation between the various self and mutual inductances shown in Figure 1 which must obtain in order that a single adjustment of the neutralizing capacity C_3 will produce simultaneous primary and secondary balance, i. e., balance for arbitrary values of i_1 and i_2, and this condition is therefore herein termed the "simultaneous balance condition".

By experimental investigation I have found that the voltage E_0 may, in the case of such types of transformers as are now in common use in so-called "neutrodyne" receivers, be regenerated up to 30% or 40% above its cold tube value due to primary unbalance, even though an exact secondary balance has been obtained in the familiar way. In some instances the voltage E_0 may be considerably degenerated because of primary unbalance, even though exact secondary balance obtains. According to my invention I have determined relations which, if satisfied, will produce a simultaneous balance for both primary and secondary currents, so that, with proper shielding and by-passing as is now well known in the art, a true one-way amplifier stage may be obtained with this type of neutralized circuit, without the necessity of employing any particular degree of coupling, such, for example, as unity coupling which has been found to have many disadvantages. Hitherto it has always been necessary in this type of circuit, so far as I am aware, to employ substantially unity coupling between primary and neutralizing coils, with lumped coils for these windings, in addition to shielding and by-passing, in order to obtain a true one-way amplifier stage.

By the use of my invention it is possible, also, to produce, as an alternative to complete simultaneous balance as described above, deliberate controlled departures from primary balance of such a nature as to modify the curve representing amplification as a function of wavelength, while maintaining exact secondary balance. For example the coils L_1, L_2 and L_3 may be so relatively proportioned that a degenerative departure from the primary balance condition is obtained, resulting in a greater depression of the short wave gain than of the long wave gain. For condenser-tuned systems this results in a more uniform amplification characteristic.

The fulfillment of the conditions expressed in equation (4) above, I have found, imposes certain requirements upon the geometry and relative arrangement of the windings of the transformer. For example, in one particular circuit which I have successfully employed, the circuit constants and geometry of the windings were as follows:

L_1=40 T #30 Double silk covered copper wire on 1¾″ form (close wound)

L_3=20 T #30 Double silk covered copper wire on fish paper over L_1

L_2=90 T #28 Enamel copper wire on 1½″ form

Figure 3 illustrates in a diagrammatical manner, in longitudinal cross-section, a transformer having the constants and geometry described above. In this arrangement the position of the primary winding L_1 is fixed relative to that of the secondary winding L_2. Adjustment for simultaneous balance is made by sliding the neutralizing coil L_3 in the direction of the arrows. If simultaneous balance is obtained with the coils as shown, regenerative unbalance may be obtained by sliding the coil L_3 from this balance position toward the high potential or grid end of the coil L_2; and similarly a degenerative primary unbalance is obtained by moving L_3 from its balance position toward the filament end of the winding L_2. It will be observed that when the coil L_3 is moved as described above, the mutual inductance M_{13} varies at a different rate from the ratio $\frac{M_{12}}{M_{32}}$, thus making the adjustments effective to accomplish the simultaneous balance condition, or degree of unbalance, which is desired.

It should be understood that my invention is not limited to the exact fulfillment of the mathematical relations set forth herein, since in certain physical embodiments and structures involving my invention such exact fulfillment may be difficult or impossible to accomplish. A substantial or approximate fulfillment of these mathematical conditions in a physical structure is therefore definitely within the scope of my invention. Such a substantial fulfillment of the foregoing mathematical conditions may be accomplished by the structure of Figure 3, or by other suitable arrangements, of which a further example is that shown in Figure 4 in which coil L_2 is a single layer solenoid of conventional design, while coils L_1 and L_3 are shorter coils which may be independently rotated about an axis K in order to obtain the magnetic couplings with L_2 and with each other which are required in order to satisfy the above simultaneous balance condition. It is clear that many variations of this particular construction may be alternately employed, and Figures 3 and 4 are intended to be illustrative only. With such constructions as those of Figures 3 and 4, I have determined experimentally that complete balance may be obtained in actual practice, and that by changing the relative position of the coils a regenerative or degenerative unbalance may be produced as desired, as described above.

Figure 2 illustrates an electrical network including a three-coil transformer of the type above referred to and a tube of the four-electrode or "double-grid" type. My invention is of course equally applicable to networks such as that herein illustrated, and extends also to arrangements in which the neutralizing winding L_3 is connected to the grid G_2 in such a manner that the capacity between the grids G_1 and G_2 constitutes the neutralizing capacity C_3. In such an arrangement the inherent capacity between the elements of the tube may be augmented by external capacities if desired. My invention applies also to electrical networks including "double-grid" tubes of the type designed for use according to the method which comprises employing the grid, G_2, as the control element, and applying to the grid G_1 a positive bias.

It should be understood that the circuit diagrams of Figures 1 and 2 are merely illustrative of my invention. These circuits are, of course, applicable to multistage amplifiers as well as to single stages, as is well understood in this art. Moreover, the "A", "B" and "C" batteries may, of course, be replaced by suitable socket-power devices, the "C"-batteries may be replaced by grid-biasing resistances, or other suitable means and the cathodes may be of the alternating current or separate heater types. The particular transformer constructions shown in Figures 3 and 4 are also given by way of example only. Other modifications and variations of the specific circuits and transformer structures herein described fall within the scope of my invention.

I claim:

1. An electrical amplifier circuit comprising, in combination, an electron tube having at least an anode, a cathode, and a control element; an input circuit associated with said control element, an output circuit including a three-coil transformer having a primary winding connected between anode and cathode, a neutralizing winding coupled to said primary winding with less than unity coupling and so as to have effectively negative mutual inductance therewith and connected through a neutralizing capacity to said control element, and a tuned secondary winding coupled to said primary and neutralizing windings, the ratio of the mutual inductance between said tuned secondary winding and said primary winding to the effective mutual inductance between said tuned secondary winding and said neutralizing winding being substantially equal to the ratio of the self-inductance of said primary winding to the mutual inductance between said primary winding and said neutralizing winding.

2. An electrical amplifier circuit comprising in combination an electron discharge device having at least an anode, a cathode and a control element; an input circuit associated with said control element; an output circuit including a transformer having a primary winding connected between said anode and said cathode, a secondary winding coupled to said primary winding, and a neutralizing winding with less than uni-decoupling and

coupled to said primary winding so as to have effectively negative mutual inductance therewith; and neutralizing capacity connected between said control element and said neutralizing winding, said transformer being so proportioned and constructed as to produce simultaneous balance of said electrical amplifier circuit for both primary and secondary currents and means supporting two of said windings for movement relative to each other and to the third of said windings, whereby the mutual inductances may be adjusted to such relative values that said simultaneous balance of said electrical amplifier circuit may be effected.

In testimony whereof, I affix my signature.

FREDERICK H. DRAKE.