April 14, 1925. 1,533,178

J. J. GILBERT

ARTIFICIAL ELECTRIC LINE

Filed May 19, 1922 3 Sheets-Sheet 1

Fig. 1.

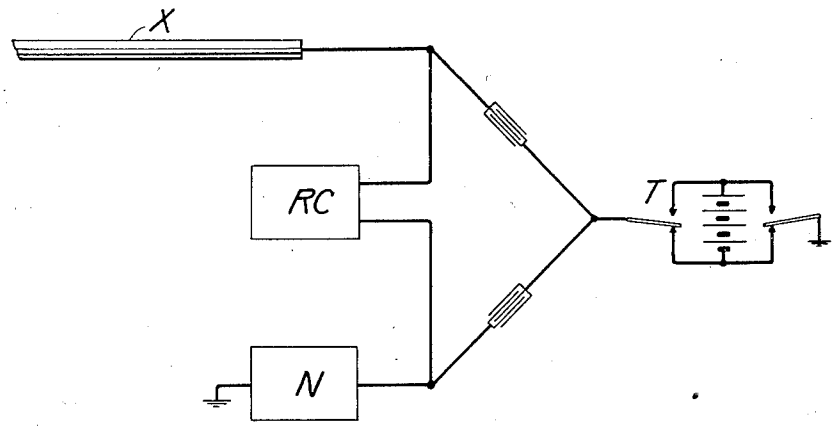
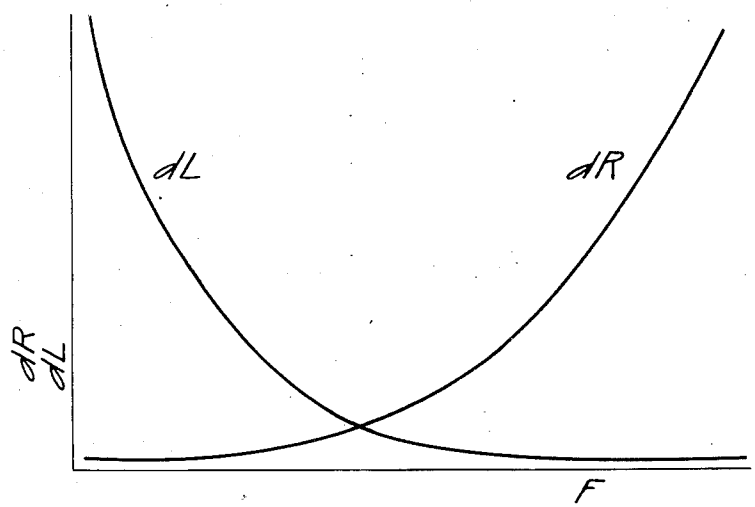


Fig. 2A



Inventor:
John J. Gilbert.
by C. G. Sprague. Atty.

April 14, 1925. 1,533,178

J. J. GILBERT

ARTIFICIAL ELECTRIC LINE

Filed May 19, 1922 3 Sheets-Sheet 2

Fig. 2B.

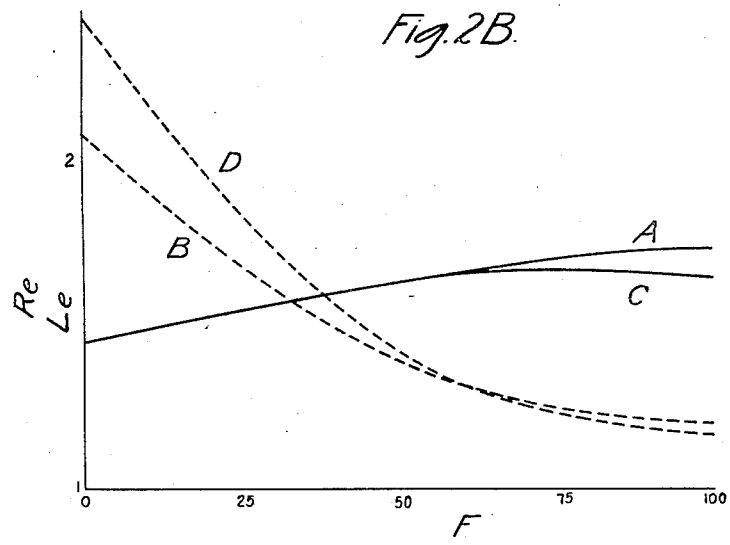
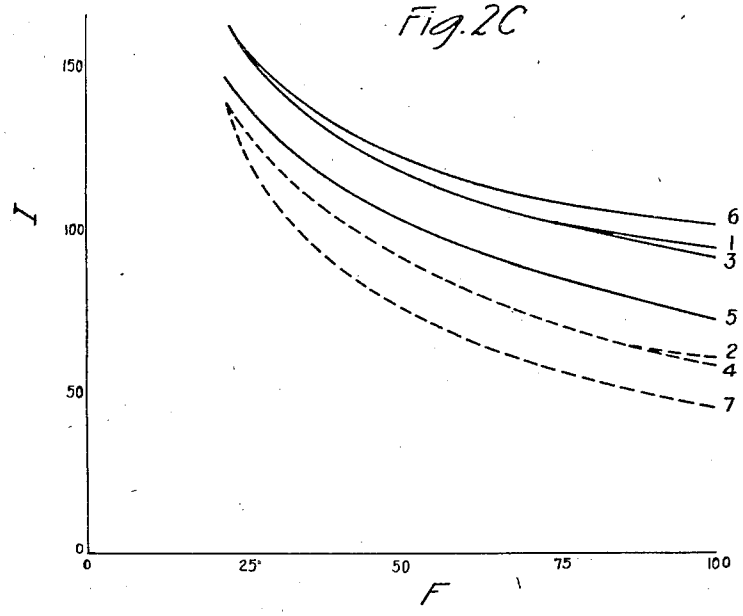


Fig. 2C



Inventor:
John J. Gilbert.
by Otto Sprague Att'y

April 14, 1925. 1,533,178

J. J. GILBERT

ARTIFICIAL ELECTRIC LINE

Filed May 19, 1922 3 Sheets-Sheet 3

Fig. 3.

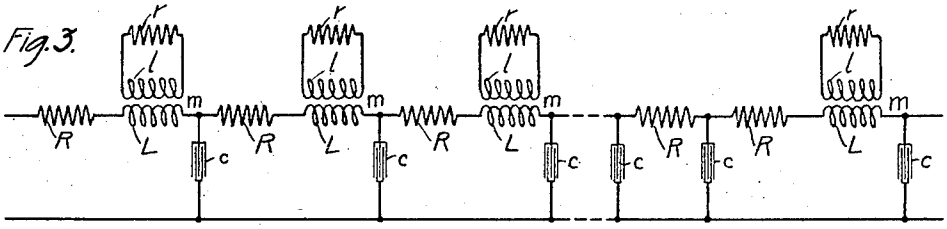


Fig. 4.

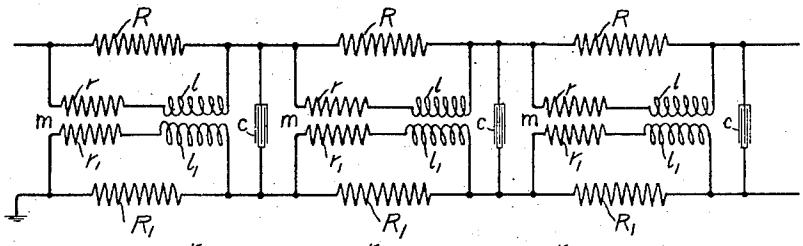


Fig. 5

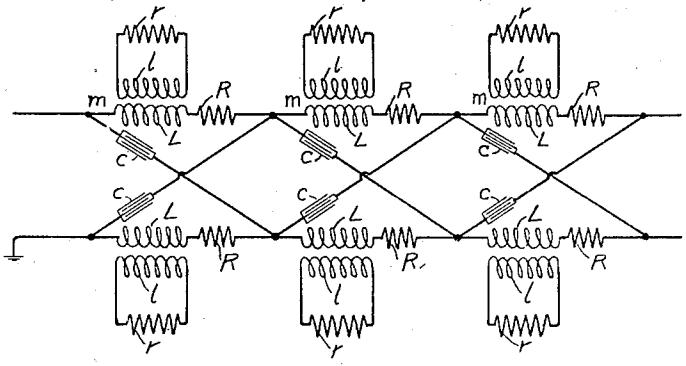


Fig. 6

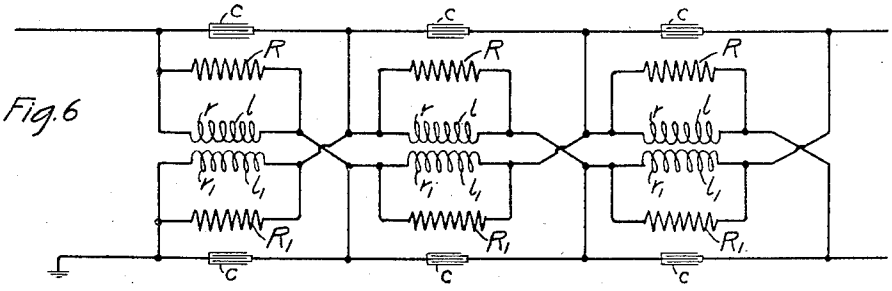


Fig. 7

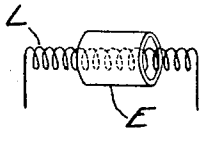
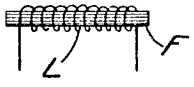


Fig. 8.



Inventor:
John J. Gilbert.
by A. C. Sprague Att'y.

Patented Apr. 14, 1925. 1,533,178

UNITED STATES PATENT OFFICE.

JOHN J. GILBERT, OF PORT WASHINGTON, NEW YORK, ASSIGNOR TO WESTERN ELECTRIC COMPANY, INCORPORATED, OF NEW YORK, N. Y., A CORPORATION OF NEW YORK.

ARTIFICIAL ELECTRIC LINE.

Application filed May 19, 1922. Serial No. 562,064.

To all whom it may concern:

Be it known that I, JOHN J. GILBERT, a citizen of the United States of America, residing at Port Washington, in the county of Nassau and State of New York, have invented certain new and useful Improvements in Artificial Electric Lines, of which the following is a full, clear, concise, and exact description.

This invention relates to submarine cable systems and to artificial lines particularly adapted for such systems but also capable of other uses to which networks of this general form are adapted.

An object of this invention is to provide a submarine cable duplex system adapted for operation at higher speeds than those now obtainable.

Another object is to provide an artificial line capable of more exactly balancing the impedance of a cable or other transmission line than those now in use.

Another object is to provide an improved form of electric network of general application.

The invention may be understood from the following description and accompanying drawings. Fig. 1 is a diagrammatic showing of the terminal apparatus of a submarine telegraph cable; Figs. 2^A, 2^B and 2^C are curves used in explanation of the invention; and Figs. 3 to 8 inclusive are diagrammatic showings of various modifications of the invention.

Referring to Fig. 1 the submarine cable X terminates in the usual duplex bridge arrangement in which the transmitter T and the receiving circuits R, C are conjugately related, the artificial line N providing a balance for the cable which prevents transmitted currents from affecting the local receiver. The essential property of the artificial line N is that, in a given range of frequencies, it shall have the same impedance as the cable. It usually is of the form shown in Fig. 3 without elements L, l, r.

The amplitude of the received signal is dependent upon the signaling speed, which must therefore be such that the received signal is legible through the disturbance due to unbalance. If by any means the magnitude of this disturbance can be reduced the speed of operation can be increased until the amplitude of the received signal again reaches the limit set by unbalance. A telegraph message consisting of a succession of positive and negative pulses can be considered as composed of a number of sinusoidal currents of all frequencies added together, the relative amplitudes of the various components being determined by the character and arrangement of the signal pulses. It is found that in order to best preserve the legibility of the message it is necessary to preserve the amplitude relations of all components up to a certain frequency. This frequency bears a certain definite relation to the frequency of the shortest pulses of the signals, the relation depending upon the code and method of reception used. In the case of the standard cable code, with recorder working, the signal frequency is roughly equal to the reversal frequency or to one-half the dot frequency. When a signal is transmitted over a submarine cable the amplitudes of all the frequency components are reduced, the loss suffered at any frequency being greater the higher the frequency. It is evident therefore, that many frequencies which are not present in a received signal will be present in the transmitted signal, and therefore the range of frequencies for which accurate balance of a duplex system is required extends beyond the signal frequency; in fact, the limit of this range may be two or three times the signal frequency. It is desirable, therefore, that in a duplex system the differences between the transmission constants of the cable and of the artificial line be reduced as far as possible for all values of frequency in the above mentioned range, exact balance for frequencies outside this range not being absolutely essential. This means that the resistance and inductance of the artificial line should be made as far as possible equal to the resistance and inductance of the cable at all frequencies inside this range.

The practice of using an artificial line such as that of Fig. 3 with elements L, l and r omitted, has been based upon the assumption that the effect of the cable inductance may be neglected and that the cable resistance is the same for all frequencies. It has been discovered, however, that due to the distribution of the return current in the sea

water, the resistance of a submarine cable, even at low frequencies, is greater than its value for steady currents and that the resistance increases with the frequency. It has been found also that the inductance of the cable is not negligible and is likewise dependent upon frequency. The effect of ignoring these facts in designing an artificial line is a lack of balance between the cable and the line at high frequencies with consequent disturbances in the receiving instrument. This invention provides a form of artificial line which takes all of these effects into account.

The impedance of an electric network depends upon the characteristic impedance K and the propagation constant P, which may be calculated by means of the formulæ:

$$P=\sqrt{\frac{pC}{2}}(E+jF) \quad K=\frac{F-jE}{\sqrt{2pC}} \quad (1)$$

where

$$E^2=\sqrt{R^2+p^2L^2}-pL, \quad F^2=\sqrt{R^2+p^2L^2}+pL$$

and R, L and C are respectively the resistance, inductance and capacity per unit length of line, p is 2π times the frequency and

$$j=\sqrt{-1}.$$

In the absence of irregularities the impedance of a long submarine cable or an artificial line is equal for all practical purposes to the characteristic impedance. If irregularities are present, however, reflections take place at these irregularities and the impedance will therefore involve the propagation constant also.

It is evident from formulæ (1) that R and L are not of equal importance in determining the transmission constants throughout the range of frequencies. At very low frequencies, for instance, L is of minor importance compared with R and therefore at these frequencies comparatively large variations of L can be permitted without affecting materially the variations in the transmission constants. At higher frequencies L becomes of increasing importance and consequently the variations permitted are smaller. In order to compare the effect of variations of R and of L, curves may be plotted showing for a given difference between the impedance of the cable and of the artificial line for each value of frequency F throughout the range employed the corresponding permissible differences dR and dL between the resistance and the inductance respectively of the cable and the line. Such curves are shown in Fig. 2^A.

On account of the fact that the elements of the artificial line are lumped, additional terms should be included in formulæ (1) which are true only for the case of uniformly distributed elements. The effect of these additional terms can always be made as small as desired by subdividing the line sufficiently, and it is assumed herein that this has been done so that the departure due to lumping is negligibly small.

Referring to Fig. 3, which shows one embodiment of the invention, the artificial line consists of a series of sections, each of which comprises a fixed resistance R and a fixed capacity c. In addition, one or more of the sections are provided with means for introducing inductance and resistance which vary with impressed frequency in the same manner as the cable. Each of these means comprises an inductance L in inductive relation to a second coil l which is in a closed circuit containing resistance r. If m denotes the mutual inductance of circuits R, L and r, l, the effective resistance R_e and inductance L_e at the frequency f and where $p=2\pi f$ are respectively:

$$R_e=R+\frac{p^2m^2}{r^2+p^2l^2}r \text{ and } L_e=L-\frac{p^2m^2}{r^2+p^2l^2}l \quad (2)$$

In Fig. 2^B is shown a set of curves representing the relationship in a particular case between frequency of transmitted current in signal pulses per second and effective resistance and inductance, the former being in ohms per kilometer and the latter in millihenrys per kilometer. Curves A and B are for the effective resistance and inductance per kilometer of a particularly long submarine cable which is not inductively loaded, and curves C and D give the effective values of the resistance and inductance for the corresponding length of artificial line as computed from formulæ (2) with properly chosen values of R, L, r, l and m. It can be seen that the condition previously stated is satisfied, namely, an equality of resistance of the cable and artificial line for lower frequencies, and equality of inductance for the higher frequencies. The values of the constants employed in this calculation were R=1.443 ohms; r=.43 ohms; $L=l=2.432\times10^{-3}$ henrys; and $m=1.82\times10^{-3}$ henrys.

For purposes of comparison calculations of the characteristic impedance I were made for the above mentioned cable and for three different designs of the corresponding artificial line. The results are shown in the curves of Fig. 2^C, which represent the relation between the characteristic impedance I in ohms and the transmitted frequency in signal pulses per second. Curves 1 and 2 show the real and imaginary parts respectively of the characteristic impedance of the cable. The corresponding quantities for the proposed type of artificial line are shown in curves 3 and 4, and for the usual type of line (Fig. 3 with L, l and r omitted) by curve 5. The effect of using a constant inductance in the artificial line is shown by curves 6 and 7.

In order to obtain the flexibility necessary for balancing the line and the cable it is desirable to construct part of the primary resistance R so that it can be varied. Condensers c and resistances r may likewise be made variable, but it is ordinarily sufficient to provide a single variable element in each section. If inductance and resistance varying with frequency are to be associated with but a single section of the artificial line, this should be the section nearest the transmitter T. It is preferred to associate such means with each of a plurality of the sections nearest the transmitter and to insert similar means at intervals separated by two or more sections throughout the remainder of the artificial line. A sufficient approximation to the impedance of the cable can thus be obtained.

In Fig. 4 is shown a type of artificial line which embodies the proposed principle and allows considerable economy of space and material. The resistance R_1 in this case serves as a secondary resistance for the winding l, and R functions similarly for l_1.

The type of line shown in Fig. 5 has the additional advantage that the characteristic impedance is exactly equal to that of the cable and is not subject to a correction on account of the "lumping."

The advantages of the two preceding types of artificial line are combined in the modification shown in Fig. 6.

Fig. 7 shows a modified form of the invention in which a sleeve E of conductive material surrounding the coil L takes the place of the secondary inductance l and resistance r of Fig. 3. It can be seen from equation (2) above that the quantities r, l may be varied at will providing the ratios M^2/Ll and r/l be kept constant. This allows a flexibility of design which permits the use of the modification shown in Fig. 7, when it is possible thereby to obtain the proper values of these variables.

There is shown in Fig. 8 a modification of the form of the invention of Fig. 7 with the substitution of a laminated core of material of high permeability for the sleeve E of Fig. 7.

The preceding discussion has been entirely with reference to non-loaded cables. The invention, however, may be equally well applied to an artificial line having the transmission characteristics of a cable or transmission line in which the inductance has been increased by means of loading. The additional factor of increased resistance due to losses in the loading material may be taken care of by the methods above described. In this case the loading may be so heavy that the total inductance is substantially constant, the resistance alone varying with the frequency. Or the loading may be of a kind or degree which will necessitate the taking into account of inductance and resistance variations due to changes in current distribution in the sea water and resistance variations due to variable losses in the loading material.

Although the invention was developed for use in a submarine cable system, it is obvious that various features of the invention are capable of wide application. These features are therefore separately claimed.

What is claimed is:

1. An electrical signaling network comprising a plurality of similar sections, each said section comprising a shunt reactive element and a resistive circuit inductively associated with the section, the effective resistance of said resistive circuits being in series relation in said network.

2. An electrical signaling network comprising a plurality of similar sections, each said section comprising a shunt capacity element and a resistive circuit inductively associated with the section, the effective resistance of said resistive circuits being in series relation in said network.

3. An electrical signaling network comprising a plurality of similar sections, each said section comprising a shunt capacity element, a series resistance element, and a resistive circuit inductively associated with the section, the effective resistance of said circuits being in series relation in said network.

4. The combination of a signaling line having a resistance which varies over the range of signaling frequencies involved, of a terminal balancing line for said signaling line comprising a plurality of similar sections, each said section comprising a capacity element in shunt relation to the line and a resistance element in series relation to the line and part only of said sections having a resistive circuit inductively associated with each section and in series relation to the balancing line.

5. The combination of a signaling line having a resistance which varies over the range of frequencies involved in signaling, of a terminal balancing line for said signaling line comprising a resistive circuit inductively associated with the balancing line and in series relation therewith, the effective resistance of said balancing line more closely simulating that of the cable at lower impressed frequencies than at higher.

6. The combination with a signaling line having a resistance which varies over the range of signaling frequencies involved, of a terminal balancing line for said signaling line comprising a plurality of similar sections, each said section having a capacity element in shunt relation to said balancing line and a resistive element inductively related to said balancing line and in series relation therewith, the resistance of said

balancing line more closely simulating that of said signaling line at lower transmitting frequencies and the inductance at higher transmitting frequencies.

7. The combination with an inductively loaded submarine cable, of means for transmitting signals thereover at such high speeds that the effective resistance varies materially within the range of frequencies involved, and a balancing line for said cable comprising a plurality of similar sections, each said section comprising a capacity element in shunt relation to said balancing line and a resistive circuit inductively related to said balancing line and in series relation thereto, the effective resistance of said line simulating the resistance of the cable more closely in the lower portion of said frequency range than in the higher.

8. The combination with a submarine cable having resistance and inductance each of which varies with impressed frequency over a certain range of frequencies, of terminal apparatus for said cable for transmitting and receiving signals involving frequency components within said range, and a terminal network for balancing said cable having inductance and resistance which vary with impressed frequencies, the resistance more closely simulating that of the cable at lower impressed frequencies and the inductance at higher impressed frequencies.

9. An electrical signaling network comprising a plurality of similar sections, each said section comprising a shunt reactive element and resistive elements on opposite sides of said reactive element, the resistive elements on corresponding sides of the several sections being in series relation, circuits in shunt to said resistances, respectively, and means inductively coupling one of said shunt circuits of each section with the other of said shunt circuits of that section.

10. An electrical signaling network in accordance with claim 9, in which said shunt reactive elements are capacity elements.

In witness whereof, I hereunto subscribe my name this 16th day of May A. D., 1922.

JOHN J. GILBERT.