April 12, 1932. A. G. GANZ **1,853,969**

CIRCUITS FOR COUPLING LINES OF DIFFERENT IMPEDANCES

Filed April 2, 1929

FIG. 1

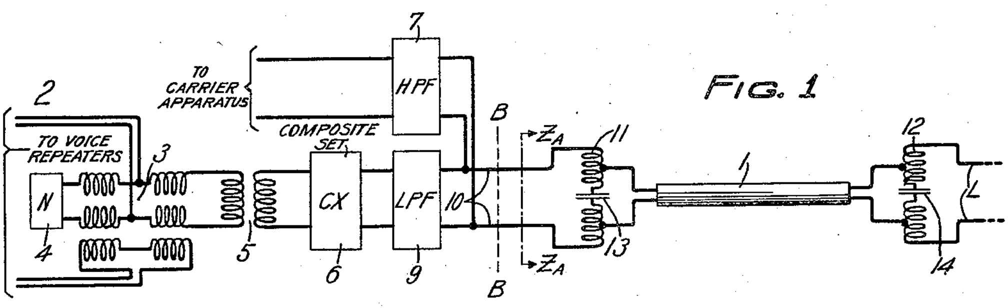


FIG. 2

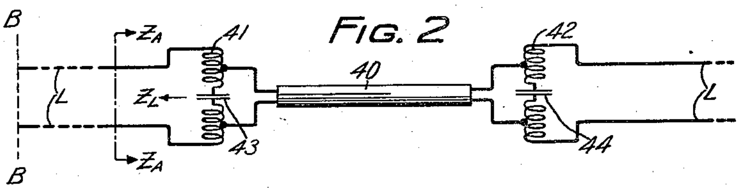


FIG. 3

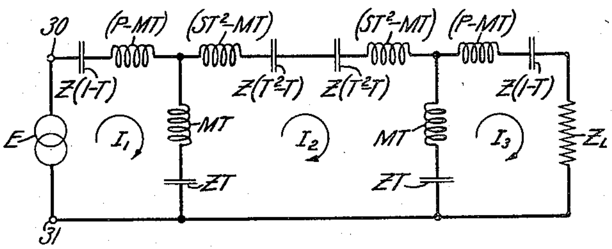


FIG. 5

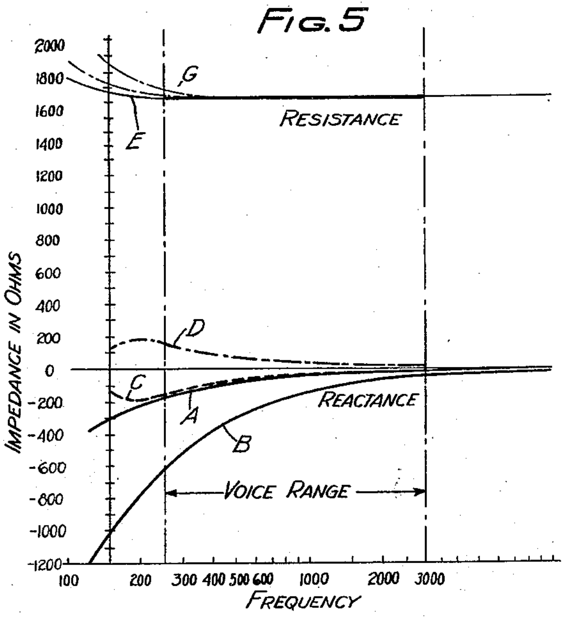


FIG. 4

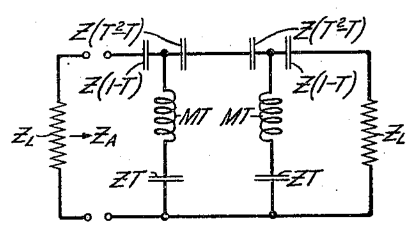
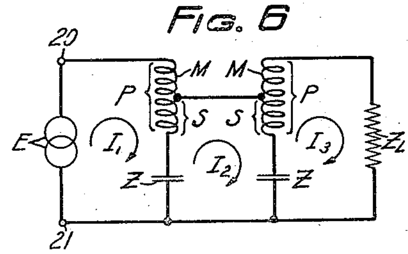


FIG. 6



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UNITED STATES PATENT OFFICE

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CIRCUITS FOR COUPLING LINES OF DIFFERENT IMPEDANCES

Application filed April 2, 1929. Serial No. 351,880.

This invention relates to transmission circuits and more particularly to means for connecting transmission line sections having different impedances.

Objects of the invention are to increase the efficiency of a telephone and telegraph circuit when incidental cable lengths are connected therein; to eliminate at voice frequencies singing in repeater circuits due to impedance distortion which may be introduced by the incidental cable sections, and to eliminate at carrier frequencies reflection effects tending to produce cross talk in adjacent circuits.

In long telephone and telegraph lines conditions are met which require sections of unloaded cable at various points intermediate to an open wire line. The impedances of the open wire line and the cable section are substantially different especially at carrier frequencies, thus requiring that some provision be made at the junction points of these sections for matching their impedances. Where each wire of the line is equipped to transmit grounded Morse telegraph signals, an auto-transformer having a condenser at the midpoint of its bridge winding has been used heretofore to provide a through direct current path for the Morse signals and to separate metallically the individual line wires from each other.

The introduction of the condenser at the mid-point of the transformer bridge winding introduces a considerable amount of impedance irregularity and detrimental reflection effects especially at the lower voice frequencies. The ideal matching of two circuits of different impedances results when the transfer of energy from one circuit to the other is a maximum with minimum reflection. However, the factors which permit maximum transfer of energy are different from those which give perfect impedance matching and complete absence of reflection so that in designing a line having sections of different impedance, some desirable feature may have to be sacrificed slightly in favor of some others. For maximum transfer of energy, the impedance looking into one section of the circuit should be the conjugate of that looking in the opposite direction, into the other section of the circuit. Two impedances are said to be conjugate to each other when their effective resistances are equal and their reactances are equal in magnitude but opposite in sign. On the other hand, for total absence of reflection the impedance looking into one section of the circuit must be the same as that looking in the other direction. Although as regards resistance, the circuits may be designed for both maximum energy transfer and minimum reflection, as regards reactance, if maximum energy transfer is desired the reactances of the two circuits must be opposite in sign, but if total absence of reflection is desired the reactances must be of the same sign. In particular cases intermediate relationships may prove more expedient.

In the type of circuit to which this invention has particular reference, two conditions are encountered depending upon whether the cable section is near a line repeater or located at a considerable distance therefrom. When near a repeater the impedance looking into the transformer at the near end of the cable section should be substantially the same as that looking in the reverse direction. In other words, the impedance looking away from the repeater must simulate the impedance of the repeater balancing network. If this were not the case the unbalance would result in singing, or a continuous transfer of energy from one branch of the repeater to the other which paralyzes the repeater and prevents it from functioning properly. At the same time equalizing the impedances at lower frequencies eliminates to a large extent undesirable reflection effects.

Another condition exists when the incidental cable section is at a point remote from the repeater. Where the line connecting the repeater with the end of the cable section is long, the manner of its termination is of small consequence since the impedance looking away from the repeater will be that of an open wire line which in turn is the same as the repeater balancing network. Consequently, the impedance looking into the transformer at the near end of the cable section need not be the same as the balancing network or the same as an open wire line, but may be the conjugate thereof to satisfy the conditions of maximum energy transfer.

For the case where the incidental cable section is in close proximity to the repeater the invention resides in means for properly balancing the repeater hybrid coil, and for the second case where the cable section is remote from the repeater in means for obtaining maximum energy transfer.

The invention is based upon the principle that the equivalent circuit of an auto-transformer with a condenser in the bridge arm when reduced to unity ratio basis is a T section having series and shunt elements, the series arms each representing the leakage impedance of the transformer plus the series component of the capacity of the condenser and the shunt arms the mutual impedance of the transformer plus the shunt component of the capacity of the condenser. Furthermore, at the lower voice frequencies where the condenser in the bridge arm of the auto-transformer introduces the impedance irregularity, the cable lengths are electrically so short that the transformers at each end of the cable may be regarded as being back to back. An equivalent network of the combination comprising the two sections of open wire line, the intermediate short section of cable and the auto-transformer and condenser couplings may comprise, therefore, two of the unity ratio equivalent circuits described above connected in tandem and terminated by impedances which equal the characteristic impedance of the open wire line. It is apparent that the transmission and impedance characteristics of this combination network may be controlled within certain limits at the lower voice frequencies by merely varying the values of the elements representing the mutual impedances of the transformers, in the shunt arms of the network with respect to the capacities of the network and the terminating impedances. In accordance with the invention, improved matching of the impedances of the unloaded cable section and the open wire line connected thereto at the carrier frequencies and a reduction in the impedance irregularities and reflection effects at lower frequencies are obtained by the proper proportioning of the unity ratio mutual impedance of the auto-transformers coupling the cable section and open wire line, with respect to the capacities of the condensers in the bridge arms thereof, and with respect to the terminating impedances of the coupled circuits. The term "unity ratio mutual impedance" may be defined as the shunt impedance of the equivalent unity ratio T section of a fixed ratio transformer. It corresponds in the physical transformer to that inductance which depends on the reluctance of the magnetic circuit common to all of the windings, and is directly proportional to that inductance. This unity ratio mutual impedance of the transformer may be controlled in the physical transformer by varying the values of an inductive element or combination of inductive elements therein without changing the transformer impedance ratio at carrier frequencies. By proper proportioning of the elements mentioned, in the case where the cable section is near a repeater element, the impedance irregularites introduced by the bridge condensers at the lower frequencies are substantially eliminated, and the repeater properly balanced so as to eliminate detrimental reflection effects tending to cause singing; and in the case where the cable section is remote from the repeater, a maximum transfer of energy between the cable and the open wire lines and in some instances an actual increase in over-all transmission efficiency is obtained.

A better understanding of the invention may be had from the following description when read in connection with the accompanying drawings, of which Figs. 1 and 2 show two different circuit conditions to which the invention is applicable; Fig. 3 an exact equivalent network of the transformers and the associated cable length shown in Figs. 1 and 2 at voice frequencies; Fig. 4 an approximation of the same equivalent network; Fig. 5 a group of impedance characteristic curves of the circuits of Figs. 1 and 2 under different conditions; and Fig. 6 a diagrammatic view of a portion of the circuits of Figs. 1 and 2 when the impedance of the cable sections are neglected as they may be under certain conditions of circuit operation.

Fig. 1 represents a circuit embodying the invention in which an incidental cable section 1 is connected in a line in close proximity to voice repeating apparatus 2. The hybrid coil 3 of the repeater is terminated in a balancing network 4 and is connected to the line in accordance with well-known practice by the repeating coil 5. A composite set 6 and high pass filter circuit 7 are provided for by-passing the telegraph and carrier currents, respectively, around the voice frequency repeater while the low-pass filter 9 excludes the carrier frequencies from the voice repeater. Since this is the case in which the incidental cable section is in close proximity to the repeater, the leads 10 are necessarily short.

The cable section 1 is electrically short in the voice frequency range and if this range were all that had to be considered, the impedance of the cable section could be neglected. However, at carrier frequencies the attenuation of the cable section is sufficiently great to require impedance matching and since each wire of the line is equipped to carry grounded Morse telegraph signals, the matching is accomplished by the use of auto-transformers 11 and 12 having the condensers 13 and 14 at their respective mid-points to properly segregate the grounded telegraph circuits. Transformers of this type are usually designed to have a very high mutual impedance, and when a condenser having the optimum value of capacity determined by telegraph considerations is used the impedance looking into the transformer 11 differs greatly from that of an open wire line at the lower voice frequencies. This is seen by a comparison of the characteristic curve A of Fig. 5 which represents the reactance characteristic over the voice range of an open wire line, and the curve B which represents the characteristic reactance looking into the transformer 11 when the transformers are designed for maximum mutual impedance. Since the balancing network 4 is commonly designed for the case where the repeater is connected to an open wire line the unbalance which is introduced between the impedance of this network and the impedance looking toward the transformer 11 is sufficiently great to cause singing of the repeater and detrimental reflection effects.

In Fig. 5 the curves E and A represent the variation of resistance and reactance with frequency, respectively, of the part of the system of Fig. 1 to the right of the transformer 12, that is, the resistance and reactance characteristics of an open wire line. The repeater system to the left of the line B—B is normally designed to be balanced when terminated at B—B in the open wire line impedance as represented by curves E and A. The invention enables the impedance of this circuit as a whole to the right of the line B—B in Fig. 1, in the case where the cable section is in close proximity to the repeater, to be designed so as to have resultant reactance and resistance characteristics over the voice range as shown by the curves C and G, respectively, of Fig. 5. A comparison of these curves with the curves A and E reveal that the impedance looking into the transformer may be made to approximate closely that of an open wire line; in other words, the repeater system to the left of the line B—B is terminated in the impedance for which it is designed, in consequence of which the tendency of the repeater to sing may be eliminated.

As mentioned heretofore, at the lower voice frequencies where the condensers associated with the transformers introduce the greatest impedance distortion, the impedance of the cable section 1 may be neglected so that the transformers 11 and 12 may be regarded as working back to back. With these conditions imposed, the equivalent circuit of the transformers 11 and 12 reduced to a unity ratio basis is shown in Fig. 3, where P, S and M are the high side impedance, low side impedance, and the mutual impedance, respectively, of the transformer, Z the condenser impedance, T the turns ratio of the high to the low side of the transformer, and Z_L is the characteristic impedance of the terminating open wire line.

The equivalency of the circuits of Fig. 1 to the right of B—B and Fig. 3 may be proved by showing that the same voltage applied to the input terminals produces the same currents in magnitude and phase in the input terminals and in the terminating impedance when the circuits are similarly terminated. For convenience in proving this, reference may be had to the circuit of Fig. 6 which is an electrical equivalent of the circuit of Fig. 1 to the right of the dotted line B—B. In this circuit the impedances of the high side of the transformers are represented by P, that of the low side by S, the mutual impedance by M, the condenser impedance by Z and the terminating impedance by Z_L, all of which are equal in value to the impedances of the circuit of Fig. 3 having the corresponding terminology. If a voltage E_0 is applied at the input terminals 20 and 21 of Fig. 6 the currents I_3 and I_1, may be ascertained by writing the voltage equations for each loop of the circuit in accordance with Kirchoff's law and solving for I_3 and I_1. These voltage equations are as follows:

$$(1)\quad E=I_1(P+Z)\quad -I_2(M+Z)$$

$$(2)\quad O=-I_1(M+Z)+2I_2(S+Z)-I_3(M+Z)$$

$$(3)\quad O=\quad -I_2(M+Z)+I_3(Z+P+Z_L)$$

If the same voltage E is applied to the input terminals 30 and 31 of the circuit of Fig. 3 which is also terminated in the impedance Z_L the following voltage equations for the loops of this circuit are obtained:

$$(4)\quad E=I_1(Z+P)\quad -I_2(MT+ZT)$$

$$(5)\quad O=-I_1(MT+ZT)+2I_2(ST^2+ZT^2)-I_3(MT+ZT)$$

$$(6)\quad O=\quad -I_2(MT+ZT)\ +I_3(Z+P+Z_L)$$

The values of I_3 and I_1 obtained by solving these equations are equal to those obtained by solving equations 1, 2 and 3, and since these equations hold true for all frequencies including zero frequency, the circuits of Figs. 3 and 6 are equivalent.

At the lower voice frequencies the effect of the series inductances of the exact equivalent circuit of Fig. 3 may be disregarded, resulting at these frequencies in the equivalent circuit shown in Fig. 4. By means of an ordinary mesh computation, the impedance of this circuit is found to be as follows:

$$(7)\quad Z_A=Z(1-T)+\frac{[MT+ZT]\left[\frac{[Z_L+Z(1-T)][MT+ZT]}{Z_L+Z(1-T)+MT+ZT}+2Z(T^2-T)\right]}{MT+ZT+2Z(T^2-T)+\frac{[Z_L+Z(1-T)][MT+ZT]}{Z_L+Z(1-T)+MT+ZT}}$$

Since the values of Z_L, Z and T are fixed by circuit requirements as heretofore pointed out, it is obvious that the impedance Z_A may be varied by ascribing different values to the mutual impedance M. The form of Equation (7) and the values of the constants therein (Z, T, Z_L) are such that in the frequency range of interest, say, from 150 to 400 cycles, the change in the resistance component with the change in M is small compared with the change in the reactance component with the change in M. Thus by properly proportioning the mutual impedance of the transformers 11 and 12 the characteristic impedance Z_A of the circuit of Fig. 1 may be designed to equal that shown by the curves C and G of Fig. 5, which for all practical purposes is equal to the impedance of an open wire line. By this invention therefore the hybrid coil 3 of the repeater in the circuit of Fig. 1 may be properly balanced, thus eliminating all tendency to sing or to produce reflection effects.

The second embodiment of the invention relates to the case where the incidental cable section is at some position in the line remote from the repeater. This condition is represented by a modification of the circuit of Fig. 1 in which the circuit to the right of the dotted line B—B is replaced by the circuit of Fig. 2. In Fig. 2, L represents a long section of open wire line while cable section 40, transformers 41 and 42 and the condensers 43 and 44 are the physical equivalents of the corresponding cable section 1, transformers 11 and 12 and the condensers 13 and 14 of Fig. 1. The resultant circuit thus differs from that heretofore described in that the long section of open wire line L having a characteristic similar to that shown by curves A and E of Fig. 5 is located between the repeater and the incidental cable section. It is well known that the characteristic impedance of a long line is but slightly affected by the manner of its termination so that in this instance the question of repeater unbalance which tends to result in singing need not be considered. In the circuit of Fig. 2 therefore the impedance Z_A looking toward the cable section 40 may be designed with reference to the impedance of the line L to give maximum energy transfer. Maximum energy transfer occurs when the impedances at the junction of two circuits looking in opposite directions are conjugate. As the characteristic impedance Z_L looking toward the open wire line would be as shown by curves A and E, it is obvious that by designing the transformers 41 and 42 in accordance with the methods heretofore set forth to make the impedance Z_A have the characteristic as given by curves D and F of Fig. 5, the relation for maximum energy transfer prevails.

Although this invention has been described in accordance with a specific type of telephone circuit the principles of impedance matching herein set forth are applicable to many different types of circuits within the spirit of the invention in view of which the invention is to be limited only by the scope of the appended claims.

What is claimed is:

1. A wave transmission system comprising two circuits, means connecting said circuits, including a transformer for matching the impedances of said circuits at certain frequencies, said transformer having its unity ratio mutual impedance properly proportioned with respect to its effective terminating impedances and the impedances of the other element of said connecting means to aid in matching the impedances of said circuits at other frequencies.

2. A wave transmission system, comprising two circuits, coupling means therebetween including a transformer for matching their impedances at certain frequencies, and a reactive element common to the two circuits, and transformer having its unity ratio mutual impedance proportioned with respect to its effective terminating impedances and the impedance of said reactive element to aid in matching the impedances of said circuits at other frequencies.

3. A wave transmission system comprising two circuits, a transformer having a condenser serially connected between the windings thereof, connecting said circuits for matching their impedances at certain frequencies, said transformer having its unity ratio mutual impedance proportioned with respect to the terminating impedances of said circuits and the capacity of said condenser for matching the impedances of said circuits at other frequencies.

4. In a transmission system, a section of cable interposed between two circuits simulating in impedance characteristics an open wire line, said cable section having negligible impedance to waves of certain frequencies but substantial impedance to waves of other frequencies, coupling means between said cable section and each of said circuits, each including a transformer for matching the im-

pedance of the cable section at said other frequencies with the impedances of the connected circuit, and a reactive element, the mutual inductance of said transformer being proportioned with respect to the effective impedances terminating said cable section and the circuits coupled thereto so as to substantially eliminate the impedance irregularity introduced by said reactive element at said certain frequencies.

5. In a transmission system a cable conductor interposed between two sections of an open wire line, said cable section having negligible impedance at voice frequencies but substantial impedances at ultra-voice frequencies, coupling means between said conductor and said line sections including an auto-transformer for matching the impedance of the cable conductor at said ultra-voice frequencies with that of the section of open wire line coupled thereto, and a capacity in series with the windings of said transformer, the the unity ratio mutual impedance of said transformer being proportioned with respect to said capacity to reduce the effect of the impedance irregularity introduced by said capacity at said voice frequencies.

In witness whereof, I hereunto subscribe my name this 1 day of April, 1929.

ALBERT G. GANZ.

CERTIFICATE OF CORRECTION.

Patent No. 1,853,969. April 12, 1932.

ALBERT G. GANZ.

It is hereby certified that error appears in the printed specification of the above numbered patent requiring correction as follows: Page 4, line 97, claim 1, for "element" read elements, and line 105, claim 2, for "and" read said; page 5, line 23, claim 5, strike out the word "the"; and that the said Letters Patent should be read with these corrections therein that the same may conform to the record of the case in the Patent Office.

Signed and sealed this 12th day of July, A. D. 1932.

M. J. Moore,
Acting Commissioner of Patents.

(Seal)