

May 26, 1942.

H. S. BLACK

2,284,555

SIGNALING SYSTEM

Filed July 30, 1940

2 Sheets-Sheet 1

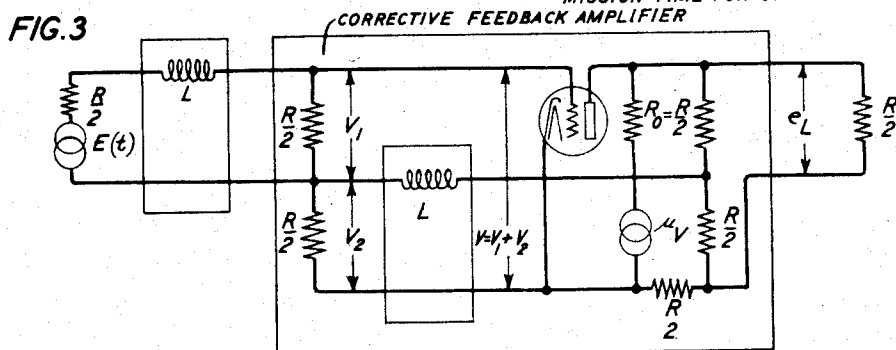
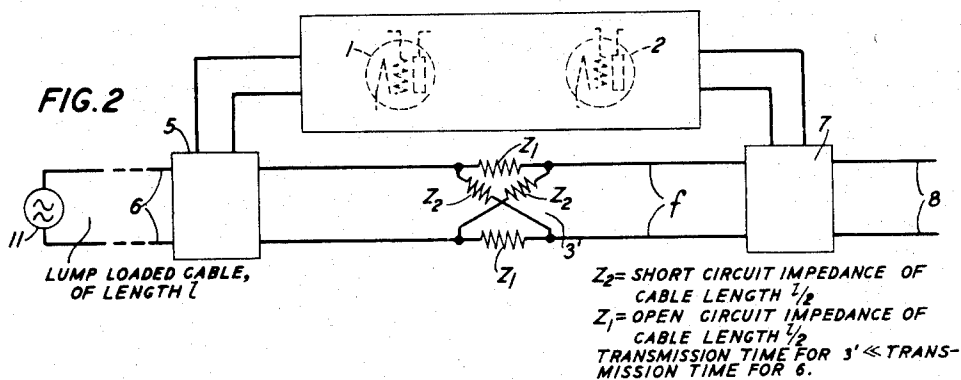
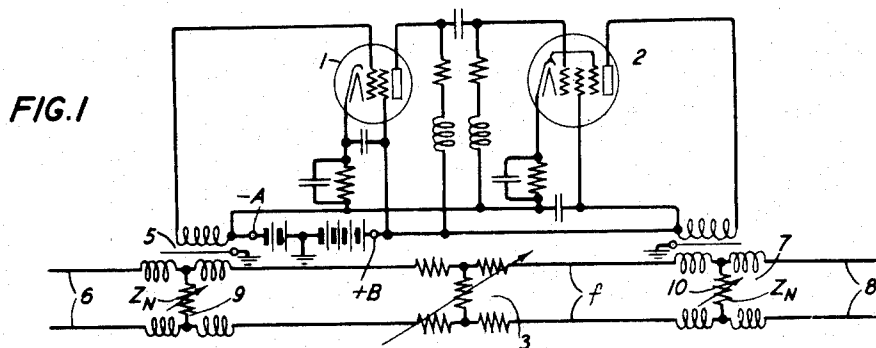
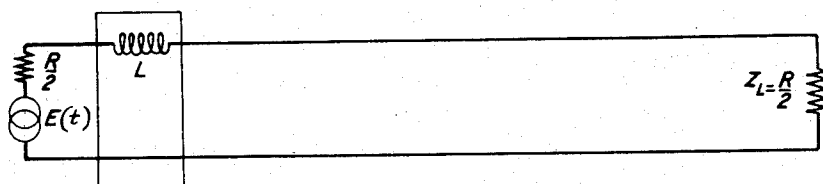


FIG. 3A



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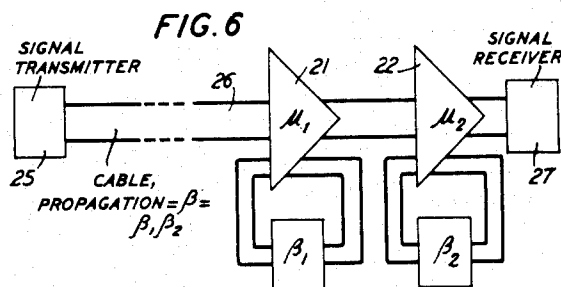
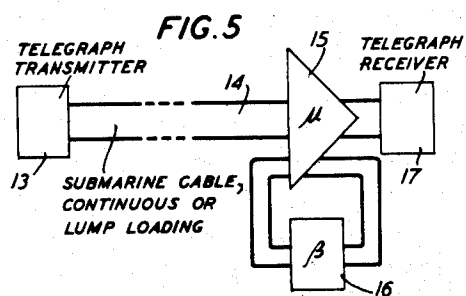
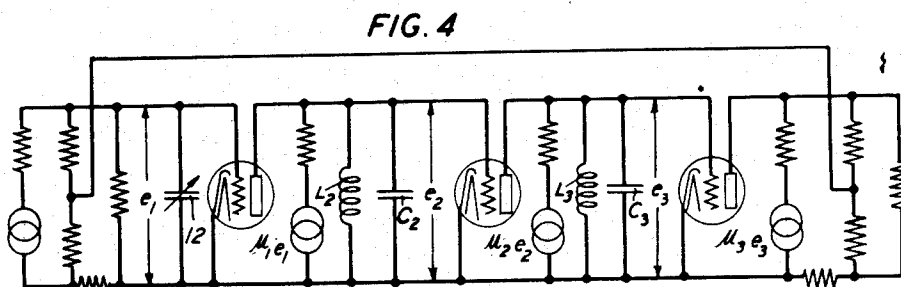
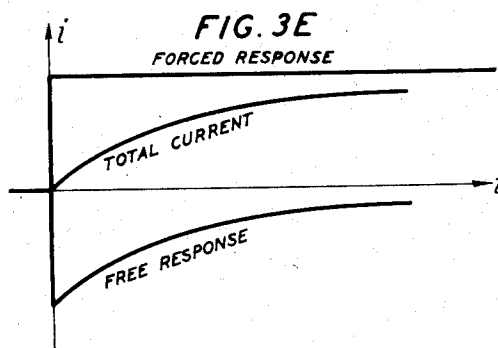
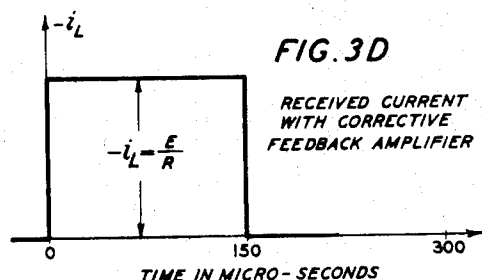
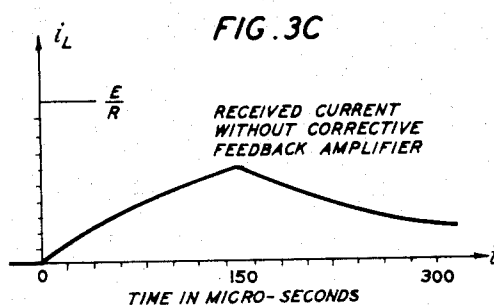
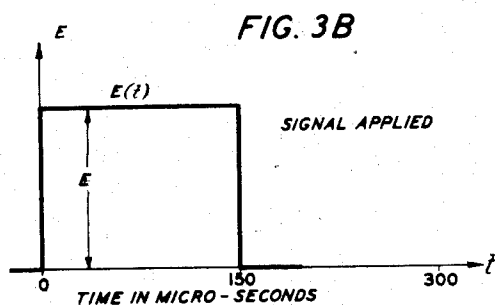
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2 Sheets-Sheet 2



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2,284,555

SIGNALING SYSTEM

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Application July 30, 1940, Serial No. 348,433

8 Claims. (Cl. 178-44)

This application is a continuation in part of my application, Serial No. 114,390, filed December 5, 1936, (Patent 2,209,955, August 6, 1940), for Wave translation systems, and relates to signal transmission, especially transmission over long circuits.

Representative objects of the invention are to reduce transmission time of such circuits, as, for example, loaded telephone or telegraph lines, and speed up transmission of signals and reduce their distortion.

In accordance with the invention, a negative feedback amplifier may be connected to the receiving end of such a line and the feedback path may be given characteristics suitably related to those of the line, as pointed out hereinafter, to reduce signal distortion, as, for example, reshape telegraph signals, and to speed up transmission, as, for instance, by preventing loading coils from increasing the transmission time of the line.

A feature of the invention relates to dividing a corrective amplifier into tandem portions, each a negative feedback amplifier, to facilitate obtaining stability against oscillation.

A further feature relates to compensating for cable modulation, due to non-linear loading elements or magnetic shielding, for example, by introducing similar modulation producing elements in the feedback path of a corrective feedback amplifier amplifying the signals from the cable.

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

In the drawings:

Fig. 1 shows schematically a system embodying a form of the invention;

Fig. 2 is a diagram of a similar system showing specific forms of line and amplifier feedback circuits;

Figs. 3 and 3A to 3E are diagrams for facilitating explanation of operation of systems in accordance with the invention;

Fig. 4 shows schematically a circuit of a feedback amplifier embodying means for reducing transient overloading;

Fig. 5 shows a submarine telegraph cable system embodying a form of the invention; and

Fig. 6 shows a transmission system embodying a corrective amplifier comprising feedback amplifiers in tandem.

The amplifier of Fig. 1 may be a stabilized feedback amplifier of the general type disclosed, for example, in the copending application mentioned above, or my Patent 2,102,671, December 21, 1937, or my paper on "Stabilized feedback

amplifiers," Electrical Engineering, January, 1934. It comprises an amplifying path or element shown as including tandem connected vacuum tubes 1 and 2, and comprises a feedback path f shown as including a transmission control network 3 of generalized impedances. The amplifying path or element may be referred to as the μ -circuit, and the feedback path may be referred to as the β -circuit, the significance of μ and β being as indicated in the Patent 2,102,671, just mentioned. The network 3 may be referred to as the β -circuit network.

An input hybrid coil 5 couples the incoming circuit 6 and the feed back path f to the input end of the amplifying path; and an output hybrid coil 7 couples the output end of the amplifying path to the outgoing circuit 8 and the feedback path. Z_N is the impedance of the balancing network associated with the hybrid coil, i. e., the impedance 9 or 10 across the bridge points of the hybrid coil.

The network 3 may be a β -circuit network for amplitude or phase equalization or correction of distortion for a section of cable or circuit in front of the amplifier. Locating the corrective network in the feedback path or β -circuit instead of ahead of the amplifier has an important advantage relating to speeding up transmission. As shown in my above-mentioned Patent 2,102,671, the amplification of a feedback amplifier with $\mu\beta \gg 1$ is approximately

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

so when the β -circuit is made such that its propagation is the same as that of the line or cable between a source of voltage e and the input to the μ -circuit, the transmission from the source of voltage e to the output of the μ -circuit is

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

(as brought out, for example, in the patent just mentioned or in my Patent 2,002,499, May 28, 1935, or F. A. Cowan Patent 2,017,180, October 15, 1935), and hence there is no delay nor distortion and the amplified signal appears instantly at the output of the μ -circuit as a replica of the signal e applied to the line or cable by the source, except reversed in sign. (There is no restriction on β other than that the amplifier comply with Nyquist's rule.) This result is obtained from theoretical considerations. The equations which are available for arriving at this conclusion are rigorous only for systems containing

lumped constants. The transmission through systems made up of continuous elements is only approximated from the lumped constant equations. Hence to this extent the above procedure will correct for amplitude distortion and phase distortion. (Applications are encountered where there are likewise important advantages in having the β -circuit correct solely for phase distortion.)

Compared to the customary way of improving cable distortion this procedure speeds up transmission. The customary way, where the network for correcting attenuation and phase over the frequency band of interest is not in a feedback path, delays the time of transmission by a period that exceeds the time required for a particular frequency to travel down the cable, this particular frequency generally being that one in the band of interest which is most slowly transmitted. In contrast to this, for the described procedure of correcting in the β -circuit, the time is the time for a particular frequency, which is the one most rapidly transmitted, or in other words, it is the time required for current no matter how trivial to make its appearance at the receiving end. All other velocities for all other frequencies for which the circuit is properly operative are made equal to this most rapid speed. In the case of a cable, this speed apparently corresponds to a speed less than the velocity of light in a vacuum, depending upon the dielectric constant and permeability of the cable. It should be noted that this time is independent of the wave form impressed at the sending end. It is also independent of lumped series inductance, either positive or negative, and likewise is independent of lumped shunt resistance, either positive or negative. Thus, by adding apparatus (the feedback amplifier) to a heavily loaded voice frequency cable, a wave can be propagated over the cable at the same speed as over the same cable non-loaded. The circuit indicated at 6 in Fig. 2 may be such a cable, for example a telephone cable fed from a source 11 of voice currents and periodically loaded with series impedance, for example, series inductance or shunt impedance, for example, shunt resistance, or both, the system of that figure being otherwise similar to the system of Fig. 1 except that in place of the β -circuit network 3 of Fig. 1 a specific form of β -circuit network 3', about to be described, is shown. However, if desired, the network 3' may be replaced by a replica of the periodically loaded circuit 6, for example to reduce effects of cable modulation as pointed out hereinafter.

Assuming the cable is many wave-lengths long, preferably the β -circuit instead of being a like section of cable may have a different indicial admittance, as now to be explained.

Considering indicial admittance of a transmission system as a transfer admittance, it is the current as a function of time at the far end in response to a unit voltage suddenly applied at time $t=0$ at the sending end, and two systems having like indicial admittances will behave identically at the receiving end for like excitations at the sending end. If two systems have like indicial admittances their steady state amplitude and phase characteristics are identical. If two systems have like amplitude and phase characteristics (that is, steady state attenuation and phase versus frequency characteristics) over a specified band of frequencies, for example f_1 to f_2 , then the received currents within this band

probably will be the same for each system for like excitations at the sending end.

Nevertheless two systems can have very nearly identical steady state attenuation and phase characteristics from $f=0$ to $f=\infty$ and yet the time taken for some current, no matter how little, to arrive at the receiving end can be entirely different.

For example, referring to Fig. 2, two such systems are on the one hand a cable 6 of length l where l is many wave-lengths and on the other hand a lattice network of one section and of finite number of lumped constants as shown at 3' in Fig. 2 whose four elements are two impedances Z_2 each equal to the cable impedance of length $l/2$ with far end short-circuited and two other impedances Z_1 each equal to the cable impedance of length $l/2$ with far end open. That is, Z_2 is the short-circuit impedance, and Z_1 the open-circuit impedance, of a length $l/2$ of the loaded cable). The lattice network can be made to match the loaded cable over a specified band as regards steady state amplitude and phase, and yet have the time for any or the first current to arrive relatively short compared to the case of the loaded cable.

The real time of transmission of a cable will be designated τ and equals l/v where v is the velocity of propagation referred to above, i. e., τ is the time for the first current to appear at the distant end.

When a feedback amplifier is to correct for a section of cable in front of the amplifier in the general manner referred to above, preferably the β -circuit should have an indicial admittance equal to the indicial admittance of the cable when, referring to the admittance characteristic of the latter, t is replaced by $(t-\tau)$. In other words, for the β -circuit the indicial admittance characteristic (i. e., the graph of current as a function of time at the amplifier input end of the β -circuit in response to unit voltage suddenly applied at time $t=0$ at the other end of the β -circuit, with $\mu=0$) preferably should be the graph or characteristic that would be obtained by shifting the indicial admittance characteristic of the cable section horizontally toward the current axis an amount τ , the amount necessary to make the displaced characteristic pass through the origin. Such indicial admittance characteristic for the β -circuit will be obtained if, except for leaving out a uniform delay τ , the β -circuit be given the same steady state attenuation and phase characteristics as the cable section from zero frequency to infinite frequency and be so constructed of lumped impedances as to have substantially zero transmission time compared to the transmission time for the cable section. Then the output of the amplifier will be a replica of the input to the cable section at the sending end except it will appear τ seconds later. As a practical matter, such amplifier output can be obtained by constructing the β -circuit network as described above for network 3', with its steady state attenuation and phase characteristics substantially the same as those of the cable section over a finite frequency range corresponding to the band of frequencies to be transmitted.

If, on the other hand, the β -circuit be a section of cable like that in front of the amplifier (assuming Nyquist's rule is satisfied by appropriately modifying μ , or by making additions to the cable to appropriately modify the cable itself) the time of transmission is still τ but for an interval τ at the beginning and a correspond-

ing interval at the end, the wave form apparently will be incorrect. This effect would be something more than multiplying the time of transmission by two as compared to the method of the preceding paragraph. It would make the received wave distorted in a manner analogous to that of a loaded cable. In other words, the received wave or wave delivered by the amplifier would not only be zero for an interval τ after the application of the excitation at the sending end of the cable, but would be a distortion wave, or wave of form different from the applied signal for a further interval of τ ; and after the removal of the excitation would not only continue for an interval τ , but for a further interval τ would be a distortion wave or wave of form different from the applied signal.

To give a physical concept of the methods described in the two preceding paragraphs for correcting phase distortion and speeding up transmission, the response without feedback to the excitation can be viewed as the forced or steady state response plus the free flow or transient response. As a result of feedback action the amplifier does not amplify the transient response for the conditions above described. Thus, the first currents to arrive of necessity carry information as to the signal impressed so that the amplifier sends out a copy of the signal wave form applied at the sending end, and, when the main body of the transmitted signal arrives later and appears at the input to the amplifier, it just is not amplified.

This concept may be made more readily apparent from consideration of the transient solution of a simple system, as for example, the system shown in Fig. 3 illustrative of the procedure of correcting phase distortion of a line by terminating it in a feedback amplifier having its β -circuit a replica of the line. (In general, the application of a voltage in a circuit results in a forced response and, in addition, natural or free responses. These free responses are considered the transient response. In other words, the total current flowing is the sum of the forced response or steady state plus the transient or free response. In evaluating transient response, as in determining the steady state in my Patent 2,102,671, mentioned above, the finite velocity of propagation around the $\mu\beta$ -path has not been taken into account. This tacitly assumes an equivalent circuit involving lumped constants treated in accordance with conventional circuit theory. It should be appreciated that conditions may be encountered in practical applications where it will not be feasible to neglect the finite velocity of propagation. It has further been assumed that all parts of the system are linear and the values of all circuit elements, resistance, inductance and capacitance, are independent of frequency.) Fig. 3A shows the system of Fig. 3 without the corrective feedback amplifier whose equivalent circuit is given in Fig. 3. The system without the feedback amplifier comprises an inductance in series with two resistances. For the system of Fig. 3 the transients of the line circuit (which would also be the transients in $Z_L=R/2$ of Fig. 3A) and the transients of the feedback amplifier can be determined separately for the reason that the grid impedance is assumed to be infinite and so does not couple the two meshes.

Provided that μ is not zero and assuming there is no other coupling path (thus assuming as zero the current usually neglected) between

the input and output of the amplifier, then it can be shown that for the line transients or free response of the line circuit, $\mu\beta$ is infinite and therefore the line transients are not amplified by the feedback amplifier. Referring to the output of the amplifier which depends upon μV , the transient that was characteristic of the line circuit, which in this case is a transient characteristic of a resistance in series with an inductance, has disappeared and in its place is a transient that is characteristic of the entire feedback loop. In this simple case, its rate of decay is increased directly as the value of $(1-\mu\beta)$ for zero frequency. Thus, the line circuit transient has vanished and the amplifier transient substituted can be made as short in duration as desired merely by increasing $\mu\beta$, but its magnitude relative to the steady state input cannot be altered. Results of computations which took R as 1200 ohms, L as 0.2 henry, and μ as $-2000+j0$, are given in Figs. 3B, 3C and 3D for an applied signal voltage $E(t)$ taken as a telegraph dot applied for 150 microseconds, these figures showing this applied signal and the computed value of signal received for this applied signal, with and without the corrective feedback amplifier. Fig. 3B shows this applied signal. Fig. 3C shows the received current i_L , i. e., the current received from the line, as computed for the case in which the corrective feedback amplifier is not used, i. e., the case of Fig. 3A. Fig. 3D shows the negative of the received current, $-i_L$, with the corrective feedback amplifier in circuit, as in Fig. 3, or, in other words, except for a reversal in signal, shows the current received by the load impedance, $Z_L=R/2$. In the case of Fig. 3, with the specific circuit constants given above the (computed) negative of the received current, $-i_L$, builds up to 0.95 of its steady state value in one microsecond. Likewise, it takes but one microsecond to similarly reduce the current.

Fig. 3E shows the free response of the line, the forced response of the line, and the total current delivered by the line, this latter current being the sum of the other two, that is, the sum of the forced response or steady state and the transient or free response. This figure indicates how, since the amplifier gain is zero for the transient of the line, the only portion of the input to the amplifier from the line that is amplified or appears in amplified form in the amplifier output is the steady state or forced response.

A point to note in connection with Fig. 3D is that with the corrective feedback amplifier the output wave is practically undistorted, that is, of practically the same form as $E(t)$, (the applied voltage shown in Fig. 3B), and, furthermore, the extent to which it is distorted can be made less than any preassigned value merely by increasing $\mu\beta$. The example presented also gives a physical concept of how, at the beginning of the pulse, although the input to the amplifier is practically zero, the output current jumps up as rapidly as desired and starts right off in its steady state or undistorted form, and, at the end of the pulse, although the voltage persists across the input to the amplifier for a long time after the excitation at the sending end of the line has been made zero, the output of the amplifier immediately drops to zero as quickly as desired provided $\mu\beta$ is made sufficiently large. The physical concept is that by making the β -circuit a copy of the line circuit, the free or

transient response of the β -circuit is the same as that of the line circuit, and because $\mu\beta = -\infty$ to the free or transient response of the β -circuit, the line transients, which in this illustration are the source of the type of distortion under consideration, are not amplified. The feedback amplifier, however, does set up its own transients, both at the beginning and at the end, and the practical duration of these amplifier transients is reduced by increasing $|\mu\beta|$.

A corrective passive network to take the place of the corrective feedback amplifier in such a system would have to give an effect equivalent to insertion of a negative inductance of value $-L$ and zero resistance, and do so over a broad band of frequencies, especially if, for the case of the amplifier, $\mu\beta$ be increased and the duration of the pulse consequently shortened.

If, for a system comprising an amplifier with $\mu\beta \gg 1$ and with the β -circuit of the amplifier a replica of the line or circuit ahead of the amplifier, the transmission from the source to the amplifier input were β and the transmission from the amplifier input to the amplifier output were

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

the over-all transmission from source to amplifier output would be

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

and this would correspond to perfect transmission at infinite speed. Practically, the speed is limited to that corresponding to a time extending from the instant a voltage is applied at the sending end of the line to the instant any resulting voltage, no matter how small, appears at the amplifier input, plus the electron transit time required for electrons to travel from the cathode to the plate of the tube, etc. When a force or excitation is suddenly applied to the sending end of the line or circuit ahead of the amplifier the result is a transient and a steady state. With the β -circuit of the amplifier a replica of the preceding line or circuit, the amplifier positively does not amplify the transient at all, because for the transient or free response $\mu\beta$ is infinite. There is a fillet or delay in building up of the signal output delivered by the feedback amplifier and also in cessation of the signal. This is the transient of the $\mu\beta$ -loop if it be opened (and properly terminated at each side of the opening) divided by $(1-\mu\beta)$. Therefore by making $\mu\beta$ as large as required this effect can be caused to be less than any arbitrarily chosen value. Therefore the corrective feedback amplifier reduces the time of transmission or speeds up transmission and reshapes the signal. The speed of propagation or transmission of the signal is the speed with which the first current makes its appearance in response to the excitation produced at the source (the output of the preceding repeater or input to the line). This speed is independent of the wave form of the excitation. The speed of all frequencies is made equal to this value, whereas present practice slows transmission down to a speed slower than the slowest velocity of any frequency in the band. (In a multiplex or multichannel system the speeds of the slow channels are increased to the speed of the fastest part of the fastest channel, whereas present day practice slows down the fastest to equal the slowest part of the slowest and then adds some additional delay besides.) Adding loading coils does not alter the time required for

a small current to first make its appearance at the receiving end, or in other words, adding lumped positive or negative inductance does not affect the speed of the system being described; whereas it is a matter of common experience that lumped loading and the methods of present practice greatly slow down the speed.

The amplifier reshapes the output signal so as to agree with the voltage or excitation E at the sending end of the line or circuit ahead of the amplifier (as indicated by Fig. 3D, for example); and a most remarkable property (due to the feedback action) is that it does this notwithstanding the fact that the input voltage applied to it may have at all times a wrong value. It nevertheless delivers signals of the proper wave form to the outgoing circuit before the wave it receives over the line at its input has attained the steady state or the wave form of the excitation E ; and it stops delivering output to the outgoing circuit when the excitation E at the sending end of the line stops. It will stop thus even though a transient due to the excitation E may appear across the input of the amplifier for a time after E is short-circuited lasting a thousand times as long as E lasted; and though the amplifier correctly refuses to amplify this transient wave it meanwhile will amplify with proper wave form any waves it should that may be applied at the sending end of the line during the time this transient appears across the amplifier input.

In the case of a multistage amplifier, it can be shown from consideration of the transient solution that, with feedback, all of the transient components appear in each of the meshes, that is, everywhere in the $\mu\beta$ -path. For example, it can be shown from evaluation of the transient response in the case of the amplifier of Fig. 4 with specific constants and with the applied wave a cosine wave of frequency approximately at the middle of the transmission or pass-band of the amplifier, that neither of the natural responses (free responses) of the amplifier without feedback appears in the amplifier with feedback. Instead, two new pairs of terms appear. One of them is a very high frequency oscillatory wave and the other a very low frequency oscillation. They both lie outside the used frequency band of the amplifier. The amplifier has shunt inductance L_2 and capacity C_2 in its first interstage circuit and has shunt inductance L_3 and capacity C_3 in its second interstage circuit. Being of configuration generally similar to that of the amplifier of Fig. 57 of my Patent 2,102,671, it requires no detailed description. Either with or without feedback it is possible for the transient response to exceed the forced response in magnitude at certain parts of the circuit. Notably, in the case of transient solution of the circuit of Fig. 4 calculated for the specific constants referred to above, at the grid of the first tube, with feedback the value of one of the free response terms exceeded the forced response by about 55 decibels. (This was with the capacity of condenser 12 equal to zero, or in other words with the condenser absent.) Considering that the excitation was in the neighborhood of mid-band frequency, the transient response evaluated is indicative of what might occur due to abrupt changes in signal input. Consequently, in a high power amplifier care should be taken to avoid a condition of transient overloading of the input tube of this magnitude because a 55-decibel transient overload, if the tube is to handle it,

corresponds to a power ratio of 316,000:1, and to increase the power capacity of even the second from the last stage by such an amount as this may become a very practical consideration. However, the calculation indicated that there was no overloading of the last tube, 55 decibels being the amount of mid-band frequency feedback so that the transient on the grid merely equaled the voltage normally fed back. As indicating that this overloading of the input tube by transients depends upon the steepness of the applied impulse, it is noted that when the suddenly applied voltage was assumed a sine wave instead of a cosine wave, the recomputed value of the free response across the grid of the first tube of the three-stage amplifier exceeded the forced response by 26 decibels instead of 55 decibels.

To avoid overloading of the first tube by transients produced by frequencies in the transmitted band it is desirable to (1) maintain the value of $\mu\beta$ considerably different from $1 \angle 0$, (i. e., keep the polar plot of $\mu\beta$ outside of a circle of considerable radius centered at the point $1, 0$), and (2) at the same time provide a suitable capacitance across the grid and cathode, for example, by adding a condenser 12 that renders the capacitance across the grid and cathode just sufficient to prevent undue overloading of the first tube by the transients. Fulfilling condition (1) does not affect the amplitude of the transient, but reduces its duration so that, with condition (2) also fulfilled the transient cannot last long enough to charge the capacity across the grid and cathode to a voltage so high as to overload the tube. A still further precaution that may be advisable for avoiding the transient overloading is to maintain the phase of $\mu\beta$ as nearly as practicable between 90 and 180 degrees, i. e., keep the polar plot of $\mu\beta$ in the second and third quadrants as nearly as practicable.

With feedback, the original transients present without feedback are eliminated and new ones are produced which are characteristic of the feedback amplifier. Of course, if the amount of feedback is not large, the new ones might not differ appreciably from the old ones because in the limit, with no feedback, $\mu\beta=0$ and the two transient responses are alike. However, in the case of the feedback amplifier, all of the transient terms appear in varying degree in every mesh of the amplifier, whereas in the non-feedback amplifier the transient terms appear only in the mesh that generates its particular transient term or terms and in succeeding meshes.

As in the case with feedback, without feedback the first interstage circuit generates a transient. That transient is amplified and appears in the output. In the second interstage mesh, a second transient is produced which in turn is likewise amplified and appears in the output. However, neither appears in the input.

On the other hand, with feedback it is impossible to ascribe any particular transient term to any particular reactance element or group of elements and the complete transient performance of the amplifier depends upon the entire number of reactances in the $\mu\beta$ -path. This, therefore, differs from the non-feedback circuit where the transient response depends upon the free response of each mesh and each particular free response can be definitely ascribed to the mesh so producing it.

Fig. 5 shows a system comprising a source 13 of telegraph signals for transmission over a sub-

marine cable circuit 14 and amplification at the receiving end of the cable by negative feedback amplifier 15, which may be a corrective amplifier having $\mu\beta \gg 1$ and having its β -circuit 16, as in the case of Fig. 2 or 3, a replica of the cable circuit, or a network with the same indicial transfer admittance as the cable circuit, or a network with the same attenuation-frequency and phase-frequency characteristics as the cable circuit but a relatively short transmission time. When the corrective feedback amplifier can speed up the telegraph transmission over the cable and reshape the signals at the receiving end of the cable, for actuation of the telegraph receiver 17, in accordance with the principles set forth above, (it being noted that the wave shown in Fig. 3C as a signal received without the corrective feedback amplifier may be considered as giving an optimistic picture of the actual telegraph problem).

In a practical signaling system transmitting, for example, over a submarine cable as in Fig. 5, or over a land cable as in Fig. 2, (unless the corrective feedback amplifier is to be allowed to oscillate with the oscillation amplitude or amplitudes maintained below the overload value for the amplifier) the matter of making the amplifier satisfy Nyquist's rule for stability needs careful consideration, especially when the β -circuit of the amplifier is made a replica of the cable or is given an indicial admittance equal to that of the cable. This is true for the case of the submarine cable, especially if the submarine cable is a long cable, as for instance a transoceanic cable; and it is true for the case of the land cable, even though the land cable may be relatively short. To facilitate compliance with Nyquist's rule, instead of one amplifier with the propagation of its β -circuit adjusted to the value β , two amplifiers may be used in tandem, at the receiving end of the cable, for example as shown at 21 and 22 in Fig. 6, with the products of the propagations of their β -circuits equal to β , which may equal the propagation of the cable. For example, designating the μ and β for one of the two amplifiers as μ_1 and β_1 , and designating the μ and β for the other of the two amplifiers as μ_2 and β_2 , then, with $\mu_1\beta_1 \gg 1$ and $\mu_2\beta_2 \gg 1$, the amplification of the two amplifiers in tandem will be

$$\left(\frac{\mu_1}{1 - \mu_1\beta_1} \right) \left(\frac{\mu_2}{1 - \mu_2\beta_2} \right) \doteq \frac{1}{\beta_1\beta_2}$$

and by making $\beta_1\beta_2 = \beta$, the proper corrective effect is obtained. Obviously, the number of tandem amplifiers can be extended to n , e. g.,

$$\beta_1\beta_2\beta_3 \cdots \beta_n = \beta \quad (1)$$

Then, (compared to construction of a single amplifier with β of proper value to make the amplifier produce the desired corrective effect yet satisfy Nyquist's rule) it is relatively easy to so make β_1 and β_2 , etc., as to satisfy (1) and at the same time make $\mu_1\beta_1$, $\mu_2\beta_2$, etc., obey Nyquist's rule, since the total phase shift required in the β -circuits can be divided between the β -paths of the tandem connected amplifiers. In Fig. 6, the signal transmitter is shown at 25, the transmission line at 26, and the signal receiver at 27. The signal transmitter 25 may be a telegraph transmitter as in Fig. 5, with circuit 26 a submarine telegraph cable such as that of Fig. 5, for example. Or, as a further example, the signal transmitter 25 may be a source of voice currents, with line 26 a telephone line such as that of Fig. 2.

In systems in which the β -circuit of the corrective amplifier is a replica of the line circuit, as for example in the system of Fig. 5 or in the system of Fig. 2 with the amplifier feedback path made a replica of the line circuit, the β -circuit of the amplifier may be made to reduce effects of non-linearity of the line circuit or cable, for example cable modulation due to loading, as, for instance, periodic loading or permalloy continuous loading, or due to magnetic shielding. Such modulation may be troublesome, especially in the case of broad-band transmission. It can be shown that, when the cable or line circuit is non-linear, if the β -circuit of the amplifier is made just like the cable and similarly loaded by signals, the modulation of the cable or line circuit, referred to the output of the amplifier, is multiplied by

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

and so is greatly reduced when $\mu\beta \gg 1$. The same method of compensating for line or cable modulation is readily applicable in systems in which the compensating line or cable that is just like the transmission line or cable is divided, with the portions forming the β -circuits of tandem connected corrective amplifiers, for example in Fig. 6.

What is claimed is:

1. A signaling system comprising a signal transmission line for transmitting signals of given frequency range, loading elements spaced along said line for periodically loading said line, an amplifier connected to receive and amplify signals from said line, and means for preventing said loading elements from increasing the transmission time of said line comprising a feedback path for said amplifier having its characteristics of attenuation versus frequency and phase shift versus frequency the same as those of said periodically loaded line over the frequency range of the signals and forming with said amplifier a negative feedback loop having a loop transfer factor of larger order of magnitude than unity.

2. A wave translating system comprising a lump loaded signal transmission line for transmitting signals of given frequency range, an amplifier for receiving and amplifying signals from said line, and means for preventing the loading elements of said line from increasing the transmission time of said line comprising a negative feedback path for said amplifier having its transmission time of smaller order of magnitude than the transmission time of said lump loaded line, said path having the same attenuation-frequency and phase-frequency characteristics as said lump loaded line over the frequency range of the signals, and said path forming with said amplifier a feedback loop having a loop transfer factor of larger order of magnitude than unity.

3. A transmission system comprising a signaling line whose length is many times greater than the wave-length of the lowest signal frequency, and an amplifier for receiving and amplifying signals from said line having a negative feedback path forming therewith a feedback loop with loop transfer factor of larger order of magnitude than unity, said path having its transmission time of smaller order of magnitude than the transmission time of said line and consisting essentially of a lattice network of one section

whose four elements are two impedances each equal to the short-circuit impedance of half the length of the line and two other impedances each equal to the open-circuit impedance of half the length of the line.

4. In combination, a lump loaded signal transmission line whose length is many times the wave-length of the lowest signal frequency, and an amplifier for receiving and amplifying signals from said line having a feedback path forming therewith a negative feedback loop whose loop transfer factor has a larger order of magnitude than unity, said path having its transmission time of smaller order of magnitude than the transmission time of said loaded line and consisting essentially of a lattice network of one section whose four elements are two impedances each equal to the short-circuit impedance of half the length of the lump loaded line and two other impedances each equal to the open-circuit impedance of half the length of the lump loaded line.

5. A signaling system comprising a source of telegraph signals, a loaded transmission line for said signals, and an amplifier connected to the receiving end of said line for amplifying and reshaping the transmitted signals and increasing their speed of transmission comprising a negative feedback path with its transmission time small compared to that of said line and with its attenuation-frequency and phase-frequency characteristics like those of said line over a frequency range including the essential frequency range of the signals, said amplifier with said feedback path having its loop transfer factor of larger order of magnitude than unity.

6. A signaling system comprising a source of telegraph signals, a loaded circuit connected to said source for transmitting said signals, an amplifier connected to the receiving end of said circuit for amplifying the transmitted signals, a telegraph receiver for receiving the amplified signals, and means for causing said amplifier to reshape the transmitted signals and increase the speed of their transmission from said source to said receiver comprising a feedback path for said amplifier having the same indicial admittance as said loaded circuit and forming with said amplifier a negative feedback loop whose loop transfer constant has greater order of magnitude than unity.

7. A signaling system comprising a source of signals, a loaded circuit connected thereto producing modulation due to non-linearity of elements of said circuit, an amplifier connected to the receiving end of said circuit for amplifying signals received thereby from said circuit, and a negative feedback path for said amplifier comprising a like loaded circuit for compensating for said modulation.

8. A wave translating system comprising a signal transmission line, and connected to said line at the receiving end thereof, a plurality of amplifiers in tandem for amplifying signals received thereby from said line, each of said amplifiers having a feedback path, the propagations of said feedback paths having their product equal to the propagation of said line and each of said feedback amplifiers having its loop propagation of larger order of magnitude than unity in the signal frequency range.

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