Sept. 21, 1926. 1,600,283

H. W. HITCHCOCK

ARTIFICIAL LINE

Filed Oct. 20, 1921 2 Sheets-Sheet 1

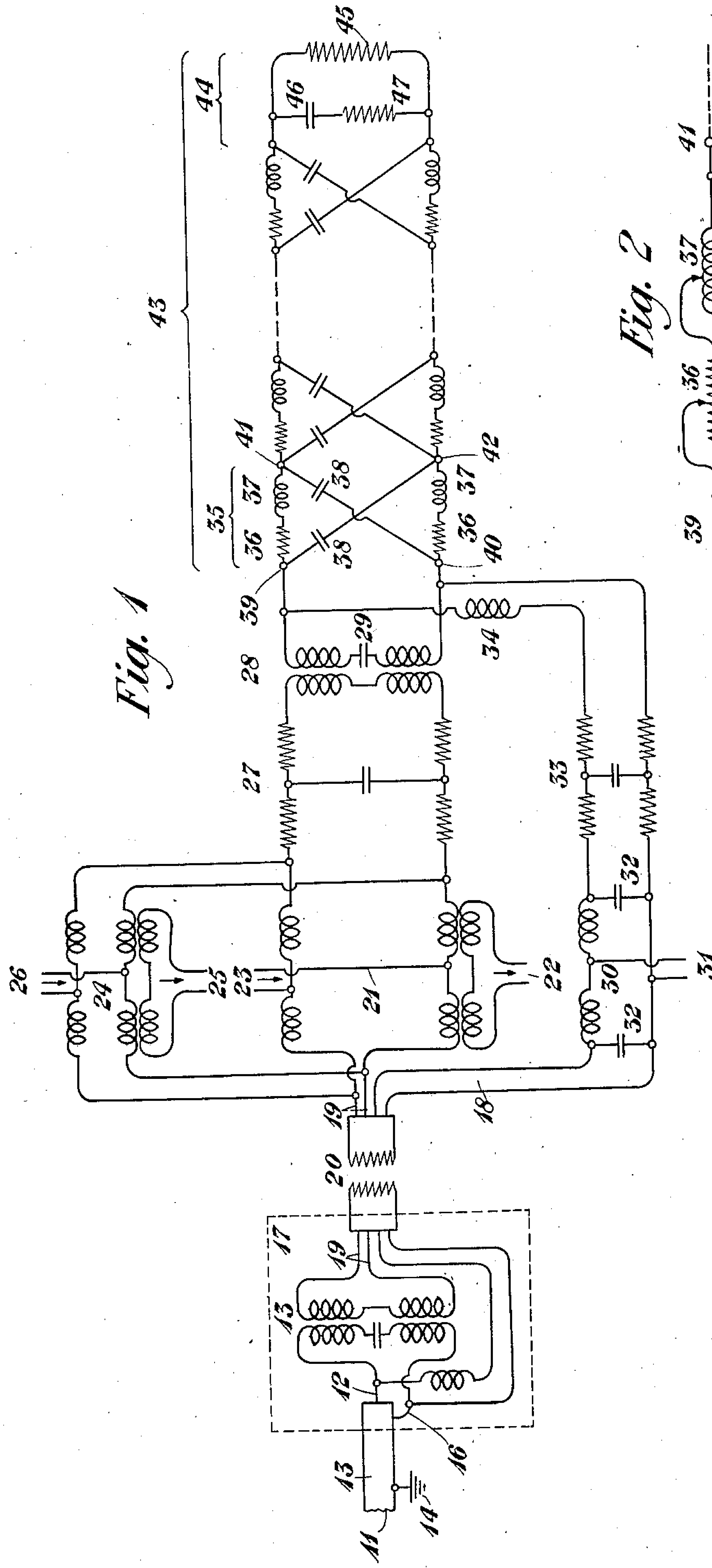

Fig. 1

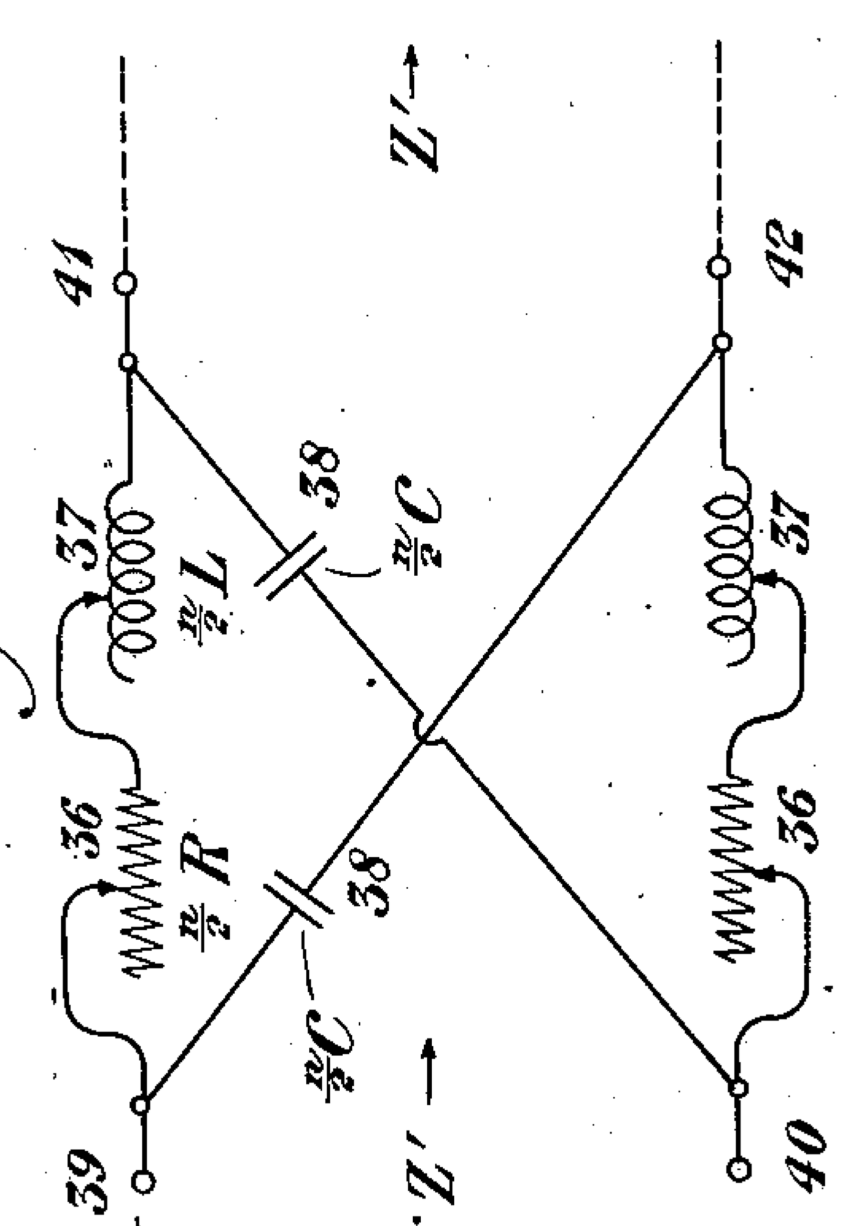

Fig. 2

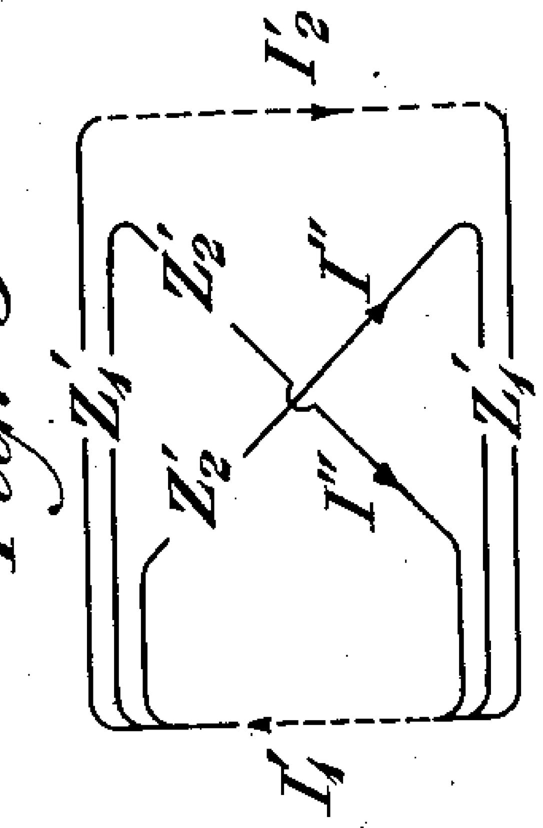

Fig. 3

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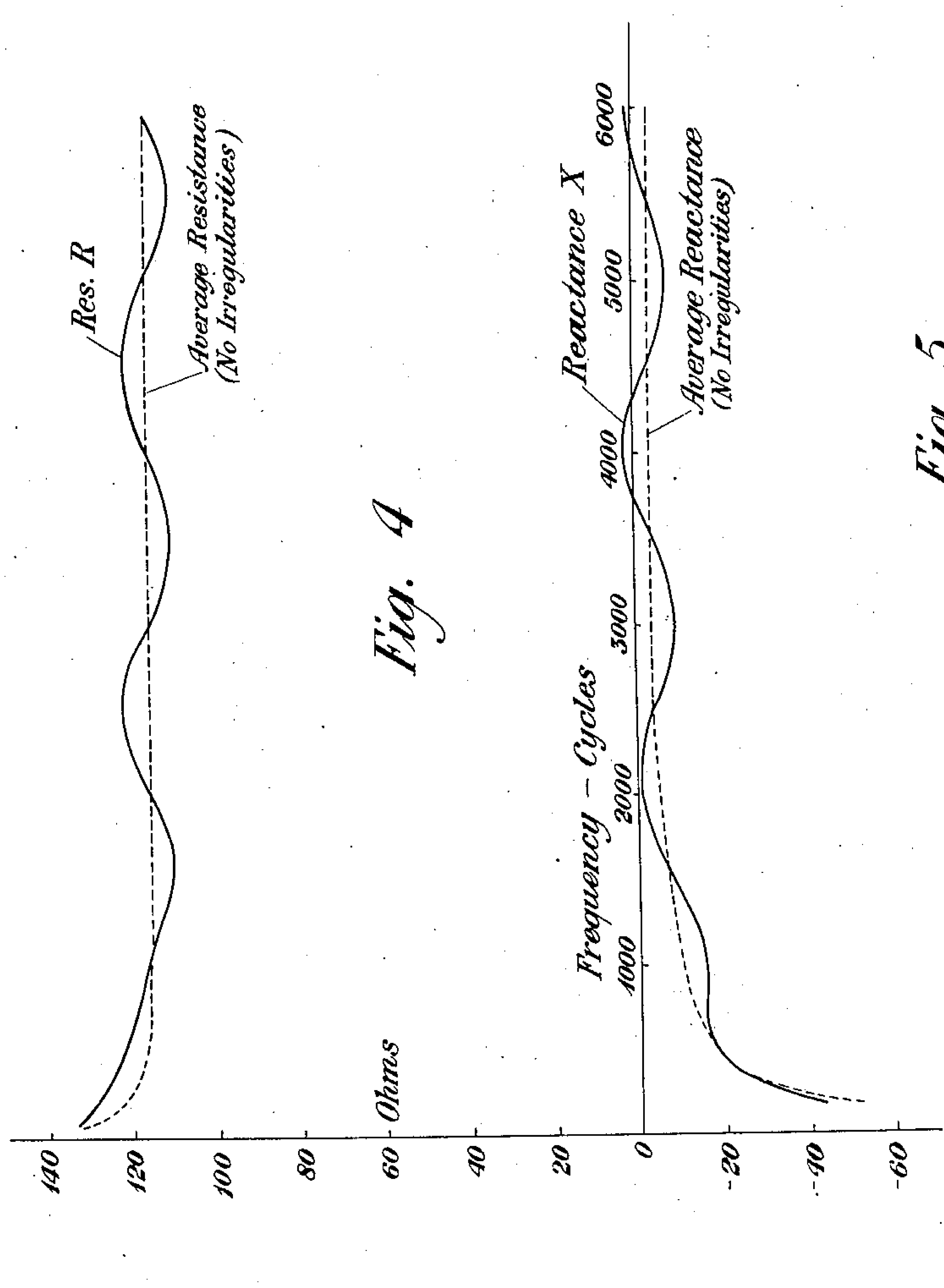

Fig. 4

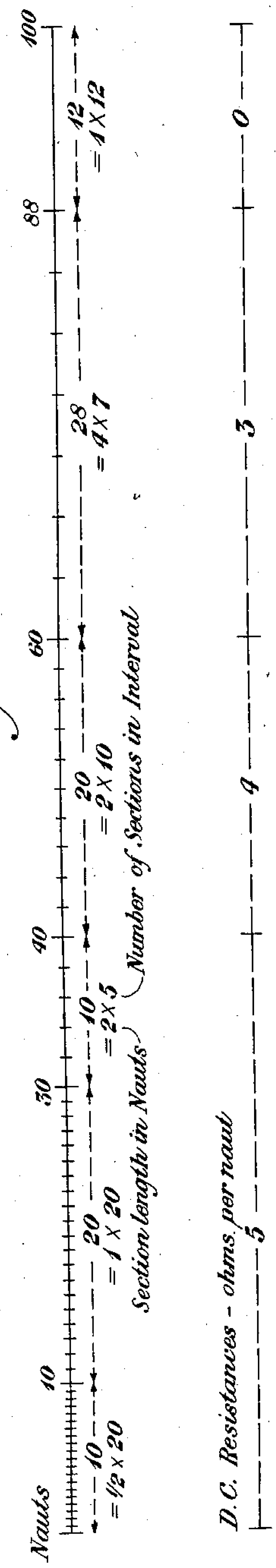

Fig. 5

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Patented Sept. 21, 1926. **1,600,283**

UNITED STATES PATENT OFFICE.

HARRY W. HITCHCOCK, OF NEW YORK, N. Y., ASSIGNOR TO AMERICAN TELEPHONE AND TELEGRAPH COMPANY, A CORPORATION OF NEW YORK.

ARTIFICIAL LINE.

Application filed October 20, 1921. Serial No. 508,945.

The principal object of my invention is to provide an electrical network which may be made closely to simulate a given geographically extended signal transmitting line with respect to impedance, attenuation and phase shift over a wide frequency range. Such an artificial line may be used to balance the geographical line for duplex operation. Another object of my invention is to provide an artificial line of sections, each of which is a simple crossed or bridge type network. Still another object of my invention relates to making such a network to balance a line employed for simultaneous superposed telegraphy both of ordinary and carrier current type. Other objects of my invention relate to making the sections of properly graded length and electrical characteristics and providing for adjustment of the several sections to take care of local irregularities in the geographical line. All these objects of my invention and others will be appreciated upon consideration of a specific embodiment of its principle which I now proceed to describe in the following specification. It will be understood that the scope of my invention is defined in the appended claims.

Referring to the drawings, Figure 1 is a general diagram, Fig. 2 is a more detailed diagram of a single section of the artificial line, Fig. 3 is a diagram for resolving the currents into their components in this section, Fig. 4 is a diagram showing the variation of impedance with frequency, and Fig. 5 is a diagram showing how the section lengths and characteristics are graded along the artificial line.

The special example here presented to illustrate the principle of my invention is an artificial line designed and constructed to balance a certain continuously loaded ocean cable of length about 100 nauts (nautical miles) and adapted for simultaneous superposed ordinary and carrier current telegraph and telephone operation, in which all current frequencies up to 6,000 cycles per second may be involved.

The cable 11 to be balanced has a central conductor terminal 12 and a metallic armor sheath 13 which is connected to the conductor terminal 16, and is of course grounded as indicated at 14. This cable 11 is not of uniform physical character throughout its length, but its shore ends are specially armored to guard against shallow water hazards. Thus it is that the cable consists of a plurality of sections graded slightly in their characteristics from the middle toward the ends. Moreover, in the manufacture of such a cable, it is commonly made up in sections, each about two nauts long, which are spliced together, and it is impracticable in the manufacture of these sections to make them identical in their electrical characteristics. It is among the objects of my invention to provide facility for adjustment of the artificial line to match it to all such irregularities. The shore end of the cable 11 with the terminal conductors 12 and 16 are in the cable hut 17, where there is located a transformer 13 with a condenser 14 in the coil connected to the conductors 12 and 16. The other coil of the transformer 13 is connected to the conductor pair 19. Branch conductors 18 for direct current telegraphy, with an interposed retardation coil 15 are connected to the conductors 12 and 16 between the cable end and the transformer. Both conductor pairs 19 and 18 are laid in a cable 20 leading from the cable hut to the cable terminal office.

At this office, branch conductors from the main conductor pair 19 lead to respective hybrid coil transformers 21 and 24. The input 23 and the output 22 for telephone circuits are connected to the transformer 21 in the usual manner as shown. Likewise the input 26 and the output 25 for a carrier current telegraph channel are connected to the transformer 24, as shown. The frequency range for this telegraph channel lies above the normal essential voice frequency range. These input and output branches 22, 23, 25 and 26 have the usual suitable filters to separate the frequencies. Other frequency ranges may be utilized by other hybrid coil transformers in parallel with 21 and 24, with suitable filters in their input and output connections. The parallel branches of the conductor pair 19, through the respective transformers 21 and 24, are united and lead through the network 27, which balances the part of the conductors 19 in the cable 20;

the transformer 28 and condenser 29 duplicate and balance the transformer 13 and the condenser 14 at the cable hut 17.

A conductor pair 18 goes through retardation coils 30 with shunted condensers 32, as shown, and then through the network 33 and a retardation coil 34, and thence these conductors unite with the terminals of the transformer 28 on the distant side with respect to the transformers 21 and 24. The network 33 balances the part of the conductors 18 within the cable 20. A channel for ordinary duplex direct current telegraphy is connected to the terminals 31.

It will be seen that the apparatus at the cable hut 17 is balanced by the transformer 28, and the terminals 39 and 40 correspond respectively to 12 and 16. Connected to these terminals 39 and 40 is my improved artificial line 43 which balances the cable 11.

This artificial line 43 consists of a large number of sections 35 connected in serial order. These sections are alike in general plan but differ in equivalent length and in ohmic resistance as will be pointed out presently. Each section 35 between the two terminals 39 and 40 on one end and 41 and 42 on the other end consists of a resistance 36 and inductance 37 in series on one side, a like series combination of resistance 36 and inductance 37 on the other side, and a pair of equal cross-connected condensers 38. The resistances 36 and inductances 37 are adjustable as indicated in Fig. 2.

When the resistances 36, inductances 37 and the capacities 38 of the section of Fig. 2 are given proper values, determined by the series resistance and inductance of the geographical line and its distributed shunt capacity, then the artificial line section is practically equivalent to a length of the geographical line. These electrical characteristics are chosen to make the equivalent lengths of the sections comparatively short at the end near the office and not so short at the remote end. The exact dimensions in this illustrative example of my invention are indicated in Figs. 5, which shows 20 half-naut sections next to the office end, then 20 one-naut sections, followed by longer sections until the remote section with an equivalent length of twelve nauts is reached.

Assuming for the conductor pair of the geographical line that the ohmic resistance per naut is R ohms, inductance per naut is L henrys, and distributed shunt capacity per naut is C farads, if we make the network of Fig. 2 so that each resistance 36 is $\frac{n}{2}$R, each inductance 37 is $\frac{n}{2}$L and each capacity 38 is $\frac{n}{2}$C, where n is any number, then this network interposed in the geographical line is equivalent in impedance to a length of n nauts of that line. The proof of this proposition may be indicated briefly as follows.

The definition of characteristic impedance assumes an infinite line, and accordingly the impedance across 39, 40 is the same as across 41, 42, as indicated by the character Z′ in Fig. 2. Let the impedance of branch 39—41 be

$$Z_1' = \frac{n}{2}(R + i \cdot 2\pi f L) = \frac{n}{2} Z_1$$

and let the impedance of branch 39—42 be

$$Z_2' = \frac{2}{n(i \cdot 2\pi f C)} = \frac{2}{n} Z_2$$

where Z_1 and Z_2 are respectively the series and shunt impedances per unit length of the smooth line. Solving the network of Fig. 2 by the ordinary Wheatstone bridge formula, the result is obtained that

$$Z' = \sqrt{Z_1' Z_2'} = \sqrt{Z_1 Z_2}$$

The last expression is the familiar formula for the characteristic impedance of the smooth geographical line whose constants are R, L and C. Thus it will be seen that the characteristic impedance is the same whether the sections of Fig. 2 are great or small in equivalent length. The advantages of making them small will be pointed out presently, and it will be shown that they should be shorter near the office end.

As to the propagation constant, we know that for the smooth line, it is given by

$$P = \sqrt{Z_1 / Z_2}$$

where P is defined by the equation $e^P = I_1/I_2$ and where I_1/I_2 is the ratio of the currents at the input and output ends of a unit length of the smooth line.

Let the input and output currents for the section of Fig. 2 be I_1' and I_2'. By the symmetry of the structure it is seen that the currents through the branches 39—42 and 41—40 are equal. Call these I″. Resolving the currents in the network of Fig. 2 as shown in Fig. 3, we have by Kirchoff's law,

$$I_1'Z' = I''Z_2' + (I'' + I_2')Z_1'$$

and

$$I_2'Z' + (I_2' + I'')Z_1' = I''Z_2'$$

Eliminating I″, substituting

$$\sqrt{Z_1'Z_2'}$$

for Z′ and simplifying, we get

$$\frac{I_1'}{I_2'} = \frac{\sqrt{Z_2'} + \sqrt{Z_1'}}{\sqrt{Z_2'} - \sqrt{Z_1'}}$$

By analogy to the definition of P, let the foregoing expression equal $e^{P'}$. By definition of the hyperbolic tangent, tanh

$$P' = (e^{P'} - e^{-P'})/(e^{P'} + e^{-P'}):$$

Substituting and reducing, we get

$$\tanh P'=\frac{2\sqrt{Z_1'Z_2'}}{Z_1'+Z_2'}=\frac{2\sqrt{Z_1Z_2}}{\frac{n}{2}Z_1+\frac{2}{n}Z_2}=\frac{nP}{1+\left(\frac{nP}{2}\right)^2}$$

By a simple transformation we get

$$\tanh\frac{P'}{2}=\frac{nP}{2}$$

When $\frac{P'}{2}$ is small, $\tanh\frac{P'}{2}$ and $\frac{P'}{2}$ are nearly equal. Hence we see that by making n small we make P' and n^P to be nearly equal, and thus we make the propagation constant of the section of Fig. 2 to be nearly the same as n units of length of the smooth line. Accordingly the size of the sections is determined largely by the consideration that they should be made small enough to secure a sufficiently approximate equality of the propagation constant per section with the corresponding length of the smooth line. The specific application of this principle in the present case is exhibited in Fig. 5 where the gradation of section length is shown by appropriate legends on the drawing.

If the geographical line were perfectly smooth, the resistance and negative reactance components of its characteristic impedance would vary with frequency somewhat according to the smooth curves of Fig. 4. Due to the inevitable slight irregularities in the geographical line that have already been mentioned, a test of the characteristic impedance for varying frequencies gives a plot that may depart from the smooth curves, for example, somewhat as indicated by the dotted curves of Fig. 4. These departures are due to partial reflections of current waves from the junction points of sections of differing characteristics. They may be analyzed by graphical or analytical methods, and the actual distance of the irregularities from the cable hut may be determined in this way, and thereupon adjustments may be made in the proper artificial line sections to match these irregularities. These adjustments will be made when the cable is started in operation and will be made once for all, because the irregularities in the geographical line are permanent, and therefore the corresponding adjustments of the artificial line are equally permanent.

For high frequencies, as already stated, the sections should be small, in order to make the propagation constant nearly equal to that for the geographical line. But the high frequency currents are most rapidly attenuated, and for this reason the sections may be made longer at the distant end of the artificial line. Also because the current is far less attenuated in the near sections than in the remote sections, much finer adjustment may be necessary in the near sections.

At the remote end of the artificial line the current is so highly attenuated that, even if a considerable part of it were reflected back to the office, its effect there would scarcely be noticed. This is true for higher frequencies, say above 300 cycles per second, though lower frequencies would not be so much attenuated and might be reflected back and noticed at the office. The artificial line is terminated at its remote end by a network 44, consisting of a series resistance 45 shunted by a condenser 46 and series resistance 47. The impedance of this combination approximates sufficiently to the impedance of the distant terminal apparatus when looking into it from along the actual line.

In the discussion hitherto it has been tacitly assumed that the series resistance R of the geographical line is constant, but in fact it is a variable function of frequency. For low frequencies the return current spreads out in the sea water, whereas for high frequencies it is largely confined to the cable sheath, thus increasing the circuit resistance. Moreover the inductive loading involves more or less eddy current and hysteresis loss, which are functions of frequency and increase with frequency and therefore increase the apparent resistance to the current flow in the signaling circuit. It is impractical to construct the artificial line to make its resistance vary correspondingly. It is necessary to make the direct current resistances of the artificial line equal that of the cable, to secure a balance for the duplex direct current telegraph channel. But the effective resistance of the cable core for alternating currents of considerable frequency is much greater than its direct current resistance.

Accordingly a compromise is effected by making the proximate sections of the artificial line with a resistance that will match the cable resistance at about 1000 cycles per second. This is too high for direct current and therefore the resistance is reduced for the sections farther out, so that the total direct current resistance of the cable has the proper value.

In the foregoing specification, I have disclosed a network with sections of different "equivalent length"; by this term I mean the length of the extended line to which the network section is approximately equivalent in its transmission properties. A network of short equivalent length is one which is equivalent to a short length of the extended line.

I claim:

1. An artificial line consisting of sections in serial order, each intermediate section

being connected with the adjacent section on one side at two points and with the adjacent section at the other side at two points, impedances connecting each point on one side with each point on the other side, one pair of non-adjacent impedances consisting each of a resistance and an inductance in series and the remaining pair of impedances consisting each of interposed condensers.

2. An artificial line of sections in serial order, each section being a bridge type network, the sections near the input end being made small enough in equivalent length so that the propagation constant per section shall be approximately the same as its limiting value when the size of the sections is made indefinitely small in equivalent length.

3. An artificial line of sections in serial order, each section being a bridge type network with the impedance values of its arms so related to the characteristics of a given smooth line that the sections simulate definite lengths of that line for characteristic impedance, the sections being made small enough in equivalent length so that the propagation constant per section shall be approximately the same as for the corresponding length of the smooth line.

4. An artificial line of sections in serial order, each section being a bridge type network, the sections being small in equivalent length and each section being matched closely to a definite finite length of a given smooth line.

5. An artificial line of sections in serial order, each section being a bridge type network, the sections being small in equivalent length at the input end and increasing in size away therefrom, and each section being closely matched to a definite corresponding finite length of a given smooth line.

6. An artificial line of sections in serial order, each section being a bridge type network between two pairs of terminals, each pair of terminals on one side being connected to a pair of the next succeeding section on that side, and having a pair of its arms of adjustable impedance whereby they can be matched to local irregularities in an actual smooth line simulated by the artificial line.

7. In combination, a submarine signaling conductor, and an artificial line to balance it, said line consisting of bridge type networks in serial order, having their arms of proper value to match the said conductor for characteristic impedance and propagation constant at a certain frequency, and having resistance elements graded to decrease from the input end so that the line and cable shall match in resistance for direct current.

8. An artificial line of sections in serial order, each section lying between two pairs of terminals with each pair of terminals on one side connected to a pair of the next succeeding section on that side, each section being a bridge type network having adjustable resistance and adjustable inductance in series in each of one pair of opposite arms, and having capacity in each of the other pair of opposite arms.

9. An artificial line of sections in serial order, each section being a bridge type network having the series impedance of each arm of one pair of arms equal to half the series impedance of a definite length of a given smooth line and having the admittance of each arm of the other pair of arms equal to half the shunt admittance of the same length of the given smooth line, the equivalent lengths of said sections being graded in decreasing magnitude toward the input end.

10. In combination, a loaded signaling conductor and an artificial line to balance it, said line consisting of sections in serial order, the sections near the input end being made short enough in their equivalent length so that the propagation constant per section shall be approximately the same as its limiting value when the size of the sections is made indefinitely short in equivalent length.

11. An artificial line of sections in serial order, each intermediate section being connected at two points with the adjacent section on one side and at two other points with the adjacent section on the other side, the two points on one side being connected with the two points on the other side by four impedances of which two non-adjacent impedances are alike and the remaining two are alike, one pair of like impedances each consisting of a resistance and an inductance in series and the remaining pair each consisting of capacities.

12. In combination, a loaded signaling conductor and an artificial line to balance it, said line consisting of sections in serial order, the sections near the input end being made short enough in their equivalent length so that the propagation constant per section shall be approximately the same as its limiting value when the size of the sections is made indefinitely short in equivalent length, and the sections farther away from the input end being made longer in equivalent length.

In testimony whereof, I have signed my name to this specification this 18th day of October, 1921.

HARRY W. HITCHCOCK.