July 9, 1935. H. S. BLACK 2,007,172

WAVE TRANSLATION SYSTEM

Filed March 29, 1933

FIG. 1

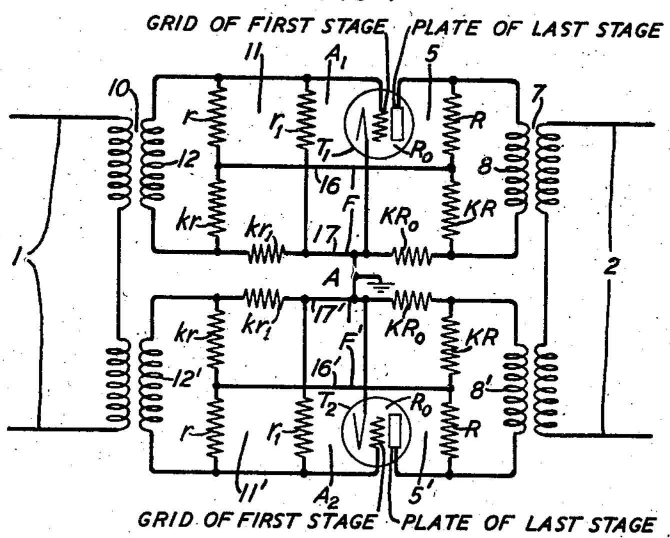
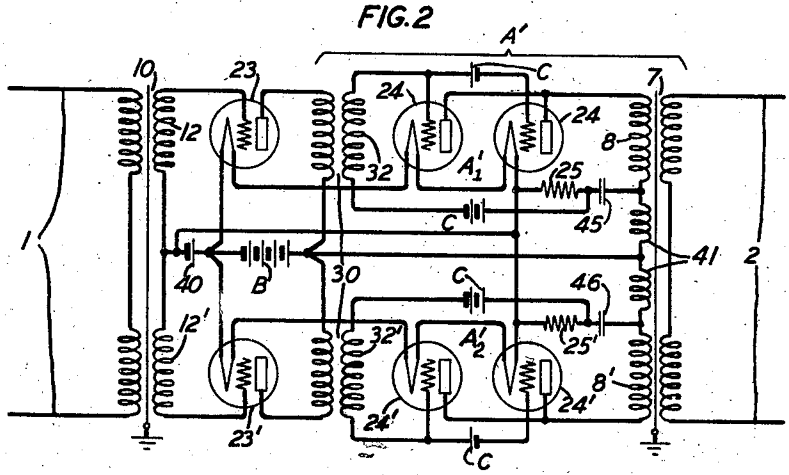


FIG. 2



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WAVE TRANSLATION SYSTEM

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Application March 29, 1933, Serial No. 663,316

8 Claims. (Cl. 179—171)

This application is a continuation in part of my copending application, Serial No. 606,871, filed April 22, 1932, for Wave translation systems.

This invention relates to wave translation systems, as for example, electric wave amplifying systems.

Objects of the invention are stabilization, distortion suppression and impedance control in such systems.

In accordance with one feature of the invention, in a push-pull or balanced system in which balance suppresses distortion to a degree dependent upon the degree of balance attained, the degree of balance is increased by retroaction or feedback in the system, for example, as explained hereinafter.

In accordance with another feature of the invention, reduction of distortion is achieved by choosing for a push-pull or balanced system a load impedance which causes objectionable modulation produced in the system to be less than if the load impedance had the value of the output impedance which it would face in the absence of feedback, and then, as indicated hereinafter, for example, causing feedback to match the output impedance to the chosen load impedance in order to prevent objectionable wave reflection, which might result in objectionable crosstalk, for instance. (For any given frequency the impedance of a network between any two points is considered the ratio that a voltage applied across the points from an external network would bear to the internetwork current.)

Also, in accordance with the invention, the above mentioned features may be combined.

In one specific aspect, the invention is an amplifier with negative feedback of fundamental and distortion waves so as to increase stability of operation and reduce distortion production as explained in the above mentioned copending application, the amplifier being of the balanced or push-pull type in accordance with the present invention. It has been found that the distortion suppression attainable in such a negative feedback amplifier exceeds the sum of that attainable by the balancing action without feedback and that attainable by the feedback action without balance; because, as explained hereinafter, the feedback can improve the balance or make the two sides of the push-pull system more nearly alike as regards their transmission properties. In general, attainment of this improvement in balance is facilitated by making the two sides of the push-pull amplifier independent as regards feedback operation or in other words by making each side an individual feedback amplifier so that neither side of the push-pull system will materially affect the feedback operation of the other side, and is also facilitated by preventing reaction of the input or output connecting circuit for either side of the push-pull circuit upon the feedback operation of that side. To indicate in a simple way why this is so, and how the negative feedback action can make amplifiers more nearly alike as regards their transmission properties, certain aspects of operation of feed-back amplifiers will now be pointed out, after the significance with which this specification uses certain terms and symbols relative to operation of vacuum tube amplifiers has been indicated.

Amplification of an amplifier without feedback is what the voltage on the grid of the first tube must be multiplied by to obtain the phase and magnitude of the resulting voltage generated in the plate circuit of the last tube, or the voltage of an equivalent fictitious generator in series with the internal plate resistance of the last tube. This amplification will be designated as μ (and is a complex quantity). Amplification ratio is the absolute value of the amplification. By the term gain as used in this specification is meant voltage gain, i. e., twenty times the logarithm of the amplification ratio.

The complex quantity $\mu\beta$ will be used herein to designate the ratio by which a voltage of a wave is modified in a single propagation around the closed feedback loop of a feedback amplifier. It follows that β is the complex quantity by which a driving voltage in the space path of the last tube, in series with the internal plate-filament impedance R_0 of that tube, must be multiplied to give the voltage that it—the driving voltage alone—acting through the feedback path, will produce on the grid of the first tube.

As shown in the above mentioned copending application, the amplification of a feedback amplifier is

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

and the corresponding change in amplification caused by the feedback action is

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

The quantity

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

is a quantitative measure of the amount of feedback, and herein, as in that application, the feedback is described as positive feedback or negative feedback according as the absolute value of

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

is greater or less than unity.

As pointed out in that application, when $\mu\beta >> 1$ the amplification with feedback approaches

$$-\frac{1}{\beta}$$

which is largely independent of the amplification or variations in amplification of the tubes. Consequently, in a push-pull amplifier consisting of two feedback amplifiers operating back to back under this condition, by making β equal in the two amplifiers, the gains and the phase shifts through the two amplifiers (from the grid of the first tube to the driving voltage in the last tube) are made equal, and therefore, the suppression, by balance, of the even order modulation products generated in the last stage is greatly facilitated and the usual difficulties of obtaining sufficiently close matching of tubes, interstage networks, etc., are greatly reduced. Moreover, this equality of gains and phase shifts is not affected by tube changes, changes in direct current plate and grid voltages, etc., but is constant or stable with time.

In one specific embodiment of the invention disclosed hereinafter, with the amplification in each of the two amplifiers in the two sides of the push-pull circuit substantially equal to

$$-\frac{1}{\beta}$$

the angle of β is made substantially zero, and consequently the phase shift through each amplifier approaches 180°. However, as indicated hereinafter, the invention is not limited to having the angle of β substantially zero, nor to having $\mu\beta > 1$.

In an amplifier, ordinarily negative feedback action (apart from balance) reduces distortion products of odd and even orders approximately equally, whereas balance by push-pull action (apart from the feedback action) reduces the even order products primarily. Therefore, since the second order products are usually very much greater than the modulation products of higher orders, it is especially fortunate that by employing both negative feedback and balance, the second order products can be reduced not only directly by feedback action, but also by balance and further by improvement of balance produced by the negative feedback.

In accordance with one feature of the invention, each side of the push-pull circuit can be prevented from unduly affecting the feedback operation of the other side, for example, by employing separate output bridge networks for the two sides (i. e., employing output bridges individual to the two sides), and feeding back from the output bridge network on each side of the circuit to the input of that side of the circuit, with each output bridge network giving conjugacy between the feedback path for its side of the circuit and the output connecting circuit for that side of the circuit, or giving any desired closeness of approach to such conjugacy. If desired, in accordance with the invention, an input bridge, also, can be used in each side of the push-pull amplifier, each input bridge giving conjugacy (or any desired closeness of approach to conjugacy) between the feedback path for its side of the push-pull circuit and the input connecting circuit for that side of the push-pull circuit, so that the input connecting circuits can not unduly affect the feedback operation of either side of the circuit or in other words can not affect the β in either side of the circuit.

However, the invention is not limited to the use of the input bridges or the output bridges.

In one specific aspect the invention is a push-pull amplifier with negative feedback improving the balance as described above and with a load impedance substantially greater than the output impedance that the load impedance would face if there were no feedback, and with the feedback raising the output impedance to a value that matches the load impedance. (The amplifier output impedance without feedback is the value that the amplifier output impedance would have if μ could in some way be reduced to zero and, at the same time, the remaining properties of the $\mu\beta$-path or closed feedback loop or system not be altered.) Objectionable modulation produced by the amplifier is reduced by thus working the amplifier into a load impedance larger than the value that the amplifier output impedance would have in the absence of feedback; yet, since the feedback action matches the output impedance to this increased load impedance, objectionable wave reflection is obviated. Such reflection might, for example, result in objectionable cross-talk, for instance, in the case of a multiplex carrier telephone amplifier.

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

Figs. 1 and 2 are circuit diagrams of two different embodiments of the invention.

Fig. 1 shows a push-pull vacuum tube amplifier A for amplifying waves received from circuit 1 and transmitting the amplified waves to circuit 2. The amplifier A comprises two single string or single line vacuum tube amplifiers A_1 and A_2, which are alike, connected back to back in push-pull relation. Amplifier A_1 comprises a vacuum tube or any number of vacuum tube stages T_1 in tandem; and amplifier A_2 comprises a tube or stages T_2 like the tube or stages of amplifier A_1.

The tubes T_1 and T_2 are connected to the outgoing circuit 2 through two output bridge networks 5 and 5′ and output transformer 7. The transformer has two primary windings 8 and 8′. The winding 8 forms one diagonal of the bridge circuit 5; and the winding 8′ forms one diagonal of the bridge circuit 5′. The four ratio arms of the bridge circuit 5 comprise four resistances or impedances R_0, KR_0, KR and R, respectively, the impedance R_0 being the plate-cathode impedance in the last of the tubes or stages T_1. The four ratio arms of bridge circuit 5′ likewise comprise four resistances or impedances R_0, KR_0, KR and R, of which the impedance R_0 is the plate-cathode impedance in the last of the tubes or stages T_2.

The incoming circuit 1 is connected to the tubes T_1 and T_2 through input transformer 10 and two input bridge networks 11 and 11′. The transformer 10 has two secondary windings 12 and 12′. The winding 12 forms one diagonal of the bridge circuit 11; and the winding 12′ forms one diagonal of the bridge circuit 11′. The four ratio arms of the bridge circuit 11 comprise resistances r_1, kr_1, kr and r, respectively, the grid and cathode of the first of the tubes T_1 being connected across arm r_1. The four ratio arms of bridge circuit 11' likewise comprise four resistances r_1, kr_1, kr and r, the grid and cathode of the first of the tubes T_2 being connected across this resistance r_1. Negative feedback in amplifier A_1 is provided through a feedback path F comprising conductors 16 and 17, and, as explained in the above mentioned copending application, renders the operation of the amplifier more stable than it would be without feedback and reduces distortion produced by the amplifier. Similarly, negative feedback in amplifier A_2 is provided through a feedback path F' comprising conductors 16' and 17', and increases the stability of operation of the amplifier and reduces its distortion. As indicated above, the feedback action improves the balance of the two amplifiers for second order modulation components, rendering their fundamental driving voltages in the last stage more nearly equal and opposite. Over the utilized frequency range, each of the amplifiers may have $\mu\beta >> 1$ so that the amplification for each is approximately

$$-\frac{1}{\beta}$$

and β may be the same constant quantity for each amplifier. As noted above, with the phase angle of β equal to zero, the phase shift through each amplifier (from the first grid to the last space path driving voltage) approaches 180°.

As described above, the windings 8 and 12 are in diagonals of bridges 5 and 11, respectively. The other diagonals of these bridges comprise the feedback path F, so the path F is rendered conjugate to the windings 8 and 12 by the bridges 5 and 11, respectively. Similarly, path F' is rendered conjugate to windings 8' and 12' by bridges 5' and 11', respectively. Thus, neither of the amplifiers A_1 and A_2 can affect the operation of the other, (i. e. neither amplifier can act as a transducer, either active or passive, affecting the value of β for the other amplifier), nor can any of the input or output transformers or connecting circuits for either amplifier affect β or the feedback operation of either amplifier. In the circuit, as shown, when the bridges are balanced and their ratio arms are resistances, the angle of β is substantially zero. The output bridges, especially, are advantageous in preventing the feedback in either of the amplifiers A_1 and A_2 from being affected by the output from the other amplifier. However, if desired either the input bridges or the output bridges, or both, can be omitted; and moreover, with or without the omission of bridges, the feed-back for the push-pull amplifier can be effected through the input or output transformers, or both, so as to reduce the distortion introduced in the transmitted waves by the transformer as pointed out in the above mentioned copending application, or can be effected without feeding back by primary-to-secondary transmission through the transformers.

Only the alternating current circuits of the amplifier A are shown in Fig. 1, the electromotive force sources, choke coils, stopping condensers, etc., required for energizing the amplifier or conditioning it for operation being omitted for the sake of simplicity as they can readily be supplied by those skilled in the art, for example, in the general manner indicated in connection with the circuit of Fig. 2, about to be described, or Figs. 56, 57, 65 or 66 of the above mentioned copending application.

Fig. 2 shows a two-stage push-pull amplifier embodying a form of the invention in which negative feedback is applied to the last stage only, and which has feedback loops with $\mu\beta<1$ and without input or output bridges such as those of Fig. 1. The amplifier of Fig. 2 may be suitable for amplifying frequency waves of a wide frequency range, as for example, for use in repeaters of an open wire multiplex carrier telephone system of the general type of the present commercial type C carrier telephone system described by Messrs. H. A. Affel, C. S. Demarest and C. W. Green in the Bell System Technical Journal, July 1928, pages 564 to 629. In such cases it is important, especially from the point of view of reducing reflection or suppressing crosstalk, that the amplifier output impedance match the load impedance. (The load impedance may here be considered as including the impedance of the amplifier output transformer; and the amplifier output impedance may be considered as the impedance facing the load, or as the impedance facing the primary or high impedance winding of the amplifier output transformer in the case of a carrier telephone repeater as just mentioned.) As described hereinafter, in the system of Fig. 2 the negative feedback is of such character as to increase amplifier output impedance, so that the value required for the load impedance that is to match (i. e. equal) the amplifier output impedance becomes correspondingly greater and, consequently, objectionable modulation products are reduced.

In the push-pull amplifier of Fig. 2, the first stage comprises two tubes 23 and 23' in push-pull relation. The second stage comprises two tubes 24 in parallel and two tubes 24' in parallel, the tubes 24 being connected in push-pull relation with the tubes 24'. Each of these six tubes may be, for example, Western Electric 101-F type tubes. An interstage transformer 30 connects the two stages. It has two secondary windings 32 and 32'. Winding 32 is connected in the input circuit of tubes 24, in series with a 450-ohm feedback resistance 25 which is common to their input circuit and their output circuit. Similarly, winding 32' is connected in the input circuit of tubes 24', in series with a 450-ohm resistance 25' which is common to their input circuit and their output circuit. Thus, the second stage is a push-pull, negative feedback amplifier A' comprising two separate single string or single line negative feedback amplifiers A'_1 and A'_2, the amplifier A'_1 comprising tubes 24 in parallel, and the amplifier A'_2 comprising tubes 24' in parallel. Batteries C are grid biasing batteries for the tubes 24 and 24'; battery B is a common plate battery for all six tubes; and battery 40 is a common filament heating battery for all six tubes. A retard coil or choke coil 41 and stopping condensers or by-pass condensers 45 and 46 function as usual in separating the alternating current output circuits of tubes 24 and 24' from the source of unidirectional plate current for those tubes. With respect to the circuit of Fig. 2 and also the circuit of Fig. 1, the designation of amplifiers on opposite sides of a push-pull circuit as separate has reference to their transmission circuit, and not to the circuits for energizing the amplifiers or conditioning them for operation.

Each of the amplifiers A'_1 and A'_2 in Fig. 2, having a feedback impedance 25 or 25' common to the input and output circuits of the amplifier, is a negative feedback amplifier circuit of the type referred to in the above mentioned copending application as the common impedance type, shown in Fig. 34 of that application. As indicated in the description of that figure, the negative feedback action increases the amplifier output impedance, (from Z_0, its value without feedback), by the factor $[1-(\mu\beta)_z]$. The expression $(\mu\beta)_z$ designates the value that $\mu\beta$ would have if the load impedance were zero; and

$$Z_0=R_0+\frac{r(G_0+C)}{r+G_0+C}$$

the significance of R_0, r, G_0 and C being as follows: R_0 is the plate-cathode impedance, which faces the feedback impedance and the load impedance in series, r is the feedback impedance (such as **25** and **25'** in Fig. 2 herein); G_0 is the grid-cathode impedance, which faces the incoming circuit (winding **32** or **32'** in Fig. 2) and the feedback impedance in series; and C is the impedance of the incoming circuit. Thus, in Fig. 2 the negative feedback action can be caused to increase the output impedance of amplifier A'_1 and also that of amplifier A'_2 to a value, for example, approximately twice R_0, i. e. twice the plate-cathode impedance in tube **24** or tube **24'**. The transformer **7** then can be given the proper impedance transformation ratio to match the impedances on the two sides of the transformer, so that circuit **2** will be terminated in its own impedance at the amplifier and reflection, consequently, will be obviated and at the same time the transformer will present to the tubes twice their own impedance.

The 101-F type of tube, when worked into twice its own impedance, has a better modulation characteristic (i. e. has a lower modulation power output for a given fundamental power output) than when worked into a matched impedance; and the circuit of Fig. 2 combines (1) this improvement in linearity due to working the output tubes into twice their impedance with (2) the improvement in linearity that the negative feedback action produces by reducing the ratio of modulation voltage to fundamental voltage generated in the tubes **24** and **24'** (3) the improvement in stability that the negative feedback action produces in the operation of each of the amplifiers A'_1 and A'_2, (4) the improvement in linearity that results from merely push-pull operation, and (5) the improvement in linearity that results from the improvement that the negative feedback produces in the balance of the two sides of the push-pull circuit, (as explained above in connection with Fig. 1). Thus, modulation is reduced in four ways simultaneously, the reduction produced directly by push-pull action and that produced directly by feedback action combining and being augmented by that due to the increased load impedance made feasible by feedback and that due to the improvement in balance effected by feedback.

Since the amount by which negative feedback action in amplifier A' reduces the amplifier gain depends on the amount of the negative feedback, the gain reduction may be made small by having the amount of feedback small. Moreover, since the load impedance has been increased (by increase in the ratio of transformer **7**) to match the amplifier output impedance as increased by the negative feedback, the alternating plate current of the output stage has thereby been decreased for a given power output to the load and consequently the electron emission from the cathodes of the last stage need not be as great as in the case of the lower load impedance. Therefore, in the case of the increased load impedance, tubes may be used in the last stage which require less heating energy than the tubes that would be required in the case of the lower load impedance; and this not only effects important economy in power supply but facilities using tubes of higher amplification factor, to compensate for the effect of the negative feedback in reducing the amplifier gain, so that the amplifier gain may, for example, be approximately the same as it would be if the tubes of lower amplification factor were employed and no feedback were employed. The feedback tends to reduce the amplifier gain; but this tendency can be counteracted by increasing the amplification factor of the tubes, (since $\mu\beta<1$), so that while the amplifier output impedance is changed not only by the use of tubes of higher amplification factor or plate resistance, but moreover, by the feedback action; nevertheless, the amplifier gain remains substantially unaltered. It has been found that in the system of Fig. 2 employing the negative feedback and using the 101-F type tubes mentioned above, which have a normal filament current of approximately one half ampere, the gain and the power output capacity of the system may be substantially as great as for the system without the feedback but with tubes (two Western Electric 101-D or L-type tubes in the first stage and four Western Electric 104-D or O-type tubes in the last stage) having a normal filament current of approximately one ampere, and that the modulation produced by the system is reduced sufficiently to render unnecessary tube selection for push-pull balance, which was a practical necessity without the feedback.

It is noted that the output transformer in Fig. 2 may step the amplifier output impedance down to the impedance of circuit **2**, the negative feedback action in the amplifier being used to increase the amplifier output impedance from a value greater than the impedance of circuit **2** to a value still greater.

As indicated above, the invention is not limited to having $\mu\beta<1$. It is within the scope of the invention to have $\mu\beta>>1$ in the circuit of Fig. 2 as well as in the circuit of Fig. 1. (Ordinarily, doing so in the circuit shown in Fig. 2 would tend to increase the degree in which the feedback raises the output impedance).

Moreover, control of impedance by feedback, as contemplated for the invention, is not limited to raising impedance. For instance, in a negative feedback amplifier circuit in which the voltage to be fed back is derived from a voltage across the load, the negative feedback can lower the amplifier output impedance, as pointed out, for instance, in connection with Fig. 31 of the above mentioned copending application showing such a circuit, and in accordance with the present invention such negative feedback, for example, can be used to lower the output impedance of a push-pull amplifier and at the same time to match the output impedance and the load impedance (for example, the impedance of the high impedance winding of a step-down transformer facing the amplifier output impedance and forming part of the load). This may be desired, for instance, in case the tubes of the last stage of the amplifier are pentodes, it being customary (without feedback) to work such tubes into approximately one fifth of their impedance rather than into a matching impedance, in order to improve their operation, as for example, in order to reduce objectionable modulation that they produce.

While in accordance with the present invention, impedance is controlled by feedback in specific types of circuits or systems, the above mentioned copending appplication and my copending application Serial No. 663,317, filed of even date herewith, for Wave translation systems, present dominating claims not limited to those specific types of circuits or systems.

What is claimed is:

1. A negative feedback, push-pull amplifier comprising two feedback paths for the two sides of the push-pull circuit, respectively, two outgoing circuits for the two sides of the push-pull circuit, respectively, and two output bridges for the two sides of the push-pull circuit, respectively, each bridge connecting in conjugate relation one of said feed-back paths and one of said outgoing circuits.

2. A negative feedback, push-pull amplifier comprising two feedback paths for the two sides of the push-pull circuit, respectively, two incoming circuits for the two sides of the push-pull circuit, respectively, and two input bridges for the two sides of the circuit, respectively, each bridge connecting in conjugate relation one of said feedback paths and one of said incoming circuits.

3. A push-pull system having a load impedance of value that causes objectionable modulation produced in the system to be less than if the load impedance had the value that the output impedance of the push-pull system would have in the absense of feedback, and means for producing in said system negative feedback that matches the output impedance of the system to said first mentioned load impedance.

4. A wave translating system, comprising a push-pull, multiplex carrier signaling wave amplifier having a load impedance of value that causes objectionable modulation produced in the amplifier to be less than if the load impedance had the value that the amplifier output impedance would have in the absence of feedback in the amplifier, and means for producing in the amplifier negative feedback that improves the push-pull balance of the amplifier and matches the amplifier output impedance to said first mentioned load impedance.

5. A wave translating system comprising an amplifying valve and a load therefor having an impedance that causes objectionable modulation produced in the system to be less than if the load impedance had the value that the output impedance of the valve would have in the absence of feedback, and means for producing in said system negative feedback that matches the output impedance of the valve to said first mentioned load impedance, said valve having electrode structure giving it transmission characteristics, with said feedback, approximately the same as those of a corresponding valve of the same power capacity without feedback.

6. A wave translating system comprising a vacuum tube amplifying device, means producing negative feedback in said device, and a load for said device, said device having its feedback, its load impedance and its amplification factor such that the amplification of said device is substantially the same and its ratio of output fundamental to output of modulation is at least substantially as great as if the feedback were absent and said device were replaced by one of the same type, but with lower amplification factor and with power capacity in the absence of feedback equal to the power capacity of the first mentioned device with its feedback.

7. A wave translating system comprising two negative feedback amplifiers, each having $\mu\beta$ of greater order of magnitude than unity, an incoming circuit, an outgoing circuit, and means connecting said amplifiers in push-pull relation between said incoming and outgoing circuits, said means comprising a pair of input circuits and a pair of output circuits for said amplifiers and means oppositely associating said input circuits with said incoming circuit and oppositely associating said output circuits with said outgoing circuit.

8. In combination, a negative feedback amplifier comprising a feedback path individual thereto rendering feedback therein negative, a second negative feedback amplifier comprising a feedback path individual thereto rendering feedback therein negative, and input and output circuits for said amplifiers, said amplifiers being symmetrically and oppositely disposed with respect to each of said circuits.

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