July 21, 1931. J. W. MILNOR ET AL 1,815,629

ARTIFICIAL LINE NETWORK

Filed Sept. 4, 1929 4 Sheets-Sheet 1

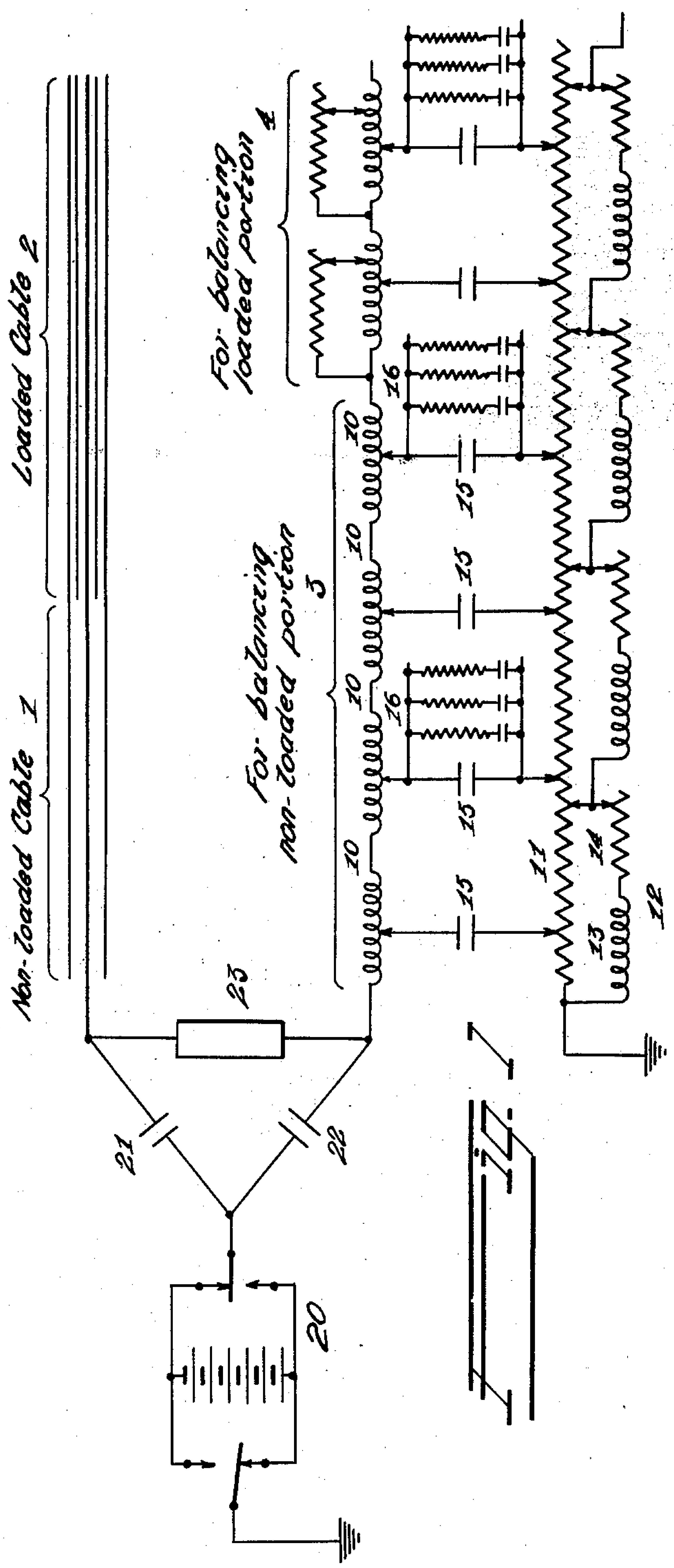

Fig. 1

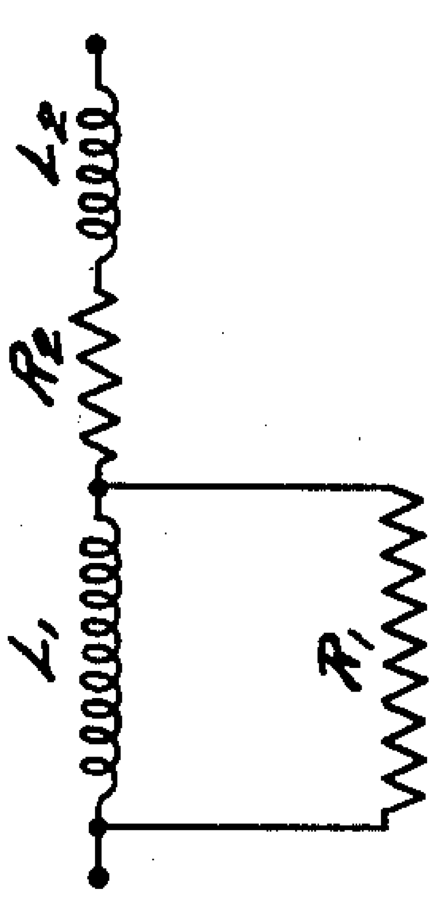

Fig. 2

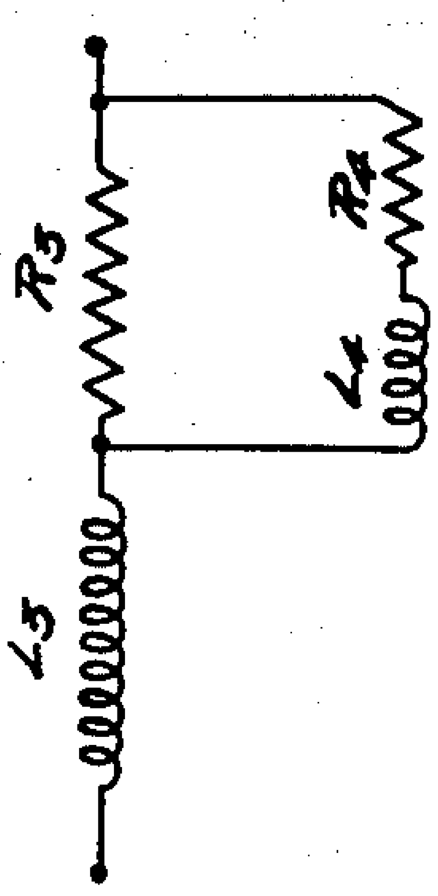

Fig. 3

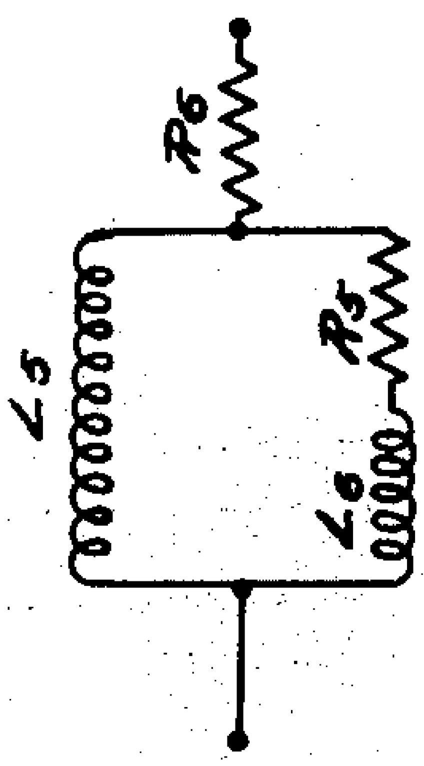

Fig. 4

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ARTIFICIAL LINE NETWORK

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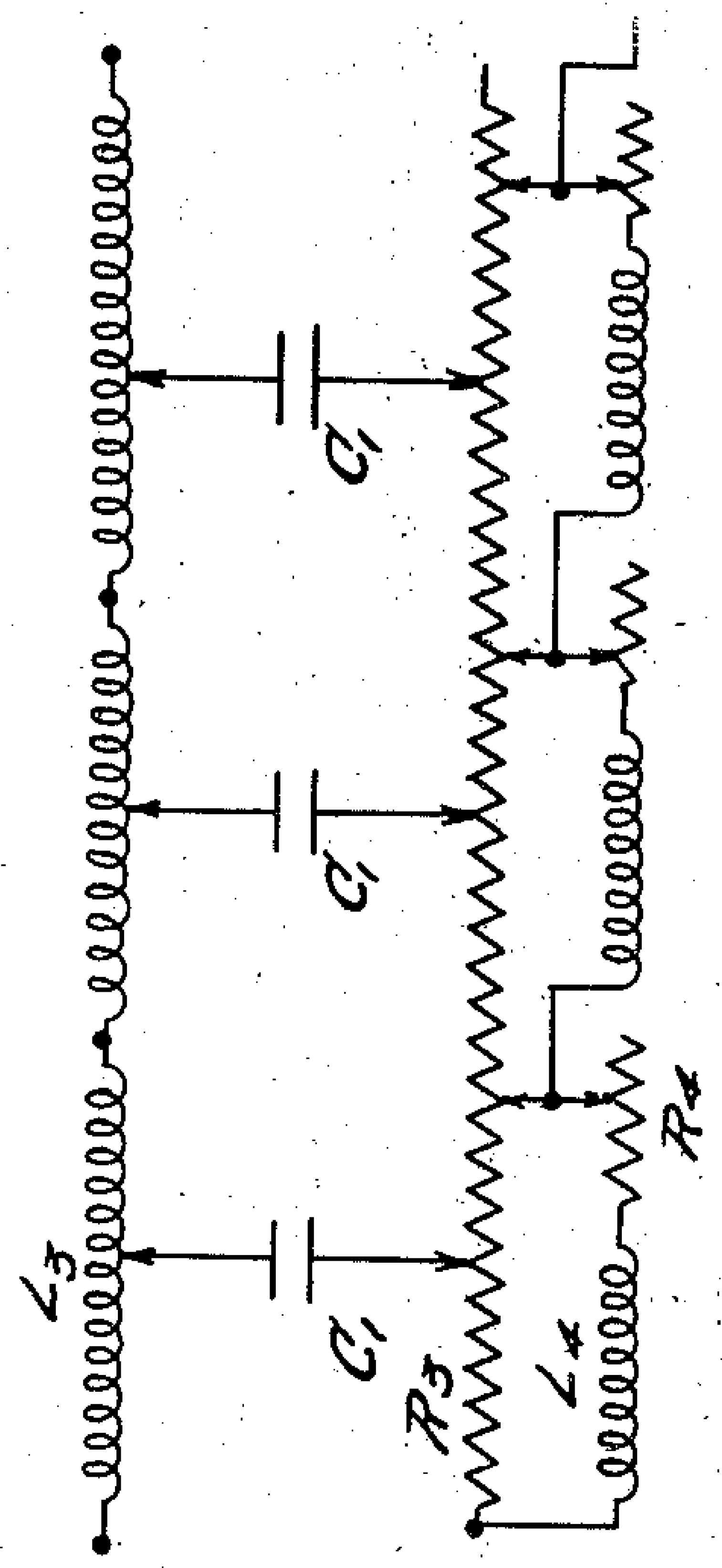

Fig. 6

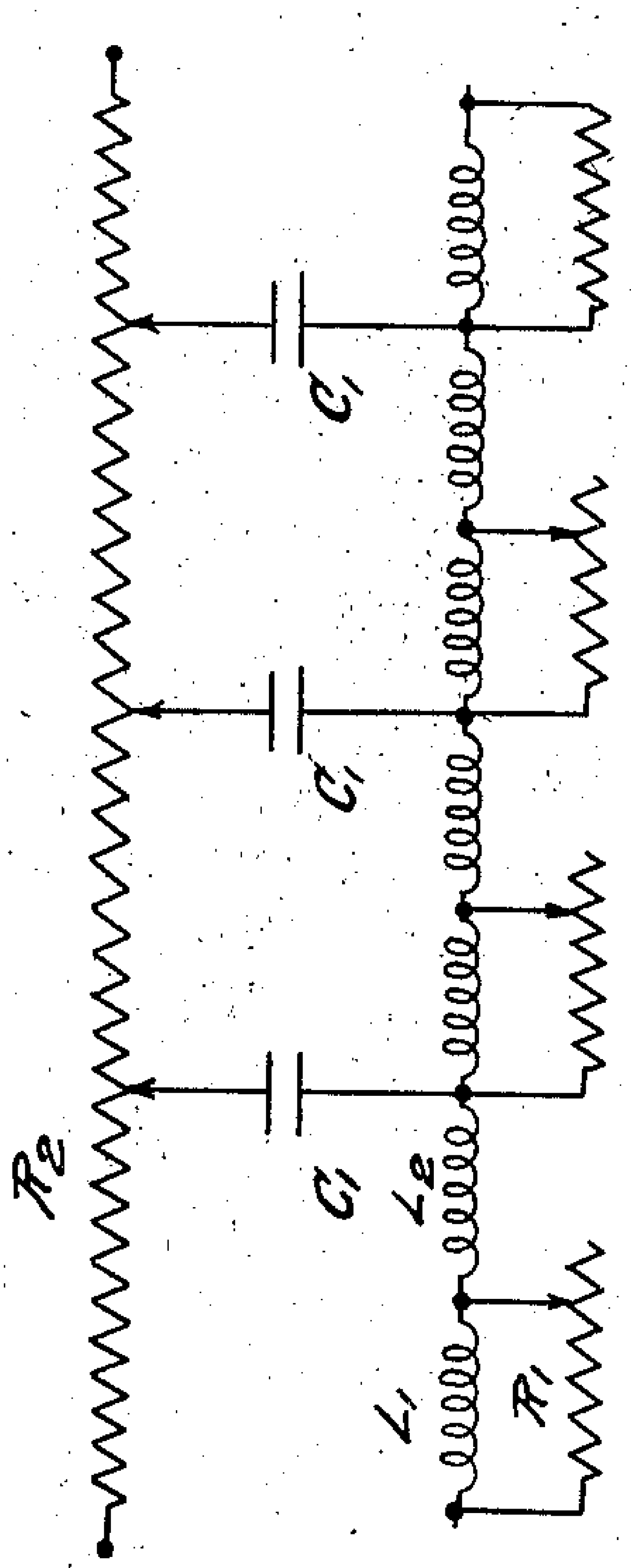

Fig. 5

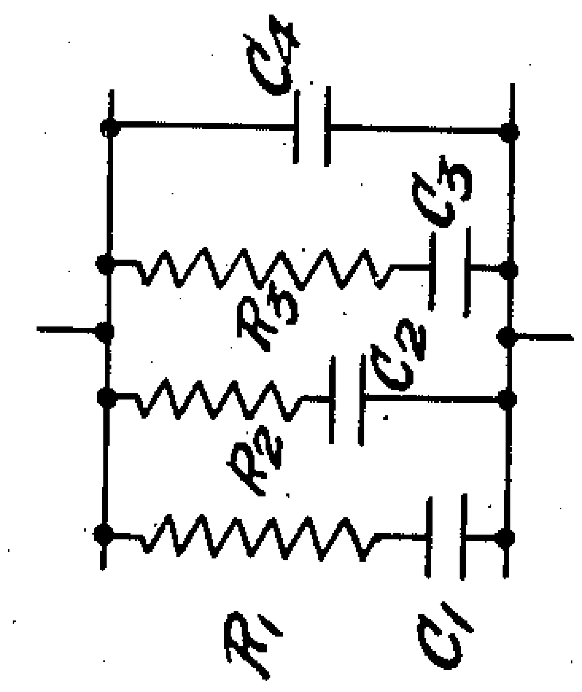

Fig. 9

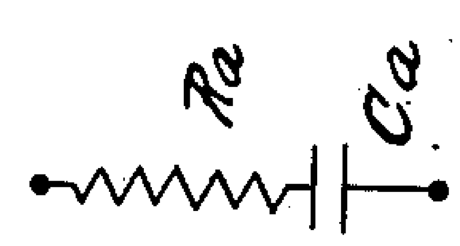

Fig. 8

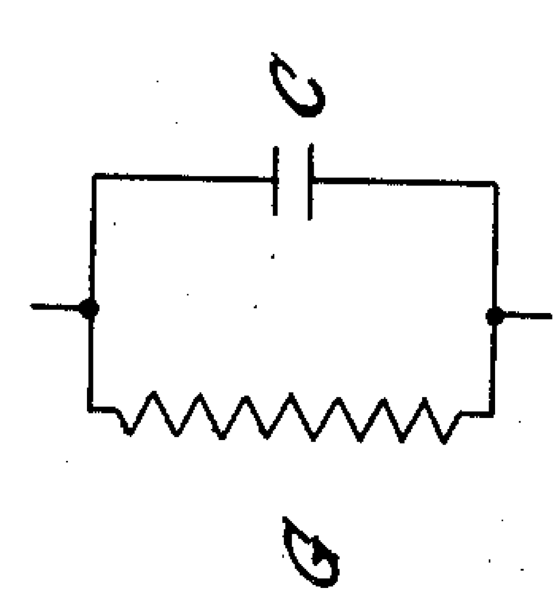

Fig. 7

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ARTIFICIAL LINE NETWORK

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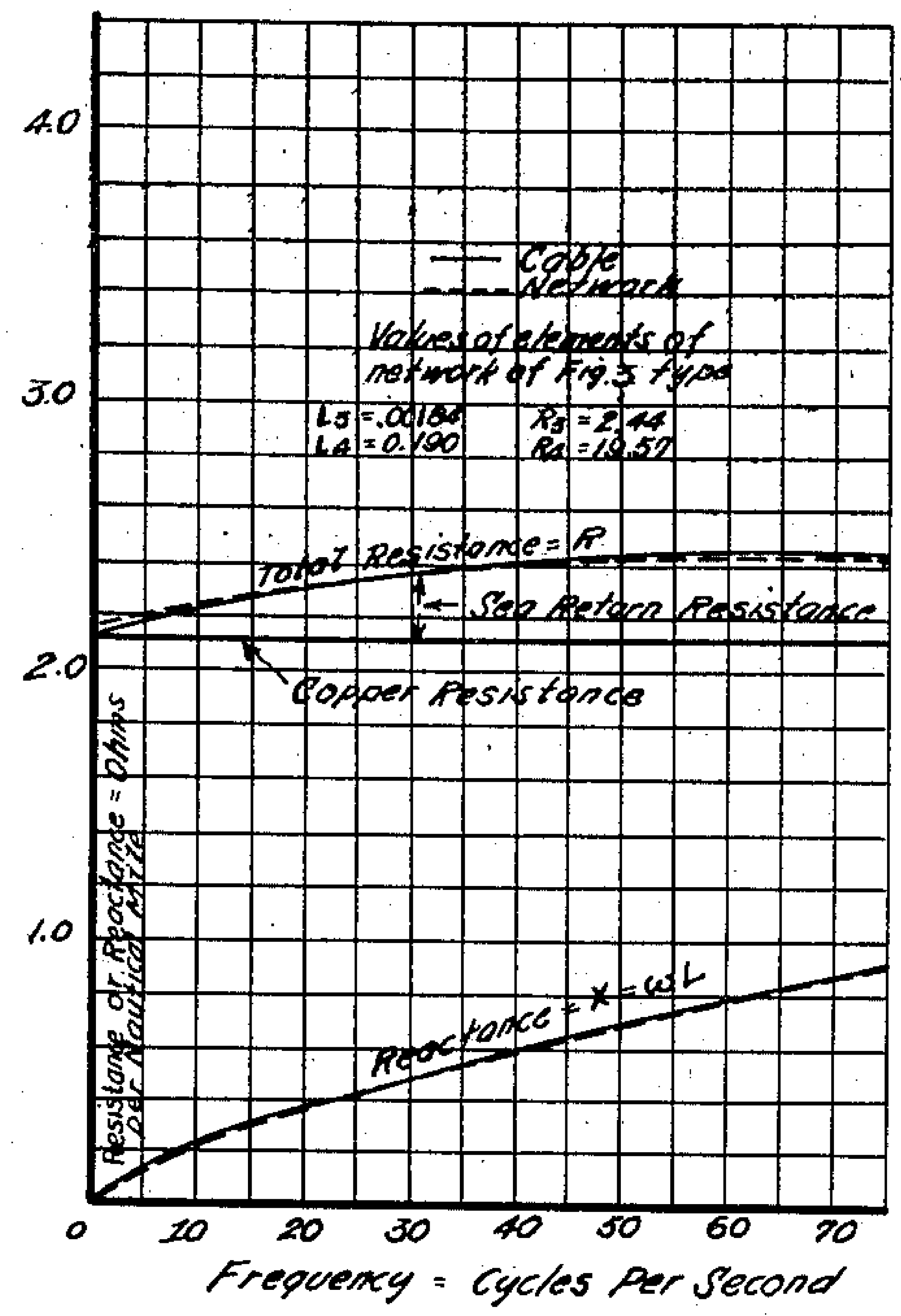

Fig. 10

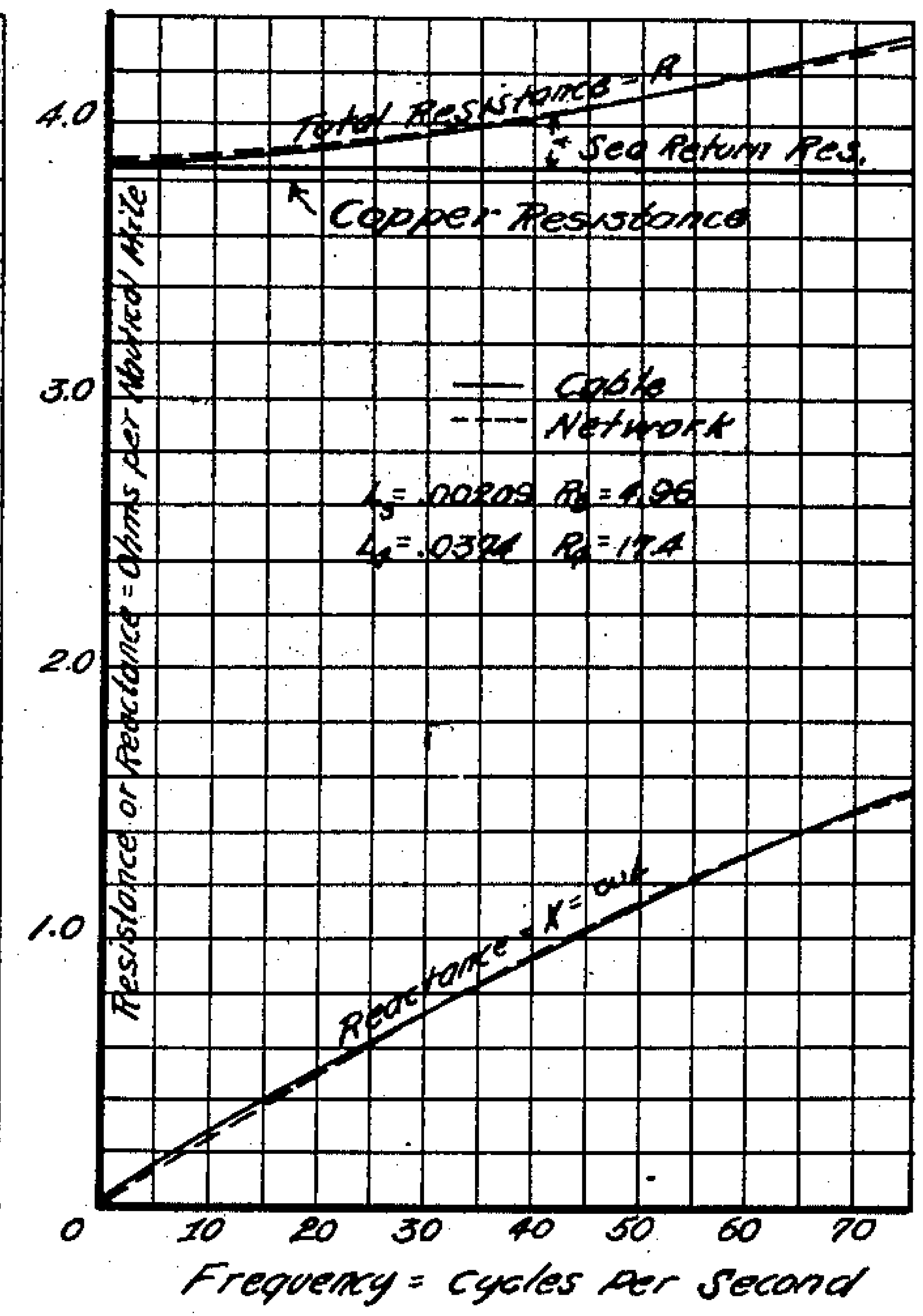

Fig. 11

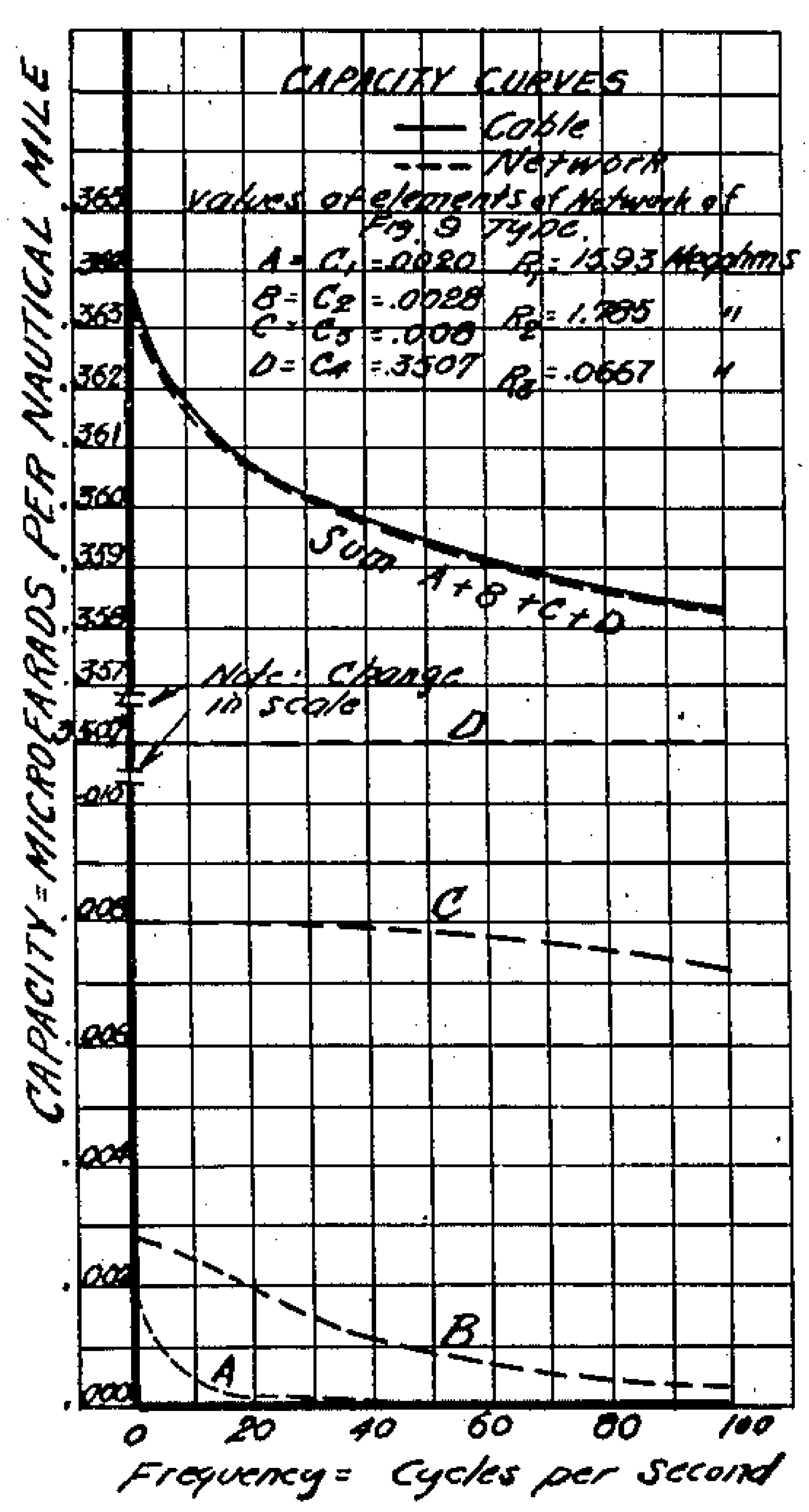

Fig. 12

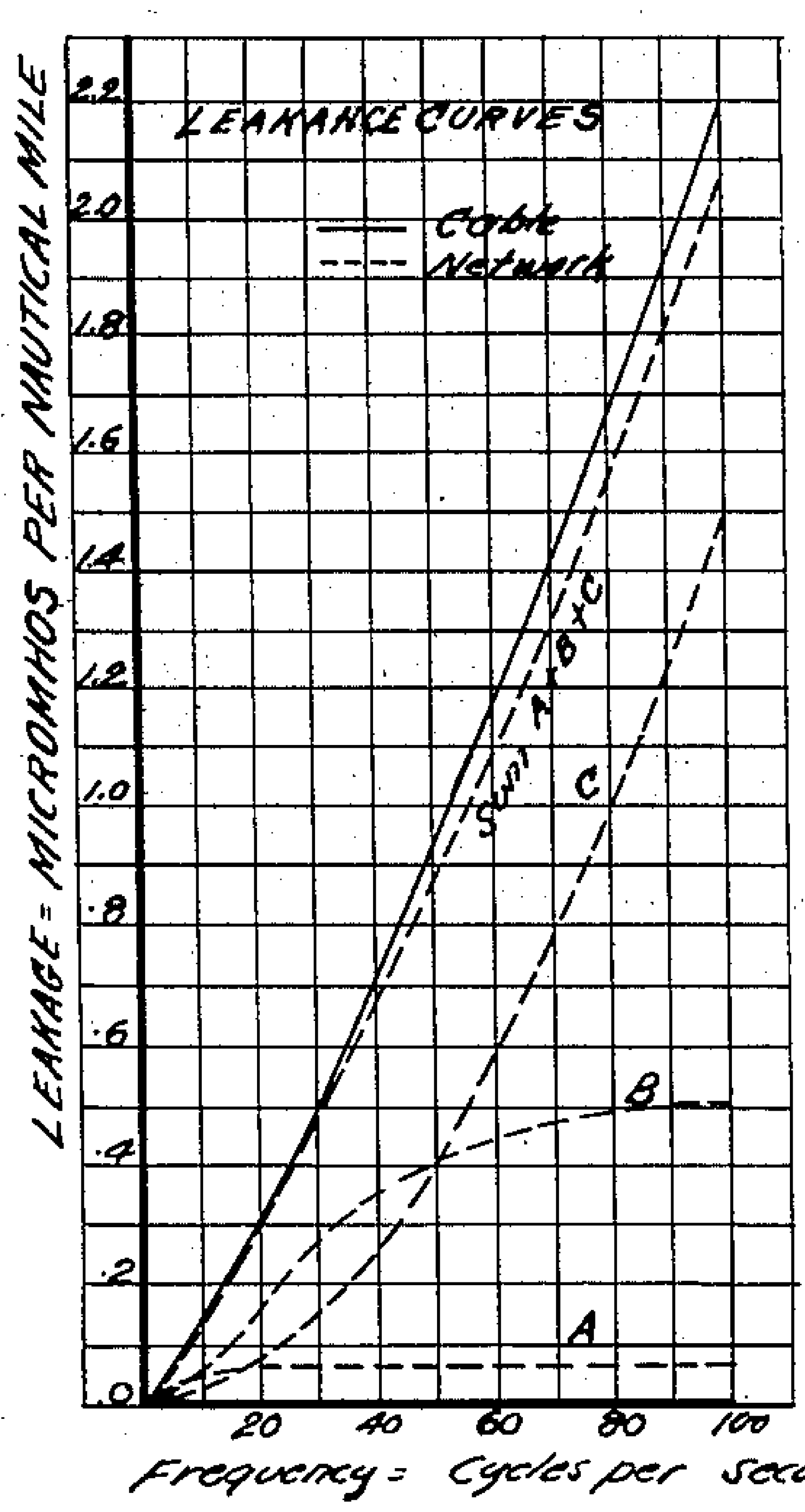

Fig. 13

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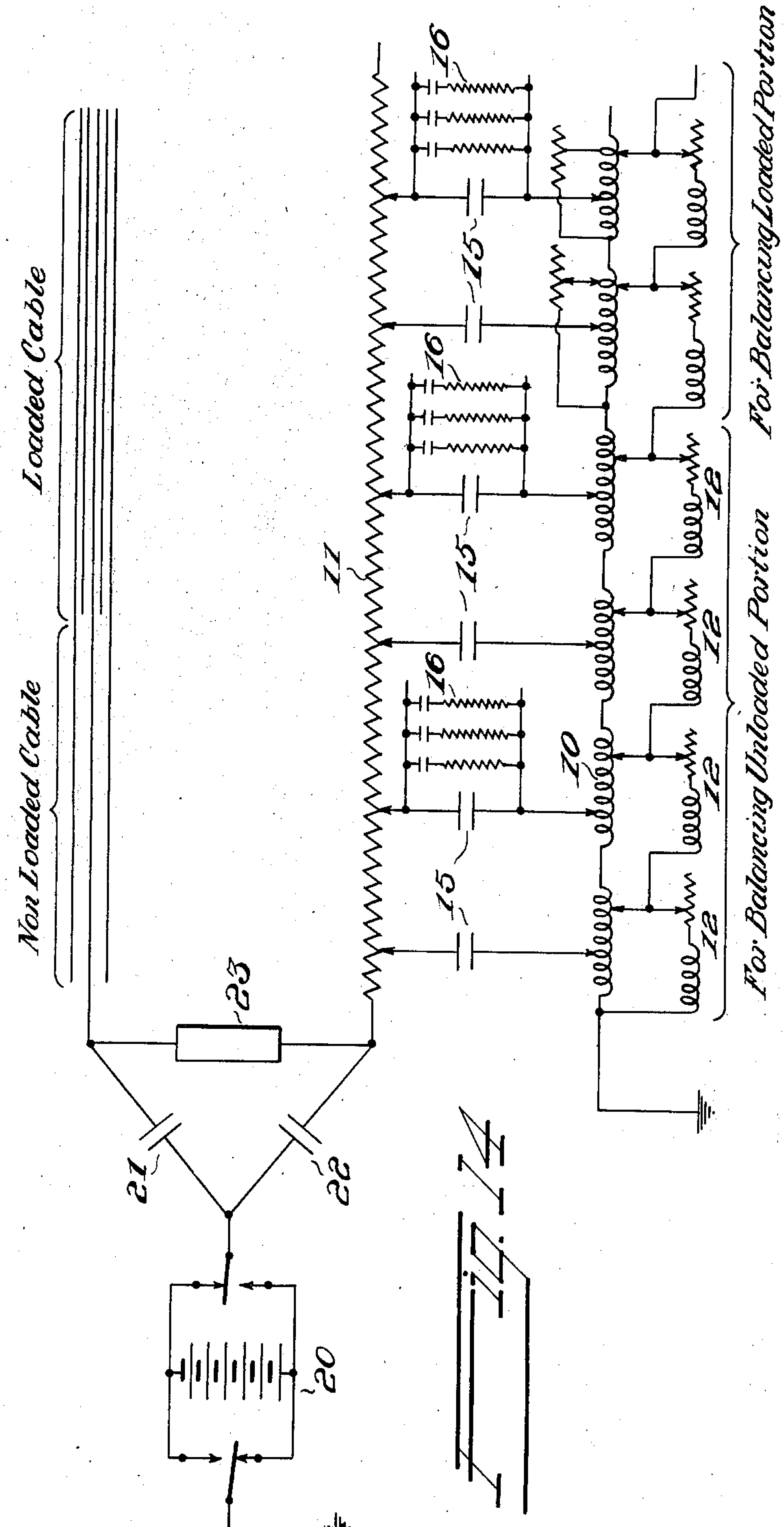

Fig. 14

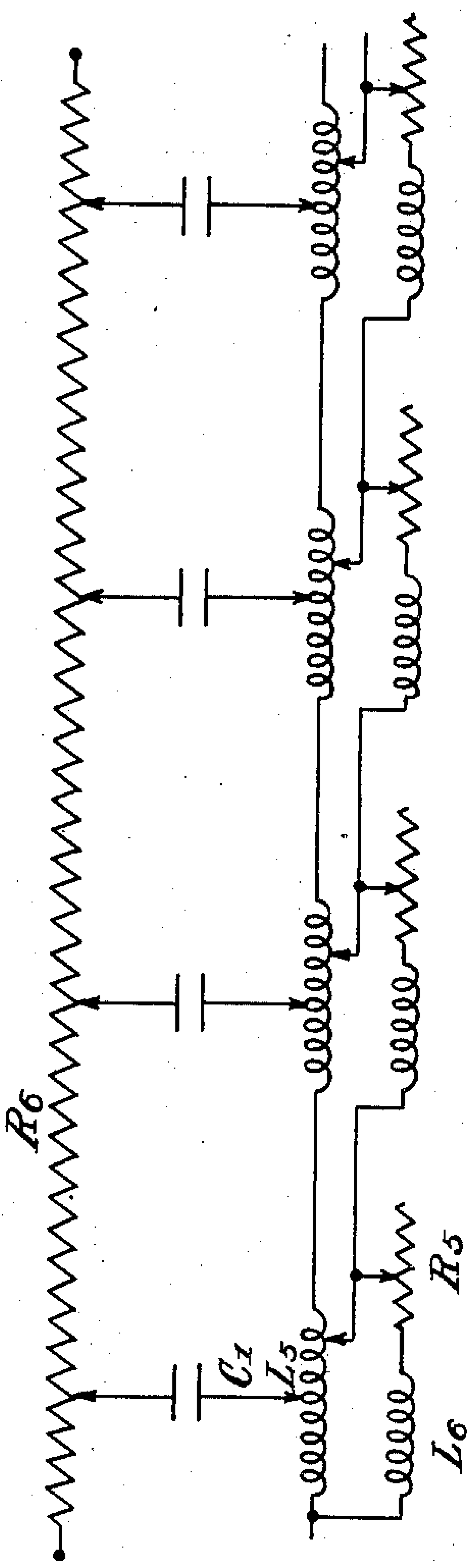

Fig. 15

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Patented July 21, 1931 | 1,815,629

UNITED STATES PATENT OFFICE

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ARTIFICIAL LINE NETWORK

Application filed September 4, 1929. Serial No. 390,348.

This invention relates to submarine cable systems and to a method of and means for balancing a long submarine telegraph cable by artificial line networks especially adapted for use in such systems.

It relates particularly to the balancing of long high speed submarine cables for duplex operation, and especially to loaded cables which employ non-loaded end sections for the purpose of reducing the severity of the balance requirements. However, the methods and means of the invention are in general applicable to any type of long cable either loaded or non-loaded.

Previously it has been practicable to successfully balance long submarine cables of the non-loaded type only. On these cables the attenuation was so high that only moderate speeds were possible and a balance was required for relatively low frequencies only. It was ordinarily sufficient here to balance the resistance and capacity by a fairly simple network; the small amount of inductance of the cable was approximately balanced by introducing certain irregularities in the resistance-capacity network, or by introducing a few inductance coils placed near the head of the artificial line; or by the use of a special network such as shown in Patent No. 1,519,870. In some cases the inductance balance was omitted altogether.

Cables of recent construction however have been designed to transmit signals at higher speeds. The higher speed necessitates a substantially perfect balance over a higher and a wider frequency range, and in a loaded cable this balance is complicated by the fact that the characteristics of the loading material are variable with frequency and current. Also certain other characteristics of the cable such as reflections, leakage, and dielectric absorption, which in the past could be largely neglected, assume considerable prominence under these conditions. An artificial line of the type described in the preceding paragraph may balance the terminal impedance of a uniform cable, but it cannot accurately balance the propagation constant. In order that duplex operation may be obtained on a loaded cable having non-loaded ends, it is essential that a balance be obtained for both the surge impedances and the propagation constants of each portion or type of cable. Such a balance is necessary in order that reflections from points where the cable changes in type, may be received in proper time relation on the artificial line.

The specific objects of the invention are:

To provide an improved means of balancing the copper resistance and the sea return impedance of loaded or of non-loaded cables.

To balance the capacity and the dielectric absorption of the insulating material of the cable.

To reduce the effect of reflected currents on the receiving instrument.

To balance both the surge or characteristic impedance and the propagation constant of the various types of cable which make up the completed cable.

The invention will be understood by reference to the accompanying figures in which:

Fig. 1 represents the invention applied to a cable of the type disclosed in Patent 1,607,473 in which the main portion is loaded while the shore ends are left unloaded. This type of cable is referred to hereinafter as a "composite" cable.

Figs. 2, 3 and 4 illustrate forms of networks having characteristics suitable for balancing the seat return impedance of a submarine cable.

Fig. 5 shows a complete artificial line embodying the network of Fig. 2.

Fig. 6 shows a complete artificial line embodying the network of Fig. 3.

Fig. 7 is a theoretical showing of a simple network for balancing the dielectric losses of a long submarine cable in which it is assumed that the capacity and leakage of the cable do not vary with frequency.

Fig. 8 shows an element of a network having a frequency variable characteristic, and

Fig. 9 shows a plurality of elementary networks like that of Fig. 8 connected in parallel with each other and also in parallel with a larger fixed condenser, for simulating the dielectric properties of the submarine cable.

Figs. 10 and 11 show, in full line curves, the resistance and reactance in accordance with frequency of the conductor and sea return circuit of two typical kinds of non-loaded submarine telegraph cable, and in dotted lines the characteristics of equivalent networks chosen in accordance with the principles of this invention to simulate the values of resistance and reactance of the cable.

Figs. 12 and 13 show in full lines the capacity and leakance of the cable, and in dotted lines the characteristics of the individual elementary networks making up the network of Fig. 9, and in dotted lines marked "Sum" the characteristics of the complete network including the three elementary networks in parallel to each other and to the large fixed condenser.

Figure 14 is a diagrammatic illustration of a complete cable similar to Figure 1, but embodying the network arrangement disclosed in Figure 4.

Figure 15 shows the artificial line embodying the network of Figure 4.

Referring to Fig. 1, the long submarine cable is represented as being made up of a non-loaded cable section 1 at the shore end and a loaded cable section 2. By thus removing the loaded portion, which is the most difficult to balance, to a considerable distance from the terminal apparatus, a more accurate balance can be obtained. The cable is balanced for duplex operation, in accordance with the principles laid down in Patent No. 1,607,473, by an artificial line divided into two portions, portion 3 for balancing the non-loaded cable 1 nearest the shore, and portion 4 for balancing the loaded cable 2.

The artificial line portion 3 comprises networks for balancing the conductor and sea return impedance, and the dielectric losses of the cable. The design of these networks, in the specific form shown, is based on the forms of networks shown in Figs. 3 and 9. The network for simulating the conductor and sea return impedance is made up of series inductances 10 and series resistance 11 with shunt paths 12 conductively connected about the series resistances 11, 11. The network for simulating the dielectric properties of the cable comprises shunt condensers 15, and additional networks 16 in shunt about some, but not necessarily all, of the shunt condensers 15. The additional networks 16, are made up of elementary networks each comprising resistance and capacity in series, the elementary networks being connected in parallel to each other and to the fixed shunt condenser 15.

Since portion 4 of the artificial line is designed to balance the loaded portion of the cable, the individual sections must necessarily contain a much larger amount of inductance. The shunting resistances are for the purpose of simulating the eddy current losses in the loading material. The sea return impedance is balanced by sections of the type shown in Fig. 3.

The terminal apparatus of the composite cable system of Fig. 1 is represented diagrammatically by a transmitter 20 connected to ground and to the junction of the bridge arms 21 and 22, the receiving apparatus 23 being connected in usual manner across conjugate terminals of the bridge.

An understanding of the principles involved in designing the artificial line of our invention may be had by consideration of the following:

The propagation constant may be written

$$\sqrt{(R+j\omega L)(G+j\omega C)}$$

and the surge impedance

$$\sqrt{\frac{R+j\omega L}{G+j\omega C}}$$

The expression

$$R+j\omega L$$

represents the linear resistance and reactance of the copper conductor together with the sea return path, and the expression

$$G+j\omega C$$

represents the leakance and capacity reactance of the insulating material where,

R = resistance
L = inductance
G = leakage
C = capacity
$\varpi = 2\pi$ times the frequency
$j = \sqrt{-1}$

In order that both the propagation constant and the surge impedance may be balanced in any given section or type of cable, it is essential that the values of

$$R+j\omega L$$

and

$$G+j\omega C$$

shall be properly balanced in each section of cable. Each of the quantities R, L, G, and C, in themselves change somewhat with frequency. The manner in which G and C change is referred to as the "dielectric absorption." In artificial lines customarily used in the past for balancing non-loaded cables, errors introduced by incorrectly balancing the inductance have been partly compensated for by incorrectly balancing the capacity and absorption.

Reference to Figs. 10 and 11 will show how the resistance and reactance of the conductor and sea return circuit of a submarine cable may vary with frequency. Figs. 12 and 13 will show how the capacity of the cable and its leakage also vary with frequency.

In addition to resistance a non-loaded submarine telegraph cable contains inductive reactance for which in former practice a careful balance was generally unnecessary. It has been found that this reactance can be balanced by a simple form of network which can be readily incorporated into the artificial line. This network in its simplest form is shown in Fig. 2.

The manner in which the elements of this network may be determined so as to closely approximate the resistance and reactance of the conductor together with the sea return path of the cable, will be apparent from the following:

The impedance of the network of Fig. 2 using the symbols shown on the drawing, is:

$$Z=\frac{j\omega L_1R_1}{R_1+j\omega L_1}+R_2+j\omega L_2 \quad (1)$$

Dividing this expression into its real and imaginary components, and dividing each by the length l so that the values apply to a unit length of cable:

$$R_c=\frac{1}{l}\left(\frac{\omega^2L_1^2R_1}{R_1^2+\omega^2L_1^2}+R_2\right) \quad (2)$$

$$X_c=\frac{1}{l}\left(\frac{\omega L_1R_1^2}{R_1^2+\omega^2L_1^2}+\omega L_2\right) \quad (3)$$

in which R_c and X_c designate the real and imaginary parts of the conductor impedance.

Differentiating (2) and (3) with respect to frequency:

$$\frac{dR_c}{df}=\frac{1}{l}\left[\frac{4\pi\omega L_1^2R_1^3}{(R_1^2+\omega^2L_1^2)^2}\right]=A \quad (4)$$

$$\frac{dX_c}{df}=\frac{1}{l}\left[\frac{(R_1^2-\omega^2L_1^2)2\pi R_1^2L_1}{(R_1^2+\omega^2L_1^2)^2}+L_2\right]=B \quad (5)$$

These expressions are called, for convenience, A and B.

In order to determine the best values of the constants of the network, the values of R_c, X_c, A and B are determined from the solid curves in Fig. 10 or Fig. 11, the values being read at that frequency which is most important as determined from the operating frequency of the cable. These values are substituted in Equations 2, 3, 4 and 5, from which the values of L_1, R_1, L_2 and R_2 are computed.

The dotted lines in Figs. 10 and 11 show the characteristics of equivalent networks chosen to simulate the values of R_c and X_c. The values of inductance and resistance of the network are given in the figures. It will be seen that the characteristics of the network closely match those of the cable throughout the essential frequency range of the particular cable here chosen for illustrative purposes.

The relative importance of the resistance and reactance of a non-loaded conductor is proportional to the height of the solid lines in Figs. 10 and 11. Thus, the reactance is of relatively small importance at the lower frequencies but becomes of increasing importance at the higher frequencies. That is, a higher percentage accuracy of adjustment of the reactance is needed at the higher frequencies. At all frequencies, however, an accurate matching of the resistance in a non-loaded conductor is in general considerably more important than an accurate matching of the inductance, that is, the percentage accuracy of adjustment of the resistance must be much closer than the percentage accuracy of adjustment of the reactance.

Another network which is identical in characteristics but of more convenient form in practice is shown in Fig. 3. The expression for its impedance is the same as that for Fig. 2, when the following relations exist, using the symbols shown in the figures:

$$\left.\begin{array}{ll} R_4=R_2+\dfrac{R_2^2}{R_1} & R_3=R_1+R_2 \\ L_3=L_2 & L_4=L_1\left(1+\dfrac{R_2}{R_1}\right)^2 \end{array}\right\} \quad (6)$$

Fig. 4 also is identical in characteristics under the following conditions:

$$\left.\begin{array}{ll} R_6=R_2 & R_5=R_1\left(1+\dfrac{L_2}{L_1}\right)^2 \\ L_5=L_1+L_2 & L_6=\dfrac{L_2}{L_1}(L_1+L_2) \end{array}\right\} \quad (7)$$

Either of these three or other equivalent networks may be used for the purpose as practical considerations dictate.

The network of Fig. 2 when embodied in a complete artificial line will have the form shown in Fig. 5, corresponding elements bearing the same designating characters. The condensers C_1, C_1, C_1 simulate the capacity of the cable.

Similarly, the network of Fig. 3, when embodied in an actual artificial line, will have the form shown in Fig. 6. The network of Fig. 4, when embodied in an artificial line, will have the form shown in Fig. 15. A complete cable terminal embodying this artificial line is shown in Fig. 14.

It has been the custom to use high grade mica or paper condensers for balancing the capacity of long ocean cables. Although some small losses are present in such condensers, they ordinarily comprise a more perfect capacity than that which is presented by the cable, and as a consequence they do not balance the cable with respect to certain loss characteristics of the cable dielectric. These characteristics are referred to as "dielectric absorption". They have the nature of an absorption loss and are variable with frequency. For reasons previously stated, these characteristics should preferably be taken into account and should be balanced in the artificial line, in order to obtain the best possible balance.

The method of simulating dielectric absorption in the artificial line is given below:

If the capacity of the cable and the leakage did not vary with frequency, they could be represented by the simple network shown in Fig. 7 which embodies a pure capacity C and a leakance G in parallel to represent the losses. Measurements of the dielectric of an actual cable treated as a network like Fig. 7 give a different value of C and G for every frequency, the pure capacity varying as shown by the full-line curve of Fig. 12 while the leakance, expressed as a conductance varies according to the full-line curve of Fig. 13. It is desirable therefore to give to the artificial line capacity these same frequency-variable characteristics. This cannot be accomplished by the Fig. 7 network alone as the mathematical expressions for it lack a frequency term.

Certain types of simple network, however, have been found to be variable with frequency. If the network of Fig. 8 is examined, the expressions for its equivalent capacity and conductance are found to be:

$$C_x=\frac{C_a}{1+\omega^2C_a^2R_a^2} \quad (8)$$

$$G_x=\frac{C_a\omega^2R_aC_a}{\omega^2R_a^2C_a^2+1} \quad (9)$$

By placing this network in parallel with another condenser which is several times as large, it is possible to obtain a rough approximation to the leakage and capacity (i. e., the dielectric absorption) of an actual cable throughout the essential range of frequencies.

However, much better results will be obtained if about three networks similar to Fig. 8 are placed in parallel with each other and also in parallel with a larger fixed condenser. The resulting network is shown in Fig. 9. Each of the component networks will have characteristic equations of the type shown in Equations 8 and 9. The characteristics of the complete network may be obtained simply by adding the characteristics of each component network. For each component network the product C × R should be different from the others. In general, in practice the capacity C_4 may be 20 to 40 times as large as the combined capacities of C_1, C_2, C_3.

The results which may be obtained by such a network are shown in Figs. 12 and 13. In these curves the dotted lines A, B and C respectively show the characteristics of the three networks R_1—C_1, R_2—C_2, and R_3—C_3. The dotted lines marked "Sum" show the characteristics of the complete network including the condenser D. It is evident that this network gives a close approximation to the dielectric properties of the cable itself as indicated by the full lines.

If necessary, a still closer balance could be obtained by using four or more resistance-capacity networks instead of the three shown in Fig. 9. If there were any leakance in the cable which did not vary with frequency, a shunting resistance, not in series with capacity, could be added in parallel with the network.

The values of these capacities and resistances could have been calculated directly but the procedure is lengthy and complex, while with a little experience the method of successive approximations will give quite accurate duplication of the cable characteristics.

The network shown has been found satisfactory for balancing dielectric absorption, but it is to be understood that any one of numerous equivalent types of network could be used instead.

The resitance-capacity corrective branches do not need to be distributed to the same extent as the main capacities C_4. It is usually sufficient to correct the dielectric absorption in unit sections ranging from say 15 mile lengths at the head of the cable to lengths of several hundred miles some distance out. As the three branches operate independently of each other they can be distributed independently over the section as desired Each branch of the correction can be used either as a T-section or as a π-section.

Instead of the arrangement of series inductances 10 and series resistance 11 as shown in Fig. 1, it is evident that these elements may be interchanged, that is, the resistance 11 may be located at the head end of the artificial line while the inductances may be at the earth end, as shown in Fig 14, the network embodied in this figure being that of Fig. 4. In this figure the network for simulating the conductor and sea earth impedance is made up of series resistance 11 and series inductances 10, with shunt paths 12 conductively connected about the series inductances 10.

While the features of this invention have been described with special reference to non-loaded cables and to composite cables, it is clear that their applicability extends to completely loaded cables, the difference being only one of degree on the part of the inductance.

It is well known that when electric waves are incident upon discontinuities in a conductor, reflections of the waves occur. Small irregularities are frequently present in a cable due to differences in the manufacture of adjacent sections, or for other reasons. In constructing a balancing artificial line similar irregularities are placed in the artificial line at points corresponding to the locations of the irregularities as located in the actual cable. However, unless the section of cable between the irregularity and the transmitting terminal is accurately matched in the artificial line the two reflected waves will differ slightly in magnitude and time of arrival so that the neutralization will not be complete and a disturbing voltage will be impressed on the receiving instrument. In the cable of Figure 1 the transition from the non-loaded to the loaded portion is accomplished by increasing the weight of loading at a very gradual rate but slight reflections are still liable to occur which at the high speeds and low current values used may injuriously affect incoming signals.

However, with similar discontinuities accurately located in the artificial line the reflection effects can be rendered negligible by balancing the terminal section of the cable according to this invention. With the high degree of conjugacy which will obtain, such reflected waves as may be present will be attenuated and retarded to the same degree in both the cable and the artificial line.

If an artificial line normally designed to accurately balance the primary constants, R, L and C, of a long submarine cable, embodies as well refined means for balancing the lesser quantities such as the dielectric absorption and the inductance of non-loaded portions, together with the variations with frequency of each quantity, it is clear that the overall balance will be greatly enhanced. With the aid of these refinements the duplex speed in each direction will be a maximum, thus obtaining the greatest possible message capacity of the cable.

We claim:

1. An artificial line adapted to balance a submarine cable over a range of frequencies forming a signaling range, comprising a plurality of sections, each section including series impedance having resistance and inductive reactance, and shunt capacity, and a path containing inductance and resistance conductively connected in shunt to a portion of said series impedance, the values of the impedance elements being so related that both the resistance and the reactance of said artificial line vary with frequency substantially in accordance with the variation with frequency of the corresponding constants of the submarine cable over the whole of the range of signal frequencies.

2. An artificial line adapted to balance a submarine cable over a range of frequencies forming a signaling range, comprising a plurality of sections, each section including series impedances having resistance and inductive reactance, and shunt capacity, a resistance path conductively connected in shunt to a portion of said series impedance, both the resistance and the reactance of said network being variable with frequency substantially in accordance with the variation with frequency of the corresponding constants of the submarine cable over the whole of said signaling range, and additional means in a number of said sections for simulating the dielectric losses of the cable.

3. An artificial line adapted to balance a submarine cable over a range of frequencies forming a signaling range, comprising a plurality of sections, each section comprising series impedances having resistance and inductive reactance, and shunt capacity, a resistive path conductively connected in shunt to a portion of said series impedance, the resistance and the reactance of said network being variable with frequency substantially in accordance with the variation with frequency of the corresponding constants of the submarine cable over the whole of said signaling range, and shunt paths about the capacities in a number of said sections, said shunt paths comprising resistance and capacity in series.

4. The combination with a submarine cable having resistance and inductance, the impedances of which vary over a signaling range, of a network for balancing the cable, said network having resistance and inductance whose impedances vary with frequency over said range, the resistance closely simulating that of the cable over substantially the whole of said range and the inductive reactance closely simulating that of the cable over at least the upper portion of the range.

5. The combination with a submarine cable having a sea return path whose impedance varies with frequency over a signaling range, of a network for balancing the sea return impendance over said range comprising series inductance and resistance elements and resistive paths in shunt to some of said elements, the impedances of said elements and resistive paths being so adjusted that the total resistance of the network closely simulates the resistance of the cable and sea return path over substantially the whole of said range and the reactance of the network closely simulates the reactance of the sea return path over at least the upper portion of the signaling range.

6. In combination, a submarine cable and an artificial line network arranged to balance the cable for duplex operation over a range of frequencies said network comprising means for simulating the propagation constant of the cable and means for simulating the characteristic impedance of the cable, said means including series elements and shunt elements and frequency-variable resistive paths in parallel with some of said shunt elements.

7. An artificial line network designed to balance a conductor having resistance, inductive reactance, capacity and leakance that are variable with frequency over a given range of frequencies forming a signaling range, which comprises a plurality of sections each comprising series inductance and resistance and shunt capacity, a path in shunt to at least one of said series elements comprising inductance and resistance whose values are adjusted so that the combined re-

sistance and reactance of the network simulates the corresponding constants of the conductor over the given range, and a path in shunt to at least one of said condensers comprising resistance and capacity whose values are adjusted so that the combined capacity and leakance of the network simulate the corresponding constants of the conductor over the whole of said given range.

8. In combination, a composite cable having a central loaded portion and non-loaded end sections, and an artificial line associated with one end of said cable in balancing relation, said artificial line comprising a part designed to balance the non-loaded portion of the cable and a part designed to balance the loaded portion of the cable, and means associated with said first mentioned part for balancing the sea return impedance through a range of frequencies.

9. In combination, a composite cable having a central loaded portion and non-loaded end sections, and an artificial line associated with one end of said cable in balancing relation, said artificial line comprising a part designed to balance the non-loaded portion of the cable and means associated with the first mentioned part for balancing both the characteristic impedance and the propagation constant through a range of frequencies.

10. The method of increasing the accuracy and range of balance of a submarine cable balancing network which comprises balancing the capacity of the cable over a range of frequencies to a first approximation and successively introducing losses which vary with frequency till the combined capacity and leakance of the network simulates the capacity and leakance of the cable over the said range of frequencies.

11. An artificial line for balancing the dielectric properties of a cable comprising condensers in spaced, parallel paths across the sections of the artificial line and means for causing the capacity and leakage of certain of said paths to vary with frequency in accordance with the variation with frequency of the capacity and leakage of the cable to be balanced, said means comprising resistance capacity shunts for a plurality of said condensers.

12. In an artificial line for balancing a cable, a network including a path having resistance and capacity in series and a parallel path comprising a capacity which is large with respect to said first mentioned capacity, the values of the resistance and capacity elements being proportioned so that the leakance and capacity of the network approximate the leakance and capacity of the cable over the range of frequencies for which the cable is balanced.

13. In an artificial line designed to balance the dielectric absorption of a cable, a network comprising a plurality of paths each having resistance and capacity in series, and a parallel path comprising a capacity which is large with respect to said first mentioned capacities, the product of capacity and resistance for each of the said plurality of paths being different.

14. In combination, a composite cable having a central loaded portion and non-loaded end sections, and an artificial line associated with each end of said cable in balancing relation, each artificial line including a part designed to balance the adjacent non-loaded portion of the cable and a part designed to balance the central loaded portion, and means associated with said parts for balancing the sea return impedance of the cable.

15. The combination of a submarine cable having a return current path including inductance, and an artificial line in balancing relation therewith, said artificial line having means for simulating the impedance of the return path comprising inductance and resistance elements in series, one of said elements being shunted by an additional impedance element.

16. An artificial line network designed to balance a conductor having resistance, inductive reactance, capacity and leakance that are variable with frequency over a given range of frequencies forming a signaling range, which comprises a plurality of sections each comprising series inductance and resistance and shunt capacity, a path containing inductance and resistance in shunt to at least a portion of one of said series elements and having values so adjusted that the combined resistance and reactance of the network simulates the corresponding constants of the conductor over the given range, and a path in shunt to at least one of said condensers comprising resistance and capacity whose values are adjusted so that the combined capacity and leakance of the network simulate the corresponding constants of the conductor over the whole of said given range.

17. An artificial line network designed to balance a conductor having resistance, inductive reactance, capacity and leakance that are variable with frequency over a given range of frequencies forming a signaling range, which comprises a plurality of sections each comprising series inductance and resistance and shunt capacity, a path containing inductance and resistance in shunt to at least a portion of said series inductance, comprising inductance and resistance whose values are adjusted so that the combined resistance and reactance of the network simulates the corresponding constants of the conductor over the given range, and a path in shunt to at least one of said condensers comprising resistance and capacity whose values are adjusted so that the combined capacity and leakance of

the network simulate the corresponding constants of the conductor over the whole of said given range.

In testimony whereof we affix our signatures.

JOSEPH W. MILNOR.
WILLIAM D. CANNON.