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H. S. BLACK

2,131,365

WAVE TRANSLATION SYSTEM

Original Filed March 29, 1933

FIG. 1

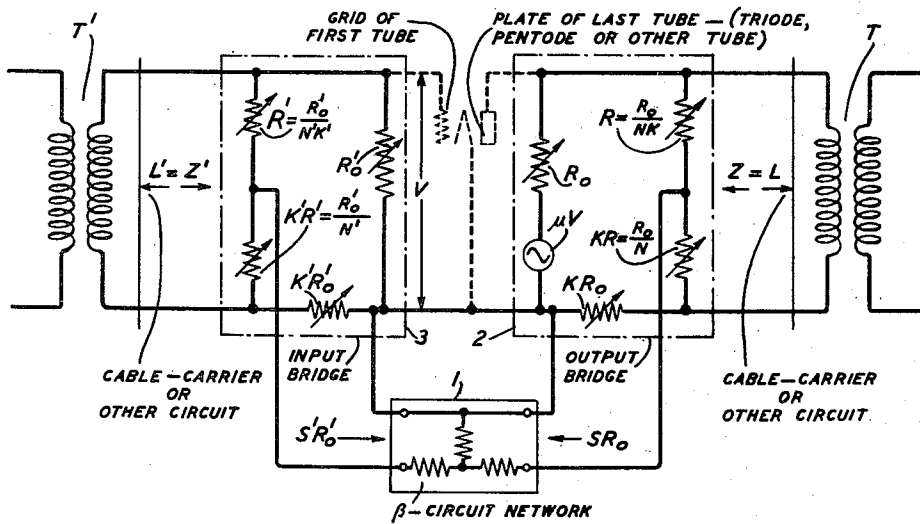


FIG. 2

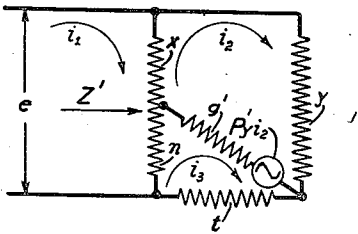
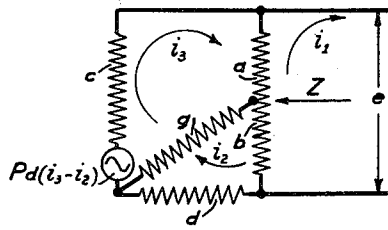


FIG. 3



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WAVE TRANSLATION SYSTEM

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Application March 29, 1933, Serial No. 663,317
Renewed February 19, 1936

43 Claims. (Cl. 179-171)

This application is a continuation in part of my copending application Serial No. 606,871, filed April 22, 1932, which issued as Patent 2,102,671, December 21, 1937, for Wave translation system.

5 This invention relates to wave translation systems, as for instance systems involving wave amplifying means.

An object of the invention is to control transmission properties of such systems, as for example to control impedance relations, modulation, wave reflection, cross-talk, resistance noise, transmission efficiency, gain frequency relations or singing tendencies involved in the systems.

10 A feature of the invention relates to effecting such control by feedback of waves in the system. If desired the feedback may be negative feedback or feedback that reduces amplification, such feedback increasing stability of operation and reducing distortion as pointed out in the above
20 mentioned copending application.

In accordance with a feature of the invention as applied for example to a feedback amplifier, the feedback changes the amplifier input or output impedance that faces the sending or receiving circuit, making the controlled impedance approach or match the impedance it faces. The feedback may be negative feedback, if desired.

30 In accordance with a feature of the invention as applied for example to a negative feedback vacuum tube amplifier, the negative feedback action (1) produces substantial change of the amplifier output impedance, making it approach any desired finite value independent of the value of the final stage plate-cathode impedance R_0 or (2) produces substantial change of the amplifier input impedance, making it approach any desired finite value, independent of the value of the initial stage grid-cathode impedance R_0' . The desired value for the controlled impedance
40 may be, for example, a value matching or approximating the value of the sending or receiving impedance that faces the controlled impedance.

45 The control of the input impedance and the control of the output impedance, referred to in connection with the above mentioned features, may be effected both at the same time, if desired.

50 In one specific aspect the invention is a negative feedback vacuum tube amplifier that has an output bridge so connecting the plate-cathode impedance R_0 in the tube (or tubes) of the final stage to the load or receiving impedance and to the feedback path that the feedback path would
55 be conjugate to the load if the bridge were bal-

anced, but that has the bridge unbalanced. The negative feedback tends to make the amplifier output impedance independent of the impedance value of the R_0 arm of the bridge, and changes the amplifier output impedance to render it less
5 different from the value it would have if the bridge were balanced by adjustment of R_0 . If desired the negative feedback is made large, so that its impedance stabilizing effect is powerful, which causes the amplifier output impedance to
10 approach or approximately equal the value it would have if the bridge were balanced by adjustment of R_0 , and renders it substantially independent of R_0 .

15 If desired, by making the impedance of one of the bridge arms other than the R_0 arm so differ from its value for balance as to properly unbalance the bridge, as for example by making the impedance of the arm adjacent the cathode structure sufficiently greater than its value for
20 balance, the feedback can be caused to increase the amplifier output impedance to a value high compared to the tube impedance R_0 ; so the tube can be worked into an impedance that is high compared to the tube impedance R_0 , and at the
25 same time, and without necessitating material power loss between the tube and the load, the amplifier output impedance and the load or receiving impedance can be matched, for example, by proper adjustment of the impedance ratio of
30 an amplifier output transformer, which, if used, may be regarded as included in the receiving circuit or load. When the tube is, for example, a triode or a coplanar grid tube, the increase of the impedance into which it works can reduce objectionable modulation produced by the amplifier.
35 The matching of the amplifier output impedance and the load impedance obviates reflection, and consequent objectionable cross-talk effects in the case, for example, of a cable carrier telephone
40 amplifier.

45 If desired, the unbalance of the bridge without feedback, required to make the feedback raise the amplifier output impedance and the impedance into which the tube works, can be effected
50 by making the bridge arm opposite the plate-cathode impedance in the tube or tubes of the last stage too low, or the arm adjacent the plate structure too high, for bridge balance without
55 feedback, instead of making the arm adjacent the cathode structure too high. This flexibility is of importance for instance in facilitating control of the loop phase shift (i. e. the phase shift produced in waves by their transmission once around

the closed feedback loop of the amplifier), for example to reduce singing tendency.

By varying the degree of unbalance of the bridge without feedback, flexibility is readily obtained in control of the relation between the amount of the change of amplifier output impedance produced by the feedback and the amount of negative feedback employed. This is of importance, for example, in facilitating control of the distortion reduction effected by the feedback, which increases with increase of the amount of negative feedback, and in facilitating control of singing tendency, which tendency, in general, increases with increase in the amount of negative feedback employed at frequencies in the utilized frequency range.

If desired, the feedback can be made to lower the output impedance of the amplifier instead of raise it, for instance by making the impedance of the bridge arm adjacent the cathode structure, or of the opposite arm, lower, instead of higher, than required to balance the bridge without feedback, or for instance by making the bridge arm opposite the space discharge arm higher than required for bridge balance without feedback; so the final stage tube can be worked into an impedance low compared to the tube impedance R_o , and at the same time the feedback action can be made to match the amplifier output impedance and the load impedance, for example, the impedance of the high impedance winding of a step-down amplifier output transformer. This may be desired for instance where the last stage employs the pentode type of tube, in order (without undue transmission loss) to match the amplifier output impedance and the load impedance and yet have the pentode work into an impedance much lower than its plate-cathode internal impedance R_o for the purpose of improving its operation, as for reducing objectionable modulation that it produces. Moreover, with the negative feedback lowering the amplifier output impedance and matching it to the load impedance as just described, in accordance with the invention, the impedance of the feedback path is made low compared to R_o , for example being matched to the output bridge impedance which it faces. As explained hereinafter, this can be done without necessitating undue loss in transmission from the final tube of the amplifier to the load, and having the impedance of the feedback path low facilitates design of transmission control networks that may be used in the feedback path and reduces singing tendency of the amplifier.

The negative feedback can be made to correct objectionable variation with frequency that, without feedback, might be produced in the amplifier output impedance by variation of the final stage plate-cathode impedance. For example, the feedback can be made to correct for the poor impedance which, without feedback, triodes and coplanar grid tubes present on their output side at high frequencies, such as the higher of the frequencies of a wide frequency range to be transmitted. This high frequency effect is mainly due to the coupling through the grid-plate capacitance which affects the output impedance of the tube. In this case, the output bridge can be designed as though the plate-cathode impedance were pure resistance, and then, because of the impedance stabilization effected by the negative feedback, the amplifier output impedance at high frequencies (and consequently the low side impedance presented at high frequencies by an output transformer, if such a transformer is used)

becomes much better with feedback than without, i. e. it approaches, over a wider band, more nearly an ideal sending impedance, which is a pure constant resistance. If desired, the feedback effecting this improvement can also change the amplifier output impedance throughout the utilized frequency range or match it to the load impedance, or both, as referred to above.

In one specific aspect the invention is a negative feedback vacuum tube amplifier, which may be of the type referred to above having the unbalanced output bridge, if desired, with an input bridge so connecting the grid-cathode impedance R_o' of the initial stage to the sending impedance and to the feedback path that the feedback path would be conjugate to the sending impedance if the input bridge were balanced, but with the input bridge unbalanced. The negative feedback tends to render the amplifier input impedance independent of the impedance value of the R_o' arm of the bridge, and changes the amplifier input impedance to render it less different from the value it would have if the bridge were balanced by adjustment of R_o' . If desired, the negative feedback is made large, so that its impedance stabilizing effect is powerful, which causes the amplifier input impedance to approach or approximately equal the value it would have if the bridge were balanced by adjustment of R_o' , and renders it substantially independent of R_o' .

The amplifier may be, for example, a cable carrier telephone amplifier with the noise in the output of the amplifier approaching that due to the resistance noise delivered to the initial grid, and with the negative feedback lowering the amplifier input impedance and the impedance attached to the R_o' arm of the bridge and matching the amplifier input impedance to the sending impedance in a manner which is somewhat analogous to the manner described above in which negative feedback lowers the amplifier output impedance and the impedance attached to the R_o arm of the output bridge and matches the amplifier output impedance to the receiving impedance, and which is referred to more in detail hereinafter. The matching of the input impedance to the sending impedance reduces wave reflection at the junction of those impedances, and consequent objectionable cross-talk; and, at the same time, since the feedback lowers the input impedance, the value that the input impedance would have without feedback can be chosen high compared to the sending impedance, to increase the ratio of signal to resistance noise in the amplifier output, as referred to more in detail hereinafter.

If desired, the feedback changing the amplifier input impedance or output impedance to match the sending impedance or the receiving impedance, respectively, can supplement or replace the impedance transforming action of an amplifier input transformer or output transformer, rendering such a transformer unnecessary for impedance transformation or giving flexibility as to choice of an impedance ratio correct for such transformer from the standpoint of impedance matching for example.

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

Fig. 1 shows schematically a vacuum tube amplifier circuit embodying a form of the invention; and

Figs. 2 and 3 are circuit diagrams facilitating explanation of the invention.

Certain expressions as used herein have the

following significance with reference to vacuum tube amplifiers. Amplification of an amplifier without feedback is the quantity by which the voltage on the grid of the first tube is multiplied 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 μ (and is a complex quantity). Amplification ratio is the absolute value of the amplification. Gain is 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 $\mu\beta \gg 1$ the amplification with feedback approaches

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

which is largely independent of the amplification or variations in amplification of the tubes, and consequently the amplifier gain is stabilized; and, as also pointed out therein, the negative feedback then reduces modulation produced by the amplifier in substantially the same proportion that it reduces the gain.

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 inter-network current.

The amplifier of Fig. 1 comprises one or more stages of vacuum tubes, as for example, three stages. It has a feedback path shown as a β -circuit network 1, has an output bridge 2 connecting the final stage to the feedback path 1 and the amplifier output transformer T, and has an input bridge 3 connecting the first stage to the amplifier input transformer T' and the feedback path.

The input and output transformers may connect the amplifier in a cable carrier telephone or other circuit, the amplifier then being used for example for simultaneously amplifying a plu-

ality of telephone messages, all transmitted together over the cable carrier circuit from multiplex carrier transmitting apparatus (not shown). Transformer T may be considered part of the receiving circuit or load. The load or receiving impedance is designated L. Transformer T' may be considered part of the sending circuit. The sending impedance is designated L'.

The amplifier may be of the general type of those shown for example in Figs. 5, 56 and 57 of the above mentioned copending application, which have a feedback path connected between output and input bridges. The feedback may be negative feedback, and $\mu\beta$ may be large; for example, $|\mu\beta|$ may be of the order of 50 or 100 in the utilized frequency range, as in the case of the negative feedback amplifier of the Fig. 57 just mentioned.

As indicated above, the feedback path may, if desired, contain a transmission control network 1. This β -circuit network, if used, corresponds to the transmission control network in the feedback path in the Fig. 5 just mentioned. For example, the network 1 may be an attenuation equalizing network (such, for instance, as the attenuation equalizing, β -circuit networks shown in the feedback path of the negative feedback amplifiers of Figs. 56 and 65 of the above mentioned copending application). As pointed out in that application, the equalizer network, when in the feedback path, contributes transmission characteristics to the overall amplifier circuit that are the inverse of those of the network, and so, by making the attenuation-frequency characteristic of the network similar to that of the cable or circuit to be equalized, the amplifier can be made to equalize transmission over the circuit in which it is connected.

When feedback takes place through an input bridge such as 3, the amplifier input impedance Z' is modified by the feedback only if the bridge is unbalanced. The magnitude and direction of the change in Z' then depend on the manner in which the bridge is unbalanced and upon the amount of feedback. Similar conditions hold with reference to the amplifier output impedance Z for unbalances in the output bridge. Formulae are derived below for Z' and Z for variations in each of the arms of the input and output bridges.

Equations will be developed for the impedances when any single arm of the bridges is varied. It can readily be seen that these can be made to cover any case of variation of any or all arms, for variation of any one arm can always be made to rebalance a bridge no matter what the other arms may be. The variation will be represented as a multiplier $(1+\Delta)$ applied to the original value. For example R_0 changes to $(1+\Delta)R_0=R_0+\Delta R_0$. The arms of the bridge and their impedances for a balanced condition of the bridge, are represented by R_0 , KR_0 , R and KR for the output bridge and by R_0' , $K'R_0'$, R' and $K'R'$ for the input bridge. It will result in some simplification if we represent R by

$$\frac{R_0}{NK}$$

and R' by

$$\frac{R_0'}{N'K'}$$

The impedance of the β network looking from the output bridge will be SR_0 and looking from the input bridge it will be $S'R_0'$. Any of the symbols R_0 , K , S , N , R_0' , K' , S' , N' and Δ may have any realizable value either real or complex. Z' and Z will be used to represent the amplifier input and

amplifier output impedances under the specified conditions and Z_0' and Z_0 will be used for the impedances in the reference condition of balanced bridges. That is, the condition of balanced bridges will be used as the reference condition and Z_0' and Z_0 will represent the input and output impedances respectively in the reference condition.

As indicated above, the symbol $\mu\beta$ will be used to represent the complex transmission ratio for a signal making one trip around the closed loop. The value of $\mu\beta$ that will be used in these formulae is the value of $\mu\beta$ that existed in the reference condition and not the value which may exist after a change is made in one of the bridge arms. For instance, if the input impedance is to be computed for a certain unbalance in the input bridge we need to know the value of $\mu\beta$ which would exist if the input bridge were balanced and the amplifier were otherwise the same. This is a more convenient value to use because it is independent of the impedance from which, or into which the amplifier is working.

resulting expression as much as possible.
For the balanced bridge

$$g' = S' R_0'$$

$$t = K' R_0'$$

$$n = \frac{R_0'}{N'} = K' R'$$

$$x = \frac{R_0'}{N' K'} = R'$$

$$y = R_0'$$

$$P' = \mu\beta \frac{N' K' + 1 + N' S' + N' K' S'}{N' K'}$$

and

$$Z_0' = \frac{R_0'(1+K')}{(1+N'K')}$$

and is independent of $\mu\beta$.

Variations in R_0' arm

If the R_0' arm changes to $R_0(1+\Delta)$ the impedance changes as shown

$$Z' = \frac{R_0'}{N' K'} \left[\frac{(1+K')(1-\mu\beta-\mu\beta\Delta)+\Delta+\frac{(K')^2\Delta}{K'S'+S'+K'+\frac{1}{N'}}}{\left(1+\frac{1}{N'K'}\right)(1-\mu\beta-\mu\beta\Delta)+\Delta-\frac{K'S'\Delta}{K'S'+S'+K'+\frac{1}{N'}}} \right]$$

$$Z' = R_0' \left[\frac{(1+K')(1-\mu\beta-\mu\beta\Delta)+\Delta+\frac{(K')^2 N' \Delta}{N' K' S' + N' S' + N' K' + 1}}{(1+N' K')(1-\mu\beta-\mu\beta\Delta)+N' K' \Delta - \frac{(N' K')^2 S' \Delta}{N' K' S' + N' S' + N' K' + 1}} \right]$$

$$Z' - Z_0' = \frac{R_0'}{1+N' K'} \left[\frac{\Delta}{(1+N' K')(1-\mu\beta-\mu\beta\Delta)+N' K' \Delta - \frac{(N' K')^2 S' \Delta}{N' K' S' + N' S' + N' K' + 1}} \right]$$

If $\mu\beta$ is very large

$$Z' \doteq Z_0' = \frac{R_0'(1+K')}{1+N' K'}$$

Variations in R' arm

If the R' arm changes from

$$\frac{R_0'}{N' K'} \text{ to } \frac{(1+\Delta)R_0'}{N' K'}$$

$$Z' = R_0' \left[\frac{(1+K'+\Delta)(1-\mu\beta)+\frac{K'\Delta}{N' K' S' + N' S' + N' K' + 1}}{(1+N' K')(1-\mu\beta)+\Delta - \frac{N' K' S' \Delta}{N' K' S' + N' S' + N' K' + 1}} \right]$$

$$Z' - Z_0' = \frac{N' K'}{1+N' K'} R_0' \left[\frac{\left(1-\mu\beta-\frac{\mu\beta}{N' K'}\right)\Delta}{(1+N' K')(1-\mu\beta)+\Delta - \frac{N' K' S' \Delta}{N' K' S' + N' S' + N' K' + 1}} \right]$$

The mesh equations are:

$$\begin{aligned} e &= i_1(n+x) - i_2x - i_3n \\ P'izy &= i_2(g'+x+y) - i_3g' - i_1x \\ P'izy &= i_2g' + i_1n - i_3(t+n+g') \end{aligned}$$

and the value of Z' desired is

$$Z' = \frac{e}{i_1}$$

Solving simultaneously we obtain the value of

$$Z' = \frac{(g'n + g'x + nx)(t+y) + (n+x)(1-P')yt}{(g'n + g'x + nx) + (g't + tx + g'y) + (t+n)(1-P')y}$$

To obtain the input impedance in any case it is only necessary to substitute for g' , t , n , x , y , and P' the corresponding values in terms of bridge arms and transmission ratio and simplify the

$$Z' - Z_0' \doteq \frac{R_0'\Delta}{1+N' K'}$$

Variations in $K'R_0'$ arm

using, in development of the impedance formula,

If the $K'R_0'$ arm changes to $K'R_0'(1+\Delta)$

$$Z' = R_0' \left[\frac{(1+K')(1-\mu\beta-\mu\beta\Delta) + K'\Delta + \frac{K'N'\Delta}{N'K'S' + N'S' + N'K' + 1}}{(1+N'K' + N'K'\Delta)(1-\mu\beta) - \frac{K'(N')^2S'\Delta}{N'K'S' + N'S' + N'K' + 1}} \right] \quad 5$$

$$Z' - Z_0' = \frac{R_0'}{1+N'K'} \left[\frac{(1+K')(1-\mu\beta)\Delta - \Delta}{(1+N'K' + N'K'\Delta)(1-\mu\beta) - \frac{K'(N')^2S'\Delta}{N'K'S' + N'S' + N'K' + 1}} \right] \quad 10$$

If $\mu\beta$ is very largelae, the value of $\mu\beta$ which existed in the balanced case.

$$Z' \approx \frac{R_0'(1+K')(1+\Delta)}{N'K' + 1 + N'K'\Delta} \quad 15$$

$$Z' - Z_0' \approx \frac{R_0'(1+K')\Delta}{(1+N'K')(1+N'K' + N'K'\Delta)} \quad 15$$

Variations in the $K'R'$ armIf the $K'K'$ arm changes from

$$\frac{R_0'}{N'} \text{ to } \frac{R_0'}{N'}(1+\Delta)$$

$$Z' = R_0' \left[\frac{(1+K' + K'\Delta)(1-\mu\beta) + \frac{\Delta}{N'K'S' + N'S' + N'K' + 1}}{(1+\Delta + N'K')(1-\mu\beta) - \frac{S'\Delta}{K'(N'K'S' + N'S' + N'K' + 1)}} \right] \quad 25$$

$$Z' - Z_0' = \frac{R_0'}{1+N'K'} \left[\frac{\left(N'(K')^2 - \frac{1}{N'K'} \right) (1-\mu\beta)\Delta + \Delta}{(1+\Delta + N'K')(1-\mu\beta) - \frac{S'\Delta}{K'(N'K'S' + N'S' + N'K' + 1)}} \right] \quad 30$$

If $\mu\beta$ is very large

Where for the balanced case

$$Z' \approx \frac{R_0'(1+K' + K'\Delta)}{1+N'K' + \Delta} \quad 35$$

$$Z' - Z_0' \approx \frac{R_0'\Delta \left(K' - \frac{1}{N'K'} \right) N'K'}{(1+\Delta + N'K')(1+N'K')} \quad 40$$

It will be noticed that feedback tends to make the input impedance independent of the value of the R_0' arm. Thus variations of this arm of the bridge have very little effect on the amplifier input impedance. Variations in the other arms do produce an effect and the value of amplifier input impedance approached with large feedback (i. e., with $|\mu\beta|$ large) is the value which

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$$Z = R_0 \left[\frac{(1+K)(1-\mu\beta) + \Delta + \frac{K^2N\Delta}{NKS + NS + 1 + NK}}{(1+NK)(1-\mu\beta) + NK\Delta - \frac{N^2K^2S\Delta}{NKS + NS + 1 + NK}} \right] \quad 50$$

$$Z - Z_0 = \frac{R_0}{1+NK} \left[\frac{\Delta}{(1+NK)(1-\mu\beta) + NK\Delta - \frac{N^2K^2S\Delta}{NKS + NS + 1 + NK}} \right] \quad 55$$

would exist if the bridge were rebalanced by a corresponding variation in the R_0' arm.

It will also be noticed that the value of the input impedance is not dependent upon the impedance from which the amplifier works. The value of $\mu\beta$ actually existing is however dependent upon this impedance in any case of imperfect bridge balance and hence the desirability of

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Output bridge

To find the output bridge impedance (or amplifier output impedance) a similar five element network, with its elements having the designations shown in Fig. 3, is considered as follows:

$$Z = \frac{(a+b)(cg+cd+dg-Pdg) + ab(d+c)}{(cg+cd+dg-Pdg) + a(d+g+b) + b(c+g-Pg)} \quad 20$$

$$a = R = \frac{R_0}{NK} \quad 35$$

$$b = KR = \frac{R_0}{N} \quad 35$$

$$c = R_0 \quad 40$$

$$d = KR_0 \quad 40$$

$$g = SR_0 \quad 40$$

$$P = \mu\beta \frac{(NK+1+NS+NKS)}{NKS} \quad 45$$

$$Z_0 = \frac{R_0(1+K)}{(1+NK)} \quad 45$$

Variations in R_0 armIf the R_0 arm changes to $R_0(1+\Delta)$

$$Z = R_0 \left[\frac{(1+K)(1-\mu\beta) + \Delta + \frac{K^2N\Delta}{NKS + NS + 1 + NK}}{(1+NK)(1-\mu\beta) + NK\Delta - \frac{N^2K^2S\Delta}{NKS + NS + 1 + NK}} \right] \quad 50$$

$$Z - Z_0 = \frac{R_0}{1+NK} \left[\frac{\Delta}{(1+NK)(1-\mu\beta) + NK\Delta - \frac{N^2K^2S\Delta}{NKS + NS + 1 + NK}} \right] \quad 55$$

If $\mu\beta$ is large

$$Z \approx Z_0 = \frac{R_0(1+K)}{1+NK} \quad 60$$

Variations in the R armIf the R arm of the bridge changes from

$$\frac{R_0}{NK} \text{ to } \frac{R_0}{NK}(1+\Delta) \quad 65$$

$$Z = R_0 \left[\frac{(1+K+\Delta)(1-\mu\beta) + \frac{K\Delta}{NKS + NS + 1 + NK}}{(1+NK)(1-\mu\beta) + \Delta - \frac{N^2K^2S\Delta}{NKS + NS + 1 + NK}} \right] \quad 70$$

$$Z - Z_0 = \frac{R_0NK}{1+NK} \left[\frac{\left(1-\mu\beta - \frac{\mu\beta}{NK} \right) \Delta}{(1+NK)(1-\mu\beta) + \Delta - \frac{N^2K^2S\Delta}{NKS + NS + 1 + NK}} \right] \quad 75$$

If $\mu\beta$ is large

$$Z \approx \frac{R_o(1+K+\Delta)}{1+NK}$$

$$Z - Z_o \approx \frac{R_o\Delta}{1+NK}$$

the value of $\mu\beta$ effective in determining the input impedance depends on the load worked into and similarly the value of $\mu\beta$ effective in determining the output impedance depends on the impedance from which the amplifier works. Unless the bridges are very much unbalanced the effect will not be nearly so prominent.

As noted above, the value for change in output impedance due to variation in the R_o arm is

$$Z - Z_o = \frac{R_o}{1+NK} \left[\frac{\Delta}{(1+NK)(1-\mu\beta) + NK\Delta - \frac{NK^2S\Delta}{NKS+NS+1+NK}} \right]$$

Variations in KR_o arm

If the KR_o arm changes to $KR_o(1+\Delta)$

$$Z = R_o \left[\frac{(1+K)(1-\mu\beta-\mu\beta\Delta) + K\Delta + \frac{NK\Delta}{NKS+NS+1+NK}}{(1+NK+NK\Delta)(1-\mu\beta) - \frac{KN^2S\Delta}{NKS+NS+1+NK}} \right]$$

$$Z - Z_o = \frac{R_o}{1+NK} \left[\frac{(1+K)(1-\mu\beta)\Delta - \Delta}{(1+NK+NK\Delta)(1-\mu\beta) - \frac{KN^2S\Delta}{NKS+NS+1+NK}} \right]$$

If $\mu\beta$ is large

$$Z \approx \frac{R_o(1+K)(1+\Delta)}{1+NK+NK\Delta}$$

$$Z - Z_o \approx \frac{R_o(1+K)\Delta}{(1+NK)(1+NK+NK\Delta)}$$

From this equation it can be seen that if NK is small

$$Z - Z_o \approx \frac{\Delta R_o}{1-\mu\beta}$$

Thus, for large values of feedback, where the quantity $\mu\beta$ is large, the change in output impedance due to ΔR_o may become negligible, as noted above.

In accordance with the invention, this feature can be used to correct the output impedance

Variations in KR arm

If the KR arm changes from

$$\frac{R_o}{N} \text{ to } \frac{R_o}{N}(1+\Delta)$$

$$Z = R_o \left[\frac{(1+K+K\Delta)(1-\mu\beta) + \frac{\Delta}{NKS+NS+1+NK}}{(1+NK+\Delta)(1-\mu\beta) - \frac{\Delta}{K(NKS+NS+1+NK)}} \right]$$

$$Z - Z_o = \frac{R_o}{1+NK} \left[\frac{(NK^2-1)(1-\mu\beta)\Delta + \Delta}{(1+NK+\Delta)(1-\mu\beta) - \frac{S\Delta}{K(NKS+NS+1+NK)}} \right]$$

If $\mu\beta$ is large

$$Z \approx \frac{R_o(1+K+K\Delta)}{1+NK+\Delta}$$

$$Z - Z_o \approx \frac{R_o\Delta(NK^2-1)}{(1+NK)(1+NK+\Delta)}$$

when a tube is used which, in the absence of feedback, does not cause the amplifier output impedance to match the impedance of the output transformer. The procedure is to design the output bridge as if the tube had a value of R_o that, without feedback, would produce the match; for then, with large values of feedback, the feedback action will substantially produce the match, since the change in amplifier output impedance produced by ΔR_o will approximate ΔR_o divided by $(1-\mu\beta)$.

One illustration of practical application of this feature occurs where the output tube of a circuit such for example as that of Fig. 1 is a pentode and it is desired to work the pentode into $\frac{1}{2}$ its output impedance, as is customary for pentodes. To do this, an output transformer is used having a high side impedance of approximately $\frac{1}{2}$ the tube impedance, (assuming the case in which K and NK are small as is usually desirable for avoiding undue loss in transmission to the load, i. e., KR_o is small and R large compared to L and consequently the impedance into which the tube works is not materially different from the load impedance L or high side impedance of the transformer). Under these conditions, and with the bridge balanced, the low side impedance is about five times as great as is necessary for impedance matching. Corrective networks for improving this condition ordinarily would introduce excessive transmission loss. However, in accordance with this invention, the condition can be cor-

The equation for the input impedance when the R_o arm varies is very similar to that of the output impedance when the R_o arm varies. In the case of the other three arms the corresponding equations take exactly the same form for the input and the output impedances.

The output impedance is practically independent of the value of the R_o arm for large values of feedback (i. e., with $|\mu\beta|$ so large that unity can be neglected in comparison to $|\mu\beta|$) and is entirely independent of the impedance of the load into which the amplifier works. Variations in the other arms do produce an effect, and the value of amplifier output impedance approached with large feedback is the value which would exist if the bridge were rebalanced by varying the R_o arm.

If both bridges have some unbalance, then (especially if the feedback path contains no network such as (1) the input impedance Z' will depend to some extent upon the load impedance and the output impedance will depend to an extent upon the impedance from which the amplifier works. This is similar to the case of amplifiers having no conjugacy of the feedback path and line impedances. The reason for this is that

rected without such networks or loss; for by reducing KR_0 to $\frac{1}{2}$ the value required to balance the bridge, the low side impedance is corrected although the tube still works into $\frac{1}{2}$ its output impedance.

In cases for instance where it is desired to maintain a close match between the load impedance and the amplifier output impedance and at the same time, for example, obtain the advantages of a pentode, the invention has the further advantage that the impedance out of which the β -circuit works can be materially reduced over the value that it would have without the invention, assuming that in the two cases the transmission loss from the plate circuit generator to the load and into the β -circuit is unaltered.

The ability to reduce this impedance without changing the β -circuit loss very often facilitates the design of β -circuit networks.

For instance, the feedback path may contain an attenuation equalizing or other transmission control network as described above; and then decreasing the impedance that SR_0 faces will permit reduction of SR_0 for a given transmission loss from the last plate generator through the β -circuit. This facilitates reduction of the inductances and increase in the capacitances of the network. This diminishes the difficulties due to inherent capacities of induction coils and to inherent wiring capacitance appreciable in comparison with the capacities of associated condensers. Moreover, reducing SR_0 is important as reducing singing tendency of the amplifier caused by the capacities-to-ground of the network condensers and coils acting as capacities across the feedback path, the effect of these shunting capacities in producing the singing tendency being greater the higher the value of SR_0 .

Another practical application is found in correcting for the poor impedance which three element and coplanar grid tubes present at higher frequencies. As indicated above, this high frequency effect is mainly due to coupling through the grid plate capacitance which affects the output impedance of the tube. The tube may be, for example a triode or coplanar grid tube in the last stage of an amplifier such as that of Fig. 1. In this case the bridge 2 is designed as if the output impedance R_0 of the tube were a perfect resistance, the result being that, at high frequencies the low side impedance presented by the output transformer is much better with feedback than without.

Another application pointed out by way of example occurs where, for instance in a vacuum tube amplifier such as that of Fig. 1 with the last stage using a triode or coplanar grid tube, objectionable modulation voltages generated in the last tube are made small by making the receiving impedance L large compared to R_0 , and the bridge is unbalanced, for instance by increasing KR_0 , to make the negative feedback raise the output impedance Z to a value approaching or matching the large receiving impedance L . Matching the impedances and making the modulation small may be desired for example in order to reduce objectionable cross-talk effects, for instance where the amplifier amplifies simultaneously a plurality of carrier telephone messages transmitted over a multiplex cable carrier or other circuit in which the amplifier is connected.

From these illustrative applications it is clear that important advantages can be obtained by purposely unbalancing the output bridge 2.

For example, as just indicated, by having KR_0

properly depart from the value for balance, a triode or other suitable tube can be worked into an impedance high compared to its own impedance R_0 to reduce modulation and at the same time, and without undue transmission loss, the impedance that presents itself by the secondary side of the output transformer to the connecting cable or circuit can be made any specified value, frequently a matched impedance being sought. Likewise, as just indicated, by having KR_0 properly depart from its value for balance, a tube such as a pentode can be worked into an impedance very low compared to its own impedance R_0 and a similar result obtained. Further, where it is desired to use a transformer whose ratio, however, on the basis of a balanced bridge, would be wrong, the impedance relations can be corrected by unbalancing the bridge 2, for example by having KR_0 properly depart from the balance value.

Like results can also be obtained by properly unbalancing the R or KR arms of bridge 2, and as indicated above, an advantage is that the same desired impedance correction will be obtained irrespective of the arm manipulated whereas the effect of unbalancing the bridge 2 upon the phase shift around the β -path might be harmful if one of these arms KR_0 , KR and R is varied although it can be made beneficial, for instance by reducing singing tendency of the amplifier, if another of these three arms is varied instead.

These applications of unbalancing the output bridge illustrate an important feature of the invention that, where the output impedance without feedback as presented by an amplifier is desirable for important transmission reasons, but is wrong for impedance reasons (for example, impedance matching), then by feedback the latter aspect is corrected, and, if desired, without appreciably affecting the former.

The input bridge 3 has properties similar to those of the output bridge 2, and in accordance with the invention advantage is taken of the effects of unbalance of the input bridge, as in the case of the output bridge.

To illustrate, in cable carrier and at the higher frequencies the cable noise approaches thermal agitation, and if the voltage step-up of the input transformer T' is made sufficiently high to cause the resistance noise and the signal to override the noise introduced by the tubes, for example, of the amplifier, then the noise at the output of the amplifier will tend to approach this thermal noise at the input magnified by the gain of the amplifier. This is the case for matched sending and input impedances, i. e. for $L' = Z'$. As indicated for example by United States patent to H. W. Dudley, No. 1,836,841, dated December 15, 1931, if the input impedance is high, instead of a match for the attached sending impedance, the amplifier gain goes up 6 decibels but the thermal noise at the output will be increased only 3 decibels, so there is a net improvement in signal to-noise ratio of 3 decibels. It is also to be noted that, for all configurations of negative feedback amplifiers, the thermal noise at the output is reduced by the amount of feedback or in other words is, as without feedback, the noise at the input amplified by the gain of the amplifier.

Consequently, in accordance with the invention the impedance Z' is made high without feedback; and then, because one of the four arms of the input bridge 3 is adjusted to properly unbalance the bridge, with feedback the impedance Z' matches the impedance L' of the input con-

necting circuit. Curiously enough, while the impedance is thus matched as with a balanced bridge having its arms of proper impedance values, the signal-to-noise ratio at the output is improved 3 decibels. A decibel obtained in this way is as highly useful as a decibel increase in level.

What is claimed is:

1. A wave translating system, a circuit associated therewith and a path producing negative feedback therein in the utilized frequency range, said system comprising means connected between said circuit and said path and causing said path to approach but not attain conjugacy with respect to said circuit, the departure from conjugacy being adjusted to control the impedance of said system facing said circuit.

2. A wave translating system, means supplying waves thereto and a path producing negative feedback therein, said system comprising a network connected between said means and said path and causing said path to approach but not attain conjugacy with respect to said means, the departure from conjugacy being adjusted to control the impedance of said system facing said means.

3. A wave amplifying system having an input and an output, a wave source having impedance coupled to said input, and a path feeding back waves from said output to said input to control the operation of said system, said system comprising a bridge network connected between said source and said path and causing said path to approach but not attain conjugacy with respect to said source and including said input in one of its ratio arms, the departure from conjugacy being adjusted to control the input impedance of said system facing said source.

4. A wave translating system, a load therefor and a path producing negative feedback therein, said system comprising means connected between said load and said path and causing said path to approach but not attain conjugacy with respect to said load at a utilized frequency, the departure from conjugacy being adjusted to control the impedance facing said load.

5. A wave amplifying system having an input and an output, a load having impedance coupled to said output, and a path feeding back waves from said output to said input to control the operation of said system, said system comprising a bridge network connected between said load and said path and causing said path to approach but not attain conjugacy with respect to said load and including said output in one of its ratio arms, the departure from conjugacy being adjusted to control the output impedance of said system facing said load.

6. A wave translating system comprising a wave amplifier with a sending circuit supplying waves thereto and a receiving circuit receiving waves therefrom, and with means producing in said amplifier feedback that causes substantial change in its input impedance, the impedance of said sending circuit substantially matching the changed input impedance of the amplifier.

7. A wave translating system comprising a wave amplifier with a sending circuit supplying waves thereto and a receiving circuit receiving waves therefrom and with means producing in said amplifier feedback that causes substantial change in its output impedance, the impedance of said receiving circuit substantially matching the changed output impedance of the amplifier.

8. A wave translating system comprising wave translating means, means producing negative feedback in said translating means, and a circuit connected to said translating means and having an impedance of value that is nearer to the value of the impedance which it faces in said translating means than would be the case in the absence of the feedback in the translating means.

9. A wave translating system comprising wave amplifying means with its input impedance substantially changed by negative feedback, and a circuit connected to said input impedance and having impedance substantially matching said changed input impedance.

10. A wave translating system comprising wave amplifying means with its output impedance substantially changed by negative feedback, and a circuit connected to said output impedance and having impedance substantially matching said changed output impedance.

11. The method of operating a wave translator and its associated sending impedance which comprises producing substantial change in the translator input impedance by negative feedback of waves in the translator, and matching the associated sending impedance to the changed input impedance.

12. The method of operating a wave translator and its associated receiving impedance which comprises producing substantial change in the translator output impedance by negative feedback of waves in the translator, and matching the associated receiving impedance to the changed output impedance.

13. A wave translating system comprising a source of waves, a vacuum tube amplifier having a grid connected to said source for amplifying said waves, and means producing negative feedback to said grid of waves from said source amplified by said amplifier, the impedance of said source matching the amplifier input impedance that it faces.

14. A wave translating system comprising an amplifier, a wave source attached to the input impedance of said amplifier, and means for substantially reducing the amplifier input impedance and the difference between that impedance and the attached impedance of said source, said means comprising means producing negative feedback in said amplifier.

15. A wave translating system comprising an amplifier, a multiplex carrier telephone circuit attached to the input impedance of said amplifier and so shielded from extraneous noise that its resistance noise is the principal noise it delivers to said amplifier, said amplifier comprising means so amplifying waves from said circuit that the principal noise in the amplifier output is said resistance noise amplified, and means for substantially reducing the amplifier input impedance and the difference between that impedance and the attached impedance of said circuit, whereby for a given approach to matching of the amplifier input impedance and the attached impedance of said circuit, in the amplifier output the ratio of signal to resistance noise is increased, said last means comprising means producing negative feedback in said amplifier.

16. A wave amplifying 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 system would have in the absence 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.

17. A wave translating system comprising a 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 increases the output impedance of the amplifier and matches it to said first mentioned load impedance.

18. A wave translating system comprising an amplifier having a pentode valve in its last stage, 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.

19. An amplifier comprising an amplifying element, a feedback path for producing negative feedback in the amplifier for stabilizing operation of the amplifier and reducing modulation in the amplifier, a load attached to the amplifier, and an amplifier output bridge having said feedback path and said load in its diagonals, respectively, and having the output of said amplifying element in one of its balancing arms, said bridge being unbalanced, for controlling transmission properties of the amplifier.

20. An amplifier comprising an amplifying element, a feedback path for producing negative feedback in the amplifier for stabilizing operation of the amplifier and reducing modulation in the amplifier, a sending impedance attached to the input impedance of the amplifier, and an amplifier input bridge having said feedback path and said sending impedance in its diagonals, respectively, and having the input of said amplifying element in one of its balancing arms, said bridge being unbalanced, for controlling transmission properties of the amplifier.

21. An amplifier comprising an amplifying element, a feedback path for producing negative feedback in the amplifier for stabilizing operation of the amplifier and reducing modulation in the amplifier, a load attached to the amplifier, and an amplifier output bridge having said feedback path and said load in its diagonals, respectively, and having the output of said amplifying element in one of its balancing arms, said bridge being so unbalanced that if said one arm had the value required to balance the bridge the amplifier output impedance without feedback would match the load impedance facing the amplifier output impedance.

22. An amplifier comprising an amplifying element, a feedback path for producing negative feedback in the amplifier for stabilizing operation of the amplifier and reducing modulation in the amplifier, a sending impedance attached to the input impedance of the amplifier, and an amplifier input bridge having said feedback path and said sending impedance in its diagonals, respectively, and having the input of said amplifying element in one of its balancing arms, said bridge being so unbalanced that if said one arm had the value required to balance the bridge the amplifier input impedance without feedback would match the sending impedance facing the amplifier input impedance.

23. An amplifier comprising an amplifying element, a feedback path for producing negative feedback in the amplifier for stabilizing operation of the amplifier and reducing modulation in the amplifier, a load attached to the amplifier, and an amplifier output bridge having said feedback path and said load in its diagonals, respectively, and having the output of said amplifying element in one of the balancing arms of the bridge, one of the remaining balancing arms so departing from the balancing value that a prescribed value of amplifier output impedance is obtained which is substantially different from the value that would be obtained without feedback, and which approaches the value that would be obtained without feedback if the bridge were balanced by adjusting the first mentioned balancing arm.

24. An amplifier comprising an amplifying element, a feedback path for producing negative feedback in the amplifier for stabilizing operation of the amplifier and reducing modulation in the amplifier, a load attached to the amplifier, and an amplifier output bridge having said feedback path and said load in its diagonals, respectively, and having the output of said amplifying element in one of the balancing arms of the bridge, the opposite balancing arm so departing from the balancing value that a prescribed value of amplifier output impedance is obtained which is substantially different from the value that would be obtained without feedback, and which approaches the value that would be obtained without feedback if the bridge were balanced by adjusting the first mentioned balancing arm.

25. An amplifier comprising an amplifying element, a feedback path for producing negative feedback in the amplifier for stabilizing operation of the amplifier and reducing modulation in the amplifier, a load attached to the amplifier, and an amplifier output bridge having said feedback path and said load in its diagonals, respectively, and having the output of said amplifying element in one of the balancing arms of the bridge, an adjacent balancing arm so departing from the balancing value that a prescribed value of amplifier output impedance is obtained which is substantially different from the value that would be obtained without feedback, and which approaches the value that would be obtained without feedback if the bridge were balanced by adjusting the first mentioned balancing arm.

26. An amplifier comprising an amplifying element, a feedback path for producing negative feedback in the amplifier for stabilizing operation of the amplifier and reducing modulation in the amplifier, a load attached to the amplifier, and an amplifier output bridge having said feedback path and said load in its diagonals, respectively, and having the output of said amplifying element in one of the balancing arms of the bridge, the remaining balancing arms of the bridge having values such that the output impedance of the amplifying element, the output impedance of the amplifier and the load impedance each has approximately the same prescribed value, this prescribed value substantially differing from the value of amplifier output impedance that would be obtained without feedback and approaching the value of amplifier output impedance that would be obtained without feedback if the bridge were balanced by adjusting the first mentioned balancing arm.

27. A wave translating system comprising an

amplifier, a load therefor, and means for lowering the value of the amplifier output impedance and making it nearer the value of the load impedance, said means comprising a feedback path for the amplifier containing a transmission control network.

28. In combination, a wave translating system, a circuit associated therewith, and means producing in said system two components of negative feedback whose effects upon the magnitude of the impedance of said system facing said circuit are each substantial and are opposite in sense and substantially different in amount, whereby the relation between said impedance and the resultant amount of feedback may be controlled.

29. The method of operating a signal wave translating device which comprises reducing wave reflection at the input of said device without reducing the ratio of signal to resistance noise in the output of the device.

30. A signal wave translating device having input impedance high compared to its attached sending impedance, and means for feeding back in said device waves that reduce reflection at the junction of said impedances without reducing the ratio of signal to resistance noise in the output of the device.

31. A wave translating system comprising an amplifier, a circuit attached to the input impedance of said amplifier, and means for substantially reducing the amplifier input impedance and the difference between that impedance and the attached impedance of said circuit, whereby for a given approach to matching of the amplifier input impedance and the attached impedance of said circuit, in the amplifier output the ratio of signal to resistance noise is increased, said last means comprising means producing negative feed-back in said amplifier.

32. A wave translating circuit having its input impedance high compared to the sending impedance which faces the input impedance, and means feeding back in said circuit waves that reduce reflection at the junction of those impedances.

33. A wave translating system having its input impedance substantially different from the sending impedance which faces the input impedance, and means for reducing said difference, said means comprising a circuit for feeding waves back in said system in gain-reducing phase and with amplitude sufficient to produce substantial alteration of said input impedance.

34. A bridge network comprising an amplifying device, a feedback path for producing negative feedback in said device, a circuit for connection to said device, and interconnecting means for connecting said device to said circuit and to said feedback path, said interconnecting means including an impedance element for imperfectly balancing the impedance of said device in said bridge network in the absence of said feedback, the impedance without feedback viewed from said circuit in the direction of said interconnecting means being dependent upon the impedance of said path viewed from said interconnecting means, and said feedback reducing the effect of changes of said second mentioned impedance upon said first mentioned impedance.

35. A wave translating system comprising an amplifying device, a feedback path for producing negative feedback in said device in the used frequency range, a circuit for connection to said device, and a bridge network connecting said

device to said circuit and to said path, said bridge network being unbalanced in the absence of said feedback, and the voltage amplification ratio for propagation once around the feedback loop having a value of a higher order of magnitude than unity.

36. A wave translating system comprising an amplifying device, an incoming circuit for connection thereto, and means for feeding back in said device a portion of its output waves in the used frequency range in gain-reducing phase, said means comprising a feedback path and a bridge network interconnecting said amplifying device, said feedback path and said incoming circuit, said bridge network being unbalanced in the absence of feedback through said feedback path, and the feedback through said feedback path tending to balance said bridge network.

37. A thermionic valve amplifier having an output stage which comprises a thermionic valve of the pentode type, wherein there is provided a negative feedback circuit which is connected and arranged to feed back from the output circuit of said stage to the input circuit thereof a voltage dependent upon the voltage set up across the load impedance and reducing the amplifier output impedance below its value with zero feedback from said output circuit to said input circuit.

38. A thermionic valve amplifier having an output stage comprising a thermionic valve of the pentode type, wherein there is provided a negative feedback circuit which is connected and arranged to feed back from the output circuit of said stage to the input circuit thereof a voltage dependent both upon the voltage set up across the load and upon the current in the load, and wherein the arrangement is such that, if it were used with a load which, by virtue of the feedback, were matched, the magnitude of the feedback voltage would be dependent more upon the voltage set up across the load than upon the current in the load.

39. A thermionic valve amplifier having an output stage comprising a thermionic valve of the triode type, wherein there is provided a negative feedback circuit which is connected and arranged to feed back from the output circuit of said stage to the input circuit thereof a voltage dependent both upon the voltage set up across the load and upon the current in the load, and wherein the arrangement is such that, if it were used with a load which, by virtue of the feedback, were matched, the magnitude of the feedback voltage would be dependent more upon the current in the load than upon the voltage set up across the load.

40. A thermionic valve amplifier, which comprises in its output stage a valve of the pentode type which is required to feed power to a substantially matched load of substantially constant resistive value, wherein there is provided a negative feedback circuit for producing negative feedback dependent in magnitude more upon the voltage across the load than upon the current in the load.

41. A thermionic valve amplifier according to claim 40, wherein the modified anode impedance of said valve is matched to the load impedance by means of one or more transformers of suitable ratios.

42. A wave translating system comprising a pentode space discharge device having an input circuit and an output circuit, a load circuit connected to said output circuit and a path feeding back waves in the frequency range of the waves to be translated and of magnitude dependent on

the voltage across said load circuit from said output circuit to said input circuit in such phase and magnitude as to reduce the gain of the system and lower the output impedance of said device 5 below its value with zero feedback from said output circuit to said input circuit.

43. A wave translating system comprising a pentode space discharge device having an input circuit and an output transformer, an impedance 10 through which the alternating plate current of said device flows connected in series with said output transformer, means deriving waves from said impedance and feeding them back to said

input circuit in such phase and magnitude as to produce negative feedback that tends to raise the output impedance of said device and reduces distortion that would arise in said device in the absence of feedback in said device, and means 5 producing negative feedback in said device dependent in magnitude upon voltage across said transformer and having greater effect than said first-mentioned feedback on the output impedance of said device. 10

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