Dec. 5, 1944. A. H. ROCHE ET AL 2,364,389

NEGATIVE FEEDBACK AMPLIFIERS

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FIG. 1.

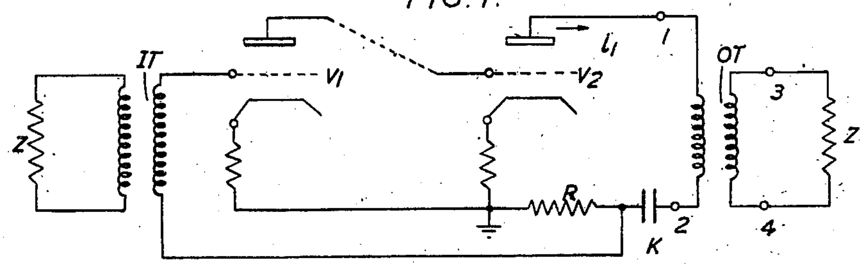

FIG. 2.

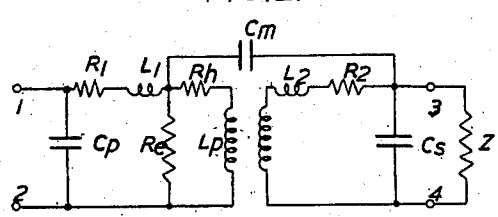

FIG. 3.

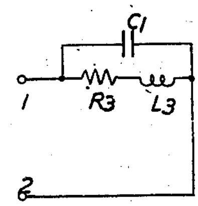

FIG. 4.

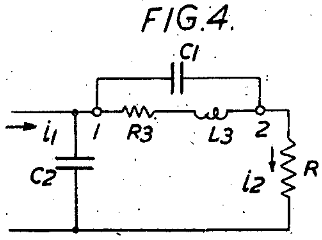

FIG. 6.

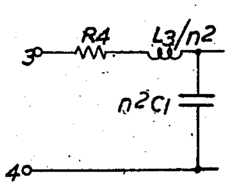

FIG. 7.

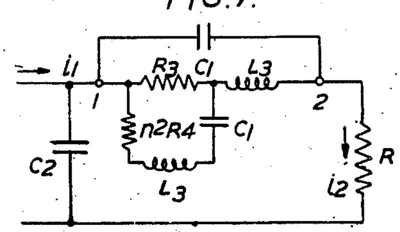

FIG. 11.

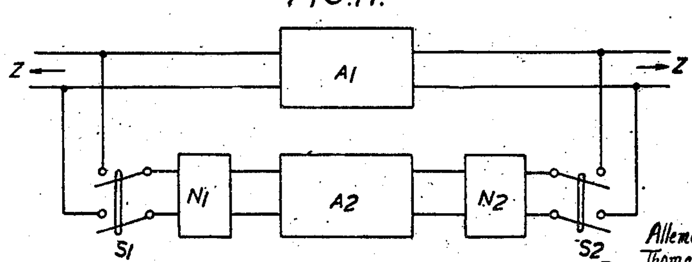

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FIG. 5.

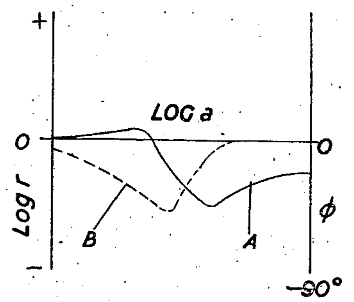


FIG. 8.

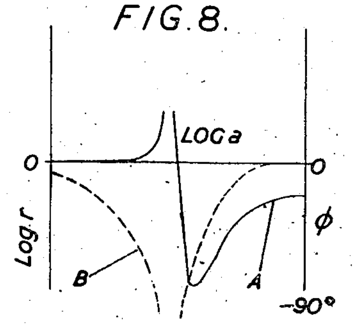


FIG. 9.

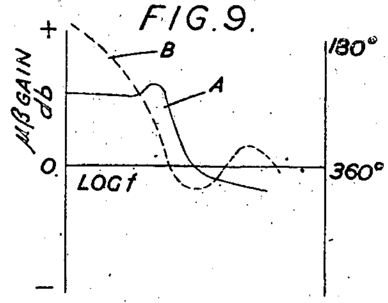
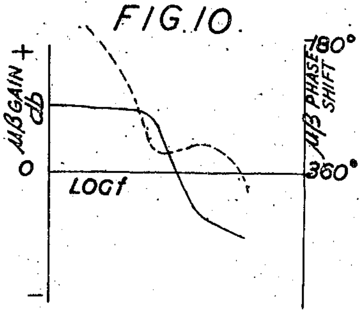


FIG. 10.



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UNITED STATES PATENT OFFICE

2,364,389

NEGATIVE FEEDBACK AMPLIFIERS

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Application November 29, 1943, Serial No. 512,174
In Great Britain December 24, 1942

11 Claims. (Cl. 179—171)

The present invention relates to electric negative feedback amplifiers, and concerns particularly arrangements for preventing instability during switching operations.

In multi-channel carrier current signal transmission systems, it is necessary to provide convenient means for replacing amplifiers which may have become defective, or for other reasons, with the minimum of delay.

In co-axial cable systems carrying several hundred channels all of which pass through the same amplifier, it is essential that any switching operation involving the amplifier shall not produce any effective disconnection, otherwise all of the several hundred channels will be interrupted; and a break of one or two milliseconds may be sufficient to destroy the intelligibility of the signals. For this reason, when replacing any normal amplifier by a spare amplifier, it is the practice first to connect the two amplifiers in parallel to the cable conductors, and then to remove the normal amplifier. In this way interruption of the service is avoided.

Since, however, the amplifiers used are now almost exclusively of the negative feedback type, it is found that although any amplifier is stable when normally connected to the line, the connection of two amplifiers in parallel in the manner explained is liable to upset the transmission conditions of the feedback loops of both amplifiers so that singing often results, which will probably have a worse effect on intelligibility than a short disconnection. The principal object of the present invention is, therefore, to overcome this difficulty by providing a switching arrangement which does not cause the parallel connected amplifiers to be unstable, and which at the same time does not entail any appreciable sacrifice in the normal performance of individual amplifiers which would otherwise have to be made for the purpose of avoiding instability during parallel operation.

According to the invention, there is provided an arrangement for connecting between two sections of an electric signal transmission line two similar negative feedback amplifiers in parallel without producing instability, each of the amplifiers having input and output transformers, comprising means for causing the frequency of series resonance of the input and/or output transformer of one amplifier to differ by a predetermined amount from the frequency of parallel resonance of the input and/or output transformer of the other amplifier, respectively.

According to another aspect, the invention consists in an arrangement for obtaining stable operation of two similar parallel connected negative feedback amplifiers inserted at a point in an electric signal transmission line comprising circuit means connected in tandem with one of the amplifiers, and adapted to prevent either amplifier from modifying the feedback loop of the other in such manner as to render it unstable.

According to a further aspect, the invention lies in an amplifying arrangement for an electric signal transmission line comprising a first negative feedback amplifier connected to the line and a second similar amplifier adapted to be connected in parallel with the first through circuit elements, the amplifiers and elements being designed so that the polar curve representing the transmission round the $\mu\beta$ path of either amplifier does not enclose the point (1,0), whether the amplifiers are operated singly or in parallel.

According to still another aspect, the invention provides an amplifying arrangement for an electric signal transmission line comprising two similar negative feedback amplifiers connected in parallel thereto, means being provided for rendering dissimilar the transmission characteristics of the $\mu\beta$ loops of the two amplifiers in such a manner that the parallel combination is stable.

The invention will be described with reference to the accompanying drawings, in which:

Fig. 1 shows a fragmentary schematic of a negative feedback amplifier to which the invention is adaptable;

Figs. 2, 3, 4, 6 and 7 show schematic circuit diagrams used to explain the effect of the transformers on the feedback loop of the amplifier;

Figs. 5, 8, 9 and 10 show curves to illustrate the transmission conditions in the feedback loop; and

Fig. 11 shows a block schematic diagram of an arrangement according to the invention.

In accordance with the practice which is now common in the art, a negative feedback amplifier will be regarded as comprising a forward amplifying path of which the voltage transfer ratio is denoted by μ, and a feedback path of which the voltage transfer ratio is denoted by β. Both μ and β are in general complex quantities and take account of the phase change as well as the corresponding gain or loss. The loop comprising the forward and feedback paths is known as the feedback loop, and $\mu\beta$ represents the voltage transfer ratio in magnitude and phase for one transit round the loop. For convenience, the feedback loop is often called the "$\mu\beta$ loop" and the gain measured in decibels for a transit round the loop is proportional to log $|\mu\beta|$, and is often called the "$\mu\beta$ gain."

In order to obtain the best advantage from feedback, $|\mu\beta|$ is usually large compared with 1, so that the effective gain which the amplifier introduces into the circuit is substantially determined by $1/\beta$.

A negative feedback amplifier of a type used on co-axial cables is shown diagrammatically in Fig. 1. This figure only shows the details necessary for an understanding of the invention, and it will be understood that the amplifier may be otherwise designed in any appropriate way.

The amplifier comprises an input transformer IT which connects the line (represented by the impedance Z) to the control grid of the first thermionic amplifying valve V_1, and an output transformer OT for coupling the anode of the last valve V_2 to the line. The anode of V_1 may be coupled in any suitable way, including further amplifying stages if necessary, to the control grid of V_2; this coupling is indicated in Fig. 1 by the dotted line connecting this anode and control grid. If the amplifier should be a single stage amplifier, then the anode of V_1 would be connected directly to the output transformer OT. It will be understood, of course, that V_1 and V_2 may all represent two or more valves connected in parallel, and may have any number of additional grids (not shown), appropriately polarised.

A feedback resistance R is connected, as shown, in series with the anode circuit of the last valve V_2, an appropriate blocking condenser K being included if necessary. The secondary winding of the input transformer IT is connected between the control grid of the first valve V_1 and the high potential terminal of R. This is an ordinary current feedback arrangement, by which a potential proportional to the output current is fed back to the control grid of the first stage.

The phase shift for transmission once round the $\mu\beta$ loop should ideally be 180° or an odd multiple thereof at all frequencies. In practice, of course, this can never be achieved, and it is well known that the amplifier may become unstable if the phase shift reaches zero or a multiple of 360° at any frequency. The condition for stability in this case is that the $\mu\beta$ gain must be zero or less at the frequency at which the phase shift is 360°. Detailed information on the stability conditions and design of these amplifiers may be found in the papers in the Bell System Technical Journal by H. Nyquist (Jan. 1932 pages 126 to 147) and H. W. Bode (July, 1940 pages 421 to 454).

In order to meet the stability requirements it is necessary to control the amplifier performance not only over the working frequency range, but also outside this range. For example, it is necessary to ensure that as the frequency is raised above the working range, the $\mu\beta$ gain becomes zero or negative before the phase shift has changed to 360° or a multiple thereof. The components which influence the $\mu\beta$ characteristics of the loop must therefore be proportioned accordingly, and the input and output transformers play an important part in this connection. The desired characteristics in the neighbourhood of the upper cut-off frequency may be substantially secured by suitably choosing the frequency at which the leakage reactance of each transformer resonates with its self capacity.

When a successful design has been achieved, by which the best possible advantage has been secured from the negative feedback in the working range, consistent with a margin of stability which is sufficient to cover safely manufacturing variations, ageing, and the like, it will probably be found that when two similar amplifiers are connected in parallel to the line, both become unstable because the presence of each amplifier changes the transformer network effective in the $\mu\beta$ loop of the other and the stability conditions are violated. To prevent this it has hitherto been necessary to sacrifice something in the design of the amplifiers, so obtaining a less efficient arrangement. The reason for the instability caused by parallel operation will be presently explained, and it will be shown how the difficulty may be avoided according to the invention without the necessity for sacrificing anything in the individual amplifier design.

In broad band high frequency amplifiers it is practically necessary to employ pentode valves. For this reason the output impedance of the last valve is very high and the output current is practically independent of the load, assuming that the feedback resistance R is small compared with the impedance of the whole anode circuit loop.

As a result the input and output transformers of such amplifiers affect the $\mu\beta$ loop in substantially the same way, and it is therefore necessary only to consider one of them and the conclusions will then equally apply to the other. Only the output transformer will therefore be considered in detail, with reference to Figs. 2, 3 and 4.

In Fig. 2 is shown the equivalent circuit of the output transformer from the terminals 1, 2 as seen from the anode circuit of the last valve V_2. In this figure the symbols have the following meanings:

L_p=inductance of the primary (high impedance) winding.
L_1=primary leakage inductance.
L_2=secondary leakage inductance.
R_1=D. C. resistance of primary winding.
R_2=D. C. resistance of secondary winding.
R_h=resistance representing the hysteresis loss.
R_e=resistance representing the eddy current loss.
C_p=self capacity of the primary winding.
C_s=self capacity of the secondary winding.
C_m=capacity between the two windings.
Z=line impedance (substantially a pure resistance).

Fig. 2 is similar to part of Fig. 101b shown on page 189 of "Radio Engineering" by F. E. Terman, second edition, 1937.

In the neighbourhood of the cut-off frequency, the quantities R_h, R_e, L_p and C_m can all be neglected in comparison with the other quantities, and the circuit then becomes simplified as shown in Fig. 3 in which all the quantities have been referred to the primary side of the transformer and in which:

$$L_3=L_1+n^2L_2$$
$$R_3=R_1+n^2(R_2+Z)$$
$$C_1=C_p+C_s/n^2$$

in which n^2 is the impedance transformation ratio.

Fig. 4 shows the network presented to the output current i_1 (Fig. 1). In this figure C_2 is the output capacity of the last valve stage, and R is the feedback resistance, which appears in series with the circuit of Fig. 3. If i_2 is the current through R, and since R is negligible compared with the impedances in either of the other branches of the network, it can be shown that, approximately

$$r=\frac{i_2}{i_1}=\sqrt{\frac{(1-ma^2)^2+a^2}{[1-ma^2(1+k)]^2+a^2(1+k)^2}}\angle\phi \quad (1)$$

where

$$\tan\phi=\frac{-ak}{(1-ma^2)[1-ma^2(1+k)]+a^2(1+k)} \quad (2)$$

in which

$a=\omega\cdot C_1\cdot R_3$ (where ω is 2π times the frequency)
$m=L_3/C_1\cdot R_3^2$

and

$k=C_2/C_1$

Fig. 5 shows the curves relating log r (curve A) and ϕ (curve B) to log a, for a typical amplifier. It will be seen that r is practically equal to 1 at low frequencies, rises slightly and then falls rather steeply at mid-frequencies and then rises again to a practically constant value less than 1 at high frequencies. The final constant value is due to the fact that the network reduces at high frequencies to the two condensers C_1 and C_2, the impedance of L_3 having risen to such an extent that its effect in shunting C_1 is negligible.

When another amplifier is connected to the line in parallel with that shown in Fig. 1, the transformer OT will have another similar transformer bridged across its secondary winding at the terminals 3 and 4. Since the second amplifier is the same as the first, the bridging impedance can be determined from Fig. 2. Fig. 6 shows a simplified circuit of the second transformer, in which C_2 has been omitted because its impedance is effectively reduced to a negligible value by the feedback. R has accordingly also been omitted since it can have no appreciable effect. This time the impedances are referred to the secondary (low impedance) winding of the transformer. The resistance R_4 is in this case equal to R_1/n^2+R_2 and is very small. The second transformer is, however, seen through the first transformer, so that all the impedance in Fig. 6 will be multiplied n^2. Fig. 6 (multiplied by n^2) is thus shunted across the n^2Z portion of R_3 Fig. 4, but since n^2Z is large compared with $R_1+n^2R_2$, the error in considering the whole of R_3 so shunted will be small. The arrangement is then substantially as shown in Fig. 7. Rather complicated expressions for r and tan ϕ similar to (1) and (2) above may be derived from simple network theory, but it is simpler to exhibit the effect in a diagram.

It will be seen that the series resonance of the path shunting R_3 occurs at substantially the same frequency as the parallel resonance of the network as a whole, and since n^2R_4 is small, the resistance R_3 is practically short-circuited. This greatly sharpens the resonance of the first transformer. The curves of Fig. 5 now appear as shown in Fig. 8. The phase change ϕ is now greater than 90° over a range of mid-frequencies, and the ratio r is greater than 1 over part of this range, so that the conditions result in serious instability.

Fig. 9 shows the $\mu\beta$ gain expressed on a decibel scale (curve A) and phase shift (curve B) related to log f, where f is the frequency, for the conditions of Fig. 7. It will be seen that the phase shift has become 360° or more over a short mid-frequency range, and there is a net gain round the loop over part of this range. The amplifier will therefore be expected to sing.

Fig. 10 is similar to Fig. 9 and shows the curves which would be obtained for either amplifier alone, that is, when not shunted by another amplifier. It will be seen that the phase shift does not reach 360° until well after the gain has become negative so that there is a very good margin of stability.

It may be pointed out in connection with Figs. 9 and 10 that if they be drawn in the form of Nyquist's polar diagrams, the point (1,0) is enclosed in the case of Fig. 9 and not in the case of Fig. 10, so that his condition for stability is satisfied in the second case and not in the first.

It may further be mentioned that the parallel connection of the amplifiers may not always result in actual singing, but even so, the state of the circuit is one of "conditional stability" in which although the point (1,0) is not enclosed, the configuration of the polar diagram is such that some small change in $\mu\beta$ such as might be due to ageing, replacement of valves and the like would cause the point to be enclosed, and the amplifiers would sing. Such a condition cannot be regarded as satisfactory.

According to the invention, the instability caused by connecting the second amplifier in parallel with the first is prevented by separating the resonance frequencies, whose coincidence is the cause of the trouble, by an amount calculated to produce a sufficient margin of stability. One way in which this may be done is to connect the second amplifier at each end through an impedance network which slightly modifies the impedance presented to the transformer of the first amplifier so that it resonates at a different frequency. This is shown in block schematic form in Fig. 11. In this figure, A_1 is the amplifier which is normally connected in the circuit and A_2 is a spare amplifier which is to replace it for a short period. Two networks N_1 and N_2 are connected in tandem with the amplifier A_2 at the input and output, respectively. S_1 and S_2 are intended to represent any suitable switching or jacking system for connecting the amplifiers in parallel. After the switches have been closed, the amplifier A_1 may be removed by other jacks or switches not shown, so that the amplifier A_2 carries the traffic in the meantime. N_1 and N_2 should therefore be designed to introduce a very small loss. If the amplifier A_1 is defective or othewise expected to be switched out for a long period, another normal amplifier may be switched in parallel with A_2, which may afterwards be removed by opening the switches S_1 and S_2, and it will then be available for use again.

Since it is necessary to change the resonance frequency of the impedance bridging the amplifier A_1, the networks N_1 and N_2 will generally be composed of reactive elements, and in one preferred arrangement each consists of a single inductance connected in series with the conductor corresponding to the central conductor of the co-axial cable; or in a balanced system, two equal inductances would be used, one connected in series with each wire. The effect is to increase one of the inductances L_3 in Fig. 7, (that is, effectively to increase the leakage inductance of the corresponding transformer) so that the two resonance frequencies are separated. It will be seen that this will increase L_3 in shunt with R_3 for A_1 and L_3 in series with R_3 for A_2.

It has been found that by choosing a suitable inductance for connecting in series with the input and output terminals of the amplifier A_2

the characteristic curves of both amplifiers differ very little from Fig. 10 which is for the normal unshunted amplifier. A completely stable arrangement is thus obtained. In a certain practical case of amplifiers used in a co-axial cable system, the inductance connected in series with the central conductor was about 4½ microhenrys.

It should be noted that according to the invention, the means for preventing instability are connected externally to the spare amplifier and accordingly it does not require the provision of any special amplifier for switching purposes. This is an important consideration in the interests of standardisation.

What is claimed is:

1. An arrangement for connecting between two sections of an electric signal transmission line two similar negative feedback amplifiers in parallel without producing instability, each of the amplifiers having input and output transformers, comprising means for causing the frequency of series resonance of one of said transformers of one amplifier to differ by a predetermined amount from the frequency of parallel resonance of the corresponding transformer of the other amplifier.

2. An arrangement for obtaining stable operation of two similar parallel connected negative feedback amplifiers inserted at a point in an electric signal transmission line comprising circuit means connected in tandem with one of the amplifiers and adapted to prevent either amplifier from modifying the feedback loop of the other in such manner as to render it unstable.

3. An amplifying arrangement for an electric signal transmission line comprising a first negative feedback amplifier connected to the line and a second similar amplifier adapted to be connected in parallel with the first through circuit elements, the amplifiers and elements being designed so that the polar curve representing the transmission round the $\mu\beta$ path of either amplifier does not enclose the point (1.0), whether the amplifiers are operated singly or in parallel.

4. An amplifying arrangement for an electric signal transmission line comprising two similar negative feedback amplifiers connected in parallel thereto, means being provided for rendering dissimilar the transmission characteristics of the $\mu\beta$ loops of the two amplifiers in such manner that the parallel combination is stable.

5. An arrangement according to claim 4 in which the said means is adapted effectively to operate at frequencies outside the signal frequency range.

6. An arrangement according to claim 4 in which the said means comprises an impedance network connected externally to one of the amplifiers.

7. An arrangement according to claim 1 in which the said means comprises means for effectively increasing the leakage inductance of one of the transformers.

8. An arrangement according to claim 4 in which the said means comprises two impedance networks, connected respectively at the input and output of one of the amplifiers.

9. An arrangement according to claim 4 in which the said means comprises an impedance network composed substantially only of reactance elements.

10. An arrangement according to claim 4 in which the said means comprises a single inductances connected in series with one of the conductors connecting the amplifiers together.

11. An arrangement according to claim 4 in which the said means comprises a pair of inductances connected respectively in series with the conductors leading to and from the amplifier.

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