Sept. 23, 1930. G. CRISSON 1,776,310

TWO-WAY NEGATIVE IMPEDANCE REPEATER

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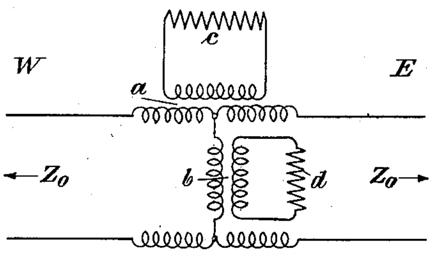

Fig. 1

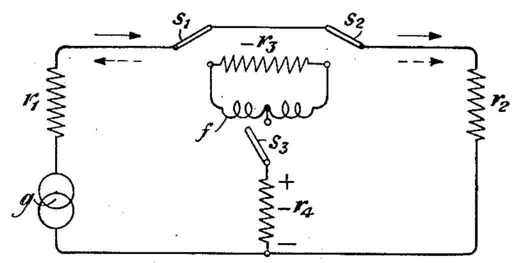

Fig. 2

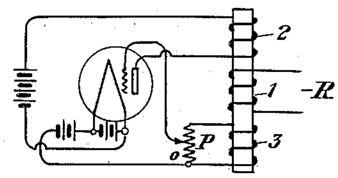

Fig. 3

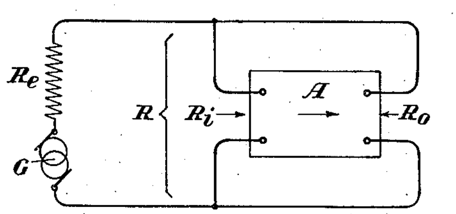

Fig. 3a

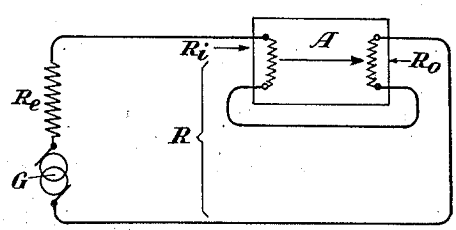

Fig. 4a

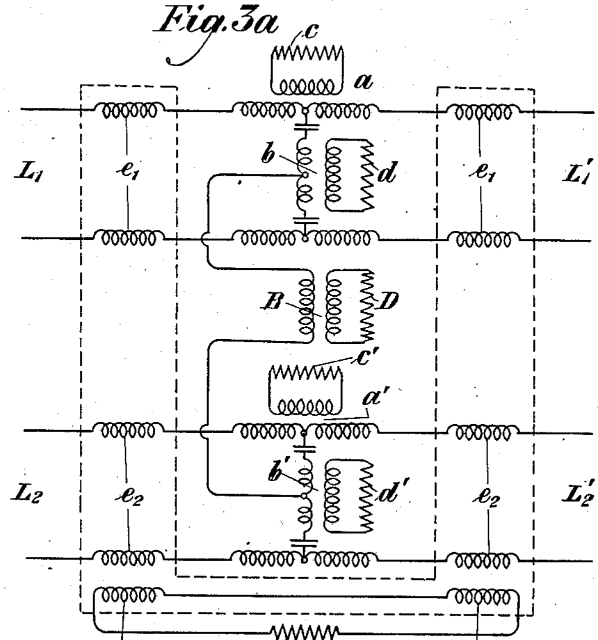

Fig. 5

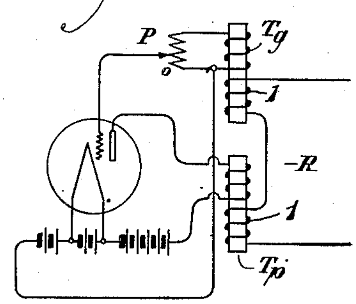

Fig. 4

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TWO-WAY NEGATIVE IMPEDANCE REPEATER

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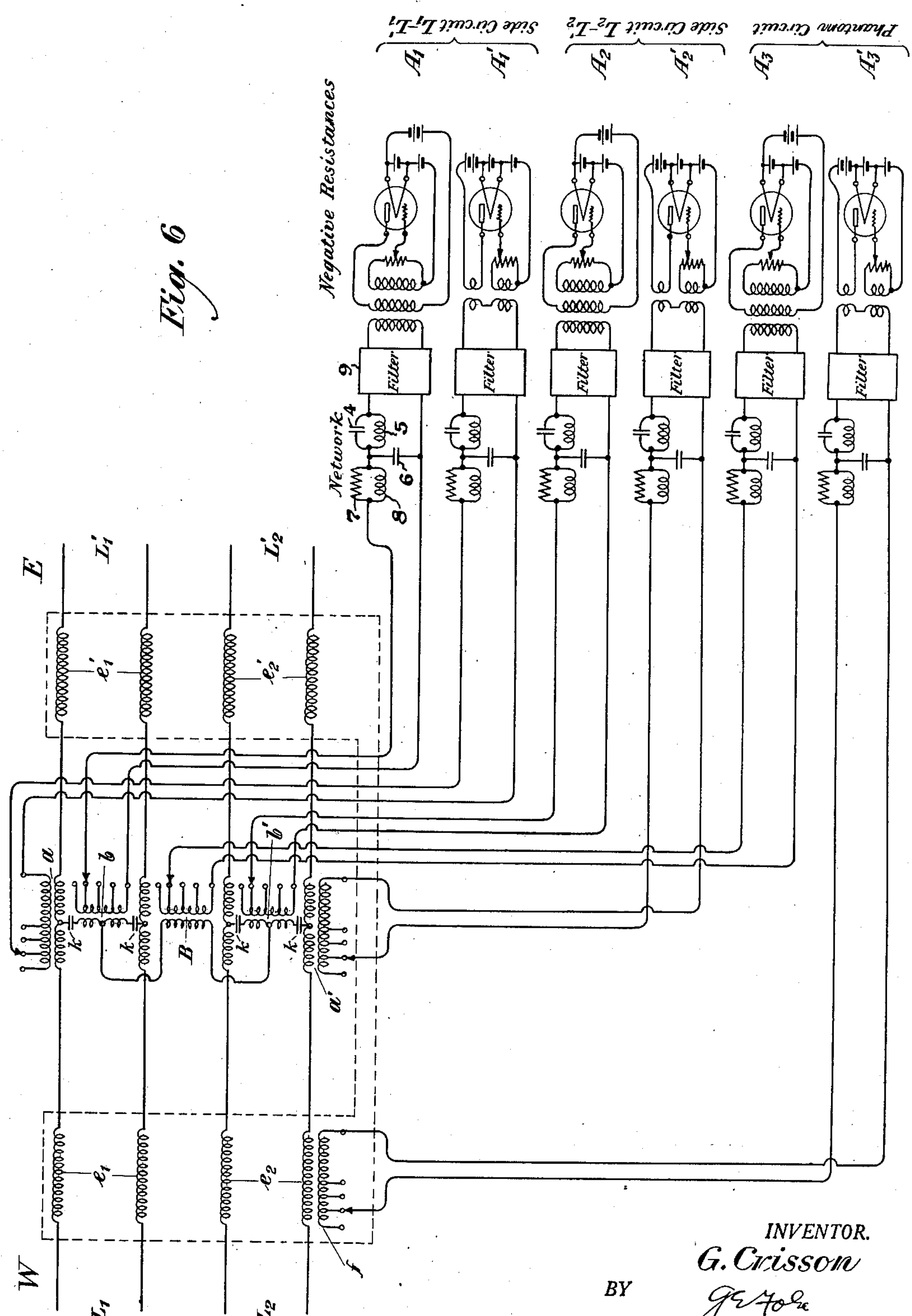
Fig. 6



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Patented Sept. 23, 1930 1,776,310

UNITED STATES PATENT OFFICE

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TWO-WAY NEGATIVE-IMPEDANCE REPEATER

Application filed May 19, 1928. Serial No. 279,060.

This invention relates to repeater systems, and particularly to one characterized by the use of two negative impedances.

A positive impedance, as the term is commonly used, includes a resistance component which is positive and a reactance component which may be positive or negative. A negative impedance includes a negative resistance and a reactance component which may be negative or positive. The negative impedance corresponding to a given positive impedance is one in which each component is of equal magnitude but opposite sign to the corresponding component of the positive impedance.

When an electric current flows in a part of a circuit whose impedance includes a positive resistance, electrical energy is absorbed. It may be changed into some other form of energy as heat, light or mechanical energy, or it may be transferred as electrical energy into some other circuit. When the resistance is negative, electrical energy is developed. A part of a circuit having a negative resistance must include some means, for example, a vacuum tube, by which the energy is introduced.

A form of negative resistance which is well known in the art consists of a one-way amplifier whose input and output circuits are coupled together. I have discovered that there are two kinds of negative resistance whose properties differ with respect to their tendency to sink when connected to an external circuit. The type of negative resistance resulting from the coupling of the input and output circuits depends upon the manner in which such connection is made. The types and the manner in which they are created is more fully described hereinafter. I have further discovered that by employing dissimilar types of negative resistances with a hybrid coil network, it is possible to produce a repeater having very desirable characteristics not attainable by either of the negative resistances alone.

My invention resides in the combination of negative resistances having dissimilar characteristics and so proportioned that the amplified energy will not be transmitted back toward the transmitting station.

Other objects of my invention will be apparent from the following description, when read in connection with the attached drawing, of which Figure 1 shows schematically an impedance network which illustrates the description of the principle underlying my invention; Fig. 2 is a modification of Fig. 1; Figs. 3 and 3^a illustrate the shunt type, and Figs. 4 and 4^a the series type of negative resistances by means of which important results are attainable; and Figs. 5 and 6, respectively show in detail the application of negative impedances of different types as repeaters in physical and phantom circuits.

For a complete understanding of my invention, it seems desirable to describe somewhat in detail the transmission principles upon which it is based, which are illustrated schematically in Figs. 1 and 2. Fig. 1 shows a hybrid set connected between sections of a line designated E and W, which sections have the same characteristic impedance Z_0. The hybrid coil comprises the line windings in series between the sections E and W and also the winding connected with the impedance *c*. One of the windings of the transformer *b* is connected between the midpoints of the line windings of the hybrid coil and the other windings of that transformer is connected with the impedance *d*. The hybrid coil *a* and the transformer *b* are assumed to be designed so that complete balance and no reflection loss exist when equal impedances are connected with the four pairs of terminals, although the variable impendances *c* and *d* may be given other desired normal values by altering the ratios of the transformers to suit the impedances employed. When each of the impedances *c* and *d* has the normal value Z_0, there is an infinite transmission loss from either section of the line to the other, but at the same time the impedance presented by the hybrid set toward each line, assuming perfect transformers, is equal to Z_0. If the values of the impedances *c* and *d* are varied reciprocally from their normal values by any ratio, that is, if one is multiplied by the factor N (a real number), and the other is divided by N, the transmission loss in either direction becomes finite, being given in TU by the formula

$$L = 20 \log_{10} \frac{1+N}{1-N} \quad (1)$$

The impedance, however, presented by the hybrid set toward both lines remains equal to Z_0. The formula (1) shows that if the factor N is made negative, the transmission loss becomes a gain; and also, since the impedance of the hybrid set is independent of N (provided the impedances c and d preserve their reciprocal relation), the impedance presented by the hybrid set toward the lines remains equal to Z_0. It therefore follows that by giving the impedances c and d suitable negative values, the hybrid set becomes a repeater adapted to amplify transmission in both directions between the sections E and W.

It is desired to make clear that a hybrid coil has been described as the means for connecting the negative impedances with the line because such connecting means constitutes the preferred type owing to the conjugate relationship established between apparatus connected with the terminals of the hybrid coil. It is to be understood, however, that the invention is not limited to an arrangement employing a hybrid coil inasmuch as other means for connecting the negative impedances with the line may be employed without departing from the claims defining the invention.

While certain practical advantages of my negative impedance repeater will be more fully described hereinafter, it is desirable to point out at this time that the arrangement shown schematically in Fig. 1 does not dissipate in networks or in the line toward the transmitter any of the power it develops, and both negative impedances work at the same time. Hence, if use is made of the same vacuum tubes that are now used in 21- and 22-type repeaters, and the negative resistances are designed so that no power is absorbed except in the internal impedances of the tubes, the useful amplified power will be the full output of both tubes, which is four times or 6 TU more than the useful output of the present 21- or 22-type repeater.

The manner in which the amplified energy is prevented from passing to the transmitter will be made clear by describing the arrangement shown in Fig. 2. With the switches in the positions shown, the generator g sends a current through the resistances r_1 and r_2, representing the sections of the line in the direction shown by the solid arrows. By changing the switches s_1 and s_2 to the lower contacts, the negative resistance r_3 is put in series between r_1 and r_2. This increases the current in the circuit by reducing the total resistance, the increase being in the direction shown, for example, by the solid arrows. The negative resistance r_4 is arranged to be connected by the switch s_3 with the tap at the midpoint of the retardation coil f, which offers a high inductive impedance to currents flowing from one part of the line to the other but only a low non-inductive resistance to currents flowing in or out at the tap. The direction of the potential difference across r_4 is indicated by the plus and minum signs. Due to its negative character, this element sends out current in the direction indicated by the dotted arrows. It will accordingly be seen that the current from r_4 increases the current in the section r_2 and decreases the current in the section r_1. By properly proportioning r_3 and r_4, as described above, their currents cancel each other in the section r_1 and aid each other in the section r_2 so that there is no transmission of the amplified current back to the section r_1. It will furthermore be seen that, due to the way in which r_4 is connected to the circuit, neither of the two negative resistances receives current from the other as long as the impedances r_1 and r_2 are equal.

The character of the negative impedances r_3 and r_4, which permits their operation without singing, will be apparent from considering Figs. 3, 3ª, 4 and 4ª. What has been designated the shunt type is illustrated by Figs. 3 and 3ª, and the series type by Figs. 4 and 4ª.

Referring to Fig. 3ª, representing the shunt type, if an E. M. F. E is impressed on the terminals of the amplifier A, a current

$$I_i = \frac{E}{R_i}$$

flows in the input circuit, which causes a voltage MI_i to act in the output circuit. M is the unilateral mutual impedance, representing the ratio of the voltage generated in the output circuit to the input current, and is taken as positive when the E. M. F. generated in the output circuit aids the current in this circuit. The current in the output circuit is then

$$I_o = \frac{E + MI_i}{R_o}.$$

The total current in the amplifier is:

$$I = I_i + I_o = \frac{E}{R_i} + \frac{E + M\frac{E}{R_i}}{R_o} = \frac{R_o + R_i + M}{R_i R_o} E \quad (2)$$

from which

$$R = \frac{E}{I} = \frac{R_i R_o}{R_i + R_o + M} \quad (3)$$

As M increases from zero, the resistance R decreases but it remains positive, never reaching zero.

By making appropriate changes in the amplifier or the connections, such as by reversing the two wires connected to the input or to the output terminals, M can be made negative. If now M is increased, the current I_o in the output circuit decreases and the resistance of the whole amplifier R increases. When $-M=R_i+R_o$, the current I becomes zero and the resistance R becomes infinite. At this point the amplifier just supplies its own losses and the current in the resistance R_e falls to zero. By increasing −M a little more, R becomes negative but very large and the amplifier sends a small reversed current through the resistance R_e supplying energy to it. The potential impressed upon the input circuit of the amplifier by the output circuit will be too small to sustain itself, however, without the assistance of the generator G.

Putting E_o for the E. M. F. generated within the output circuit by the current I_i in the input circuit,

$$E_o=MI_i=M\frac{E}{R_i} \quad (4)$$

In order that the voltage E may be sustained without assistance from the generator G,

$$E=E_o\frac{\dfrac{R_eR_i}{R_e+R_i}}{\dfrac{R_eR_i}{R_e+R_i}+R_o} \quad (5)$$

Substituting for E_o its value from Equation (4)

$$E=\frac{E}{R_i}M\frac{\dfrac{R_eR_i}{R_e+R_i}}{\dfrac{R_eR_i}{R_e+R_i}+R_o} \quad (6)$$

Solving for R_e,

$$R_e=\frac{R_oR_i}{-(R_i+R_o-M)}=-R \quad (7)$$

that is, when the negative resistance is equal to the positive external resistance, as will be seen in the case of the series negative resistance, a disturbance becomes self-sustaining.

By increasing −M still further, which reduces −R still more, the amplifier supplies more than enough energy to sustain a disturbance once started and the disturbance grows until overloading reduces −M or losses in the system increase to such an extent that $R_e=-R$, after which the disturbance persists with constant magnitude.

Physically it is readily seen that by making R_e small, the connection between the output and input terminals of the amplifier is short circuited so that feeding back cannot occur and the generator G must supply a voltage in order to make the system active even though the amplifier may actually be supplying energy to the generator. By making R_e large or opening it, feeding back becomes possible and the amplifier can oscillate.

The shunt negative resistance will therefore sing when it is smaller than the external positive resistance R_e but will not sing when it is larger. In this respect its properties are the reverse of the series resistance which will now be fully described. Fig. 3 shows a particular arrangement of a vacuum tube and associated apparatus which will exhibit in its winding 1 a negative impedance having the shunt characteristics described above in connection with Fig. 3[a].

Referring to Fig. 4[a], representing the series type, a one-way amplifier A is connected with the circuit that includes the generator G and the external resistance R_e. This amplifier has its input and output terminals connected in series with each other and with the external circuit in the manner shown. The resistance between the input terminals of the device A is represented by R_i, and the resistance between the output terminals by R_o. When current flows in the input circuit, an electromotive force is generated in the output circuit. The unilateral mutual impedance, which is the ratio of this electromotive force to the current in the input circuit, is designated M. M is, in this case, considered positive when the direction of the electromotive force is such as to oppose the current, and negative when it aids the current in the input circuit. If the generator G sends a current I through the circuit, the potential difference across the whole amplifier is

$$E=(R_i+R_o+M)I \quad (8)$$

and the resultant resistance offered by the amplifier to the passage of the current is

$$R=\frac{E}{I}=R_i+R_o+M \quad (9)$$

The larger M is made, as, for example, by turning the knob of a potentiometer within the amplifier, the higher the total resistance becomes, but it never becomes negative.

It will be apparent that M can be made negative by appropriate changes in the amplifier or in its connections, as, for example, by reversing the two wires connected to the input terminals or the output terminals. This causes the electromotive force set up by the amplifier to aid the current from the generator and reduces the resistance R presented by the amplifier to the source. When $-M=R_i+R_o$, the voltage E across the whole amplifier and the resistance R become zero. The amplifier now supplies enough energy to the system to overcome its own internal losses but supplies no energy to the external resistance R_e.

By making −M still larger, E and R reverse in sign and the amplifier supplies energy to the external resistance R_e. When

$$-M=R_e+R_i+R_o \quad (10)$$

the amplifier supplies all energy required for the circuit and if the generator G is removed, leaving R_e in the circuit, the oscillation will continue indefinitely.

If the circuit is opened, and the amplifier is adjusted so that $-M>R_e+R_i+R_o$ and the circuit again closed, any disturbance, however small, which causes a current in the input of the amplifier, will result in a voltage in the output large enough and properly directed to increase the current. The disturbance will then grow until it becomes so large that M is reduced by overloading (or the resistance of some part of the circuit increases) to such an extent that

$$-M=R_e+R_i+R_o,$$

after which the disturbance will persist at a constant value.

Looking at the matter from a physical standpoint, if R_e is made very large, the E. M. F. developed in the output circuit of the amplifier cannot send a large enough current into the input circuit to sustain itself, while if R_e is made small, a large current can flow. This system is therefore nonsinging for values of R that are negative and less than R_e but sings when R is negative and greater than R_e.

Fig. 4 shows a particular arrangement of a vacuum tube and associated apparatus which will exhibit in its windings 1—1 a negative impedance having the series characteristics described above in connection with Fig. 4ª.

When the series type negative resistance is substituted for r_3 of Fig. 2 and the shunt type for r_4, the two-element repeater thus constituted will function without singing. The gain of such a repeater may be adjusted by varying the ratio N. This may be done either by changing the value of the negative resistance or by changing the ratios of the transformers *a* and *b* by means of taps. The latter is probably the preferable form and its use is shown in greater detail in Fig. 6.

The application of the invention to physical and phantom circuits is shown schematically in Figs. 5 and 6, respectively. In these figures, L_1 and L_1' represent parts of one side circuit of a phantom group which are connected through the negative impedance repeater, and L_2 and L_2' represent parts of the second side circuit. Connected with the side circuits are hybrid coils *a* and *a'* having the transformers *b* and *b'* bridged across the line windings thereof. Negative resistances *c* and *c'* of the series type are connected to the windings of *a* and *a'*, and negative resistances *d* and *d'* of the shunt type are connected across windings of the transformers *b* and *b'*. The midpoints of bridged windings of the transformers *b* and *b'* are connected with the winding of the transformer B, with which is connected a negative resistance D which is of the shunt type and functions in connection with the phantom circuit. Furthermore, it will be seen that each conductor of each line circuit contains two other windings, those connected with L_1 and L_1' being designated e_1, and those with L_2 and L_2' being designated e_2. These windings are inductively related with the windings *f* and *f'* with which is connected the negative resistance C, which is of the series type and functions in connection with the phantom circuit. When transmission takes place from L_1 to L_1' or from L_1' to L_1, the negative impedances *c* and *d* co-act to send an amplified wave into the receiving line without returning a wave toward the speaker. The other negative impedances are not affected. Similarly, L_2 to L_2' or from one part of phantom to the other.

As will be seen in Fig. 6, the apparatus windings of the hybrid coils and of the phantom transformers are arranged with a plurality of taps in order to control the gain of the repeaters. One repeater, comprising the negative resistances A_1 and A_1', is connected with the line sections L_1 and L_1'; another repeater, comprising the negative resistances A_2 and A_2', is similarly connected with the sections L_2 and L_2'; a third repeater, comprising the negative resistances A_3 and A_3', is connected with the phantom circuit. The gain adjustment of each of the repeaters is independent of that of the others, but the taps of both transformers of any repeater or the values of the corresponding negative resistances must be changed at the same time. The filters and the networks shown in connection with the repeaters in Fig. 6 are intended to adapt the repeaters for loaded cable circuits.

The structures disclosed hereinbefore are capable of producing negative resistances having the desired series or shunt characteristics. Since in practice the repeaters are used in line sections, the impedances of which vary with change of frequency, it is necessary that the negative impedance of the repeater should likewise vary. If the negative impedances of the repeater were made constant in value, the gain of the repeater would vary with frequency. Moreover, the effects of series and shunt impedances would not balance each other at all frequencies, and consequently, waves would return toward the talker at some frequencies. To avoid such difficulty it is necessary that each negative impedance shall vary with frequency in a manner depending on the varition of the line impedance. Such an arrangement is shown in Fig. 6 by the network located in each branch circuit of the repeater.

The network that is associated with each negative resistance for accomplishing the purpose just stated comprises a condenser 4 in parallel with the inductance 5, which combination is in series with the branch circuit effectively connecting the negative resistance A_1 across the line L_1. Bridged across the branch circuit is a condenser 6 and connected in series with the said branch circuit is another combination of elements, namely, the resistance 7 and the inductance 8, the purpose of all of which elements and combinations will be presently described. As mentioned before, it is necessary that each negative impedance shall vary with frequency in a manner depending upon the variations of the line impedance with frequency in order to avoid the detrimental effects mentioned. If the line with which the repeater is connected were distortionless so that its impedance would be a pure constant resistance, it would be unnecessary to use additional apparatus in order to make the simple negative resistances function properly throughout any range of frequencies. Such networks are necessary when the negative resistances are used in connection with lines whose impedances are not pure constant resistances.

It has been found and shown by Hoyt in his Patent 1,243,066, dated October 16, 1917, that the resistance component of the impedance of a coil-loaded line, measured from a point .8 of a section away from the first loading coil, is approximately constant over a wide frequency range. The negative of this resistance component may therefore be closely approximated by the negative resistances described above. He also found that the reactance component of the line impedance can be neutralized by a network consisting of an inductance and condenser in parallel, which combination is connected in series with the line. The reactance of this combination of inductance and capacity is therefore the negative of the reactance of the line and by connecting the combination in series with the negative resistance the negative of the impedance of the line at .8 section is obtained.

It is of course desirable to adapt the negative resistance A_1 to any desired end section of a loaded line, preferably a half section. This result is accomplished by connecting the condenser 6 across the branch circuit that extends from the transformer *b* to the negative resistance A_1. This is equivalent to removing negative bridged capacity from the negative impedance and gives the negative of the line impedance for end sections less than .8 section.

The combination made up of the elements 7 and 8 that forms part of the adjusting network is an additional refinement. The effect of conductor resistance of a line is to cause a rise in the resistance component of the line impedance at low frequencies and to introduce a negative reactance also at low frequencies. By introducing the elements 7 and 8 and increasing the value of the negative resistance to offset the positive resistance 7 at high frequencies the negative impedance of the combination is caused to increase at low frequencies and a positive reactance increasing as the frequency is lowered is introduced. These effects make it possible to simulate the negative of the effect of line resistance at low frequencies. By omitting the condensers 4 and 6 and the inductance 5 the negative of the impedance of a non-loaded or continuously loaded line having a finite conductor resistance can be obtained.

The employment of a network made up some or all of the elements 4, 5, 6, 7 and 8 in the form shown enables the negative resistances to function properly in connection with any type of transmission line throughout a given range of frequencies.

Owing to the fact, however, that the simulation afforded by the network just described becomes imperfect at frequencies near zero and near the cut-off frequency of the line, and that the return loss of the line tends to become low as the frequency rises, it is necessary to provide means such as filter 9 to modify the negative resistances such as A_1 at the extreme frequencies to prevent singing and to permit satisfactory gains to be obtained in the useful range of voice frequencies.

While I have described only the network and the filter associated with the branch circuit containing the negative resistance A_1, it is to be understood that the networks and filters shown in connection with the other branch circuits of Fig. 6 are similar to those just described.

The negative impedance repeater disclosed in this application not only possesses the advantage found in the 21-type repeater, which consists in having the line conductors continuous through the repeater circuit but it also possesses an advantage which has hitherto been found only in the 22-type repeater, namely, that it does not send speech waves back toward the transmitting station.

The result is that the conductors of the circuits, as shown, may be employed for telegraph or other unidirectional or low frequency alternating currents without the use of composite sets to carry such currents around the repeater. It is merely necessary to use the condensers "*k*" to prevent the short circuiting of these currents through the bridged circuits. Furthermore, the undesired reaction toward the transmitter which is found in the 21-type of repeater is avoided. This arrangement also avoids the necessity for using phantom repeating coils to separate the side and phantom circuits in order to insert the repeaters.

While the invention has been disclosed as embodied in particular forms, it is capable of embodiment in other and different forms without departing from the spirit and scope of the appended claims.

What is claimed is:

1. A repeater comprising two negative impedances, one of the series type and the other of the shunt type, one of which impedances is effectively connected in series with the line and the other impedance effectively in shunt with the line.

2. The combination with a line of a repeater connected between sections thereof, the said repeater comprising two negative impedances, one of the series type and the other of the shunt type, one of which impedances is effectively connected in series with the line and the other impedance effectively in shunt with the line.

3. The combination with a line of a repeater connected between sections of the said line, the said repeater comprising two negative impedances, one of the series type and the other of the shunt type, the said impedances being so connected with the said sections that the current in one of said sections arising from one negative impedance opposes the current in that section arising from the other negative impedance.

4. The combination with a line of a repeater connected between sections of the said line, the said repeater comprising two negative impedances, one of the series type and the other of the shunt type, the said impedances being so connected with the said sections that the current in one of said sections arising from one negative impedance neutralizes the current in that section arising from the other negative impedance.

5. The combination with a hybrid coil between two sections of a line, of a series type negative impedance serially coupled to the line through the hybrid coil and a shunt type negative impedance connected in parallel relation to the line at the bridge points of the hybrid coil, the vector magnitudes of said negative impedance being in reciprocal relation to the line impedance.

6. The combination with a hybrid coil between two sections of a line, of a series type negative impedance serially coupled to the line through the hybrid coil, a shunt type negative impedance connected in parallel relation to the line at the bridge points of the hybrid coil, the vector magnitudes of said negative impedance being in reciprocal relation to the line impedance, and means for varying the magnitude of said impedances without destroying the reciprocal relation.

7. The combination with a line, of a series type negative impedance serially associated with the line and a shunt type negative impedance associated in parallel relation with the line.

8. The combination with a line, of a series type negative impedance serially associated therewith, and a shunt type negative impedance associated in parallel relation to the line, the said negative impedances being in conjugate relation to each other.

9. The combination with a phantom group comprising two side circuits and a phantom circuit, of series type negative impedances serially associated with each circuit, and shunt type negative impedances associated in parallel with each circuit, the series and shunt type negative resistances of each circuit being in conjugate relation to each other.

10. A repeater comprising a hybrid coil connected between two line sections, a negative impedance serially related to the line through the windings of the hybrid coil, the said negative impedance comprising reactance elements and a negative resistance obtained by connecting the input and output terminals of a one-way amplifier effectively in series with each other; a second negative impedance bridged across the line at the midpoints of the hybrid coil, said second negative impedance comprising reactance elements and a negative resistance obtained by connecting the input and output terminals of a second one-way amplifier effectively in parallel with each other, the magnitudes and phase angles of said negative impedances being in reciprocal relation to the line impedance at all important frequencies, and means for effectively varying the magnitudes of said negative impedances without destroying the said reciprocal relation.

11. The combination with a phantom group of transmission circuits comprising two sides circuits and a phantom circuit, of three repeaters in accordance with claim 10 connected between the parts of said phantom group extending in opposite directions, each of said repeaters being adapted to amplify the waves traversing one of said circuits.

12. A repeater comprising negative impedances, one of the series type and the other of the shunt type, the said series type impedance being effectively connected in series with the line with which the said repeater cooperates and the said shunt type impedance being effectively connected in shunt with the said line.

13. The combination with a line of a repeater connected between sections thereof, said repeater comprising negative impedances, one of the series type and the other of the shunt type, the said series type impedance being effectively connected in series with the line and the shunt type impedance being effectively connected in shunt with the line.

In testimony whereof, I have signed my name to this specification this 17th day of May, 1928.

GEORGE CRISSON.