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H. WHITTLE ET AL

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ELECTRICAL TRANSMISSION SYSTEM

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FIG. 2.

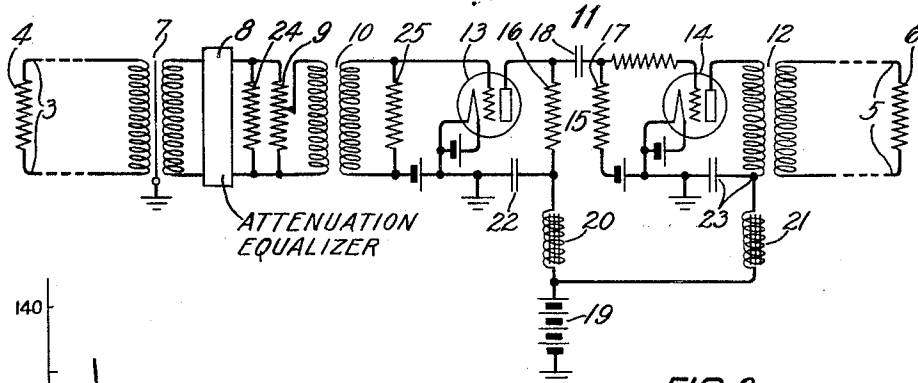


FIG. 3.

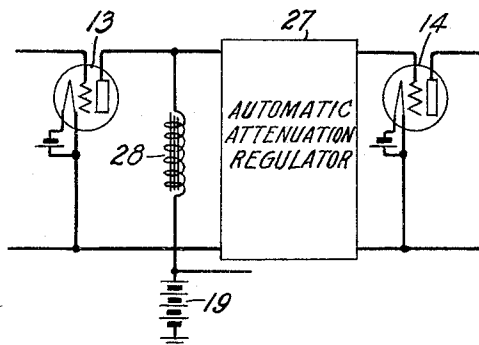
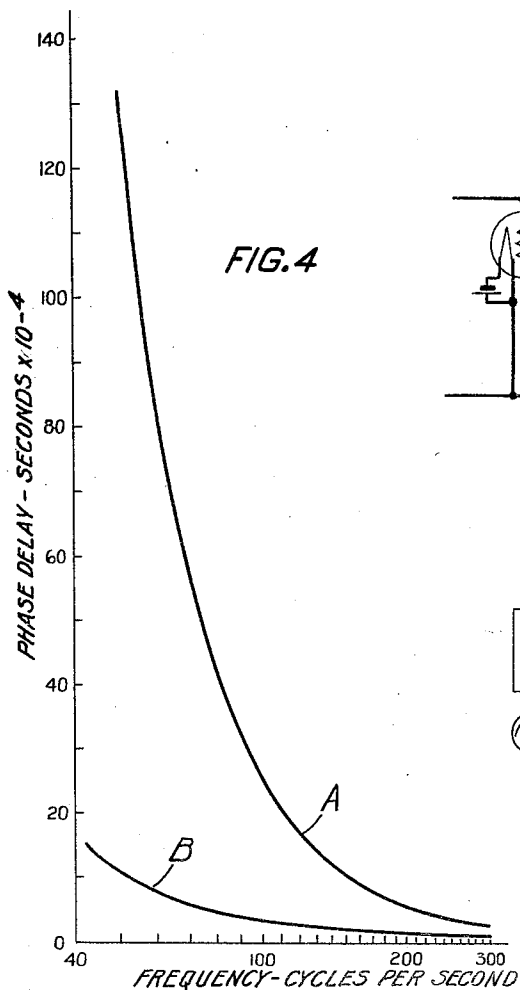
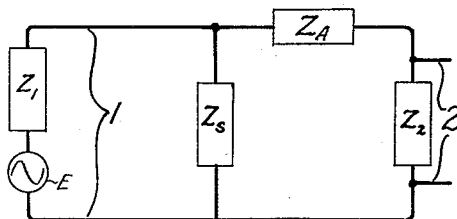


FIG. 1.



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ELECTRICAL TRANSMISSION SYSTEM

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This invention relates to electrical transmission and particularly to reducing the distortion of different frequency components incident to the transmission of electrical currents or waves through transmission elements such as transformers and the like.

The invention has particular reference to systems or apparatus utilized for transmitting electrical signaling currents or waves comprising a wide band of frequencies, such as those included in the voice and music frequency range.

An object of the invention is to minimize the distortion of signaling currents in transmission circuits due to differential retardation therein of the different frequencies.

In the transmission of signaling currents within the speech or music frequency range over transmission lines, two types of distortion are encountered—first, the components of the various frequencies may be attenuated over the line in different degrees, and second, the frequency components may be retarded differently by the line.

The first type of distortion, i. e., unequal attenuation of different frequencies, may be overcome by the use of an attenuation equalizer, this expedient having been brought to a high state of development in theory and practice. The second type of distortion, i. e., unequal retardation of the different frequencies is of relatively small magnitude and has not required correction in ordinary commercial telephone systems in the past in which it has sufficed to transmit a relatively narrow range of frequencies.

The art of wire broadcasting of speech and musical programs has now developed to the point where it has become desirable to transmit over telephone cables for long distances—say, 750 miles or more—frequencies ranging from about 50 to 5000 cycles per second or more. To obtain efficient transmission of signaling currents over long telephone cables it is common practice to insert loading

elements, such as loading coils, at frequent intervals along the cable. It is also necessary to utilize repeaters at frequent intervals, usually every 50 miles, along the cables to compensate for the attenuating effect of the cable on the signaling frequencies transmitted. Each of these repeaters usually comprises a plurality of transmission devices including reactive elements, such as transformers, capacitive coupling networks, retard coils, etc. Each of the loading elements in the line and the reactive transmission devices in the repeater circuits contribute to the second type of distortion, i. e., unequal retardation at different frequencies.

In a high quality transmission system in which signaling waves comprising a wide band of frequencies are to be transmitted over a telephone cable of such length that many repeaters connected in tandem along the cable are necessary to compensate for the attenuation in the transmitted waves, the phase distortion produced by the system in the transmitted waves becomes of increasing importance. In such a system, the phase distortion produced in the transmitted waves of the lower frequencies is largely due to the repeaters, and the phase distortion in the transmitted waves of the higher frequencies is due to the cable. Corrective networks of well-known design may be satisfactorily utilized in the system to reduce the phase distortion in the waves of high frequencies to amounts within the allowable limits. It has been found, however, that it is uneconomical with previously existing repeaters from a transmission standpoint to use such corrective networks to introduce the amount of phase distortion correction required in the case of the transmitted waves of low frequencies. In high quality systems, it is therefore desirable that each of the repeaters used therein be designed so as to introduce a minimum amount of phase distortion in the transmitted waves of low frequencies.

The distortion produced by the repeaters on the waves of low frequencies transmitted therethrough is due to the difference in phase delay between the waves of different frequencies. As the phase delay produced by the repeaters on waves of high frequencies is usually negligible, the phase distortion in waves of low frequencies may be considered as directly proportional to the phase delay.

In the development of the present invention, formulæ have been derived giving the phase delay introduced by each of the types of transmission networks most used in repeater circuits, in terms of the constants of the networks and the impedances of the circuits to which they are connected. These formulæ may be utilized in predetermining the type of network which will be most suitable for any particular phase delay requirement or in determining the phase delay which will be introduced by a given network of known constant.

A feature of the invention relates to the design of the reactive networks utilized in telephone repeaters including repeating coils, input transformers, output transformers retardation coils and capacitive coupling networks, for minimum phase delay, so as to obtain for a repeater the lowest overall phase delay consistent with the desired requirements as to uniform transmission and high amplification.

Transmission networks for repeater circuits have been designed in accordance with the principles of the invention to produce such low phase delay on the repeated currents that a large number—say, 15 or more—of these repeaters may be operated in tandem in a telephone system 750 miles or more in length without introducing an overall phase delay sufficient to cause appreciable quality distortion in musical programs comprising a range of frequencies from 50 to 5000 or more cycles per second transmitted over the system.

The invention will be clear from the following description when read in connection with the accompanying drawing in which,

Fig. 1 shows a simplified circuit equivalent to that of any transmission network of the types commonly used in repeater circuits, and contributing to the phase delay in waves repeated thereby;

Fig. 2 shows a schematic diagram of a repeater of the type which has been used in long high quality wire broadcasting systems;

Fig. 3 shows a modification of a portion of the repeater circuit of Fig. 2 required when an automatic attenuation regulator is used therewith; and

Fig. 4 shows curves illustrating the improvement as to phase delay distortion which has been obtained in the repeater circuit of Fig. 2 by designing the transmission net-

works thereof in accordance with the principles of the invention.

The amount of phase distortion introduced in a circuit by a transformer or other transmission network is indicated at any frequency by the slope of the phase shift-frequency characteristic at that frequency, assuming the network has a constant attenuation, where phase shift is defined as the change in phase angle of the current in the outgoing circuit due to the insertion of the network, or, in the case of the input circuit of a vacuum tube, the phase angle between the voltage of the source and the voltage applied to the grid due to the network. The phase delay introduced by the network may be expressed in time units at any frequency as

$$\frac{d\Phi}{d\omega}$$

seconds, where Φ is the phase shift and ω is 2π times the frequency. In specifying the requirements as to the limiting phase distortion of a transmission network, it is customary to state that the phase delay produced by the network in the transmitted waves should not be greater than a given fraction of a second at a given frequency, a convenient unit of time being $1/10,000$ of a second.

For trial designs and preliminary phase delay computations a transformer, retardation coil, or other elements in a repeater with their associated circuits, may be represented by an equivalent simplified network, the proper choice of which depends on the types of elements, the frequency of the currents to be repeated, and other conditions of use. For example, a transformer operating between two equal resistances may be approximately represented at low frequencies by a single shunt inductance connected across two resistances or at some higher frequency by a single inductance connected in series between the two resistances. For more exact computations, a more complicated network consisting of more than one element, of resistance, inductance and capacity will be needed to represent the transformer conditions, and the phase delay formulæ become correspondingly more involved.

In the simplified diagram of Fig. 1, the box Z_1 represents the net impedance of an electrical circuit 1 through which a current is driven by a source of electromotive force of value E shown in series therewith, this source of electromotive force for simplification being assumed to be an alternating current generator having zero internal impedance. The box Z_2 represents the impedance of a load circuit 2 into which a current is introduced from circuit 1 by means of a coupling network, which may be a transformer or other type of network, and which in Fig. 1 is represented by an equivalent simplified network of impedance elements comprising

shunt impedance elements indicated by the box Z_s , and series impedance elements indicated by the box Z_A . The series and shunt impedances in the boxes Z_A and Z_s may comprise any required combination of resistance, inductance and capacity to simulate the characteristics of the transmission network represented thereby.

The method of developing formulæ for the phase delay of transmission networks of the different types used in repeater circuits may be shown by the following typical examples.

The first case which will be explained will be that where the transformer or other network and its terminating impedances may be represented by a single shunt impedance Z_s operating between two terminating impedances Z_1 and Z_2 corresponding to the impedance or the incoming and outgoing circuits coupled by the network. Referring to Fig. 1, in this case, the series impedance Z_A will be zero. Prior to the insertion of the transmission network Z_s , the current I_1 in the output circuit of impedance Z_2 due to the voltage E in series with the input circuit of impedance Z_1 is

$$I_1 = \frac{E}{Z_1 + Z_2} \quad (1)$$

When the shunt impedance Z_s is inserted, the new output circuit current I_2 is

$$I_2 = \frac{EZ_s}{Z_1 Z_2 + Z_1 Z_s + Z_2 Z_s} \quad (2)$$

The ratio of the two currents is

$$\frac{I_2}{I_1} = \frac{Z_s(Z_1 + Z_2)}{Z_1 Z_2 + Z_1 Z_s + Z_2 Z_s} \quad (3)$$

In the simplest case, where the shunt impedance is a pure inductive reactance JX_L or a pure capacitive reactance $-jX_C$, where X_L equals $2\pi fL$ and X_C equals

$$\frac{1}{2\pi fC}$$

with the frequency f expressed in cycles per second, the inductance L in henries, and the capacitance C in farads, and where the input and output impedances Z_1 and Z_2 are pure resistances R_1 and R_2 , respectively, expressed in ohms, the current ratio becomes for the inductive shunt

$$\frac{I_2}{I_1} = \frac{JX_L(R_1 + R_2)}{R_1 R_2 + JX_L(R_1 + R_2)} \quad (4)$$

or, rationalizing the denominator,

$$\frac{I_2}{I_1} = \frac{(X_L)^2(R_1 + R_2)^2 + JX_L(R_1 + R_2)(R_1 R_2)}{(R_1 R_2)^2 + (X_L)^2(R_1 + R_2)^2} \quad (5)$$

and for the capacitive shunt

$$\frac{I_2}{I_1} = \frac{(X_C)^2(R_1 + R_2)^2 - JX_C(R_1 + R_2)(R_1 R_2)}{(R_1 R_2)^2 + (X_C)^2(R_1 + R_2)^2} \quad (6)$$

The phase shift Φ introduced by the net-

work in the transmitted waves is the angle between I_2 and I_1 , the tangent of which is expressed by the ratio of resistance to reactance at frequency f . In the case of the inductive shunt,

$$\tan \Phi = \frac{R_1 R_2}{(R_1 + R_2)X_L} = \frac{R_1 R_2}{(R_1 + R_2)\omega L} \quad (7)$$

and in the case of the capacitive shunt,

$$\tan \Phi = -\frac{R_1 R_2}{(R_1 + R_2)X_C} = -\frac{R_1 R_2 \omega C}{R_1 + R_2} \quad (8)$$

The phase delay introduced by the network, as noted above, may be defined as the rate of change of phase shift with frequency (assuming a network of constant attenuation), or

$$\frac{d\Phi}{d\omega},$$

which is expressed in seconds. For the pure inductive and capacitive shunt the phase delays are, respectively,

$$S = \frac{d\Phi}{d\omega} = -\frac{(R_1 R_2)(R_1 + R_2)L}{[(R_1 + R_2)\omega L]^2 + (R_1 R_2)^2} \text{ seconds} \quad (9)$$

and

$$S = \frac{d\Phi}{d\omega} = -\frac{(R_1 R_2)(R_1 + R_2)C}{(R_1 + R_2)^2 + (R_1 R_2 \omega C)^2} \text{ seconds} \quad (10)$$

where negative time denotes a delay of I_2 with respect to I_1 .

Similarly, for the case in which the coupling network may be represented by an impedance Z_A , comprising a pure inductive or capacitive reactance in series with terminating resistance R_1 and R_2 , the shunt impedance Z_s in this case being infinite,

$$I = \frac{E}{Z_1 + Z_2 + Z_A} \quad (11)$$

In the case of the series inductive and series capacitive reactance, respectively,

$$\frac{I_2}{I_1} = \frac{Z_1 + Z_2}{Z_1 + Z_2 + Z_A} = \frac{R_1 + R_2}{R_1 + R_2 + JX_L} = \frac{(R_1 + R_2)^2 - JX_L(R_1 + R_2)}{(R_1 + R_2)^2 + (X_L)^2} \quad (12)$$

and

$$\frac{I_2}{I_1} = \frac{R_1 + R_2}{R_1 + R_2 - JX_C} = \frac{(R_1 + R_2)^2 + JX_C(R_1 + R_2)}{(R_1 + R_2)^2 + (X_C)^2} \quad (13)$$

The phase shift for the series inductive reactance is

$$\tan \Phi = -\frac{X_L}{R_1 + R_2} = -\frac{\omega L}{R_1 + R_2} \quad (14)$$

and that for the series capacitance is

$$\tan \Phi = \frac{X_C}{R_1 + R_2} = \frac{1}{(R_1 + R_2)\omega C} \quad (15)$$

The phase delay of the series inductance is

$$S = \frac{d\Phi}{d\omega} = -\frac{L(R_1 + R_2)}{(R_1 + R_2)^2 + (\omega L)^2} \text{ seconds} \quad (16)$$

which for small delays simplifies to

$$S = -\frac{L}{R_1 + R_2} \quad (17)$$

and that for the series capacitance is

$$S = \frac{d\Phi}{d\omega} = -\frac{C(R_1 + R_2)}{(R_1 + R_2)^2(\omega C)^2 + 1} \text{ seconds} \quad (18)$$

In the case where the transmission network and its terminating impedances may be represented by a shunt inductance L between terminating resistances R_1 and R_2 , the inductance which is necessary in order to meet a given delay requirement of S seconds at a given frequency

$$f = \frac{\omega}{2\pi}$$

is obtained from equation (9) for the phase delay of the inductive shunt as follows:

$$[(R_1 + R_2)^2 \omega^2 S] L^2 - [(R_1 R_2)(R_1 + R_2)] L + [(R_1 R_2)^2 S] = 0 \quad (19)$$

$$L = \frac{(R_1 R_2)(R_1 + R_2) \pm (R_1 R_2)(R_1 + R_2) \sqrt{1 - 4\omega^2 S^2}}{2\omega^2 S(R_1 + R_2)^2} = \frac{(R_1 R_2)(1 \pm \sqrt{1 - 4\omega^2 S^2})}{(R_1 + R_2)2\omega^2 S} \quad (20)$$

In the usual case where $[4\omega^2 S^2]$ is small with respect to unity, the expression

$$\sqrt{1 - 4\omega^2 S^2}$$

is approximately equal to unity and the value of L simplifies to

$$L = \frac{R_1 R_2}{(R_1 + R_2)\omega^2 S} \quad (21)$$

which is the minimum shunt inductance which may be used in order to meet the maximum phase delay requirement of S seconds.

The following equations may be similarly obtained for the maximum series inductance L , maximum shunt capacitance C , or the minimum series capacitance c which may be used in the coupling network without exceeding the maximum delay requirement of S seconds at the frequency

$$f = \frac{\omega}{2\pi}$$

$$L = \frac{(R_1 + R_2)(1 \pm \sqrt{1 - 4\omega^2 S^2})}{2\omega^2 S} \quad (22)$$

which for small (normal) values of series inductance simplifies to:

$$L = (R_1 + R_2)S \quad (23)$$

$$C = \frac{(R_1 + R_2)(1 \pm \sqrt{1 - 4\omega^2 S^2})}{2R_1 R_2 \omega^2 S} \quad (24)$$

which for small (normal) values of shunt capacity simplifies to:

$$C = \frac{(R_1 + R_2)S}{R_1 R_2} \quad (25)$$

and

$$C = \frac{1 \pm \sqrt{1 - 4\omega^2 S^2}}{2(R_1 + R_2)\omega^2 S} \quad (26)$$

which for normal values of series capacity simplifies to:

$$C = \frac{1}{(R_1 + R_2)\omega^2 S} \quad (27)$$

For the case in which the coupling network and its terminating impedances may be represented by a shunt reactance L operating between a resistive impedance R_1 and a capacitive impedance C_1 , as for example, the case of an input transformer working from a line into a vacuum tube, the phase delay is obtained from the phase shift between the line voltage and the voltage applied to the grid caused by the transformer, as follows:

$$\frac{E_2}{E_1} = \frac{Z_2 Z_S}{Z_1 Z_2 + Z_1 Z_S + Z_2 Z_S} \quad (28)$$

the phase shift is

$$\tan \Phi = \frac{R_1(1 - \omega^2 L C_1)}{\omega L} \quad (29)$$

the phase delay is

$$S = \frac{d\Phi}{d\omega} = -\frac{R_1(1 + \omega^2 L C_1)}{\omega^2 L} \quad (30)$$

and the minimum shunt inductance which may be used in order to meet the maximum phase delay requirement of S seconds is

$$L = \frac{R_1}{\omega^2(S - C_1 R_1)} \quad (31)$$

In Fig. 2 is shown a schematic circuit of a type of repeater to which the invention is applicable and which has proved successful in a high quality cable broadcasting system of approximately 750 miles in length in providing uniform gain throughout the length of the cable for transmitting speech and music programs comprising frequencies occupying a range from 50 cycles per second to 5000 cycles per second or more. This system comprises about 15 repeaters in tandem spaced at intervals of approximately 50 miles along the cable. As shown in Fig. 2, each of these repeaters comprises (connected in tandem between an incoming line 3, the impedance of which looking from the repeater may be represented by the resistance 4, and an outgoing line 5, the impedance of which looking from the repeater may be represented by the resistance 6), a repeating coil 7, an attenuation equalizer 8, a gain adjusting po-

tentiometer 9, an input transformer 10, a two-stage amplifier 11 and an output transformer 12.

The amplifier 11 comprises two vacuum tubes 13 and 14 coupled by the network 15 comprising resistances 16 and 17 and condenser 18. The vacuum tubes 13 and 14 which are of the well-known three-electrode type have the usual filament heating and grid biasing batteries. The tubes 13 and 14 are supplied with space current from the direct current source 19 through retardation coils 20 and 21, respectively. The by-pass condensers 22 and 23 provide paths for alternating currents in the output circuits of tubes 13 and 14 respectively around the direct current source 19.

The attenuation equalizer 8 is provided for the purpose of equalizing the variations in attenuation with frequency produced in the transmitted waves of the higher frequencies by the preceding section of line, and may be of any suitable design. As for economical reasons the attenuation equalizer 8 is unbalanced, the repeating coil 7 with a grounded shield between its windings is connected between the attenuation equalizer 8 and the balanced cable circuit 3.

The input transformer 10 is designed to have a leakage inductance of such value as to resonate with the combined distributed capacity of its windings and the input capacity of tube 13 at a frequency greater than the upper limit of the band to be transmitted. The resistance 25 in shunt to the secondary winding of input transformer 10 and the combined resistance of resistance 24 and potentiometer 9 effectively in shunt to the primary winding provide the desired matching of impedances, and are relatively proportioned so as to damp the resonance at said upper limiting frequency, thereby providing a flat voltage amplification characteristic over the entire frequency band to be transmitted. This feature is described and claimed in the copending application of H. Whittle, Ser. No. 181,530, filed April 6, 1927, which became Patent 1,752,043, March 25, 1930.

The overall repeater gain characteristic is kept substantially flat (within 0.1TU) over the transmitted frequency band of 50 to 5000 cycles or more by making the increased gain of the input transformer 10 at the high frequencies in the band equalize the transmission losses of the repeating coil 7 and the output transformer 12 at these frequencies. The high inductance of the reactive elements in the repeater at low frequencies necessary for a satisfactory phase delay tends to hold up the gain of the repeater at the low end of the transmitted frequency band to a satisfactory value.

In Fig. 3 is shown schematically a modification of a portion of the circuit of Fig. 2 which has been utilized in another repeater

circuit which otherwise is essentially the same as the repeater circuit of Fig. 2, adapted for automatic regulation of attenuation. In this repeater circuit, an automatic attenuation regulator 27 of the type disclosed and claimed in the Patent No. 1,615,911 issued on February 1, 1927, to H. Nyquist is connected between the vacuum tube stages 13 and 14, and it was necessary to use a retardation coil 28 instead of the condenser-resistance combination 15 of the circuit of Fig. 2 as a coupling between the attenuation regulator 27 and the output of vacuum tube stage 13 to prevent interference with the performance of the attenuation regulator.

As a preliminary step in the design of the reactive apparatus in the repeaters of a high quality transmission system, the maximum phase delay in the transmitted waves which each repeater may introduce is determined in consideration of the length of the transmission system, the number of repeaters therein and the standard of quality desired. In the special cable broadcasting system in which repeaters of the non-regulating type of Fig. 2 and the regulating type modified as shown in Fig. 3 were used, it was desired to transmit waves of frequencies ranging from 50 to 5000 cycles or more over a cable having a length of 750 miles, and it was necessary to utilize therein 15 repeaters spaced at intervals of 50 miles to obtain the required gain and quality throughout the system. The standards of quality which were imposed on this system necessitated that the overall phase delay at 50 cycles per second should not be substantially more than 11.5×10^{-4} seconds per repeater.

The allowable phase delay for each repeater being known this delay must be allotted among the various types of transmission elements so as to keep the total cost of these elements as low as possible. For a first trial, the allowable phase delay is divided equally among the various transmission elements. Each of these elements and its associated circuits may be represented by some modification of the equivalent network of Fig. 1. Having selected the equivalent network which best represents each of the transmission elements a first approximation of the values for the constants of the transmission element for the allotted phase delay may be determined by substituting the allotted value of phase delay in the particular one of the formulae given above applying to that type of equivalent network.

For example, in the circuit of Fig. 2, the repeating coil 7 and its associated circuits may be approximately represented by a shunt inductance operating between two resistances representing respectively the effective resistance 4 of incoming line 3 and the effective resistance looking from the secondary winding of repeating coil 7 towards the attenuation equalizer 8, and the proper value of this in-

ductance in order that the repeating coil will produce the allotted amount of phase delay at a particular frequency may be determined by substituting this delay for S and the values of the terminating resistances for R_1 and R_2 in Equation (21).

The input transformer 10 and its associated circuits may be represented by an inductance in shunt to a resistance representing the equivalent resistance of the circuit connected to the primary winding of the input transformer, and to a capacity representing the input capacity of tube 12, and the value for this inductance to produce the allotted phase delay at a particular frequency may be determined by substituting this delay for S and the values for the terminating resistance and the terminating capacity for R_1 and C_1 , respectively, and the value of ω in Equation (31).

Similarly, the coupling network 15 may be represented by a series capacity connected between two resistances, and the value for this capacity at a particular frequency may be obtained by substituting the allotted phase delay for S , the value of ω , and values of the terminating resistances for R_1 and R_2 in Equation (27).

The output transformer 12 and its associated circuits may be represented by an equivalent network comprising a shunt inductance L equal to the inductance of the primary winding of transformer 12 and a series capacitance equaling in value that of series condenser 23 connected between a resistance R_1 equivalent to that of the output circuit of tube 14 and a resistance R_2 equivalent to that of the outgoing line 5, represented in Fig. 2 by the resistance 6, multiplied by the impedance ratio of transformer 12. The retardation coil 21 need not be considered in connection with output transformer 12, as ordinarily its inductance is of high value and it is by-passed by a large capacity condenser so that its effect on the phase delay is so small that it may be neglected. The phase delay formula for this equivalent network derived in a manner similar to the derivations given above is

$$S = \frac{d\Phi}{d\omega} = -\frac{(R_1 R_2 + L)(2\omega^2 Lc + 1)}{(2\omega^2 Lc - 1)^2 R_1 R_2} \quad (32)$$

A first approximation for the value of inductance L to give the allotted phase delay at a particular frequency may be obtained by substituting the values for S , R_1 , R_2 , ω and c in Formula (32) and solving for L .

The phase delays for the other reactive elements in the repeater circuit of Fig. 2, including the parallel combination of retardation coil 20 and condenser 22, are so small in comparison with those of the particular elements mentioned above that these other elements may be neglected in designing the repeater circuit.

The modified interstage coupling circuit of Fig. 3 may be represented by an equivalent network comprising a shunt inductance L , corresponding to the inductance of retardation coil 28, connected between two resistances R_1 and R_2 , which are respectively the equivalent resistance of the output circuit of tube 13 and the input resistance of the automatic attenuation regulator 27. When R_1 and R_2 are equal the inductance L to give the allotted phase delay at a particular frequency may be obtained by substituting the values of the constants in Equation (21). If the resistances R_1 and R_2 are unequal, the value of this inductance may be obtained by substituting the values of S , R_1 , R_2 and ω in the following equation and solving for L :

$$S = \frac{d\Phi}{d\omega} = -\frac{R_1 R_2 (R_1 + R_2) L}{(R_1 + R_2) \omega L^2 + (R_1 R_2)^2} \text{ seconds} \quad (33)$$

The cost of producing the various transmission elements of the computed constants for this equal allotment of phase delay is then determined, and also the cost of increasing or decreasing the phase delay by changing, that is raising or lowering, the value of the constants for each element, and then a new allotment of the allowable overall phase delay between the various transmission elements is made in accordance with these cost considerations. The new allotted value of phase delay for each element is substituted in the appropriate one of the formulae for the equivalent networks thereof given above and the formulae are solved to obtain the values for the constants of the elements which will give these new values of phase delay at a particular frequency. This process is repeated until a proper balance is obtained between phase delay allotted to each of the various elements and the cost of obtaining these low delays.

By means similar to that described it was determined that the best allotment of allowable phase delay for the various elements in the repeater circuit of Fig. 2 at a frequency of 50 cycles per second would be such that the delay for the repeating coil 7 was 1.15×10^{-4} seconds, for the input transformer 10, 3.00×10^{-4} seconds, for the output transformer 12, 6.20×10^{-4} seconds, and for the other elements contributing to the overall phase delay of the repeater circuit including the coupling network 15, the parallel combination of retardation coil 20 and by-pass condenser 22, and the parallel combination of retardation coil 21 and condenser 23, the combined allowable phase delay is 1.15×10^{-4} seconds. In the case of the regulating repeater in which the modified interstage coupling of Fig. 3 was used, it was determined by means similar to that described above that the retardation coil 28 should have such an inductance as to produce not more than 1.2×10^{-4} seconds.

seconds delay at a frequency of 50 cycles per second.

By a method similar to that outlined above, it was determined that in the circuit of Fig. 2 in order to obtain the allowable phase delay for each of the networks, the constants of the elements should be as follows: the repeating coil 7 should have an effective inductance of approximately 30 henries; the input transformer an effective inductance of approximately 40 henries; the primary winding of output transformer 12 an effective inductance of approximately 85 henries; and the by-pass condenser 23 a capacity of 8 mf. In the modification of the repeater shown in Fig. 3, it was determined that in order to obtain a phase delay within the allowable limits the retardation coil should have an effective inductance of 500 henries.

In the phase delay design formulae given above no account has been taken of the copper and core losses of the various coils, as to do so would needlessly complicate these formulae. It was found to be much more convenient to add corrections to the values obtained by the formulae to take account of these losses later. The values given above were obtained by making such corrections to the computed values. For most purposes, such corrections are not required.

By using well known methods for increasing the inductance of the various networks, such as the use of magnetic alloy laminated cores, and for minimizing the leakage of the high inductance coils, such as by interleaving the windings thereof, transformers and retardation coils for the repeaters of Figs. 2 and 3 have been actually constructed to have the high inductances predetermined by the design formulae, and when tested in the repeater circuit have been found to satisfy the low frequency phase delay requirements and at the same time to be satisfactory from a transmission standpoint in other respects when the repeater is utilized for repeating frequencies ranging from 50 to 5000 cycles or more.

In Fig. 4 are shown curves illustrating the improvement which has been obtained as regards phase delay in the repeater circuit of Fig. 2 by designing the transmission networks therein in accordance with the principles of the invention. Curve A of this figure shows the overall phase delay produced by the repeater of Fig. 2 on the transmitted waves of the lower frequencies when the best transmission networks of the prior art known to applicants are utilized therein. Curve B shows the overall phase delay produced by this repeater when the transmission networks therein are designed in accordance with the methods described above.

In connection with another cable broadcasting system to be utilized for transmitting without appreciable distortion waves of fre-

quencies ranging from 40 to 8000 cycles per second, or more, over a cable of 3000 miles or more in length, a repeater circuit having the same elements as the circuit of Fig. 2 but having an overall delay as low as 6.70×10^{-4} seconds has been designed in accordance with the principles of the invention. In this repeater the phase delay at a frequency of 50 cycles per second produced by the repeating coil is about 150×10^{-4} seconds, that of the input transformer, 1.05×10^{-4} seconds, that of the output transformer, 4.15×10^{-4} seconds, and that of the interstage coupling when equipped for automatic regulation of attenuation, 0.7×10^{-4} seconds.

It is to be understood that the particular values of phase delay and constants of networks to give this delay are set forth above merely by way of example and do not limit the invention.

Although the invention has been described in connection with a repeater circuit of one particular type comprising more or less simple types of transmission networks, it is to be understood that the invention is not limited to such a repeater or such networks but it applies also to other repeaters and more complicated types of networks which may be represented by the simplified circuit of Fig. 1 or other types of simplified networks such as the T or π type, and is capable of various and widely different embodiments within the spirit and scope of the appended claims.

What is claimed is:

1. In a long, high quality transmission system for waves of a wide range of frequencies representing speech and music, comprising a line and a plurality of tandem-connected attenuation correcting devices therein each including one or more reactive elements, the method of controlling the overall phase distortion in the system to bring it within predetermined quality limits, which method consists in determining the amount of phase delay in transmitted waves of at least one of the lower frequencies in said range as compared with the phase delay in transmitted waves of the higher frequencies in said range, contributed to the total phase delay for the system in transmitted waves of said lower frequency by each of said reactive elements, and proportioning the value of each of said reactive elements with respect to the impedances of other elements in said devices co-operating therewith and to the frequency of the transmitted waves to reduce the effective phase delay for each reactive element at said one frequency to a value such that the overall distortion for the system for all frequencies is within said predetermined limits.

2. In a long, high quality transmission system for waves of a wide range of frequencies representing speech and music, comprising a line and a plurality of tandem-connected repeaters therein each including one or more

reactive elements, the method of controlling the overall phase distortion of the system to bring said distortion within predetermined quality limits, which method consists in determining the amount of phase delay in transmitted waves of at least one of the low frequencies of said range as compared with the phase delay in transmitted waves of the higher frequencies in said range, contributed by each of said reactive elements to the total phase delay for the system in transmitted waves of said low frequency, selecting from said reactive elements the particular ones contributing appreciably to said total phase delay, and proportioning the value of said particular reactive elements with respect to the impedances of the portions of the repeaters cooperating therewith and the frequencies of the transmitted waves to reduce the effective phase delay for each of said particular elements so that the overall phase distortion of the system for all frequencies is within said predetermined limits.

3. A transmission device in which transmission takes place principally by mutual induction between elements of the device, for transmitting electrical waves comprising a wide band of frequencies between an incoming and an outgoing circuit, said device having at least one of its constants: mutual impedance, leakage impedance, shunt capacitance and series capacitance proportioned with respect to the impedances of the circuits between which it operates and the frequency of the transmitted waves so that the device produces a transmission delay on any frequency in the transmitted band less than a predetermined value.

4. A transmission device for transmitting between an incoming circuit and an outgoing circuit, electrical waves comprising a band of frequencies at least as wide as the band representing the important speech range, said transmission device having one or more reactive elements, the values of which are proportioned with respect to the values of the impedances of the circuits between which said device operates, the frequencies to be transmitted thereby, and the phase distortion of the various frequency components in said band, such that the device produces on any frequency in the transmitted band a phase distortion at least as small as seven ten-thousandths of a second.

5. A transmission device for transmitting between an incoming and an outgoing circuit electrical waves comprising a wide band of frequencies, said device comprising a winding, the inductance of which is proportioned with respect to the impedances of the circuits connected by said device and the frequencies of the transmitted waves so that said device produces on the lowest frequency in the transmitted band a phase delay at least as small as seven ten-thousandths of a second.

6. A transmission device for transmitting signaling waves comprising a wide band of frequencies between an incoming and an outgoing circuit, said device comprising elements including a condenser element, the capacity of which is proportioned with respect to the impedances of the circuits between which said device operates and the frequency of the transmitted waves so that said device produces a phase delay on any frequency in the transmitted band less than one ten-thousandth of a second.

7. A transforming device for transmitting with limited phase delay waves comprising a wide band of frequencies between an incoming circuit and an outgoing circuit, said device comprising a winding in shunt to the circuits connected thereby, said winding having an inductance in henrys which is at least as great as

$$\frac{R_1 R_2}{\omega^2 S (R_1 + R_2)},$$

where R_1 and R_2 are the respective impedances expressed in ohms of said connected circuits, ω is 2π times the lowest frequency in said band expressed in cycles per second, and S is the maximum permissible phase delay in seconds for said lowest frequency.

8. A transforming device for transmitting with limited phase delay between an incoming circuit and an outgoing circuit, electrical waves comprising a wide band of frequencies, said device comprising a primary winding connected to said incoming circuit and a secondary winding connected to said outgoing circuit, the ratio of the inductance of said primary winding to the effective resistance of said incoming circuit effectively in shunt therewith being at least as great as the reciprocal of $2\omega^2 S$, where ω is 2π times the lowest frequency in said band expressed in cycles per second and S is the maximum allowable phase delay in seconds in the transmitted waves of said lowest frequency.

9. A transmission device for transmitting with limited phase delay between an incoming and an outgoing circuit electrical waves comprising a wide band of frequencies, said device comprising a transformer having a primary winding connected to the incoming circuit and a secondary winding connected to the outgoing circuit, the ratio of the inductance in henrys of said primary winding to the effective impedance in ohms of the circuit to which it is connected being at least as great as $20/f^2$, where f is the lowest frequency in said band expressed in cycles per second.

10. A transmission device for transmitting with limited phase delay between an incoming circuit and an outgoing circuit electrical waves comprising a wide band of frequencies, said device comprising a transformer having a primary winding connected to said incoming circuit and adapted to pass superimposed

direct current of a value at least as large as 10 milliamperes, and a secondary winding connected to the outgoing circuit, the ratio of the inductance in henrys of said primary winding to the effective impedance in ohms of the incoming circuit connected thereto being at least as great as $20/f^2$, where f is the lowest frequency in said band expressed in cycles per second.

11. A network for transmitting with limited phase delay between an incoming circuit and an outgoing circuit waves comprising a wide band of frequencies, said network being substantially equivalent at some frequency in the transmitted band to an inductive element connected effectively in series with the impedances of said incoming circuit and said outgoing circuit, the ratio of the inductance expressed in henrys of said inductive element to the sum of the impedances expressed in ohms of the circuits connected thereby being as small as or smaller than the maximum allowable phase delay expressed in seconds for transmitted waves of any frequency in said band.

12. A transmission device for transmitting with limited phase delay electrical waves comprising a band of frequencies at least as wide as the band representing the important speech range between an incoming circuit which viewed from said device is substantially a pure resistance and an outgoing circuit offering to the transmitted waves a substantially capacitive impedance, such transmission device comprising a transformer having a primary winding connected to said incoming circuit and a secondary winding connected to said outgoing circuit, said transformer having at least one of its constants, mutual impedance or leakage impedance proportioned with respect to the effective resistive impedance of said incoming circuit, the capacitive impedance of said outgoing circuit and the frequency of the transmitted waves so that the phase delay produced by said device on any frequency in the transmitted band is at least as small as 3.5×10^{-4} seconds.

13. A transmission device for transmitting between an incoming circuit and an outgoing circuit electrical waves comprising a band of frequencies ranging from 50 cycles per second to 5000 cycles per second or more with a predetermined amplification and quality of transmission, said device comprising a transformer having a primary winding and a secondary winding respectively connected to said incoming circuit and said outgoing circuit, said transformer having a high mutual inductance between its windings, and a low leakage inductance, the ratio of said mutual inductance in henrys to the square root of the product of the impedances of the circuits between which it operates being at least as great as 20 divided by the square of the

frequency in cycles per second, whereby said device produces on waves of the lowest frequency in said band transmitted thereby a phase delay of less than 700 microseconds.

14. A transmission device for transmitting signaling waves comprising a wide band of frequencies between an incoming circuit and an outgoing circuit, said device comprising a single winding in shunt to the circuits connected thereby, and adapted to pass superimposed direct current of a value at least as large as 6 milliamperes, the reactance of said winding being proportioned with respect to the effective impedances of said incoming and outgoing circuits connected thereto and the frequency of the transmitted waves so that said device produces a phase delay on a frequency in the transmitted band which is at least as small as 1.2×10^{-4} seconds.

15. In a system for transmitting waves comprising a band of frequencies at least as wide as the band representing the important speech range, an incoming circuit, an outgoing circuit, and an amplifier providing substantially uniform amplification for all frequencies in the transmitted band, said amplifier comprising reactive elements including an input transformer coupling the input of said amplifier to said incoming circuit and an output transformer coupling the output of said amplifier to said outgoing circuit, the impedance of each of said reactive elements being proportioned with respect to the effective impedances to which it is connected and the frequency components in said band so that said amplifier produces on each frequency in the transmitted band a phase delay at least as small as one thousandth of a second.

16. In a system for transmitting waves comprising a band of frequencies at least as wide as the band representing the important speech range, a two-stage amplifier adapted for providing substantially uniform amplification for all frequencies in the transmitted band, said amplifier comprising reactive elements including an input transformer and an output transformer, the impedance of each of said reactive elements in said amplifier being proportioned with respect to the effective impedances to which it is connected and the frequencies in said band, so that said amplifier produces a total phase delay on each frequency in the transmitted band which is at least as small as eleven ten-thousandths of a second.

17. In a system for transmitting waves comprising a band of frequencies at least as wide as the band representing the important speech range, an incoming circuit, an outgoing circuit and a repeater for obtaining a desired uniform amplification of the frequencies in said band transmitted from said incoming circuit to said outgoing circuit, said repeater comprising connected in tandem a

repeating coil, an input transformer, an
amplifier comprising reactive elements and
an output transformer, the impedance of said
repeating coil, said input transformer, said
5 output transformer and said reactive ele-
ments in said amplifier being proportioned
with respect to the effective impedances of
the circuits connected thereto, and the fre-
quencies in the transmitted band, so that said
10 repeater produces on each frequency in the
waves in transmission from said incoming to
said outgoing circuit, a phase delay which is
at least as small as fifteen ten-thousandths of
a second.

15 In witness whereof, we hereunto subscribe
our names this 22nd day of August, 1928.

HORACE WHITTLE.
LINWOOD B. HILTON.

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