Sept. 27, 1927. 1,643,332

G. A. CAMPBELL

ELECTRICAL NETWORK

Filed March 25, 1921

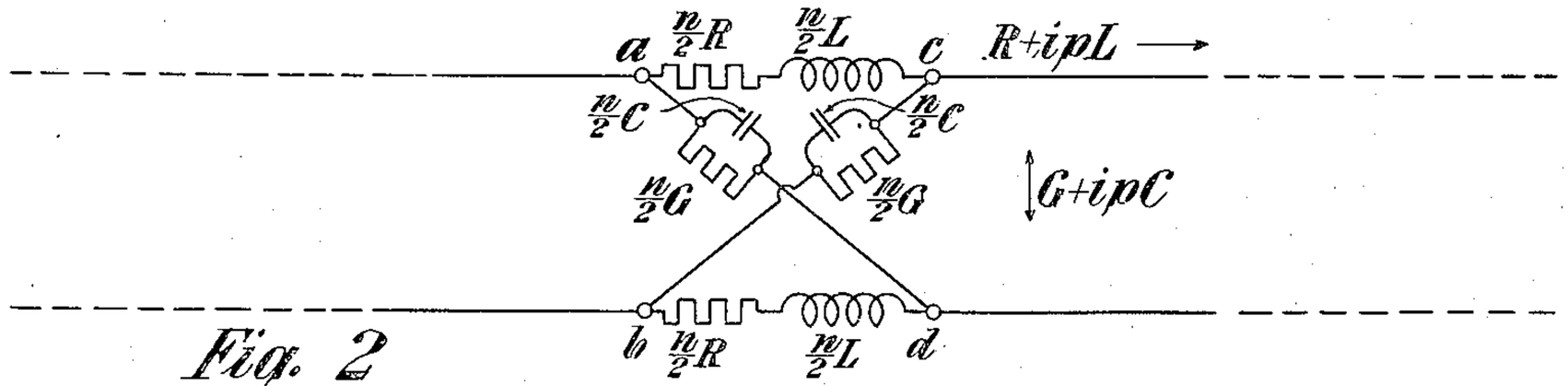

Fig. 2

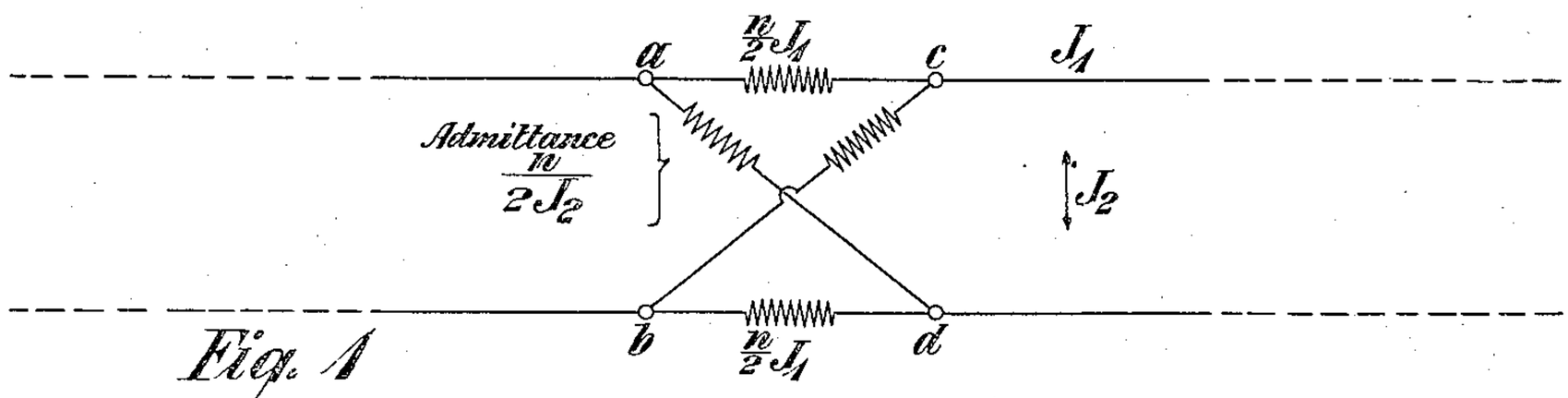

Fig. 1

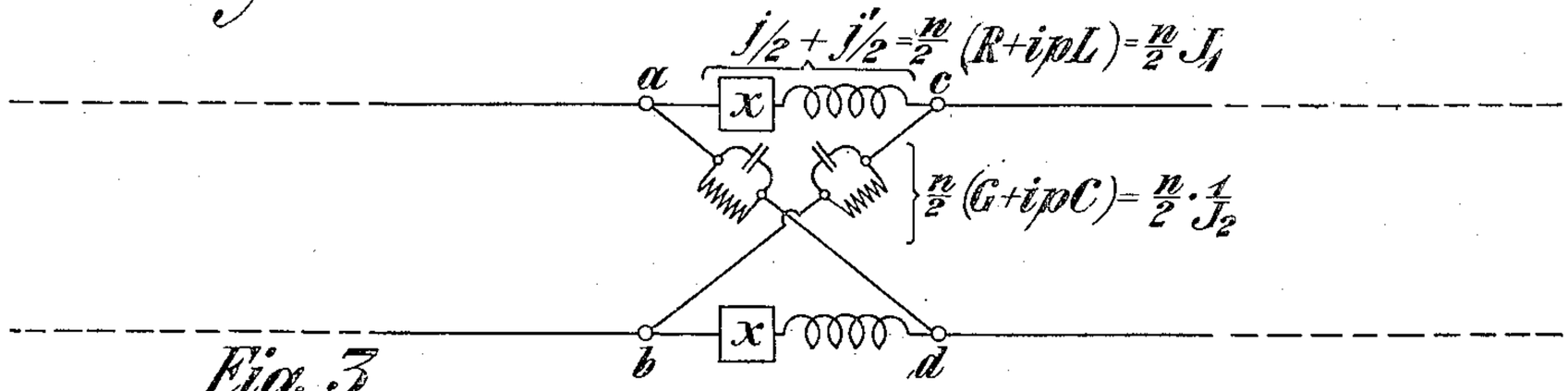

Fig. 3

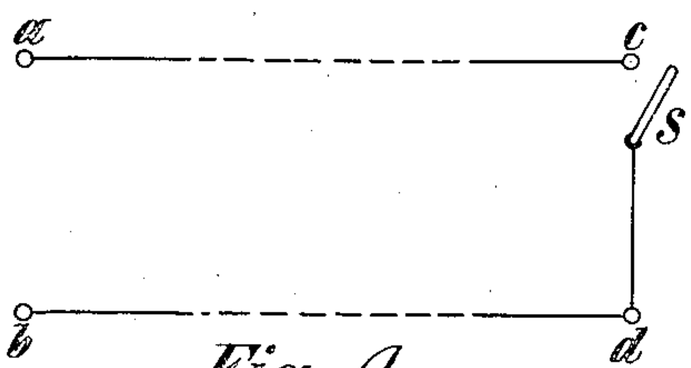

Fig. 4

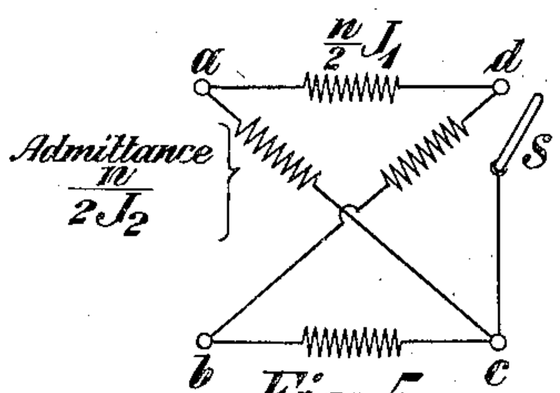

Fig. 5

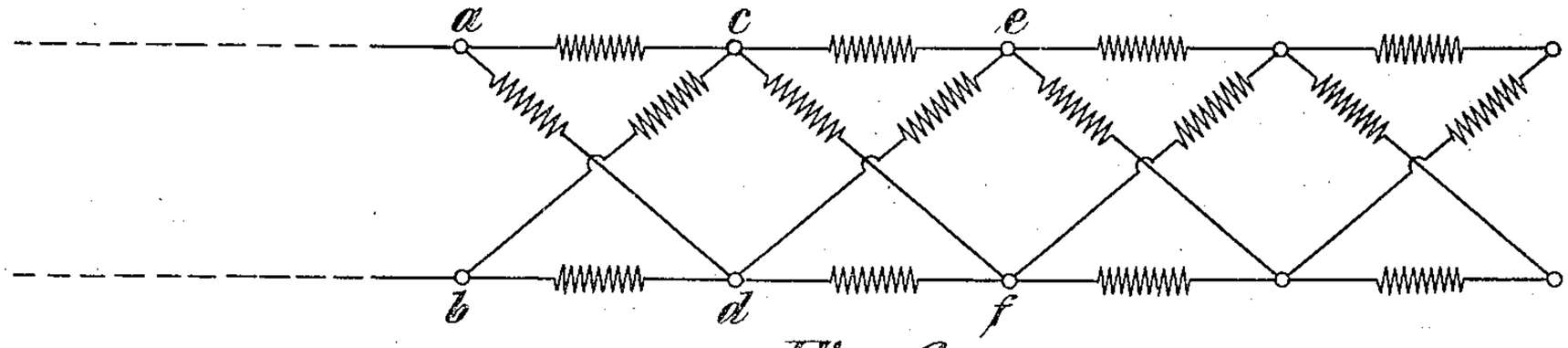

Fig. 6

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UNITED STATES PATENT OFFICE.

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ELECTRICAL NETWORK.

Application filed March 25, 1921. Serial No. 455,670.

The principal object of my invention is to provide a new and improved network having certain useful properties that adapt it for operation in connection with telephone transmission lines. Another object of my invention is to provide a network such that having given a piece of apparatus to be connected in a line, this apparatus may be made an element of this network and the network may be introduced in the line without affecting its characteristic impedance. Still another object of my invention relates to the provision of a unit network, of which a series may be employed as sections in a recurrent periodic network to serve for various purposes, among them for an artificial line to simulate and balance an actual transmission line. These and other objects of my invention will become apparent on consideration of examples disclosed herein.

In the accompanying drawings I have shown a few examples of specific embodiments of my invention, and I now proceed to describe them with the understanding that the scope of the invention will be defined in the appended claims.

Referring to the drawings, Figure 1 is a generalized diagram showing my improved unit network inserted in a transmission line, Fig. 2 is a corresponding diagram for a network of more definite properties than indicated in Fig. 1, Fig. 3 illustrates the use of my network for inserting a piece of apparatus in series in a transmission line, Figs. 4 and 5 are diagrams to which reference will be made in demonstrating the theory of my improved network and Fig. 6 is a diagram illustrating employment of the network in an artificial line to balance a long transmission line.

Referring to Fig. 1, this shows a long transmission line extending indefinitely to right and left with my improved network interposed between the terminals a, b, and c, d. The line is assumed to have a series impedance of J_1 units per unit length and a distributed shunt impedance of J_2 units per unit length, where J_1 and J_2 will be complex numbers in general.

Having the line with the properties defined by the constants J_1 and J_2 as just stated, if n is any number, I interpose the impedances $\frac{n}{2}J_1$ in series between a and c and between b and d, and I interpose the impedances $\frac{2}{n}J_2$ diagonally between a and d and between b and c. If this is done, then it is a fact which I will demonstrate presently that the network between a, b, and c, d is precisely like a definite length of the line, for every frequency, so far as the characteristic impedance is concerned. In other words, looking to the right, the impedance across a, b will be the same as across c, d, that is, the same as the characteristic impedance across any two points of the line. Of course, for a physical conception of characteristic impedance it is assumed that the line extends indefinitely to the right.

In the case of a smooth transmission line, the series impedance represented by J_1 in Fig. 1 will be more definitely represented by $R+ipL$ as in Fig. 2, where R and L are respectively the series resistance and series inductance per unit length of the line. Likewise the shunt impedance which is represented by J_2 in Fig. 1 corresponds to the shunt admittance $1/J_2$ which becomes $G+ipC$ in Fig. 2, where G and C respectively stand for the distributed shunt conductance and distributed shunt capacity per unit length of the line. Accordingly, the elements of the network in Fig. 2 become correspondingly more definite and have the values indicated by the attached legends in the drawing.

Suppose that it is desired to introduce some piece of apparatus, a relay for example, at an intermediate point in a long transmission line, and that this is to be done without changing the characteristic impedance and without the introduction of any irregularity due to reflection. A suitable network for doing this is shown in Fig. 3. The apparatus which it is desired to introduce in the line, a relay for example, is represented by the reference letters x, comprising two equal parts similarly dis-

posed to the two sides of the line, so as to preserve the balance of the line. Suppose the impedance of the two parts of x together is represented by j, then the impedance of the part in each side of the line will be $j/2$. Suppose, to make the illustration definite, that the resistance component of x stands in greater ratio to R than its inductance component stands in relation to L, then by adding inductance $j'/2$ on each side of the line, I can bring the impedance between the points a and c so that its ratio to $R+ipL$ is a real number, which I will call $n/2$. The factor n being known, it follows at once that the shunt elements of the network are known according to the principles explained for Figs. 1 and 2, and the network of Fig. 3 becomes completely defined as indicated by the legends thereon.

Thus it will be seen that it becomes possible to introduce apparatus represented by the reference characters x without impairing the transmission qualities of the line. It will be evident that if the apparatus to be introduced had had excessive inductance, then pure resistance might have been put in series therewith. Also if the apparatus has a capacity reactance it may be put in one or both of the shunt arms of the network, in which case such apparatus will be represented by one or both of the condensers of Fig. 2.

I will now point out how the useful property of my improved network may be demonstrated. It is a well-known theorem that in the case of a finite line, if we measure its impedance at one end with the opposite end open on one occasion and short-circuited on another occasion, then the characteristic impedance of that type of line is a mean proportional between the two impedance results obtained by such measurements. For example, in Fig. 4. if we measure the impedance across a, b when the switch S is open and again when the switch S is closed, then the characteristic impedance will be the mean proportional between the two results. This is true not only for smooth lines but for any artificial line consisting of like recurrent sections. Accordingly, the characteristic impedance of such a series of sections extending indefinitely from given terminals may be ascertained by taking a limited number of the sections, or even a single one of them, and getting the two impedances, and then their mean proportional in the same manner.

Thus, referring to Fig. 5, if the impedance across a, b is measured on two occasions, first with the switch S open, then with the switch S closed, the mean proportional of the two results is the characteristic impedance of a recurrent line of such unit networks as shown in Fig. 5.

Now it is apparent at once that the impedance across a, b in Fig. 5 with the switch S open is

$$\frac{1}{2}\left(\frac{n}{2}J_1+\frac{2}{n}J_2\right)$$

and the impedance across the same points a, b, with the switch S closed is

$$2\frac{J_1J_2}{\frac{n}{2}J_1+\frac{2}{n}J_2}$$

The mean proportional of these two results is

$$\sqrt{J_1J_2}.$$

But this is known to be the characteristic impedance of the smooth line of Fig. 1, and hence the proposition advanced is demonstrated.

This same proposition can be proved in other ways. For example, the complete network to the right of a, b in Fig. 5 is a Wheatstone bridge, and if its impedance be computed by ordinary network theory, taking the impedance across c, d to be

$$\sqrt{J_1J_2},$$

the result will be obtained that the impedance across a, b is the same, namely

$$\sqrt{J_1J_2}.$$

My network can also be used as a phase-shifter without introducing reflection effects. Suppose that in the transmission line of Fig. 1 or Fig. 2, it is desired to produce a phase shift θ. Now θ is the coefficient of the imaginary term of the propagation constant of the network, which is known to be equal to the anti-hyperbolic tangent of the square root of the quotient of the closed circuit impedance divided by the open circuit impedance; that is

$$M=\tanh^{-1}\sqrt{\frac{2J_1J_2}{\frac{n}{2}J_1+\frac{2}{n}J_2}+\frac{1}{2}\left(\frac{n}{2}J_1+\frac{2}{n}J_2\right)}$$

which reduces to

$$M=\tanh^{-1}\frac{4nm}{n^2m^2+4}$$

where

$$m=\sqrt{J_1/J_2},$$

that is, the propagation constant of the smooth line.

By ordinary transformations, this equation may be put in the simpler form

$$M=2\tanh^{-1}\frac{nm}{2}$$

Hence the procedure to get a phase shift

of θ is to put the foregoing equation in the form

$$R+i\theta=2\tanh^{-1}\frac{nm}{2}$$

where R is the real part of M, from which it follows that $i\theta$=imaginary component of

$$2\tanh^{-1}\frac{nm}{2}$$

This may be regarded as a design equation to get the proper value of n for a desired phase shift θ.

To illustrate briefly, suppose R and G are negligible, then $i\theta$=imaginary component of

$$2\tanh^{-1}\frac{n}{2}\sqrt{Lpi\cdot Cpi}$$

which reduces to

$$\theta=2\tan^{-1}\frac{np}{2}\sqrt{LC}$$

or

$$n=\frac{2}{p\sqrt{LC}}\tan\frac{\theta}{2}$$

by which n may be determined for a desired phase shift θ.

In Fig. 6 I have indicated the use of a series of unit networks for an artificial line to balance the long transmission line coming from the left to the terminals a, b. A sufficient number of sections should be employed so that the attenuated current in the terminal section at the right will be negligible, compared to the input current at a, b. By taking the values of the impedance elements large enough, a few sections would suffice, or one might be enough, but by providing a large number of sections as indicated in Fig. 6, any individual section can be adjusted and thus the artificial line can be matched more accurately to the real geographical line. In this connection, it may be remarked that there would be no reflection between the sections even if they represented different lengths of the same uniform line, but the attenuation and the phase shift in the sections would differ according to their size.

I claim:

1. In combination, a transmission line comprising like outgoing and return conductors and a network interposed therein symmetrically to said conductors and having substantially the same impedance at every frequency as the characteristic impedance of said line.

2. A network consisting of a series of like recurrent sections serially arranged, each section having a pair of input terminals and a pair of output terminals and four separate impedance elements respectively connecting each input terminal with each output terminal, the two output terminals of each section except the last of the series being connected respectively to the two input terminals of the succeeding section in the series.

3. In combination, a transmission line comprising two conductors leading to a pair of terminals a and b and two conductors leading from another pair of terminals c and d and an interposed network consisting of two like impedances, one between a and c and the other between b and d, and two other like impedances, one between a and d and the other between b and c.

4. In combination, a transmission line, apparatus to be interposed at an intermediate point in that line and a network of which said apparatus is a part, said network comprising two diagonal impedance branches and two direct impedance branches one on each side, the impedances of these branches being proportioned so as to make the characteristic impedance the same as that of the line.

5. An artificial line consisting of a series of like connected sections, each section consisting of a pair of input terminals and a pair of output terminals, and four separate reactances respectively connecting each input terminal with each output terminal.

6. A transmission line, a piece of apparatus to be interposed without producing reflection effects, and a network comprising series and shunt branches in the line and having said apparatus as an element and having the same characteristic impedance as the line.

7. In combination, a transmission line and an interposed phase shifter having a pair of input terminals connected to the line on one side and a pair of output terminals connected to the line on the other side and having two like impedances connecting each input terminal with a respective output terminal and two other like impedances cross-connecting each input terminal with an output terminal.

8. A network adapted to function as a phase shifter consisting of a pair of input terminals and a pair of output terminals, conductors from each input terminal to each output terminal, an inductance in each of a pair of the conductors from the input terminals to respective output terminals, and a capacity in each of the other two conductors.

9. A network adapted to function as a phase shifter consisting of two input terminals a and b and two output terminals c and d, with connections from a to c and b to d, each comprising an inductance, and connections from a to d and b to c, each comprising a capacity.

In testimony whereof, I have signed my name to this specification this 22nd day of March, 1921.

GEORGE A. CAMPBELL.