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H. S. BLACK

2,033,917

ELECTRIC WAVE AMPLIFYING SYSTEM

Filed Oct. 6, 1934

FIG. 1

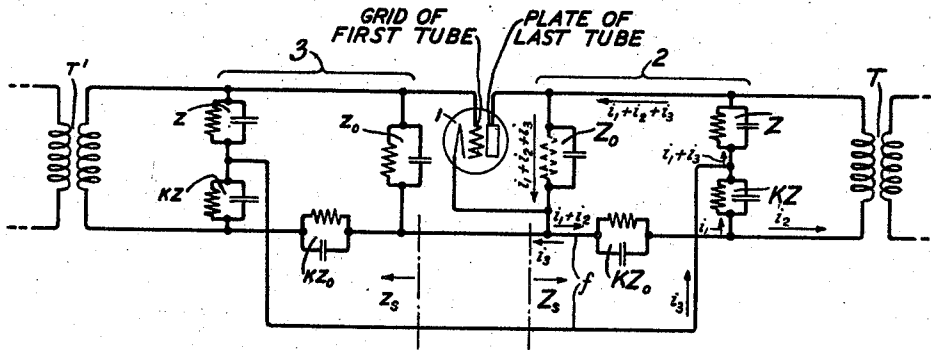
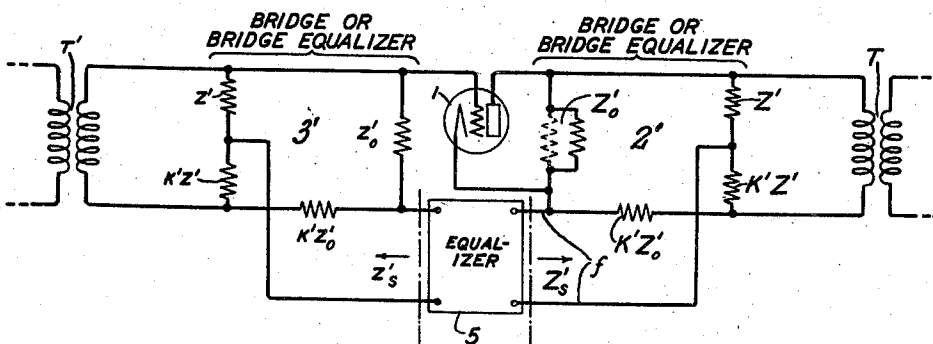


FIG. 2



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ELECTRIC WAVE AMPLIFYING SYSTEM

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Application October 6, 1934, Serial No. 747,117

10 Claims. (Cl. 178—44)

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 and especially to retroaction or feed-back in wave translating systems, as for example, in electric wave amplifying systems.

An object of the invention is to control feed-back in such systems.

It is also an object of the invention to control the phase of waves fed back in such systems.

A further object is to reduce singing tendency in such systems, as for example, to so control the phase of waves fed back as to reduce singing tendency in amplifiers that feed-back modulation or distortion components for reducing distortion or feed-back fundamental components for increasing stability, or both. Such amplifiers are disclosed, for example, in the above mentioned copending application and in my article on Stabilized feed-back amplifiers, published in Electrical Engineering, January, 1934, pages 114-120, and in the January, 1934 issue of The Bell System Technical Journal, pages 1-18.

In one specific aspect the invention is embodied in vacuum tube amplifiers of the general type in which waves, including those of the range of transmitted frequencies, are so fed back from the output to the input as to reduce the gain of the amplifier below the value it would have without feed-back in order to reduce unwanted modulation or non-linear effects and render the gain stability greater than it would be without feed-back. That type of amplifier is disclosed, for example, in the above mentioned published article and copending application.

In such amplifiers, where tube modulation reduction for modulation components of given frequencies is to be large, it is proportional to the gain (for those modulation components) in a single trip around the closed feed-back loop and consequently that gain should be large. The modulation components that it is desired to reduce by feed-back are usually waves of frequencies within the utilized frequency range, e. g. within the frequency range of the signal waves to be amplified by the amplifier. In practice, when the loop gain (i. e. the decibel gain for a single trip around the loop) is large for the frequencies of the utilized frequency range, it is greater than zero for some higher frequency, and if the loop phase shift (i. e. the phase shift experienced by waves in passing once around the loop) is zero or a multiple of 360 degrees for any frequency at which the loop gain equals or exceeds zero decibels, the amplifier may sing at that frequency. (As indicated in the above mentioned copending application, a criterion for freedom from singing is given by Nyquist's rule, in his article on Regeneration theory, published

in the January, 1932 issue of The Bell System Technical Journal, pages 126-147. Such criterion is also given in Nyquist Patent 1,915,440, June 27, 1933.) To avoid the singing condition, it is desirable to control the loop phase shift carefully with respect to the entire frequency range of loop gain. Phase shift produced by fortuitous capacities associated with the wiring and networks of the feed-back circuit (i. e. the portion of the system through which waves are fed from the output to the input of the amplifier), of the nature of shunt capacity phase shift, may produce troublesome singing tendency in the amplifier. In accordance with the invention, this difficulty is overcome by constructing this portion of the system with relatively large nominal (i. e. intended or prescribed) shunt capacity yet at the same time making its nominal phase shift suitable for avoiding singing (nominal referring to values that fail to take into account certain quantities which may actually be involved, as for example, inherent or fortuitous capacities or the unknown portions of such capacities). Then the effect of small additional inherent or extraneous fortuitous capacity in making the actual phase differ from the nominal phase shift, and consequently the effect of such fortuitous capacity upon the singing tendency will be unimportant.

For example, in its specific aspect mentioned above, the invention is a negative feed-back amplifier with an input bridge network and an output bridge network, respectively rendering the incoming and the outgoing circuits conjugate to the feed-back path (i. e. to the portion of the feed-back circuit extending from the network formed by the balancing arms of the output bridge to the network formed by the balancing arms of the input bridge) over the utilized frequency range in the general manner disclosed in my above mentioned published article and copending application, but with each balancing arm of the bridges including a capacity connected across the terminals of the arm. With these capacities, the balancing arms can be given nominal impedances that give as the nominal phase shift in transmission through the feed back circuit (i. e. the circuit from the amplifier output through the output bridge, the feed-back path and the input bridge to the amplifier input) the value zero for a frequency at which the amplifier would have a troublesome tendency to sing around the feed-back loop if the capacities were not used in constructing the feed-back circuit for nominal zero phase shift. This frequency may be, for example, a very high frequency, well above the utilized frequency range. The capacities can take into account, i. e. include, known inherent or extraneous capacities appearing across the balancing arms, or can be large in

comparison to those fortuitous capacities or any unknown or other portions thereof not taken into account, so as to greatly reduce the effects of those fortuitous capacities on the actual high frequency phase shift of the feed-back circuit and consequently on singing. Moreover, the shunt capacities included in the balancing arms reduce also the effects that fortuitous capacities in the bridge diagonals produce on this high frequency phase shift and consequently on singing tendency.

A transmission equalizer may be connected to the feed-back path in the common diagonal of the bridges, in the general manner disclosed in my above mentioned copending application or British Patent 371,887.

Either or each of the bridges may be made a transmission equalizer, of the constant impedance type if desired, in the general manner disclosed in A. L. Stillwell Patent 1,993,758, March 12, 1935, for Wave translation systems; and a supplementary equalizer may be connected in the feed-back path in the general manner disclosed in my above mentioned copending application or my Patent 1,956,547, May 1, 1934.

As indicated above, loop phase shift presents important limitations in operation of feed-back amplifiers, especially the loop phase shift at high frequencies in operation of wide band negative feed-back amplifiers for reducing modulation or distortion by feed-back action.

An object of the invention is to control such loop phase shift.

It is also an object of the invention to so control the loop phase shift as to reduce singing tendency or to increase the distortion suppression obtainable in such amplifiers, or both.

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

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

Fig. 2 shows a modification of the circuit of Fig. 1.

The amplifier circuit of Fig. 1 includes an amplifier 1, comprising one or more stages of vacuum tubes, as for example, three stages. It has a feed-back path f . An output bridge 2 connects the final stage to the feed-back path and amplifier output transformer T. An input bridge 3 connects the first stage to amplifier input transformer T' and the feed-back path. The feed-back path is in one diagonal of the output bridge and in one diagonal of the input bridge. In the output bridge the other diagonal includes the output transformer, and in the input bridge the other diagonal includes the input transformer.

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 plurality of telephone messages, all transmitted together over the cable carrier circuit from multiplex carrier transmitting apparatus (not shown).

The amplifier may be of the general type of those shown for example in Figs. 5, 56 and 57 of my above mentioned copending application and Fig. 2 of the above mentioned published article, each of those amplifiers having a feed-back path connected between input and output bridges. The feed-back may be negative (i. e. gain reducing) feed-back, and the amount of feed-back may be large, the absolute or scalar value of the loop transfer constant (i. e. of the transfer constant

for propagation once around the loop) being, for example, of the order of 50 or 100 in the utilized frequency range, as in the case of the negative feed-back amplifier of the Figs. 57 or Fig. 2 just mentioned.

The bridges may be balanced, over the utilized frequency range, to isolate f from T and T'. Each of the balancing arms comprises a resistance or generalized impedance and a capacity in parallel. The balancing arms of the output bridge and their impedance values for balanced conditions of the bridge are represented by Z_0 , KZ_0 , KZ and Z , Z_0 being the arm including the space discharge path of the tube (or tubes) of the final stage of the amplifier. The balancing arms of the input bridge, and their impedance values for balance of the bridge are represented by Z_0 , kZ_0 , kZ and z . Ordinarily it is desirable for avoiding undue loss in transmission to the load, that, over the utilized frequency range, K and KZ_0 be small and Z be large. For efficient transmission from T' to the amplifier 1, ordinarily k is small over the utilized frequency range. As indicated on the drawing, z_s and Z_s respectively designate the impedances which the feed-back path views in the directions of the input and output bridges.

With each balancing arm of the bridges including the capacity shown connected across the terminals of the arm, the arms may have such nominal impedance values as to not only satisfy the transmission requirements over the utilized frequency range, including the requirement that the bridge diagonals containing the amplifier input and output transformers be conjugate to the feed-back path f over that range, but at the same time to nominally yield a desired condition with respect to phase shift for transmission through the feed-back circuit, i. e. through the portion of the system traversed by waves in passing from the equivalent generator of the last space path to the first grid. The condition may be, for example, that of zero phase shift for a frequency, for instance, a very high frequency lying well above the utilized frequency range, at which inherent or fortuitous capacities associated with the elements of the feed-back circuit would be likely to make the phase shift of the feed-back circuit such as to cause the amplifier to sing around the feed-back loop were the nominal impedances of the bridge arms used for obtaining the nominal zero phase shift non-capacitive. The capacities shown can include or take into account known inherent or extraneous capacities appearing across the balancing arms or be large in comparison to those fortuitous capacities or any unknown or other portions thereof not taken into account, so as to greatly reduce the effects of inherent or fortuitous capacities on the high frequency phase shift and its tendency to cause singing, as just mentioned. (When the capacities shown include portions of the fortuitous capacities, those portions may be regarded as portions of the capacities shown, rather than fortuitous capacities.) Thus, where, with nominally non-capacitive balancing arms having impedances that in the absence of fortuitous capacity would give zero phase shift in the feed-back circuit, the amplifier would have a troublesome singing tendency at a given frequency, for example, a frequency far above the utilized frequency range, the impedances of the balancing arms, with the capacities shown, can be made such that the condition of zero phase shift for the given frequency would obtain for transmission through the feed-back circuit were there no fortuitous

capacities associated with the feed-back circuit. Then, even though that frequency be very high, the effect of additional inherent or extraneous or fortuitous capacities will be unimportant.

The requirement for zero phase shift for transmission through the portion of the system just mentioned, i. e. for transmission from the equivalent generator of the last space path to the first grid, is that the quantity

$$\frac{z+z_0}{z_0} \left[\frac{1+k}{K} + \frac{Z+Z_0}{z_s} \right]$$

be a numeric or in other words positive and real. This quantity is the complex ratio

$$\frac{e}{e_0}$$

of the voltage e of the equivalent generator of the last space path to the voltage e that such generator alone, acting through the feed-back path, produces on the first grid. If the voltage which that generator produces across the feed-back path f in the common diagonal of the bridges is designated e' , then

$$\frac{e}{e_0} = \frac{e'}{e_0} \cdot \frac{e}{e'} = \frac{z+z_0}{z_0} \cdot \frac{e}{e'}$$

To evaluate

$$\frac{e}{e'}$$

the current components flowing in various parts of the circuit of Fig. 1 are indicated by the arrows and their accompanying letters i with appropriate subscripts.

Then

$$\begin{aligned} e &= (i_1 + i_2 + i_3)Z_0 + (i_1 + i_2)KZ_0 + i_1KZ + (i_1 + i_3)Z \\ &= (i_1 + i_2)(1+K)Z_0 + i_1(1+K)Z + i_3(Z_0 + Z) \\ &= [1+K][(i_1 + i_2)Z_0 + i_1Z] + i_3(Z_0 + Z) \end{aligned}$$

and

$$e' = [K][(i_1 + i_2)Z_0 + i_1Z] = i_3z_s$$

whence

$$\frac{e}{e'} = \frac{1+K}{K} + \frac{Z_0+Z}{z_s}$$

Substituting this value of

$$\frac{e}{e'}$$

in the above formula for

$$\frac{e}{e_0}$$

gives

$$\frac{e}{e_0} = \frac{z+z_0}{z_0} \left(\frac{1+K}{K} + \frac{Z_0+Z}{z_s} \right)$$

As indicated above, one example of a form of circuit in which

$$\frac{e}{e_0}$$

can be a numeric is that in which the balancing arms of the bridges are resistances shunted by capacities. In this case

$$\frac{e}{e_0}$$

can be made a numeric for example by making z_s and Z_s have phase angles equal to each other. This will give zero phase shift from a generator in the space path of the last tube to the feed-back path f , and there will be zero phase shift from f to the grid of the first tube if the phase angles of the arms z and Z_0 of the input bridge are made equal to each other. It will be noted that z_s is independent of the impedance of the in-

coming line and input transformer, the value of z_s being

$$\frac{k}{1+K}(z_0+z).$$

In the case of each of the two-terminal impedances of elements of the circuit, as for example in the case of each of the arms of the bridges, its capacity at very high frequencies can be made to appear across its two terminals, by shielding the element, as for instance by inclosing the element in a copper can or casing (not shown) and connecting the casing to one terminal of the inclosed element.

In Fig. 2, showing a modification of the circuit of Fig. 1, amplifier 1 has input and output bridges 3' and 2' connecting it between input and output transformers T' and T each conjugate to feed-back path f as in Fig. 1, and a transmission equalizer 5 is shown in path f . As explained in my above mentioned copending application, British patent, and published article, the frequency variation of the equalizer attenuation contributes like frequency variation to the overall gain of the amplifier, so if the attenuation-frequency characteristic of the equalizer is made similar to that of the line or circuit to be equalized, instead of complementary to it as in the usual case of an equalizer in a line, the equalizer tends to compensate for the attenuation of the line. In Fig. 2 the balancing arms of bridges 2' and 3' are shown as generalized impedances having values indicated by the designations on the drawing, which are the same as the designations of the correspondingly connected arms in Fig. 1, except primed. If desired, the balancing arms in Fig. 2 may have the same values as their respectively corresponding arms in Fig. 1. This would make the impedances z'_s and Z'_s have the same values as the respectively corresponding impedances z_s and Z_s of Fig. 1. As noted above, the impedance

$$z_s \text{ is } \frac{k}{1+K}(z_0+z).$$

Similarly

$$Z_s = \frac{K}{1+K}(Z_0+Z).$$

Then a suitable value for the impedance of equalizer 5 would be either z_s or Z_s , so that the terminating impedance for the equalizer at one end or the other of the equalizer would match the equalizer impedance and thus facilitate obtaining the proper attenuation-frequency characteristic for the equalizer.

If desired, in the case of either or each of the bridges 2' and 3', the bridge, instead of having its balancing arms the same as those of the corresponding bridge in Fig. 1, may have the impedances of its balancing arms such as to make the bridge a transmission equalizer, for example, for serving the dual function of equalizing line attenuation and giving conjugacy between the connected line section and the feed-back path in the general manner disclosed in Fig. 65 of my above mentioned copending application and disclosed and claimed in the above mentioned copending Stilwell application. Then, if desired, the bridge arms may be given such values as to make the bridge equalizer of the constant impedance type.

With use of such constant impedance bridge equalizer (or bridge equalizers), the equalizer 5, if used, may be a supplementary equalizer, operating to supplement the action of the bridge type equalizing means in the general manner disclosed

in Fig. 65 of my above mentioned copending application and in the above mentioned Patent No. 1,956,547, so that the combined action of the equalizers gives the desired equalization of the line attenuation. In this case, if the output bridge is a constant impedance bridge equalizer, the equalizer 5 may be a constant impedance equalizer matching the impedance of the output bridge. The final termination to the first grid may be a multiple of the constant impedance of the other networks, i. e. a multiple of the constant impedance of the output bridge equalizer or the supplementary equalizer 5. The multiple may be any positive real quantity, excluding zero. In addition, if desired, the input bridge may be an input bridge equalizer of constant impedance type such as the constant impedance output bridge equalizer, with a different value of impedance if preferred.

The invention claimed in the present application is an improvement on the invention claimed in the above-mentioned copending application Serial No. 606,871, which is the generic application.

What is claimed is:

1. A wave amplifying system comprising a feed-back circuit whose fortuitous capacity tends to produce phase shift in transmission through said feed-back circuit, said feed-back circuit comprising means which, were the fortuitous capacity absent, would render the phase shift of the feed-back circuit suitable for avoiding singing, and said means including capacity connected in shunt to said feed-back circuit and sufficiently large compared to the fortuitous capacity to substantially reduce effect of the fortuitous capacity upon phase shift in the feed-back circuit.

2. A wave amplifying system comprising a feed-back circuit having associated therewith fortuitous capacity producing therein phase shift that tends to cause singing and impedances in said circuit rendering the phase shift of said circuit suitable for avoiding singing, said impedances including capacity in shunt to said circuit said latter capacity having a value which is large compared to said fortuitous capacity.

3. A wave amplifying system comprising a feed-back circuit having associated therewith fortuitous capacity producing therein, at frequencies above the utilized frequency range, phase shift that tends to cause singing, and means for reducing the singing tendency, said means comprising impedances in said circuit rendering the phase shift of said circuit substantially zero for a frequency above the utilized frequency range, and said impedances including capacity in shunt to said circuit, said latter capacity having a value which is large compared to said fortuitous capacity.

4. A wave amplifying system comprising a feed-back circuit for producing negative feed-back therein, said feed-back circuit having shunt arms, each shunt arm of said feed-back circuit including a capacity that is connected across the terminals of the arm and is large compared to the fortuitous capacity across the terminals.

5. A wave amplifying system comprising a feed-back circuit for producing negative feed-back therein, said feed-back circuit having a shunt arm including a capacity that is connected across the terminals of said arm and is large compared to the fortuitous capacity across the terminals, and means in said feed-back circuit for rendering the phase shift of said feed-back circuit

zero at a frequency above the utilized frequency range.

6. A wave amplifying system comprising a feed-back circuit constituted by two-terminal impedance each including a capacity that is connected across the terminals of the impedance and is large compared to the fortuitous capacity across the terminals, said impedances having such values as to give said feed-back circuit a value of phase shift suitable for avoiding singing through the feed-back circuit.

7. The combination with a circuit, of a wave amplifying system for connection thereto, said system comprising a negative feed-back circuit, said feed-back circuit comprising a feed-back path and a bridge network for connecting said feed-back path in conjugate relation to said first mentioned circuit, said bridge network comprising balancing arms, each of said arms including a capacity connected across the terminals of the arm and large compared to the fortuitous capacity of the arm, and said feed-back circuit being such that, were said fortuitous capacities absent, the phase shift of said feed-back circuit would be suitable for avoiding singing of said amplifying system through said feed-back circuit.

8. The combination with a circuit, of a wave amplifying system for connection thereto, said system comprising a negative feed-back circuit, said feed-back circuit comprising an attenuation equalizer and a bridge network connecting said equalizer in conjugate relation to said first mentioned circuit, said feed-back circuit comprising fortuitous shunt capacity that tends to cause singing, and said feed-back circuit being constituted by impedances which, were said fortuitous capacity absent, would render the phase shift of said feed-back circuit suitable for avoiding singing, said impedances including capacity connected in shunt to said feed-back circuit and large compared to said fortuitous capacity.

9. The combination with a circuit, of a wave amplifying system for connection thereto, said system comprising a negative feed-back circuit, said feed-back circuit comprising a feed-back path and a bridge network for connecting said feed-back path in conjugate relation to said first mentioned circuit, said bridge network comprising balancing arms, each of said arms including a capacity connected across the terminals of the arm and large compared to the fortuitous capacity of the arm, and said feed-back path and said bridge network having their impedances which face each other equal to each other.

10. A wave transmission system comprising an incoming circuit, an outgoing circuit and a wave amplifying system for connection therebetween, said amplifying system comprising a negative feed-back circuit, said feed-back circuit comprising a feed-back path, an input bridge network for connecting said feed-back path in conjugate relation to said incoming circuit, and an output bridge for connecting said feed-back path in conjugate relation to said outgoing circuit, each of said bridge networks having balancing arms comprising reactance, said feed-back path and said output bridge network having their impedances which face each other equal to each other, and said input bridge having the impedances of its balancing arms adjusted for transmitting waves from said feed-back path to the input of said amplifying system with zero phase shift.

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