May 17, 1932. H. W. DUDLEY 1,859,030

DISTORTION CORRECTION IN TRANSMISSION SYSTEMS

Filed Jan. 4, 1929

FIG. 1

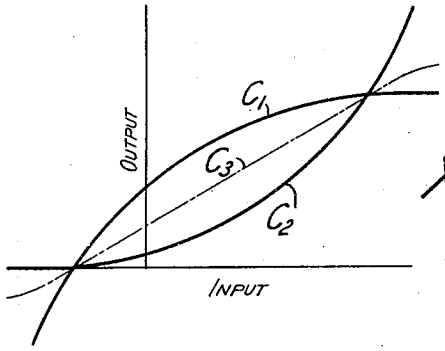


FIG. 2

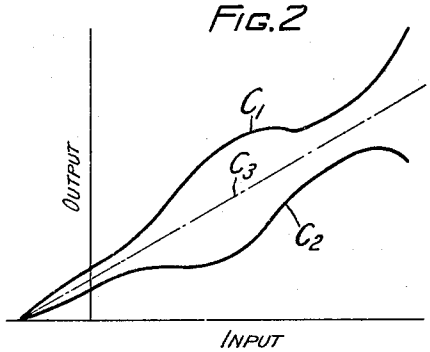
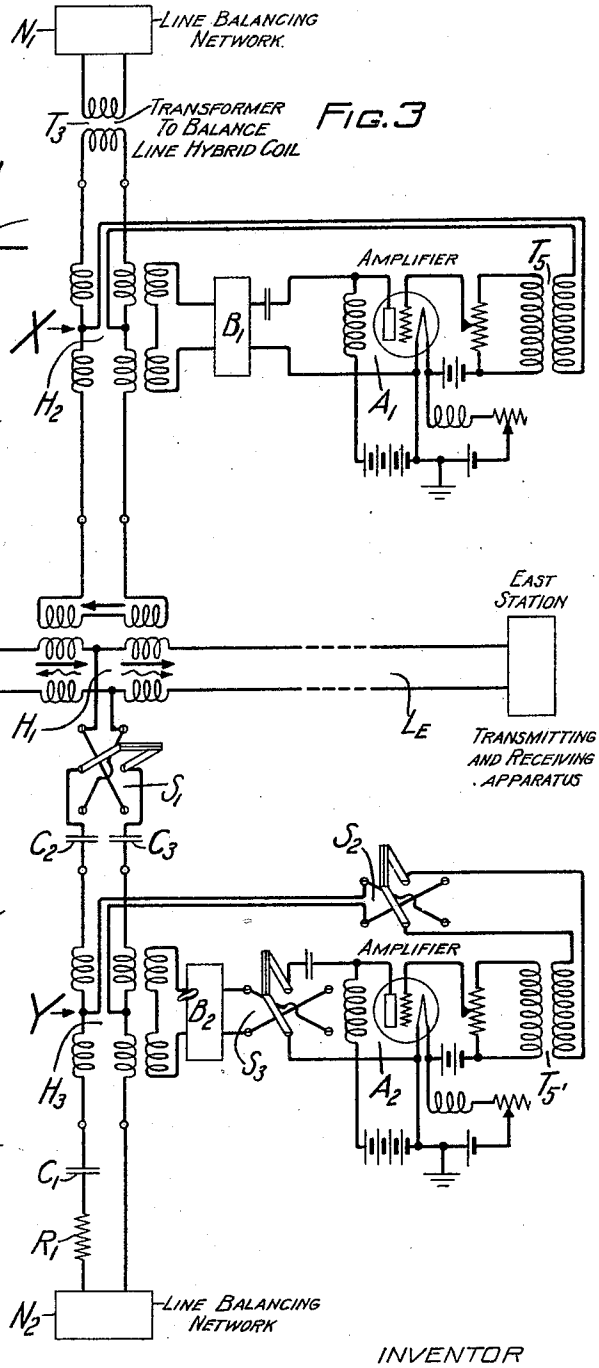


FIG. 3



INVENTOR
H. W. DUDLEY
BY H. O. Burgess
ATTORNEY

Patented May 17, 1932 1,859,030

UNITED STATES PATENT OFFICE

HOMER W. DUDLEY, OF TEANECK, NEW JERSEY, ASSIGNOR TO BELL TELEPHONE LABORATORIES, INCORPORATED, OF NEW YORK, N. Y., A CORPORATION OF NEW YORK

DISTORTION CORRECTION IN TRANSMISSION SYSTEMS

Application filed January 4, 1929. Serial No. 330,169.

This invention relates to systems for transmitting wave energy, such as telephone transmission systems and the like, and particularly to improvements in the transmission characteristics of such systems.

In systems for transmitting waves comprising a plurality of frequencies, and in which transmission apparatus having a non-linear relation between its input and output is utilized to produce certain transformations in the transmitted waves, for example, amplification, such apparatus, due to its non-linear distorting qualities introduces into the system waves of additional frequencies formed by some combination of the impressed waves. For example, space discharge amplifying devices in telephone transmission systems when overloaded produce undesired harmonics which limit the effective power that may be transmitted over the system if a given degree of articulation is to be obtained.

An object of the invention is to increase the energy-carrying capacity of transmission apparatus in such systems for a given amount of distortion produced in the transmitted waves by such apparatus.

A related object is to reduce the amount of distortion introduced by transmission apparatus in such systems in waves transmitted thereby for a given amount of energy in said waves.

These objects are attained in accordance with the invention by choosing and relatively arranging two or more of the transmission elements in a transmission system which have non-linear output vs. input characteristics, such that, without affecting the accomplishment of the original purpose of the apparatus, all or a part of the resulting distortion is effectively neutralized in any desired part of the system. This enables the apparatus to transmit a maximum amount of energy with minimum distortion.

A preferred embodiment of the invention is in connection with a telephone repeater circuit of the negative impedance type, such as is disclosed and claimed in the U. S. patent issued to G. Crisson, No. 1,776,311, on September 23, 1930. This repeater circuit comprises two 21-type vacuum tube repeaters associated with a two-way transmission line through a hybrid coil, one of these repeaters arranged to give a "series" negative impedance effect being connected to the series winding of the hybrid coil, and the other repeater arranged to give a "shunt" negative impedance effect being connected to the bridge points of the hybrid coil. This repeater circuit operates in such manner that the output currents of the two repeaters are impressed on the line so as to reinforce each other in the direction towards the receiver and to annul each other in the direction towards the transmitter, thus obtaining amplification while minimizing echo effects. A 21-type (two way-one repeater element) repeater may be defined as that type of balanced bridge repeater well-known in the art adapted to be inserted in a transmission circuit, and in which the two arms of the bridge, each comprising one section of the transmission circuit, are balanced against each other so that one repeater element may be employed for repeating currents between the sections in opposite directions without setting up a singing condition. In its usual form, the 21-type repeater comprises a three winding or hybrid coil transformer having two of its windings connected in series between the two sections of the transmission circuit and the third winding inductively related to the other two windings, and a one way amplifier circuit having its output terminals connected to said third winding and its input terminals connected across the transmission circuit at the junction points between the other two windings of the transformer.

Without affecting the desirable result obtained by the combination repeater circuit described in the above mentioned Crisson patent, additional advantages may be attained therein by a modification in accordance with the present invention. These advantages, which include the increasing of the energy-carrying capacity of this type of repeater for a given quality of transmission, or a reduction in the amount of distortion produced in the transmitted waves by the repeater for a given load, are attained by proper selection of the dis-

tortion producing apparatus in the repeater and a particular poling of the two 21-type repeater circuits with respect to the main transmission circuit.

If the amplifier tubes are so selected as to have substantially identical distortion characteristics, and the two repeater circuits are relatively poled so that the incoming voltage waves are impressed on the grids of the two repeater tubes in opposite phase, the outputs of the repeaters will be impressed on the line through the hybrid coil in such manner that the fundamental and the odd harmonics generated by the two tubes are transmitted over the line in one direction only—for example, towards the listener. As regards that one direction, however, the even harmonics generated by the two amplifier tubes neutralize each other in the line, thus improving articulation in the system. Some of the energy of the even harmonics will be returned over the line in the direction of incoming waves, but the echoes produced thereby will not seriously affect the talker as these even harmonics do not contain a great deal of intelligibility. In the general case where the voltage wave applied to the inputs of the two repeaters contains several frequencies instead of single harmonics of the impressed frequencies, it is the set of sum and difference frequencies, including the even harmonics of all the impressed frequencies, that is suppressed for one direction of transmission.

In another application of the invention to the same repeater circuit, the distortion producing apparatus is so chosen as to have substantially complementary characteristics. In this case the opposite poling of the two 21-type repeaters will result in the elimination of all combination frequencies including the even and odd harmonics of the impressed waves, in any desired branch of the system.

The objects and advantages of the invention will be brought out more clearly in the following detailed description when read in connection with the accompanying drawings in which Figs. 1 and 2 show sets of curves illustrating the theory on which the invention is based, and Fig. 3 shows an application of the invention to a two-way repeater of the negative impedance type.

In Fig. 1, the solid curve C_1 indicates the non-linear relation existing between the output and input of a given system producing distortion in the form of harmonics, and the solid curve C_2 the non-linear relation existing between the output and input of a similar distortion producing system, as may be obtained, for example, when the distortion devices in the two systems are identical vacuum tubes or other devices having substantially parabolic characteristics. If the outputs of the two systems are of the proper magnitude and are superposed in the proper phase relation the two systems together may be made to have a combined input-output characteristic, such as indicated by the dot-dash curve C_3, which is symmetrical about a certain point, the effect being that the even harmonics generated by the two systems annul each other. This may be best explained by the following mathematical analysis.

In the case of a vacuum tube the output current i is related to the input voltage e by the equation:

$$i=a_0+a_1e+a_2e^2 \quad (1)$$

to a close approximation, where a_0, a_1, and a_2 are constants determined by the tube and the system.

An infinite series in e is required to express i accurately, but in the case of vacuum tubes (due to the plate current thereof being proportional to the square of the effective grid voltage when the output impedance is small), the a_2e^2 term can be made the only distortion term of any importance.

Let it be assumed that signaling voltages represented by the following equations are respectively applied to the inputs of two similar space discharge devices in a particular system.

$$e_1=E_0+E_1 \sin \omega t \quad (2)$$

$$e_2=E_0-E_1 \sin \omega t \quad (3)$$

where E_0 represents the biasing direct current voltage applied to the grid of each tube, for example, by means of a grid battery, and the terms $+E_1 \sin \omega t$ and $-E_1 \sin \omega t$ represent A. C. waves applied to the inputs of the respective tubes 180° out of phase; that is, if the impressed waves are sinusoidal, when one tube has its grid at the maximum positive A. C. potential, the other tube has its grid at the maximum negative A. C. potential.

The output currents i_1 and i_2 of the two tubes may be represented as:

$$i_1=a_0+a_1E_0+a_1E_1 \sin \omega t+ a_2(E_0^2+2E_0E_1 \sin \omega t+E_1^2 \sin^2 \omega t) \quad (4)$$

and

$$i_2=a_0+a_1E_0-a_1E_1 \sin \omega t+ a_2(E_0^2-2E_0E_1 \sin \omega t+E_1^2 \sin^2 \omega t) \quad (5)$$

respectively.

In general, if the output currents i_1 and i_2 are fed into a common circuit, all or any part of these currents may be made to add or subtract in a branch of the common circuit. If the circuits are arranged so that the two currents add in the common circuit, the resultant current obtained therein may be expressed as

$$i_1+i_2=2(a_0+a_1E_0+a_2E_0^2)+ 2E_1^2a_2 \sin^2 \omega t \quad (6),$$

the first term of this equation representing

only direct current and the second term the second harmonic and some more direct current. This resultant current contains little intelligibility and so in general should be made to feed back towards the talker rather than towards the listener.

If the circuits are arranged so that the two currents subtract in the common circuit, the resultant current obtained therein may be expressed as

$$i_1 - i_2 = 2E_1(a_1 + 2a_2E_0) \sin \omega t \quad (7)$$

the single term of this equation representing the amplified fundamental current. As this current does possess intelligibility it should be made to flow towards the listener rather than towards the talker.

In Fig. 2 the solid curve C_1 indicates the non-linear relation existing between the output and input of a given system producing distortion in the form of harmonics and the solid curve C_2 represents the non-linear relation existing between output and input of a system in which the distortion is of a different type. If these two systems have distortion characteristics which are substantially complementary, as indicated by the shapes given to curves C_1 and C_2 of Fig. 2, and if their outputs are of the proper magnitude and are superposed in a system in proper phase relation the two systems taken together will have a linear input-output characteristic such as indicated by the dot-dash line C_3, the effect being that all combination frequencies including both the even and odd harmonics will be balanced out. This may be explained by the following mathematical analysis:

Let it be assumed that a signaling voltage e is respectively applied to the inputs of two pieces of apparatus, such as space discharge devices, having non-linear input-output characteristics which are effectively complementary. The average output current of the two tubes will then be given by an equation

$$i_0 = a_0 + a_1 e \quad (8)$$

where a_0 and a_1 are constants of the tubes and the associated circuits.

The output current of the two tubes will then be given by the Equations 9 and 10, respectively.

$$i_1 = a_0 + a_1 e + f(e) = a_0 + a_1 e + a_2 e^2 + a_3 e^3 + \ldots\ldots (9)$$

$$i_2 = a_0 + a_1 e - f(e) = a_0 + a_1 e - a_2 e^2 - a_3 e^3 - \ldots\ldots (10)$$

where a_0, a_1, a_2 and a_3 are the constants determined by the tubes and the system.

If the output currents i_1 and i_2 are fed into a common circuit all or any part of these currents may be made to add or subtract in any branch of the common circuit. If these circuits are arranged so that the two circuits add in the common circuit the resulting current obtained therein may be expressed as

$$i_1 + i_2 = 2a_0 + 2a_1 e \quad (11)$$

The first term on the right of this equation represents a D. C. component, the second a wave which is a reproduction of the original wave applied to the inputs of the distortion producing apparatus except that it is on a different scale, all distortion components produced by the two tubes having been effectively canceled out in the common circuit by combining the two output waves therein in this manner.

If the circuits are arranged so that the output currents oppose each other in the common circuit, the resultant current obtained therein may be expressed as

$$i_1 - i_2 = 2a_2e^2 + 2a_3e^3 + \ldots\ldots (12)$$

The terms of Equation (12) represent the combination waves due to the non-linear distortion apparatus, which are not canceled out. As these waves possess little intelligibility, in general, they should be made to flow in the circuit toward the talker rather than toward the listener.

In Fig. 3 is shown the application of the invention to a form of repeater circuit which is disclosed and claimed in the above mentioned Crisson patent. This repeater circuit comprises two 21-type repeaters associated with a line circuit in such a way that for transmission over the line in either direction the feed-back of echo currents toward the listener is eliminated or minimized, while at the same time the line is maintained conductively continuous through each repeater rendering unnecessary the use of composite sets when the line is used also for transmitting direct current or low frequently alternating currents, as in telegraphy. In order to bring out clearly the particular modifications which are made in the repeater circuit of the Crisson patent in accordance with the present invention, the details of the Crisson repeater illustrated in Fig. 3 and its manner of operation will be first described. Referring to Fig. 3 it will be seen that the repeater circuit illustrated includes a hybrid coil H_1 having the usual line windings and series winding, which is connected between the two parts L_W and L_E of the transmission line extending between two stations designated as the west station and the east station, respectively.

To the series winding of hybrid coil H_1 is connected a 21-type repeater circuit X, and also a transformer T_3 and a network N_1 for balancing the hybrid coil H_1 and the two parts of the associated line L_E and L_W to prevent the repeater X from singing.

The 21-type repeater X comprises a hybrid coil H_2 of the usual type connected between the terminals of the series winding of hybrid

coil H_1 and the terminals of the primary winding of transformer T_3, and an amplifier A_1 having its input circuit connected to the bridge points between the line windings of hybrid coil H_2 through an input transformer T_5, and its output circuit connected through other apparatus represented by the box B_1 to the series winding of hybrid coil H_2. The apparatus in box B_1 may, comprise for example, an output transformer, a transmission equalizer if it is necessary, a filter and any other apparatus needed.

To the bridge points between the line windings of hybrid coil H_1 is connected a circuit including the condensers C_2 and C_3, a 21-type repeater Y, a condenser C_1, a resistance R_1, and a balancing network N_2. The condensers C_1, resistance R_1 and network N_2 are provided for balancing the condensers C_2 and C_3, the resistance of the line windings of hybrid coil H_1 and the two parts of the transmission line L_E and L_W, respectively, so that the 21-type repeater Y will not sing. The condensers C_2 and C_3 serve to prevent the passage of direct current or low frequency alternating current to the 21-type repeater Y, and also, if given proper values, to equalize phase shifts introduced by the hybrid coil H_1.

The 21-type repeater Y comprises a hybrid coil H_3, which is connected between the network N_2 and the bridge points of hybrid coil H_1, and an amplifier A_2 having its input connected across the bridge points between the line windings of hybrid coil H_3 through an input transformer T_5' and its output connected to the series winding of hybrid coil H_3 through apparatus represented by the box B_2, which apparatus may be similar to that included in box B_1 of repeater X described above.

In the manner explained in detail in the above mentioned Crisson patent, the 21-type repeater X is connected with respect to the two parts of the line L_E and L_W through hybrid coil H_1 in a manner which has been designated as the direct connection, that is, a connection such that for transmission in the system in either direction the input currents to the repeater X and the resultant amplified output currents from the repeater X flow in the line wires L_E and L_W in the same direction. The repeater circuit Y, on the other hand, is connected with respect to the two parts of the transmission line L_E and L_W through hybrid coil H_1 in the manner which has been designated as the reversed connection, that is, a connection so that for transmission over the system in either direction the input currents to the repeater Y and the amplified output currents from the repeater Y flow in one part of the transmission circuit in opposite directions and in the other part of the transmission circuit in the same direction.

For example, if currents are being received over line L_W in the direction indicated by the light straight arrows, the connection of repeater X to hybrid coil H_1 is such that the resulting amplified current from repeater X flows in the two parts of the line L_W and L_E in the same direction, as indicated by the heavy straight arrows. The connection of the repeater Y with respect to the hybrid coil H_1, however, is such that for currents received over line L_W in the direction of the light straight arrows, the resulting amplified currents from repeater Y flow in the portion of the line L_W in the direction opposite to that of the received currents and in the portion of line L_E flow in the same direction as the received currents, as indicated by the wavy arrows. In this way the complete repeater comprising the two 21-type repeaters X and Y operates so that for transmission over the line in either direction an amplified wave will always be transmitted to the listener, while the waves tending to travel toward the speaker will be minimized. By properly adjusting the gains of the two 21-type repeater circuits, of course, the waves tending to travel toward the speaker may be completely neutralized so that no echoes are received by him.

Now it is well known that vacuum tube amplifiers, such as are used in the amplifiers A_1 and A_2, in repeaters X and Y, respectively, because of their non-linear distorting qualities, when overloaded, will tend to generate waves of frequencies which are some combination of the frequencies of the waves impressed on their input circuits. In the system of Fig. 3, these combination waves, or distortion waves produced by the amplifiers A_1 and A_2 when overloaded, when transmitted into the main transmission line will interfere with the speech waves therein and impair articulation.

It is a purpose of the present invention to modify the repeater circuit of the Crisson patent, which has just been described, so that without affecting appreciably its advantageous operation as regards echo elimination, the effect of at least a portion of the distortion waves may be neutralized. This is accomplished in accordance with the invention by relatively arranging the circuits of the two repeaters X and Y, or the connections thereof to the transmission circuit, so that at least portions of the distortion currents generated by the two repeaters flow in one part of the main transmission circuit in opposite directions. This will enable the energy level or power in the system to be increased without increasing the size of the tubes of amplifiers A_1 or A_2. In other words, it will enable the energy carrying capacity of given amplifier tubes and the repeater as a whole to be increased without appreciably impairing the quality of transmission in the system. A simple method of obtaining this result is by controlling the relative poling of the input circuits of the tubes in amplifiers A_1 and A_2.

This may be done by means of switches, for example the double pole switches S_2 and S_3, respectively located in the input and output circuits of the repeater X, or a switch S_1 in the connections between repeater X and hybrid coil H_1. Of course, the same result could be obtained by means of similar switches in the 21-type repeater Y and in the connections of repeater Y to hybrid coil H_1.

It is obvious that any change in the connection of the amplifier tubes A_1 and A_2 for the purpose of applying a portion of the distortion waves produced thereby to the main transmission circuit in opposite phases, which will also change the relative connection of the two amplifiers A_1 and A_2 to the hybrid coil H_1 would destroy the operation of the repeater circuit as a whole as regards elimination of echo currents.

If the connections of the two amplifier circuits X and Y are not normally such that the distortion waves or a portion thereof produced by the two amplifier tubes A_1 and A_2 are applied to a portion of the transmission circuit in opposite phases, it is, of course, possible to attain this condition by reversing the double pole switch S_2 to reverse the polarity of the grid of amplifier tube A_2. The effect of this however, would be to change repeater Y from its reversed connection to a direct connection, such as that of repeater X, and thus to defeat the main purpose of the repeater as a whole. If, however, both switches S_2 and S_3 are reversed together, the only effective change which will occur in the operation of the circuit as a whole will be that the opposite half of the wave is impressed on the grid of tube A_2. By reversing both switches S_2 and S_3 together, therefore, the input voltage waves will be impressed on the grid of amplifier tube A_2 in repeater Y and the grid amplifier tube A_1 in repeater X in opposite phase, that is, one grid will be at a maximum positive potential when the other grid is at maximum negative potential. This will insure that, as has been explained in connection with Figs. 1 and 2, at least a portion of the distortion waves produced by the two tubes will be impressed on the transmission circuit in opposite phase, but will not change the net effect of the repeater circuit as to the direction of the amplified speech waves impressed on the transmission circuit with respect to the direction of the input waves therein.

The same effect as regards the elimination of a portion of the distortion currents as is obtained with the double current reversal in repeater circuit Y by the simultaneous reversal of switches S_2 and S_3, may be obtained by reversing the single double pole switch S_1 located between the repeater Y and the hybrid coil H_1, or by reversing a similar switch located between the repeater X and the hybrid coil H_1. Reversal of the switch S_1 will change the polarity of the grid of amplifier tube A_2 but will not change the relation of repeater Y to hybrid coil H_1 as regards the relative direction of the input and amplified speech waves in the transmission circuit, for, the waves traverse the circuit including the switch S_1 twice (as input and output currents), and the net effect as to the main speech currents is the same as if switch S_1 had not been reversed.

The degree of reduction in the effective distortion in the system which may be obtained by utilizing the switches S_2 and S_3 or S_1 in the manner pointed out to properly pole the repeaters X and Y with respect to the main transmission circuit, will depend upon the choice of tubes for use therein. If the tubes selected for the two amplifiers A_1 and A_2 have complementary distortion characteristics, as explained above in connection with the description of Fig. 2 all distortion components including both even and odd harmonics of the impressed waves may be eliminated in the main transmission circuit as regards both talker and listener. If, on the other hand, the tubes selected have substantially identical characteristics, as explained in connection with the description of Fig. 1 the even harmonics of the impressed wave, which are the most troublesome, may be eliminated in the main transmission circuit as regards one direction of transmission, for example, in the direction toward the listener, thus improving articulation in the system.

In the important frequency range in the repeating system which has been described, it is desirable from a transmission standpoint that the phases of the amplified currents transmitted from the two tubes to the main transmission circuit, be the same for the odd harmonics and 180° apart for the even harmonics. Thus, if apparatus with appreciable phase shift be used in repeater X, for example, in the apparatus which has been indicated by the box B_1 therein, similar circuit apparatus should be included in repeater Y in the box B_2.

Although the invention has been illustrated and described in connection with a telephone system in which two vacuum tube amplifiers are the sources of distortion, it is, of course, not limited to telephone systems or to vacuum tube amplifying apparatus, but may be applied to signaling systems of other types employing two or more transmission elements having a non-linear relation between output and input, or to any other system or apparatus within the scope of the appended claims.

What is claimed is:

1. In a transmission system, a transmission line for transmitting electrical waves, two or more two-way repeaters for amplifying said waves, each of said repeaters having a non-linear amplification characteristic tending to

produce wave distortion in the system, said repeaters being so connected with said line that in a portion thereof the distortion energy produced by one of said repeaters opposes that produced by another of said repeaters.

2. In a transmission system, a transmission line for transmitting electrical waves, two or more transmission devices connected effectively in said line and in substantially conjugate relation with each other, each of said devices having a non-linear output vs. input characteristic tending to produce wave distortion in the system, said devices being relatively poled with respect to the applied waves so that a portion of the wave distortion produced in the system by one of said devices effectively cancels a portion of the wave distortion produced in the system by another of said devices.

3. In a transmission system, a transmission line for transmitting waves comprising a plurality of frequencies, two or more 21-type repeaters for amplifying said waves, each of said repeaters having a non-linear output-input transmission characteristic, said repeaters being so connected with said line that in a portion thereof the distortion energy produced by one of said repeaters opposes that produced by another of said repeaters.

4. In a transmission system, a transmission circuit for transmitting waves comprising a plurality of frequencies, two or more transmission devices connected effectively in said line and in conjugate relation to each other, each of said devices having a non-linear output vs. input characteristic, the method of improving the transmission qualities of the system which consists in relatively poling said transmission devices with reference to the applied waves so that a portion of the distortion energy introduced into a certain part of said system by the respective transmission devices effectively cancels another portion of said distortion energy.

5. In combination, a line for transmitting waves of a plurality of frequencies, a circuit for amplifying said waves connected between sections of said line, said circuit comprising two or more amplifying devices, having a non-linear relation between input and output, said amplifying devices being so connected with said line that the repeated waves produced in one section thereof by one of said devices are in the same direction as the repeated waves in said one line section produced by the other of said devices, and the repeated waves produced in the other section of line by said one amplifying device opposes the repeated waves in said other section of line produced by said other of said devices, said amplifying devices being relatively connected with said line so that at least a part of the harmonic frequencies of the waves applied thereto generated by said one amplifying device opposes in said one line section the harmonic frequencies of the applied waves generated by said other amplifying device.

6. The combination of claim 5 and in which each of said amplifying devices comprises a space discharge element having an input electrode and an output electrode, the input electrodes of the space discharge devices being connected with said line so that incoming waves are applied thereto in different phases.

In witness whereof, I hereunto subscribe my name this 2nd day of January, 1929.

HOMER W. DUDLEY.