June 4, 1935. H. S. BLACK 2,003,282

WAVE TRANSLATION SYSTEM

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FIG. 1

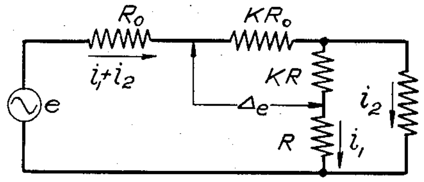

FIG. 2

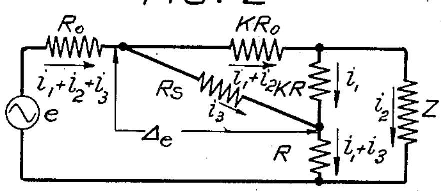

FIG. 3

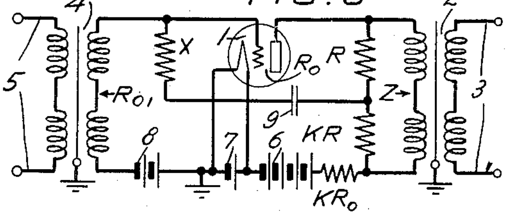

FIG. 3A

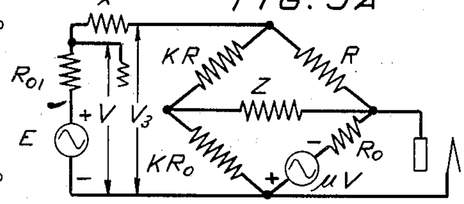

FIG. 3B

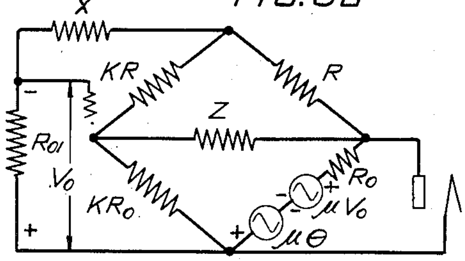

FIG. 3C

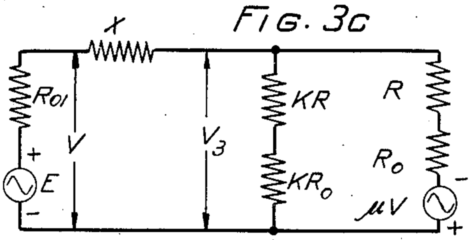

FIG. 3D

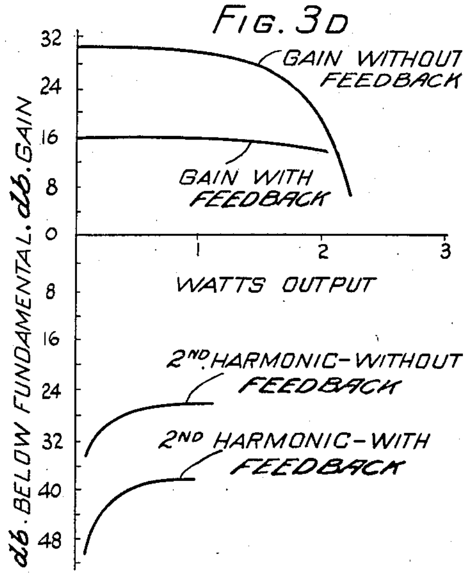

FIG. 3E

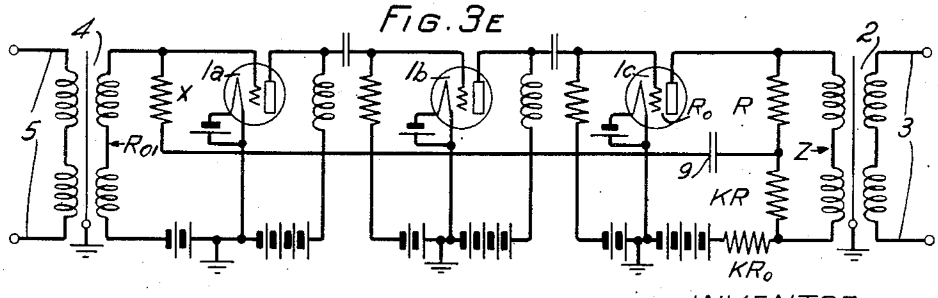

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FIG. 4

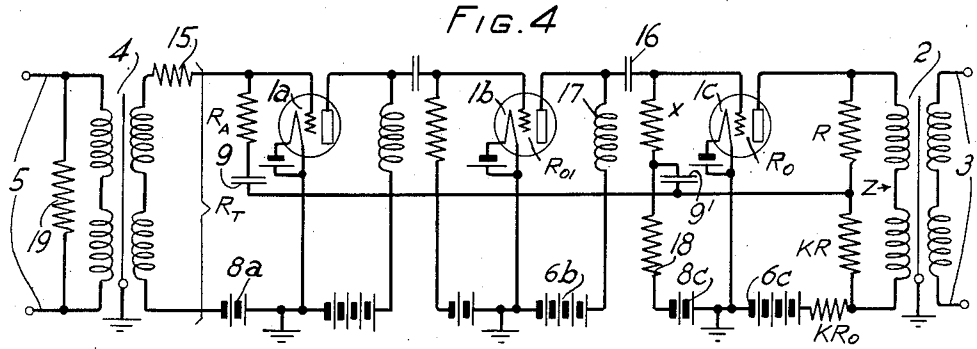

FIG. 4A

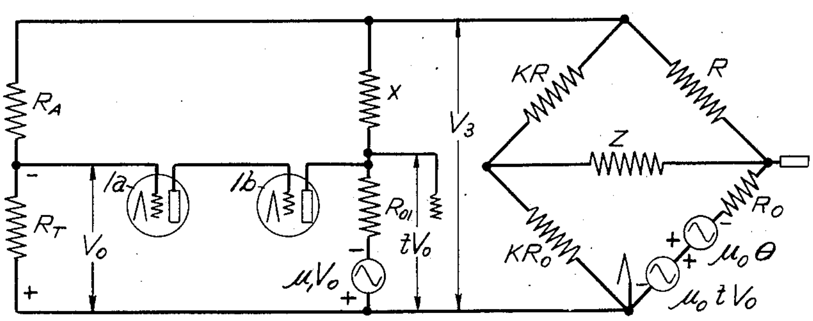

FIG. 5

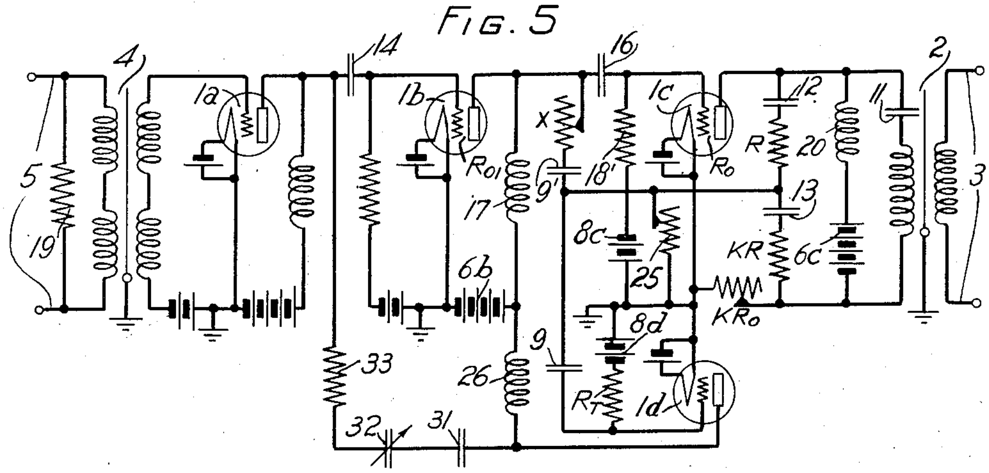

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FIG. 6

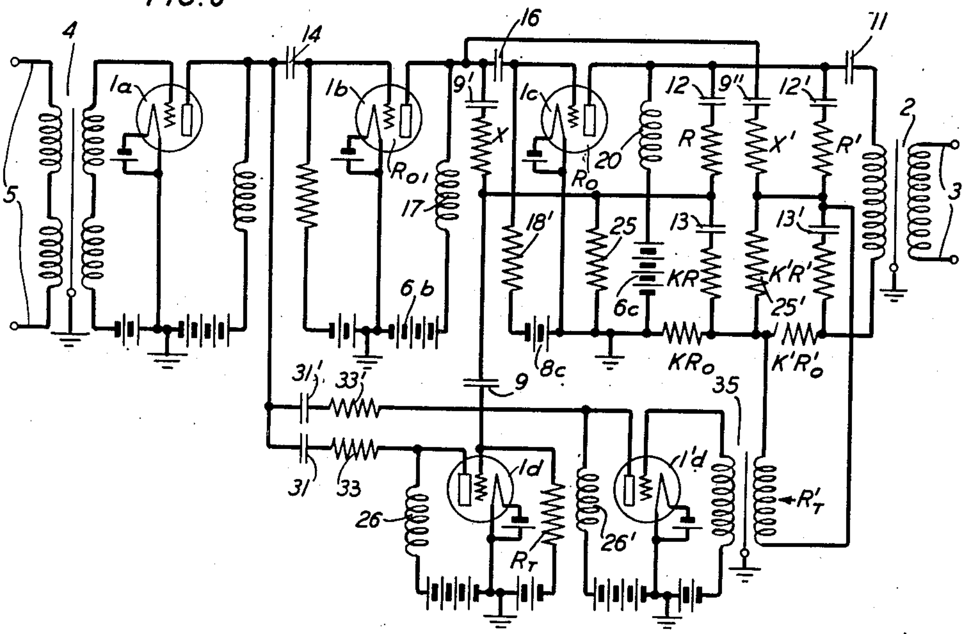


FIG. 8

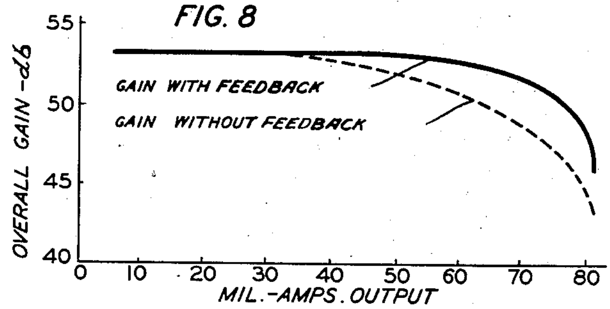
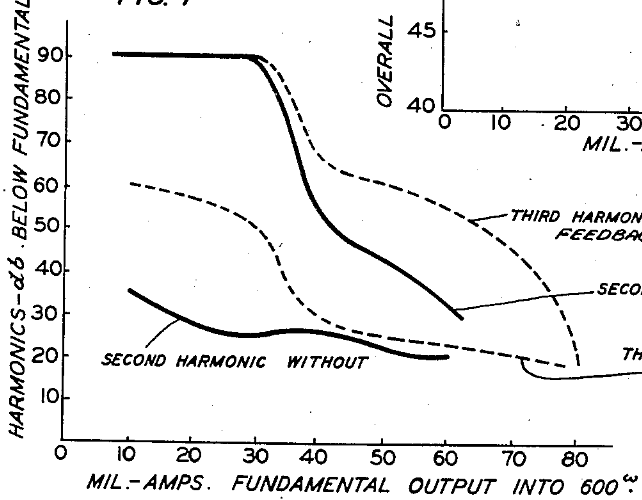


FIG. 7



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Patented June 4, 1935

2,003,282

UNITED STATES PATENT OFFICE

2,003,282

WAVE TRANSLATION SYSTEM

Harold S. Black, New York, N. Y., assignor to Bell Telephone Laboratories, Incorporated, New York, N. Y., a corporation of New York

Original application August 8, 1928, Serial No. 298,155. Divided and this application December 3, 1929, Serial No. 411,224. In Canada May 21, 1929

17 Claims. (Cl. 178—44)

This is a division of my prior application Serial No. 298,155, filed August 8, 1928 for Wave translation systems.

This invention relates to wave translation systems, as for example systems for amplifying electrical variations with the aid of electric space discharge devices.

It is common experience that increase of the power output of vacuum tubes or electric space discharge devices tends to increase distortion of signaling or other waves transmitted by the devices, and tends to lower the gain of the circuits of the devices.

At high values of output power, gain may become so low that further increase of input amplitude or decrease of output impedance produces no further increase of power output.

However, in many applications of vacuum tubes, long before the power output of the tube reaches the maximum value that the tube is capable of delivering or seriously lowers the gain of the tube circuit, distortion becomes so great as to render further increase of output power inadvisable. Representative instances in the field of application of amplifiers, for example, are voice frequency telephone repeaters, carrier frequency amplifiers common to a plurality of signaling channels in carrier wave multiplex signaling systems, amplifiers for public address systems, amplifiers for reproducing music from records, power amplifiers used as transmitting or sending amplifiers in radio or wire transmission systems, amplifiers for operating loud speaking receivers for radio sets or the like, and sending amplifiers for high quality broadcasting transmitters.

In each such instance, the higher the quality of transmission required, or in other words, the less the distortion permissible, the sooner is the maximum permissible output power reached, that is, the lower is the ratio of maximum permissible output power to the maximum output power that the tube or tubes of the amplifier stage is capable of delivering. Therefore, the higher the transmission quality demanded, the more inefficiently has the power capacity of the tube or tubes been used, and consequently when both high transmission quality and high output of power are required in systems of the types commonly employed, the power capacity of the tubes has to be especially great because only a small fraction of the total power that each tube is capable of delivering can be utilized. The present tendency in practice is toward higher and higher transmission quality, and also the number of applications and installations requiring high output power is rapidly increasing, and moreover, the tendency is toward higher quality even where enormous power is demanded and interference or disturbances tending to introduce noise in the waves transmitted is great, as in trans-Atlantic radio telephony.

In general, the design limitations for vacuum tubes of the types commonly employed are such that the highest output power capacity of the tube is obtained only at a sacrifice of maximum gain obtainable, or of operating efficiency, or of both.

In the case of a carrier frequency amplifier common to a plurality of signaling channels in a carrier wave multiplex signaling system, the tendency of the amplifier to modulate a wave of one frequency by a wave of another frequency, increases greatly with increase in the output power, and there results therefore a very large increase in crosstalk and interference between the various channels, this increase being more serious the larger the number of channels.

Therefore, a major problem in devising vacuum tube systems, as for example vacuum tube amplifier systems, is the securing of high output of power without attendant disadvantages, as for example without increase of first cost or decrease of operating efficiency of the systems, and especially in the case of vacuum tube amplifiers and repeaters, without sacrifice of quality of signal reproduction.

Representative objects of the invention are (1) economically to increase the load carrying capacity of wave translation systems, as for example, systems for amplifying electrical variations with the aid of electric space discharge devices, (2) to control modulation in such systems, (3) to amplify waves without modulation or other distortion, (4) to facilitate the handling of large loads by electric space discharge devices, and (5) to stabilize the functioning of systems comprising electric space discharge tubes, as for example to prevent variations of tubes or power from affecting gain.

In one specific aspect the invention is a signal wave amplifying system of a type claimed in my copending application Serial No. 606,871, filed April 22, 1932, for Wave translation systems. In systems of such type, fundamental or applied components and distortion components produced in an amplifying device, as for example a vacuum tube amplifier circuit, are so fed back as to reduce the magnitude of distortion components of both odd and even orders in the output circuit of the device for a given power output of fundamental and stabilize the gain and increase the load carrying capacity of the system.

In its above mentioned specific aspect the present invention is also a system of a type claimed in my copending application Serial No. 411,223, filed December 23, 1929, for Wave translation systems. In a system of that type comprising an amplifying device, in obtaining reduction of distortion, increase of gain stability and high load capacity, undesired reduction in the gain of the system is avoided by isolating the distortion components from the fundamental components and feeding back only the distortion components when the gain of the device has no tendency to depart from a normal or prescribed value, and, when such tendency exists, so controlling feedback of fundamental components as to cause reduction or prevention of departure of the gain of the system from its normal or prescribed value.

In its above mentioned specific aspect the present invention is a system of such type in which the isolated distortion components are so fed back that they are treated by the system the same as fundamental components applied to the system and consequently their feedback does not cause alteration of the value of the isolated distortion components. When they have been fed back they proceed through the system to the place of origin of the distortion components in the system and arrive at that place with their amplitude and phase substantially equal and opposite, respectively, to the original amplitude and phase of the distortion components, and therefore cancel or neutralize the original distortion components, with the result that the distortion is substantially zero in the output of the system.

Other objects and aspects of the invention will be apparent from the following description and claims.

Figs. 1 and 2 of the drawings are circuit diagrams for facilitating explanation of the invention; Fig. 3 shows a feed-back amplifier embodying one form of the invention; Figs. 3A, 3B and 3C are diagrams, and Fig. 3D a set of curves for facilitating explanation of the operation of the amplifier of Fig. 3; Fig. 3E shows a modification of the amplifier of Fig. 3; Fig. 4 shows a feedback amplifier embodying another form of the invention; Fig. 4A is a simplified circuit diagram of the amplifier of Fig. 4, for facilitating explanation of the operation of that amplifier; Fig. 5 shows a modified form of the amplifier of Fig. 4; Fig. 6 shows a modified form of the amplifier of Fig. 5; and Figs. 7 and 8 show curves for facilitating explanation of the action of a system of the type of that shown in Fig. 5.

The driving voltage in the plate circuit of an amplifier is 180° out of phase with the grid voltage which produces it. For a feed-back amplifier, it is desirable that there be available a voltage which is directly proportional to, and in phase with, the driving voltage in the plate circuit, and which is independent of the impedance of the work circuit. It will be seen from Fig. 1 and the derivation below, that the voltage Δe which is the drop across resistances KR and KR_0, fulfills these three conditions.

In the figure, R_0 is a resistance (for example, the resistance of the space discharge path between the plate and the filament of a three electrode vacuum tube); e represents, as a generator, a source of voltage e (for example, the driving voltage e produced in the discharge path by the grid voltage); and Z is an impedance (for example, the impedance of the load circuit or work circuit of the tube). Two resistances designated by their values R and KR, respectively, are connected in series across the impedance Z, K being a constant. A resistance designated by its magnitude KR_0 is connected between R_0 and the junction of KR with Z. The voltage e causes currents i_1, i_2 and i_1+i_2 to flow as indicated by the arrows.

The derivation mentioned above is as follows:

$$e=(i_1+i_2)R_0(1+K)+i_1R(1+K)$$

$$\Delta e=(i_1+i_2)R_0K+i_1RK$$

$$e=[1+K][(i_1+i_2)R_0+i_1R]$$

$$\Delta e=[K][(i_1+i_2)R_0+i_1R]$$

$$\frac{e}{\Delta e}=\frac{1+K}{K}$$

The circuit of Fig. 2 is like that of Fig. 1, except that a resistance R_s is bridged across KR_0 and KR. The current components flowing in the various parts of the circuit of Fig. 2 are indicated by the arrows and their accompanying letters i with the appropriate subscripts. However, in Fig. 2 the currents indicated by i_1, i_2 and i_1+i_2 and the voltage indicated by Δe are not in general of the same magnitudes as in Fig. 1. When a resistance R_s is connected across KR_0 and KR, the voltage Δe still fulfills the three conditions mentioned above. Referring to Fig. 2 this is demonstrated as follows:

$$e=(i_1+i_2+i_3)R_0+(i_1+i_2)KR_0+i_1KR+(i_1+i_3)R$$

$$e=(i_1+i_2)R_0(1+K)+i_1(1+K)R+i_3R_0+i_3R$$

$$e=[1+K][(i_1+i_2)R_0+i_1R]+i_3(R_0+R)$$

$$\Delta e=[K][(i_1+i_2)R_0+i_1R]=i_3R_s$$

$$\frac{e}{\Delta e}=\frac{1+K}{K}+\frac{R_0+R}{R_s}$$

Fig. 3 shows one way in which this voltage may be utilized. In this figure a three-electrode, electric space discharge amplifying device 1 has an anode-cathode space-discharge path of resistance R_0, which is associated with resistances KR_0, KR, and R, and impedance Z, in the manner of resistance R in Figs. 1 and 2. The plate-filament resistance R_0 is the reciprocal of the slope of the static characteristic of plate current versus plate voltage of the discharge device at the so called operating point, as explained in the following articles by John R. Carson in the Proceedings of the Institute of Radio Engineers: "Theory of three element vacuum tube", vol. 7, pp. 187–200, April 1919; "The equivalent circuit of the vacuum tube modulator", vol. 9, pp. 243–249, June 1921. (That is,

$$\frac{1}{R_0}=\frac{\delta i_p}{\delta e_p}$$

where i_p and e_p are instantaneous plate current and voltage, respectively.) In Fig. 3 the impedance Z is the primary-to-secondary impedance of output transformer 2 which, together with circuit 3 connected to the secondary winding of the transformer, forms the load or work circuit for the device 1. An input transformer 4 impresses waves from circuit 5 upon the grid of the device 1. These waves may be, for example, voice waves, or voice modulated carrier waves for transmission over carrier wave wire transmission systems or to radio transmitting antennae or waves received over such systems. The usual plate, filament, and grid batteries are shown at 6, 7 and 8. A circuit corresponding to the resistance R_s of Fig. 2 and comprising the secondary winding or secondary-to-primary impedance R_{01} of transformer 4, a resistance x and a blocking condenser 9 in series, is connected across the resistances KR_0 and KR. The grid is connected to the junction of x and R_{01}. The condenser is a blocking condenser of large capacity, for preventing batteries 6 and 7 from applying steady voltage to the grid. The circuit through which battery 6 supplies plate current for the tube comprises resistance KR_0 in series with two parallel paths, one extending through the primary winding of transformer 2 and the other through resistances KR and R in series.

A characteristic of this circuit of Fig. 3 is that the gain is reduced by the feed-back action. To demonstrate this, it is simpler to redraw the circuit to the form of Fig. 3A. From this it will be seen that R and KR, R_0 and KR_0 form the ratio arms of a balanced Wheatstone bridge, Z takes the place of the galvanometer and E represents a source of voltage E which is applied through a resistance of $(x+R_{01})$ that forms the input diagonal or feed-back diagonal of the bridge. For the condition of balance, it is evident that there is no current in Z due to E, the driving voltage in the grid circuit.

There is some voltage V, from grid to filament. Due to V, there will be a driving voltage μV in the plate circuit, with relative polarity as shown by the plus and minus signs. The presence of this voltage is indicated in Fig. 3A by generator μV.

To investigate the effect of the two generators or voltages E and μV acting simultaneously, use is made of the principle of superposition. This principle is that the current which flows at any point in a circuit, or the difference of potential which is established between any two points in a circuit, due to the simultaneous action of a group of E. M. F.'s located at the same or various points in a circuit, is the algebraic sum of the component currents at the first point, or the component differences of potential between the latter two points, which would be established by the individual E. M. F.'s acting alone.

Due to E alone, there will be a voltage from grid to filament, V_1 equal to

$$V_1=\frac{x+\frac{K}{1+K}(R_0+R)}{R_{01}+x+\frac{K}{1+K}(R_0+R)}E$$

Due to μV acting alone, there will be a voltage from grid to filament V_2 equal to

$$V_2=-\frac{\frac{R_{01}}{R_{01}+x}}{\frac{1+K}{K}+\frac{R_0+R}{x+R_{01}}}\mu V$$

or, if

$$\beta_1=\frac{1}{\frac{1+K}{K}+\frac{R_0+R}{x+R_{01}}}\left[\frac{R_{01}}{R_{01}+x}\right]$$

$$V_2=-\mu\beta_1 V$$

These specific values for V_1, V_2 and β_1 follow directly from the configuration of the specific circuit shown, but, though special to that particular configuration, are given in order to present a concrete illustration of the significance of V_1, V_2 and β_1.

By the principle of superposition,

$$V=V_1+V_2$$

$$V=V_1-\mu\beta_1 V$$

$$V=\left(\frac{1}{1+\mu\beta_1}\right)V_1$$

That is, the voltage in the grid circuit (and hence the current in the output impedance Z) is reduced from what it would be if there were no feedback action, and the impedance relations were the same, by a factor

$$\frac{1}{1+\mu\beta_1}$$

It will now be shown that any distortion (as for example modulation product) produced in the tube is also reduced by the same factor.

Consider the circuit of Fig. 3B. Let any primary distortion voltage produced in the tube be represented as a driving voltage $\mu\Theta$, in the plate circuit. Let the voltage drop between the grid and the filament, resulting from the distortion produced in the tube be V_0. This sets up another driving voltage in the plate circuit, μV_0, with polarity as shown. As before,

$$V_0=\beta_1(\mu\Theta-\mu V_0)$$

$$\mu V_0=\mu\beta_1(\mu\Theta-\mu V_0)$$

$$\mu V_0=\frac{\mu\beta_1}{1+\mu\beta_1}\mu\Theta$$

$$\mu\Theta-\mu V_0=\frac{\mu\Theta}{1+\mu\beta_1}$$

That is, the final, or resultant, driving distortion voltage in the plate circuit is reduced by a factor

$$\frac{1}{1+\mu\beta_1}$$

from what it would be without feedback action.

It will be noted that due to the configuration of the elements of the circuit, if a generator is assumed in series with Z, no current will flow in the branch $x+R_{01}$. Hence the impedance of the amplifier as seen from the load or work circuit Z is the same as it would be without regeneration, and is independent of the shunt resistance $x+R_{01}$.

Now to return to a consideration of the gain of the circuit, by the feed-back action the gain is stabilized with respect to variations of tubes and power. If due to any cause, the μ of the tube is reduced, which would reduce the gain, the effective voltage on the grid is increased. Similarly, variations in R_0 are stabilized. The curves of Fig. 3D, which are plotted from observed data, show that by the feed-back action the load carrying capacity of the amplifier is substantially increased, the variation of gain with load is reduced, and the ratio of the power output of second harmonic to the power output of fundamental is improved or decreased about 12 decibels. The curves for operation without feedback are for operation with the right hand side of condenser 9 disconnected from the junction of R and KR and connected instead to ground through an impedance (not shown) equal to the impedance with which the feed-back diagonal of the Wheatstone bridge in Fig. 3 is faced by the remainder of the bridge (i. e., equal to the combined resistance of two paths in parallel, one through KR and KR_0 in series and the other through R and R_0 in series). The resistance $(x+R_{01})$ of the feed-back diagonal is so high that substituting an equal resistance across the path through KR and KR_0

would not affect the operation of the circuit. Thus, the curves for operation without feedback are for operation with the external grid-to-filament impedance and the external plate-to-filament impedance for the tube the same as in operation with feedback.

The circuit of Fig. 3 can be modified to comprise a plurality of tubes connected in cascade, in which case μ represents the total amplification from a voltage across the grid of the first tube to a driving voltage in the plate of the last tube. For example, Fig. 3E shows one such modified circuit, with tandem connected tubes 1a, 1b and 1c replacing the tube 1 of Fig. 3. If the number of tubes be even instead of odd, then an odd number of phase reversals in addition to those produced by the tubes themselves should be produced, as for example by the introduction of an interstage or other transformer with its windings poled to reverse the phase of waves passing through the transformer.

In Fig. 3A consider voltage V_3. Its value is being contributed to by both E and μV, and these voltages tend to oppose each other. It is possible, therefore, by suitable adjustment of the circuit elements, notably x, to make $V_3=0$. The value of x to accomplish this may be found as follows:

In Fig. 3C,

$$V=(\text{Voltage drop across } x)+V_3$$

$$\therefore V=(\text{Voltage drop across } x) \text{ since } V_3=0$$

Similarly

$$\mu V=[\text{Voltage drop across } (R+R_0)]+V_3$$
$$=(\text{Voltage drop across } R+R_0)$$

The current through x must equal the current through $(R+R_0)$, for since $V_3=0$, no current flows through $(KR+KR_0)$.

$$\therefore \frac{V}{x}=\frac{\mu V}{R+R_0}$$

$$x=\frac{R+R_0}{\mu}$$

This means that if x is given the value

$$\frac{R+R_0}{\mu}$$

and a voltage is applied to the circuit in series with R_{01}, no voltage is produced across the feed-back diagonal of the bridge. (That is, V_3 in Fig. 3A is zero). This does not apply to distortion voltages, since these are present in the plate circuit, but not in the grid circuit; i. e., only one generator is acting. By giving x the value

$$\frac{R+R_0}{\mu},$$

we have two points (the ends of the feed-back diagonal) across which the potential corresponding to the fundamental or original transmitted wave is zero, and the potential of the distortion or disturbing wave is not zero. Across these points we have voltages corresponding to any disturbance present in the plate circuit which is not present in the grid circuit. We can now operate on the distortion without disturbing the fundamental or original transmitted wave components.

For example, consider Fig. 4 and Fig. 4A. Fig. 4 shows a feed-back amplifier system comprising three vacuum tubes 1a, 1b and 1c connected in tandem. Connected in series, across the grid and filament of tube 1a, are a resistance 15 and the secondary winding of input transformer 4 which connects circuit 5 with the amplifier. The resistance 15 is sufficiently great to make the impedance of this resistance and the secondary-to-primary impedance of the transformer in series substantially a pure resistance R_T. The tube 1c is connected to the load or work circuit Z, as in the case of the tube 1 of Fig. 3 and the tube 1c of Fig. 3E. As appears clearly from Fig. 4A, the impedance Z forms the output diagonal of the balanced Wheatstone bridge the ratio arms of which are R_0, KR_0, KR and R. In the feed-back diagonal of the bridge are a blocking condenser 9, a resistance R_A and the resistance R_T in series with each other and in parallel with a circuit comprising a blocking condenser 9′, resistance x, a blocking condenser 16, and the plate-to-filament space path resistance R_{01} of tube 1b in series. Preferably, the admittance of the space current supply path, through battery 6b and choke coil 17, which path is connected across R_{01}, is negligibly small for the frequencies to be amplified. So also is the admittance of resistance 18 which is connected across the feed-back diagonal of the bridge. Biasing potential from battery 8c is applied to the grid of tube 1c through resistances 18 and x in series. The blocking condensers 9 and 9′ prevent plate battery 6c from applying potential to the grids of tubes 1a and 1c, and prevent grid biasing batteries 8a and 8c from applying potentials to the grids of tubes 1a and 1c, respectively. A resistance 19 across circuit 5, and the primary-to-secondary impedance of transformer 4, in parallel, approximately match the impedance of that circuit.

In the circuit of Fig. 4 there will be no feed-back of the fundamental or undistorted wave from the last tube 1c to the first tube 1a, if x has been given the proper value so that there is no fundamental or undistorted voltage across the feed-back diagonal of the bridge. It can be shown that the value obtained for x in the above demonstrations holds when R_A and R_T and 1a and 1b are added to the circuit of Fig. 3C. However, the distortion introduced in the last stage will be reduced, as can be seen from the following consideration of Fig. 4A.

Let the distortion voltage acting in the plate circuit of the last tube be $\mu_0\Theta$ after its reduction caused by feed-back in the last tube as explained in the case of the tube of Fig. 3 but before any reduction due to feed-back from the last tube to the first tube as about to be explained. There will be some distortion voltage V_0, impressed on the grid of the first tube as a result of the distortion produced in the last tube and V_0 sets up a driving voltage $\mu_1 V_0$ that may be represented as a generator $\mu_1 V_0$ in the plate-to-filament space path of the second tube. This impresses a voltage tV_0 on the grid of the last tube, which sets up a driving distortion voltage $\mu_0 tV_0$ that may be represented as a generator $\mu_0 tV_0$ in the plate-to-filament space path of the last tube.

Since x has been given such a value that the contribution of any voltage acting in series with R_{01} to V_3 is zero, V_0 is dependent solely on $\mu_0\Theta$. That is

$$V_0=\mu_0\Theta\left[\frac{\dfrac{R_T}{R_A+R_T}}{\left(\dfrac{1+K}{K}\right)+\dfrac{R_0+R}{\dfrac{(x+R_{01})(R_A+R_T)}{x+R_{01}+R_A+R_T}}}\right]$$

or designating the bracket in this expression β_2

$$V_0=\mu_0\beta_2\Theta.$$

These specific values for V_0 and β_2 follow directly from the configuration of the specific circuit shown, but, though special to that particular configuration, are given in order to present a concrete illustration of the significance of V_0 and β_2. Then

$$\mu_0 t V_0 = \mu_0 t \mu_0 \beta_2 \Theta$$

$$\mu_0 \Theta - \mu_0 t V_0 = \mu_0 \Theta - \mu_0 t \mu_0 \beta_2 \Theta$$

$$= \mu_0 \Theta (1 - \mu_0 \beta_2 t)$$

That is, the new driving distortion voltage $(\mu_0\Theta - \mu_0 t V_0)$ is equal to the old driving distortion voltage $\mu_0\Theta$, multiplied by a factor $(1-\mu_0\beta_2 t)$. Now if $\mu_0\beta_2 t=1$, the distortion vanishes to zero. That is, if the product of the voltage amplifications and diminutions around the circuit is 1, and the phase shift is 180°, the distortion voltage is balanced out. The amount of improvement in distortion in this circuit (over and above the improvement caused by feed-back in merely the last tube) depends on the accuracy with which the circuit elements are adjusted in such a way that any distortion component fed back from the plate-filament space path of the last stage to the first stage, and amplified through the tubes again returns to the plate-filament space path of the last stage with its original amplitude but with its phase shifted 180°.

This operation of this circuit differs from that of Fig. 3 and Fig. 3E, in that the improvement in crosstalk in those circuits is obtained by continued regeneration of the distortion voltage, instead of by the balancing operation described above. In those circuit it is neither necessary nor probable that the voltage fed around the circuit will be equal to that originally present. The operation just mentioned in the circuit of Fig. 4 may be considered a single regeneration, with the voltage being fed around the circuit once, and coming back in opposite phase to that originally present.

The expressions "continued regeneration" and "single regeneration" as just used in reference to the feed-back amplifiers of Figs. 3, 3E, and 4, are in accordance with the usual explanation of the operation of feed-back amplifiers, of which it is usually said, with reference to positive feed-back action respecting the fundamental frequency, that the operation wherein the energy of the output circuit and the input circuit react upon each other repeats itself a number of times with cumulative effect. However, it is preferred to express the above noted difference in operation of a circuit such as that of Fig. 4 from circuits such as those of Fig. 3 and Fig. 3E by stating that in Fig. 4 the amplified, isolated distortion components fed to the input circuit of the tube 1c do not cause the magnitude of the isolated distortion components (appearing across the input diagonal of the bridge) to be altered, whereas in Figs. 3 and 3E the distortion components fed back to the grid of the last tube cause reduction of the magnitude of the distortion components (that appear across the feed-back diagonal of the bridge).

Fig. 5 shows a three-stage feed-back amplifier system similar to that of Fig. 4, but modified in that instead of feeding the isolated distortion components (obtained across the feed-back diagonal of the Wheatstone bridge) back to the grid of the first stage or tube 1a and amplifying the distortion components and the signal components together in that tube before passing them on to the grid of tube 1b, those isolated distortion components are amplified separately from the signal, in an amplifier shown as comprising a single tube 1d (through which the signal components do not pass), and are then fed back to the grid of tube 1b. Thus, in the system of Fig. 5 the amplification of the isolated distortion components can be controlled independently of the amplification of the signal components, and can, for example, be made greater than the amplification of the signal components. The number of phase reversing amplifying stages (or other phase reversing means) in the path through which the distortion components are passed in their transmission from the feed-back diagonal of the bridge to the grid of tube 1c should be even. Thus, in this path, the number of phase reversing means or stages (such for example as that comprising tube 1b) in which the signal components and the distortion components are amplified alike should be odd or even according to whether an odd or an even number of phase reversing means or stages (such as that comprising the tube 1d) are used in which the signal is not amplified as the distortion components are.

In Fig. 5 the space current for tube 1c is supplied from battery 6c through a choke coil 20 of negligibly low admittance for the frequencies of the waves to be amplified, the current returning to battery 6c through resistance KR_0. Condensers 11, 12, 13 and 14 as well as condensers 9, 9' and 16, are stopping or blocking condensers which have negligibly low reactance at the frequencies to be amplified. If desired, the resistance KR_0 may be adjustable, as shown, to facilitate balancing the Wheatstone bridge, the ratio arms of which are formed by the plate-to-filament space path resistance R_0 of tube 1c and the resistances KR_0, KR and R. The adjustment of KR_0 can be made to correct unbalance resulting from variations in plate impedance of tube 1c caused for example by variations in the power supply voltages for the tube or by substitution of one tube for another. The impedance of the feed-back diagonal of the bridge can be adjusted by a variable resistance 25 connected in parallel with a path comprising condenser 9', resistance x (shown adjustable), and plate-to-filament space path resistance R_{01} of tube 1b in series. Also in parallel with the resistance 25 is a path, of negligibly low admittance at the frequencies of the waves to be amplified, extending through stopping condenser 9, input or coupling resistance R_T for tube 1d, and grid biasing battery 8d for that tube, in series. In parallel with R_{01} is a path through choke coil 17 and battery 6b in series, and also a path through grid biasing battery 8c and input or coupling resistance 18' for tube 1c. The two latter paths are of negligibly low admittance at the frequencies of the waves that are to be amplified. However, if desired, the magnitude of the combined resistance of these two paths and the space path of tube 1b may be used as the magnitude R_{01} in the formulæ above. The resistance R_T in Fig. 5 corresponds to the resistance R_T in Figs. 4 and 4A and receives the voltage V_0 indicated in Fig. 4A. In Fig. 5 there is no resistance corresponding to the resistance R_A in Figs. 4 and 4A; or in other words the resistance R_A is zero for Fig. 5. The battery 6b supplies space current for tube 1d through choke coil 26. Tube 1d feeds back to the grid of tube 1b through condensers 31 and 32 and resistance 33 in series. This resistance adjusts the voltage thus fed to that grid; and these condensers adjust the phase of that voltage, the capacity of condenser 32 being variable and relatively large compared to that of condenser 31 to facilitate close or fine adjustment of the phase. As indicated above, the tube 1d in Fig. 5 corresponds to the tube 1a of Figs. 4 and 4A as regards amplification of the distortion voltage V_0. This voltage sets up the driving distortion voltage $\mu_1 V_0$ in the path R_{01}, i. e., in the plate-to-filament space path of tube 1b in Fig. 5, just as explained above for the case of Figs. 4 and 4A. This impresses the voltage tV_0 on the grid of the last tube 1c, which sets up the driving distortion voltage $\mu_0 t V_0$ in the plate-to-filament space path of tube 1c. As in the case of Fig. 4, the resistance x has such a value that the contribution of any voltage acting in series with R_{01} to the voltage V_3 across the feed-back diagonal of the bridge is zero, so that V_0 is dependent solely on $\mu_0\Theta$, the original distortion voltage in the plate-to-filament space path of tube 1c.

In an amplifier system substantially as shown in Fig. 5, if tube 1c in that figure be regarded as representing four tubes in parallel, the feed-back action reduced the energy contained in the second harmonic to 1/2,250,000 of its value without the feed-back action, and reduced the energy of the third harmonic to 1/50,200 of its value without the feed-back action. This result entailed no sacrifice of overall gain or ultimate level. Feed-back action of the type described for Fig. 3 tends to reduce the gain of the last stage (represented by tube 1c); but the circuit of the type shown in Fig. 5 preferably is operated with this tendency to gain reduction in the stage comprising tube 1c not very pronounced, and with great reduction of distortion by the balancing operation of the type described for Fig. 4. The gain of the first two stages, comprising tubes 1a and 1b, can be large, this portion of the amplifier serving as a voltage amplifier for stepping up the voltage to the power stage represented by tube 1c. The reason why the reduction of the second harmonic is greater than the reduction of the third harmonic (as appears from the ratios given above), is primarily that although the second harmonic (and all even power harmonics) originated by distortion in the penultimate tube 1b, and also all even power, sum and difference frequency components or waves so originated, are reduced by neutralizing or counteracting them (as described for the circuit of Fig. 4) with the corresponding distortion waves produced by distortion in the last stage comprising tube 1c, such balancing out does not occur for odd order harmonics or other distortion arising from the presence of odd power terms in the amplifier characteristic. The reasons for this difference will be apparent from the explanation given, for example, in U. S. patents to H. S. Read, 1,464,111, August 7, 1923, and H. Nyquist 1,570,770, January 26, 1926, of the operation of tandem amplifiers in reducing distortion waves originating in the amplifiers.

The preferable practice, in operation of the circuit of Fig. 5, is to adjust the value of x so that the amplitude of the fundamental in the work circuit is the same for operation of the system with feedback as for operation without feedback. The operation without feedback is obtained by disconnecting the right-hand side of condenser 31 from the junction of the choke coil 26 and the plate of tube 1d and connecting it instead to ground through a passive impedance, not shown, equal to the resistance of the plate-to-filament space discharge path in tube 1d. To make the distortion components balance out in the space path of the last amplifier as explained in connection with Fig. 4, that is to make $\mu_0\Theta = \mu_0 t V_0$, the magnitude of the fed back distortion components appearing across the feed-back diagonal of the bridge is controlled by adjusting resistance 25 in that diagonal, and the phase shift in tubes 1d, 1b and 1c and their associated circuits is compensated for by phase correcting means, as for example by condenser 32 which can be adjusted to give the desired phase correction. A harmonic analyzer (not shown) can be connected across circuit 3 in order to tell when the best adjustment for 25 and 32 has been effected. With the circuit of Fig. 5 operated in the manner just described, although the third harmonic is not reduced below the value produced in the penultimate stage, the reduction of the third harmonic originated by distortion in tube 1c is a very great improvement. Since the next to last stage (tube 1b) is operating at relatively low power level, and as a voltage amplifier working into a high impedance, the modulation that it produces is very small, and has generally been considered negligible.

Each of the systems shown in Figs. 3 and 4 is typical of a wide variety of possible circuits. The principles of operation described for either or both of these types of circuits are applicable in general to devices capable of amplifying waves, for improvement of their operation. These principles are of very broad and general application. Their application is by no means limited to operation intended to be mere amplification. The theory of these systems has been checked by careful tests of physical embodiments of the systems. Each of these systems reduces both odd order and even order distortion components at the same time, and can stabilize gain and afford high load capacity.

One difference between Fig. 4 on the one hand and Figs. 3 and 3E on the other hand, lies in the relative seriousness of unavoidable phase shifts in the amplifier. Since the effectiveness of Fig. 4 depends on the production of two voltage waves of equal amplitude, and opposite sign, a good balance requires that the phase difference be very close to 180°, and that the gain of the circuit change very little after a balance is once attained. However, in Figs. 3 and 3E, the improvement depends on the factor

$$\frac{1}{1+\mu\beta}$$

β indicating a factor such as β_1 or β_2 mentioned above.

If originally

$$\mu\beta = 10 + j0, \quad \frac{1}{1+\mu\beta} = .0909,$$

an improvement of 20.8 db. If we assume the gain to change by 3 db., so that $\mu\beta = 7 + j0$, then

$$\frac{1}{1+\mu\beta} = .125$$

an improvement of 18.0 db. A similar change in gain in Fig. 4 would change an infinite improvement to a 10.4 db. improvement. Similarly, if $\mu\beta = 7.07 + j7.07$ (absolute magnitude the same, but at a 45° angle)

$$\frac{1}{1+\mu\beta} = .1075$$

an improvement of 19.35 db. A similar shift of 45° in Fig. 4 would change an infinite improvement to a 2.3 db. improvement.

An important capability of the circuit of Fig. 5 is that the improvement in distortion can be augmented or made cumulative, by extending the circuit to form that of Fig. 6. A second bridge circuit is formed, with a ratio arm constituted by the network that faces the output diagonal of the first bridge. In this arm, therefore, is a voltage proportional to the residue of distortion remaining after the first balancing. The fundamental or original transmitted wave components are also present in this arm. The other three ratio arms of the second bridge are $K'R'_0$, $K'R'$, and R', corresponding respectively to the ratio arms KR_0, KR, and R of the first bridge. The output or work circuit diagonal of the second bridge is the condenser 11 and the primary-to-secondary impedance of amplifier output transformer 2 in series. The resistance x' corresponds in function to resistance x, and is of such magnitude that the voltage of the fundamental or original transmitted wave components across R_{01} and x' in series (i. e., across the feed-back diagonal of the second bridge) is zero. Thus the primary winding of a transformer 35, which is connected across the feed-back diagonal of the second bridge, receives only a voltage proportional to the residue of distortion just mentioned. This voltage is amplified in amplifier 1'd and the amplified voltage is fed through resistance 33' and condenser 31' to the grid or input circuit of tube 1b. It is apparent that the residue of distortion just mentioned is isolated from the fundamental components and fed back in the same fashion as the first process. Thus the distortion is again improved by approximately the same ratio as before. In balancing circuits which have heretofore been used for reducing distortion (such as the Colpitts push-pull circuit), only one improvement can be achieved, and that only for odd order or even order distortion components and not for both odd order and even order components at the same time; whereas the improvement obtained with the circuit of Fig. 5 can be multiplied as many times as desired by adding bridges in tandem as indicated in Fig. 6, each additional bridge reducing both odd order and even order distortion components and reducing the distortion by approximately the same factor as the circuit with only the first bridge.

In Fig. 6 the elements 9'', 12', 13', 25', 26', 31', 33' and 1'd are similar in structure and function to the elements 9', 12, 13, 25, 26, 31, 33 and 1d, respectively, and the primary-to-secondary impedance R_T of transformer 35 is connected across the feed-back diagonal of the second bridge as the impedance R_T is connected across the feed-back diagonal of the first bridge.

Fig. 7 is a set of curves plotted from observed data, showing the output of second and third harmonics as functions of output of the fundamental or original transmitted current, for a system of the type of that shown in Fig. 5. The curve for the second harmonic taken with regeneration shows that with an output of fundamental up to 30 milliamperes into an impedance of 600 ohms, the power level of the output of second harmonic is 90 decibels below the power level of the output of fundamental. This means that the fundamental power is about 900,000,000 times as great as the power of the second harmonic, and that the current ratio of fundamental to second harmonic is about 30,000. The curve for the second harmonic taken without feedback shows that up to 30 milliamperes output of fundamental the output of second harmonic is only about 30 db. lower than the output of fundamental (i. e., the power output of fundamental is only about 900 times as great as the power output of second harmonic, instead of 900,000,000 times as when feedback is employed). For current outputs greater than 30 milliamperes of fundamental, the curve for the second harmonic for operation with feedback is still well above the curve for the second harmonic for operation without feedback. Likewise, the curves for the third harmonic taken with and without feedback show great reduction of the ratio of that harmonic to the fundamental, as a result of the feedback. Moreover, similar important reduction of the output levels of other harmonics, both odd and even, (and also of the output levels of intermodulation products), as compared to the output levels of the fundamental waves, is effected by the feedback. The curves for both harmonics for operation without feedback are for operation corresponding to operation of the circuit of Fig. 5 with the right hand side of condenser 31 disconnected from the junction of the choke coil 26 and the plate of tube 1d and connected instead to ground through a passive impedance (not shown) equal to the resistance of the plate-to-filament space discharge path in tube 1d.

Fig. 8 is a set of curves plotted from observed data, showing the overall gain as a function of current output into a 600 ohm resistance, for the fundamental, in a specific system of the type of that shown in Fig. 5. Below about 30 milliamperes of output current the solid line curve, which is for operation with feedback, substantially coincides with the dotted line curve, which is for operation without feedback. This is in marked contrast to the gain-load curves of Fig. 3D for the circuit of Fig. 3, inasmuch as the feedback in the latter circuit lowers the gain. In Fig. 8 the solid line curve lies well above the dotted line curve, for outputs considerably greater than thirty or forty milliamperes, thus showing great gain stabilization effected by the feedback, this stabilization being effected without gain reduction corresponding to such reduction indicated by Fig. 3D for the circuit of Fig. 3.

It is desired to emphasize the fact that the invention increases the load carrying capacity of electric space discharge tubes (1) not only by attaining an increase in load capacity of very great importance by suppression of distortion components of frequencies other than the fundamental frequencies and thereby permitting the tubes to operate over a larger range of their grid-voltage plate-current characteristics but also (2) by attaining a second increase of very great importance in the load capacity by feedback of fundamental waves in such a way as to control gain in a desired manner, as for example, to prevent undesired lowering of gain, for the fundamental waves.

In connection with this latter increase, it should be noted that in each of the amplifying systems described herein the invention provides means for correcting for distortion caused by improper degree of amplification of fundamental waves, as for example caused by amplification of a fundamental wave of a given frequency different amounts for different input amplitudes, or as for example caused by amplification of two waves of respectively different fundamental frequencies, different amounts, respectively. If in Fig. 4 or 5, for example, a wave of a given fundamental frequency is amplified in tube 1c (or the circuits associated with the tube) to a degree less than, say, the normal amplification for the tube (and the associated circuits) then for that frequency the feed-back voltage, or regenerated voltage across the feed-back diagonal of the bridge tends to be lower than normal, i. e., less than the fundamental which is applied there from circuit 5 through R_{01} and x. As a result, the tendency toward lower than normal gain of the system for the fundamental wave of the given frequency is checked. Similarly, if the given frequency is amplified to a degree greater, instead of less, than normal in tube 1c, then for that frequency the feed-back voltage tends to be higher than the voltage of that frequency which is applied across the feed-back diagonal by circuit 5 through R_{01} and x; and as a result the tendency toward higher than normal gain of the system for the fundamental wave of the given frequency is checked. The system compensates for too low or too high gain for fundamental waves, at the same time that it suppresses components of frequencies other than fundamental frequencies.

For the sake of simplicity the invention has been explained above with reference especially to pure resistance impedances where impedances have been described as external or ratio arms of Wheatstone bridges, or as input diagonals of the bridges. However, the invention is not limited to the case in which these impedances are resistances. They, as well as the load, may be impedances of any character, (proper provision being made, of course, for the necessary supply of steady potential to the plates and grids of the tubes). That is, generalized impedances Z_0, KZ_0, KZ_2, Z, Z_f, Z_{01}, Z_A and Z_T may replace R_0, KR_0, KR, R, x, R_{01}, R_A and R_T, respectively. These replacements may likewise be made in the mathematical formulæ and expressions above. In any of the figures of the drawings the impedance Z_0 includes the tube internal plate-to-filament capacity. Where R_0 has been treated as constituting one arm of the bridge, the plate-filament capacity is so small that its reactance at frequencies of the order of those of the waves to be amplified is so great compared to the impedance R_0 as to be negligible.

What is claimed is:

1. In combination, wave translating apparatus, means for deriving waves from waves produced in said apparatus, and means capable of transmitting waves of the frequency of said produced waves, for impressing the derived waves on the input side of said apparatus without thereby altering the intensity of the derived waves.

2. In combination, wave translating apparatus, means for supplying to said apparatus waves producing modulation in said apparatus, means for deriving waves from the modulation components, and means for impressing the derived waves on the input side of said apparatus without thereby causing alteration of the intensity of the derived waves.

3. A system comprising a wave translating device that generates distortion components in response to application of waves to the input circuit of said device and that reverses the phase of waves transmitted through said device, means for deriving from said distortion components waves of frequencies exclusive of waves produced without frequency change by the applied waves, and amplifying means for amplifying the derived waves and impressing them on the input circuit of said device, in the same phase in which they are originally generated, without altering the intensity of the derived waves.

4. A system comprising a plural odd number of stages of electric space discharge devices, means for balancing waves produced by the last one of said stages in response to waves of other frequencies against said waves of other frequencies, and means for feeding waves remaining after said balancing operation back to the first of said stages without thereby causing alteration of the magnitude of the latter waves.

5. A wave translating system comprising two electric space discharge devices, means for supplying waves from the output circuit of one of said devices to the input circuit of the other of said devices, and means for reducing harmonic waves generated in said other device in response to said waves to such a value that they are balanced out by harmonic waves of like order originated in said one device.

6. A system comprising a plurality of stages of electric space discharge devices, means for balancing waves produced by one of said stages in response to other waves against said other waves at the input of said stage, and means for feeding waves remaining after said balancing operation back to another of said stages preceding said one stage without thereby causing alteration of the magnitude of the latter waves.

7. The method which comprises so operating upon fundamental waves as to produce a resulting wave containing fundamental components of the frequencies of said fundamental waves and modulation products different from said fundamental components, isolating said modulation products from said fundamental components by obtaining said fundamental waves at a point where they are undistorted and balancing said fundamental waves so obtained exclusive of other waves against said fundamental components in said resulting wave, and transmitting said modulation products to said point and so regenerating said modulation products that they reappear at their place of origin with their phase reversed.

8. The method which comprises so operating upon fundamental waves as to produce a resulting wave containing fundamental components of the frequencies of said fundamental waves and modulation products different from said fundamental components, isolating said modulation products from said fundamental components by balancing said fundamental waves exclusive of other waves against said fundamental components in said resulting wave, and so regenerating said modulation products, without thereby altering the magnitude of the isolated modulation products, that the modulation products reappear at their place of origin with their original magnitude but in reversed phase.

9. Signaling apparatus comprising a wave translating device, means for transmitting fundamental waves to said device which produce therein a resulting wave containing fundamental components that have the same frequencies as said fundamental waves and distortion products differing from said fundamental components, means for deriving from a portion of said apparatus said fundamental waves exclusive of other waves and so opposing said derived waves to said fundamental components in said resulting wave as to isolate said distortion products, and means for feeding said distortion products back to said portion of said apparatus and so regenerating said distortion products in said device that they reappear at their place of origin in reversed phase.

10. Signaling apparatus comprising an amplifier, means for transmitting fundamental waves to said amplifier which produce therein a resulting wave containing fundamental components

that have the same frequencies as said fundamental waves and incidental distortion products differing from said fundamental components, means for so opposing said fundamental waves exclusive to other waves to said fundamental components in said resulting wave as to isolate said distortion products, and means for so regenerating said distortion products in said amplifier, without thereby altering the magnitude of the isolated distortion products, that the distortion products reappear at their place of origin with their original magnitude but with their phase reversed.

11. The method which comprises so operating upon fundamental waves as to produce a resulting wave containing fundamental components of the frequencies of said fundamental waves and distortion products different from said fundamental components, isolating said distortion products from said fundamental components by balancing said fundamental waves exclusive of other waves against said fundamental components in said resulting wave, amplifying said isolated distortion components in their isolated state, and thereafter so regenerating them, without thereby altering the magnitude of the isolated distortion components, that the distortion components reappear at their place of origin in their original magnitude but in reversed phase.

12. A circuit comprising a wave translating device, means for transmitting to said device fundamental waves which produce distortion components in said device, a wave transmission path for transmitting the fundamental waves from a point in said circuit anterior to said device substantially without distortion and opposing the waves so transmitted against waves transmitted through said device, said path having such transmission efficiency and phase shift that the fundamental waves transmitted therethrough neutralize the fundamental component of the opposed distorted waves from said device and thereby yield the distortion components without fundamental waves, and means for causing these isolated distortion components to be fed back to said point in said circuit and so regenerated that they reappear at their place of origin in reversed phase.

13. A circuit comprising a vacuum tube device, means for transmitting to said device fundamental waves which produce distortion components in said device, a path for transmitting the fundamental waves substantially without distortion and opposing the waves so transmitted against waves transmitted through said device, said path having such transmission efficiency and phase shift that the fundamental waves transmitted therethrough neutralize the fundamental component of the opposed distorted waves from said device and thereby yield the distortion components without fundamental waves, and means for causing these isolated distortion components to be so regenerated in said device, without thereby altering the magnitude of the isolated distortion components, that the distortion components reappear at their place of origin with their original amplitude but with reversed phase.

14. The method of operating upon a wave which comprises so amplifying the wave as to produce fundamental and distortion components, isolating the distortion components from the fundamental components, so regenerating the distortion components as to avoid altering the magnitude of the isolated distortion components but to balance the regenerated distortion components against the original distortion components to obtain their difference as relatively small resultant distortion components, deriving from said resultant components distortion components of reversed phase and substantially the same magnitude, and balancing said components of reversed phase against said resultant components.

15. In combination, wave translating apparatus, means for deriving waves from waves produced in said apparatus and including components of frequency different from that of the derived waves, and means, capable of transmitting waves of the frequency of said produced waves, for impressing the derived waves on the input side of said apparatus without altering the intensity of the derived waves.

16. In combination, wave translating apparatus, means for supplying to said apparatus waves producing modulation in said apparatus, means for deriving odd order products from the modulation components, and means for impressing the derived waves on the input side of said apparatus without altering the intensity of the derived waves.

17. A wave translating system comprising two wave paths in parallel, vacuum tube apparatus in at least one of said paths, the respective numbers of vacuum tube stages in the two paths differing by an odd number, and means for applying waves from the output of one of said paths to their input.

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