

Sept. 28, 1926.

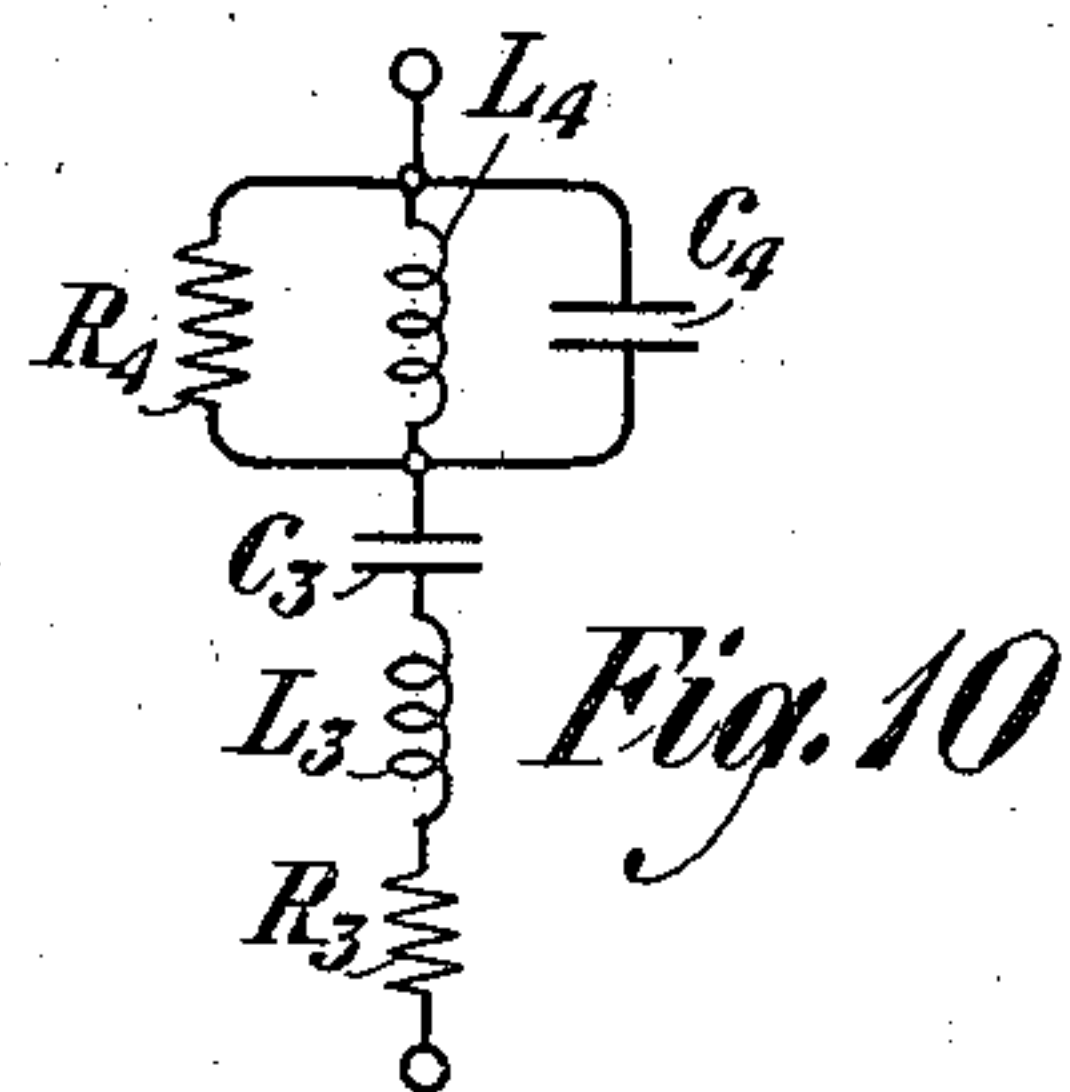
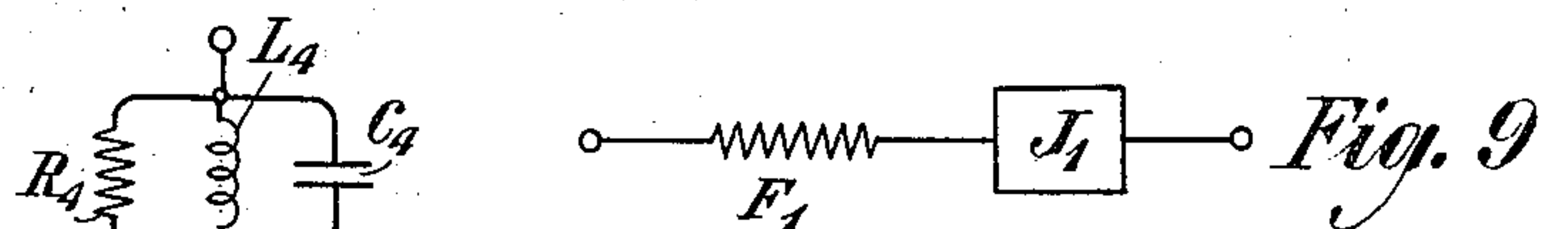
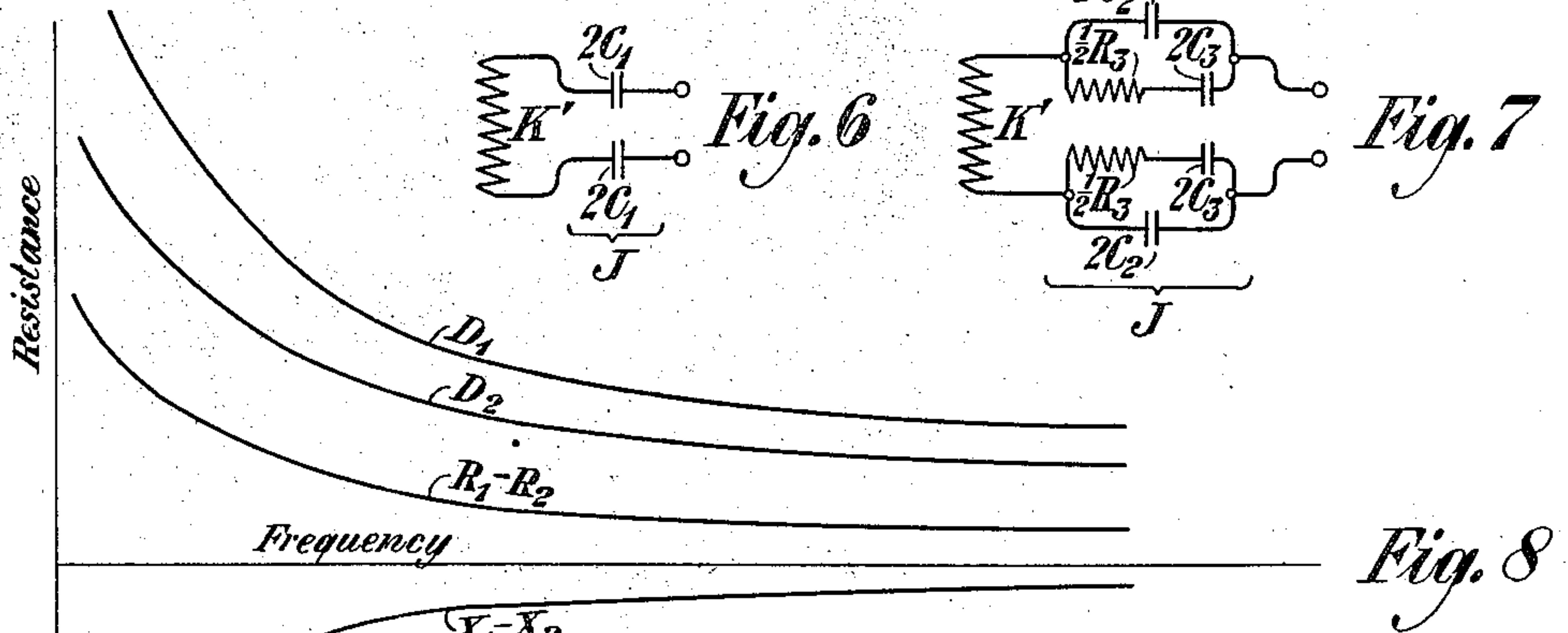
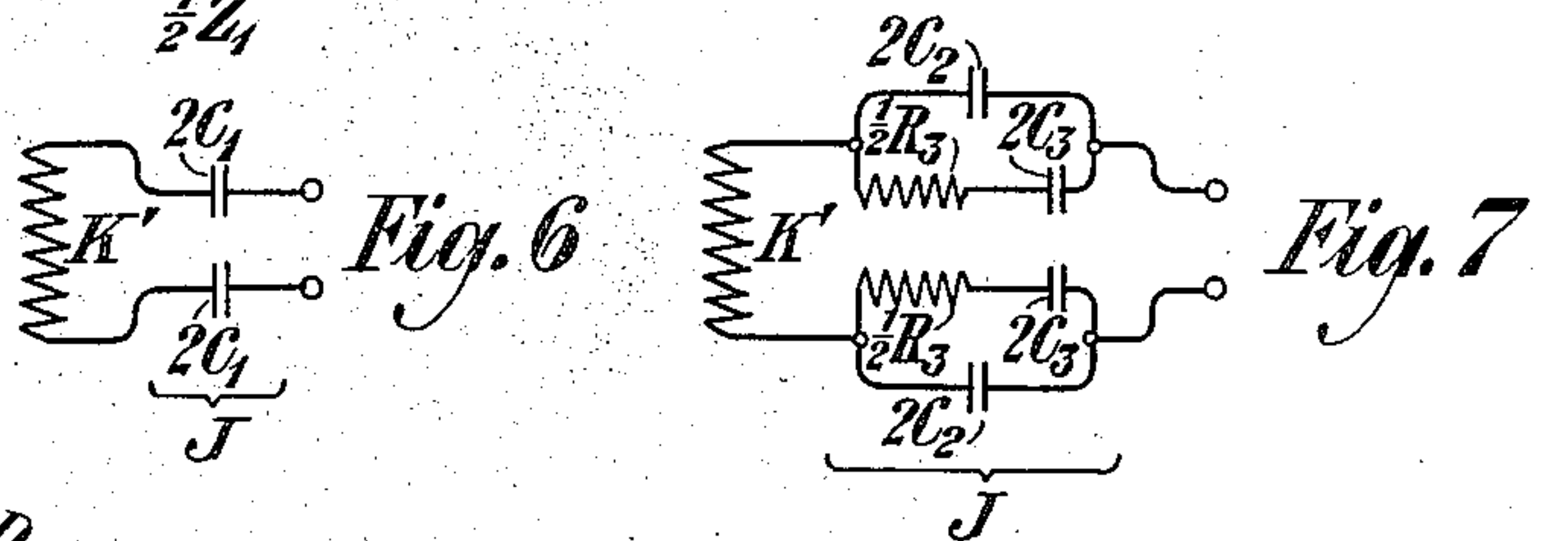
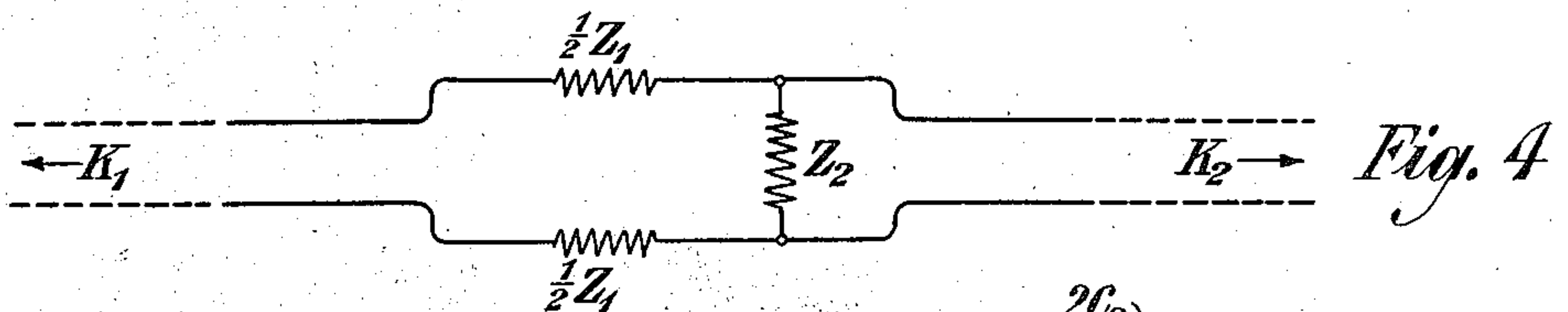
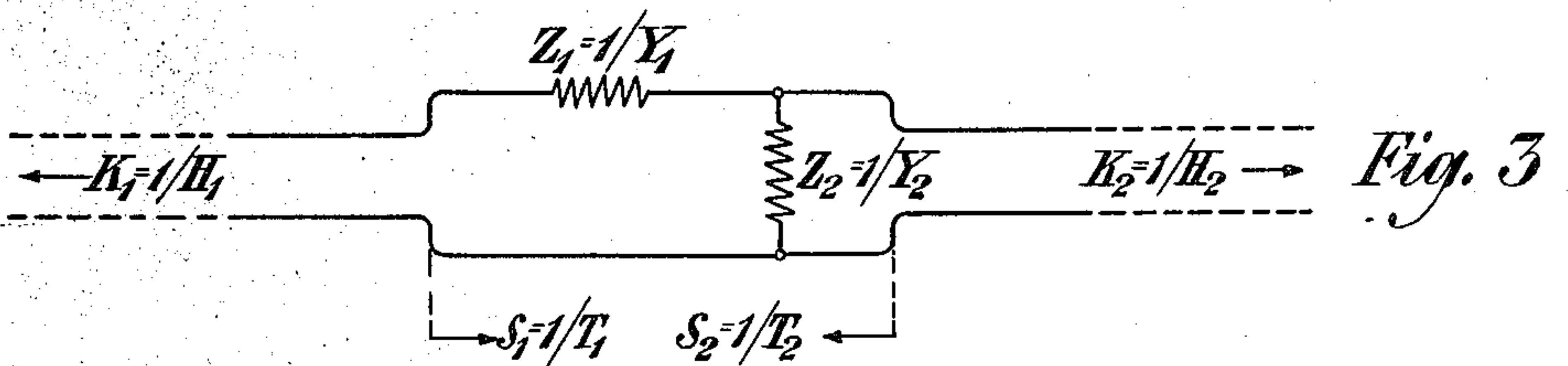
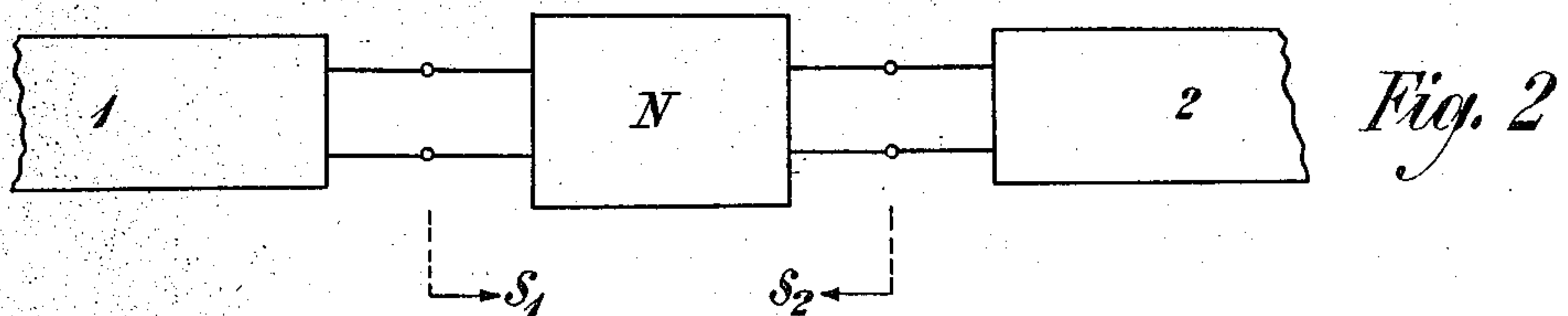
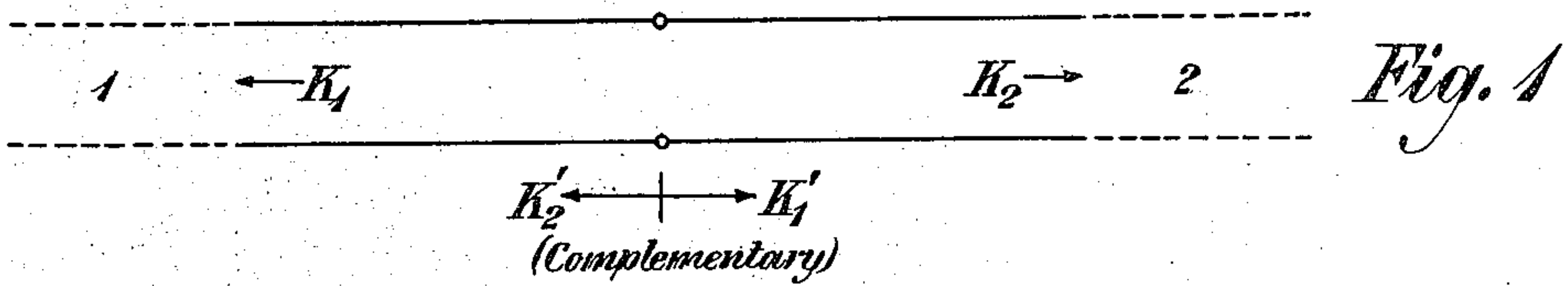
1,601,023

R. S. HOYT

ELECTRICAL SIGNALING SYSTEM

Filed Feb. 1, 1924

2 Sheets-Sheet 1



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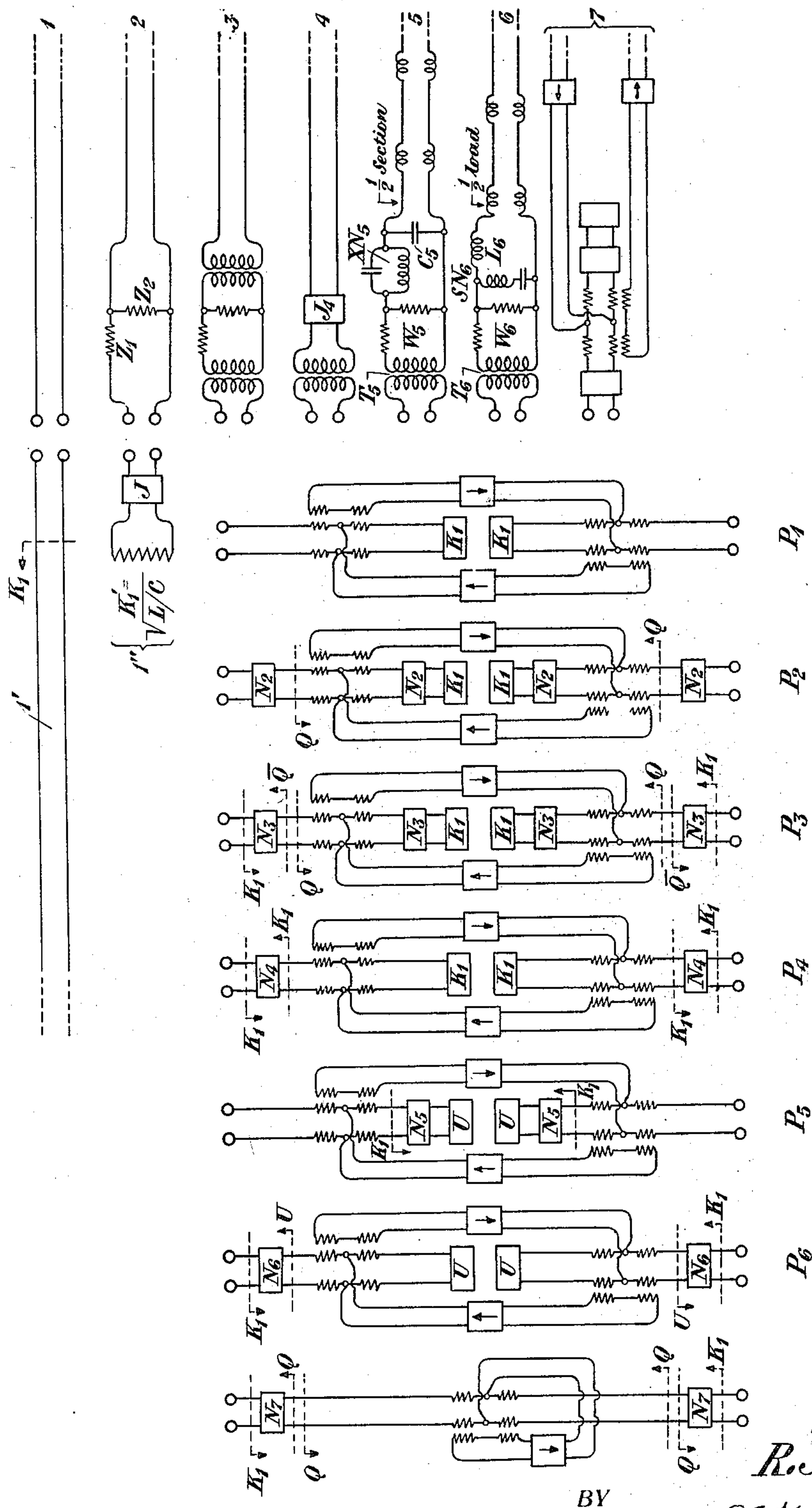
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# ELECTRICAL SIGNALING SYSTEM

Filed Feb. 1, 1924

2 Sheets-Sheet 2



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## UNITED STATES PATENT OFFICE.

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## ELECTRICAL SIGNALING SYSTEM.

Application filed February 1, 1924. Serial No. 689,992.

An object of my invention is to provide a network to be interposed between a given transmission line and another transmission line or between a given transmission line and a piece of electrical apparatus so that in the combination the impedances looking into the network on both sides shall have respective assigned values. Another object of my invention is to provide a network that may be interposed between a given line and another line or between a given line and a piece of electrical apparatus so that transmission may be made either way through the network without reflection effects. Another object of my invention is to provide a new and improved system of lines and apparatus for long distance telephone transmission between various points through a single central station. Another object is to provide a plurality of long distance telephone lines of divers character all entering a central station, and in combination therewith, means at the central station to facilitate a variety of connections between these lines with or without interposed apparatus. Still another object of my invention is to utilize the improved network to which I have referred in adapting diverse lines and apparatus for interconnection in various ways at a central station. These objects and various other objects of my invention will become apparent on consideration of a limited number of specific examples which I have chosen to illustrate the invention and which I will now proceed to disclose with the understanding that the following specification relates more particularly to these examples and that the invention will be defined in the appended claims.

In practical long distance telephony a variety of lines may be employed, such as overhead lines with the two conductors spaced wide apart, or cables in which the conductors are close together, and in each of these cases the lines may or may not be loaded. In connecting one such line to another of different character, serious reflection effects and irregularities may be caused. Such troubles appear in any case when a

line of one characteristic impedance is connected to a line of substantially different characteristic impedance. Moreover, if two lines are connected through a repeater, the same troubles will develop unless the repeater is designed properly to fit the lines. It is among the objects of my invention to combine apparatus with the respective lines at their ends entering the station, and to design the repeaters and other apparatus at the station, and to combine the proper apparatus with the repeaters, so that flexibility may be attained in the matter of the various connections in and out of the station and to and through the pieces of apparatus in the station.

Referring to the drawing, Figure 1 is a diagram showing two connected lines of different impedance values; Fig. 2 is a symbolic diagram showing an impedance compensator between two impedance constituents; Fig. 3 is a diagram showing the general design of a compensator; Fig. 4 is a diagram showing an alternative form of the compensator of Fig. 3; Fig. 5 is a diagram of a central station with a plurality of lines extending therefrom, and with a plurality of repeaters all adapted for connection in various ways; Figs. 6 and 7 show special types of excess-simulators; Fig. 8 is a diagram showing the impedance components for a representative smooth line as functions of frequencies; and Figs. 9 and 10 are diagrams for impedance elements in an impedance compensator.

At each junction point in any electrical transmission system there exists, in general, a two-way impedance irregularity in the sense that the impedance there is not ideal in either direction and, moreover, departs from the ideal differently in the two directions. Such irregularities react harmfully on any repeaters in the system; and it is desirable to compensate for the irregularities at the junction points where they arise. In telephony the compensation must hold over a wide range of frequencies.

The ideal impedance for terminating a periodically loaded line is, in general, the



complementary characteristic impedance of the line, in the sense that then the termination appears from a point within the line like an infinite continuation of the line itself, at all frequencies. Thus, in the ideal case of two periodically loaded lines connected together, the characteristic impedance of each line would be equal to the complementary characteristic impedance of the other.

In the case of a loaded line terminating at a symmetrical point (mid-section or mid-coil) the characteristic impedance and the complementary characteristic impedance are evidently equal to each other; and for a smooth line the two impedances are, of course, equal.

The only kinds of lines to be considered in the present case are smooth lines and lines having a regularly recurrent structure, of which the loaded line is an example. In the case of a smooth line the characteristic impedance will be the same looking either way at any point. In the case of lines having recurrent structure (not-smooth lines) the characteristic impedance may be different looking both ways from a given point. The two characteristic impedances looking in opposite directions from a point on such a line are said to be complementary.

At the junction of any two lines 1 and 2, as in Fig. 1, having respective characteristic impedances  $K_1$  and  $K_2$  and complementary characteristic impedances  $K'_1$  and  $K'_2$ , there is a two-way impedance irregularity which, viewed from the interior of lines 1 and 2 respectively, has the values  $K_2 - K'_1$  and  $K_1 - K'_2$ , which, in general, are equal, as will now be shown. The condition for equality of the two impedance irregularities can evidently be expressed in the form

$$K_1 + K'_1 = K_2 + K'_2;$$

and this condition is not usually fulfilled; for two smooth lines this condition is fulfilled only when the two lines are alike, and then the irregularity is zero in each direction; for two periodically loaded lines, the condition is fulfilled only when the two lines are alike in structure and in terminating points, or else are alike in structure but are terminated in complementary positions (for instance, one terminating at  $x$ -section and the other at  $(1-x)$ -section, and then the irregularity is zero in each direction); for a smooth line and a periodically loaded line the condition can never be fulfilled identically, but it is approximately fulfilled when the loaded line is terminated at about 0.2-section or 0.8-section or 0.2-coil or 0.8-coil and the two lines have approximately equal nominal characteristic impedances and approximately equal de-

grees of dissipation. By nominal impedance I mean the value approached by the impedance when the resistance, the leakance and the frequency all approach zero.

In the general case of two smooth lines, 1 and 2, the impedance irregularities, viewed from the interior of the lines, are respectively  $K_2 - K'_1$  and  $K_1 - K'_2$  and are thus the negatives of each other. This is approximately true for two loaded lines or for a smooth line and a loaded line, at frequencies low relatively to the critical frequency; but not at higher frequencies.

Fig. 2 represents symbolically a two-way impedance compensator connected between two constituents, 1 and 2, which may be, for instance, two lines, or a line and a repeater, or a line and a substation.  $S_1$  and  $S_2$  denote the impedances of the remainder of the system as viewed from constituents 1 and 2 respectively. The impedance compensator  $N$  is to be so designed that, when the impedances of the constituents 1 and 2 are given,  $S_1$  and  $S_2$  shall have preassigned values as functions of the frequency over a wide frequency range.

It will be found that in general the conditions may be satisfied by making the compensator  $N$  of series-shunt type as shown in Fig. 3; that is, between the two constituents, 1 and 2, I interpose the network shown in general form in Fig. 3, consisting of the series impedance  $Z_1$  and the shunt impedance  $Z_2$ . Fig. 4 represents this compensator in an obviously equivalent form that would ordinarily be employed in practice to preserve the symmetry or balance of the system with respect to the sides of the line. The  $K$ 's and the  $H$ 's denote respectively the characteristic impedances and the characteristic admittances of the two lines; the  $Z$ 's and  $Y$ 's are the impedances and admittances going to make up the compensator; and the  $S$ 's and  $T$ 's are the resulting impedances and admittances of the remainder of the system as viewed from the lines. Both impedance symbols and admittance symbols are provided for symmetry and completeness; and the equations are much simplified and rendered more significant physically by working partly with impedances and partly with admittances, as will now appear.

To derive general design formulas for the compensator of Fig. 3, that is, to derive formulas for the requisite values of  $Z_1$  and  $Y_2$ , we shall set up an equation expressing  $S_1$  in terms of  $Z_1$ ,  $Y_2$ , and  $H_2$ , and an equation expressing  $T_2$  in terms of  $Y_2$ ,  $Z_1$ , and  $K_1$ ; and then solve this pair of equations for  $Z_1$  and  $Y_2$  or, preferably, for the ratios  $Z_1/K_1$  and  $Y_2/H_2$ . (For simplicity we work with  $Y_2$  instead of with  $Z_2 = 1/Y_2$ , with  $T_2$  instead of with  $S_2 = 1/T_2$ , and with  $H_2$  instead of with  $K_2 = 1/H_2$ .)



By inspection of Fig. 3 it is clear that

$$S_1 = Z_1 + 1/(Y_2 + H_2) \quad (1)$$

$$T_2 = Y_2 + 1/(Z_1 + K_1) \quad (2)$$

This pair of equations suffices for determining  $Z_1$  and  $Y_2$ ; but instead of proceeding to solve them directly, it is advantageous to write them in the following equivalent forms involving various significant ratios, and then to solve for the ratios in which the unknowns  $Z_1$  and  $Y_2$  occur:

$$2 \frac{S_1 + K_1}{2K_1} = \frac{Z_1 + K_1}{K_1} + \frac{H_2}{Y_2 + H_2} \frac{K_2}{K_1} \quad (3)$$

$$2 \frac{T_2 + H_2}{2H_2} = \frac{Y_2 + H_2}{H_2} + \frac{K_1}{Z_1 + K_1} \frac{H_1}{H_2} \quad (4)$$

For brevity, denote the various ratios by single letters, as follows:

$$A_1 = (S_1 + K_1)/2K_1 \quad (5)$$

$$B_2 = (T_2 + H_2)/2H_2 \quad (6)$$

$$\rho_1 = (Z_1 + K_1)/K_1 \quad (7)$$

$$\sigma_2 = (Y_2 + H_2)/H_2 \quad (8)$$

$$r = K_2/K_1 = H_1/H_2 \quad (9)$$

The unknowns  $Z_1$  and  $Y_2$  thus appearing in the ratios  $\rho_1$  and  $\sigma_2$ . Equations (3) and (4) then become

$$2A_1 = \rho_1 + r/\sigma_2 \quad (10)$$

$$2B_2 = \sigma_2 + r/\rho_1 \quad (11)$$

$$2A_1\sigma_2 - \rho_1\sigma_2 = r \quad (12)$$

that is,

$$2B_2\rho_1 - \rho_1\sigma_2 = r \quad (13)$$

which, of course, are ultimately equivalent to the original equations (1) and (2). This pair of equations, (12) and (13), shows immediately that  $A_1\sigma_2 = B_2\rho_1$  and thus yields a simple relation between  $\rho_1$  and  $\sigma_2$ . Thereby eliminating first  $\rho_1$  and then  $\sigma_2$  from (12) or (13) we obtain quadratic equations in  $\rho_1$  and  $\sigma_2$  whose solutions are

$$\rho_1 = A_1 + A_1\sqrt{1 - r/A_1B_2} \quad (14)$$

$$\sigma_2 = B_2 + B_2\sqrt{1 - r/A_1B_2} \quad (15)$$

whence finally, by (7) and (8),

$$Z_1/K_1 = A_1 - 1 + A_1\sqrt{1 - r/A_1B_2} \quad (16)$$

$$Y_2/H_2 = B_2 - 1 + B_2\sqrt{1 - r/A_1B_2} \quad (17)$$

and these are the desired general design formulas for the series and shunt branches  $Z_1$  and  $Y_2$  of the series-shunt type of two-way impedance compensator of Fig. 3. Farther along in this specification the foregoing general design formulas (16) and (17) will be illustrated in their application to determine proper special values of  $Z_1$  and  $Z_2$  ( $Z_2$  being the reciprocal of  $Y_2$ ).

Fig. 5 shows a central station with a number of lines entering it, some of them smooth lines and some of them loaded lines, and those of each kind having diverse impedances; moreover, some of the loaded

lines enter the station at a mid-section point while others enter at a mid-load point. Also, the station has a number of repeaters, and it is desired to adapt all the lines and all the repeaters so that any two lines can be connected through any repeater without reflection effects, and so that any line can be connected directly to any other line without reflection effects.

I assume a convenient hypothetical standard line and then combine the proper apparatus with the station end of each actual line to make it operatively equivalent to this hypothetical standard as viewed from the station. Also, I modify the repeaters and other elements of apparatus located at the station, and combine the proper elements with them, so as to fit them for direct connection to this hypothetical standard line or to any one of the modified actual lines, each of which is made equivalent to the standard line.

While the assumed standard line may be either a smooth line or a loaded line, I have taken it as a smooth line 1' in Fig. 5. I assume that 1' is a line having resistance  $R$ , inductance  $L$ , capacity  $C$  and leakance  $G$  of certain definite values such that the actual lines entering the station may be conveniently equalized thereto in the manner here to be described. As is well known, the characteristic impedance is given by the formula

$$K_1 = \sqrt{\frac{R + i2\pi fL}{G + i2\pi fC}} \quad (18)$$

in which the letters have the usual significance. Let  $K'_1$  denote the "nominal impedance", that is, the value to which  $K_1$  would reduce if the line were made non-dissipative ( $R=0$  and  $G=0$ ); thus

$$K'_1 = \sqrt{\frac{L}{C}} \quad (19)$$

I define "excess impedance" by the equation,

$$E = K_1 - K'_1 \text{ or } K_1 = K'_1 + E. \quad (20)$$

Accordingly, for the hypothetical line 1' there may be substituted the lumped combination 1'', consisting of a resistance of value  $K'_1$  and an impedance of value  $E$ , represented symbolically in the drawing by J. The device J is called an "excess simulator" and may be constructed in various ways according to the degree of precision required, and other considerations. The construction of excess simulators and the theory of their design are set forth in an article by me, entitled "Impedance of Smooth Lines, and Design of Simulating Networks", published on pages 1 to 40 of the April, 1923 issue of the Bell System Technical Journal. A simple excess simulator is shown in Fig. 6 and one a little more complex in construc-



tion, and at the same time more precise, is shown in Fig. 7. For Fig. 6,

$$C_1 = \frac{2\sqrt{LC}}{R}$$

and for Fig. 7, the values of  $C_2$ ,  $C_3$  and  $R_3$  in terms of  $R$ ,  $L$ ,  $G$  and  $C$  are given in the aforesaid Bell System Technical Journal paper. (The effect of the leakance  $G$  is usually negligible.)

It will be understood that the line 1' and the artificial line 1'' are both hypothetical. They may have no real existence in the system but are shown in Fig. 1 to aid in understanding the principles involved.

A variety of lines entering the central station are shown at the right of Fig. 5 and indicated by the reference numerals 1, 2, 3, etc. 1 is an actual smooth line exactly like 1'. 2, 3 and 4 are other smooth lines, 5 and 6 are loaded lines, and 7 is a four-wire line.

Obviously, the line 1 needs no modification to equalize it to the line 1'.

A series-shunt type compensator is shown in Fig. 5 connected to the end of the line 2. This is designed to compensate the impedance so that there shall be no reflection effects when transmission is from line 1' to line 2, nor when transmission is from line 2 to line 1'. Since these are smooth lines, their complementary characteristic impedances are the same as their characteristic impedances; therefore  $S_1 = K_1$  and  $S_2 = K_2$  (or  $T_2 = H_2$ ), whence  $A_1 = B_2 = 1$  and thus equations (16) and (17) reduce to

$$Z_1/K_1 = Y_2/H_2 = \sqrt{1-r} \quad (21)$$

or, what is equivalent,

$$Y_1/H_1 = Z_2/K_2 = 1/\sqrt{1-r} \quad (22)$$

From (21), (22) and (9) the design-equation for  $Z_1$  and  $Y_2$  are thus:

$$Z_1 = \sqrt{K_1(K_1 - K_2)} = K_1 \sqrt{1 - K_2/K_1} \quad (23)$$

$$Y_2 = \sqrt{H_2(H_2 - H_1)} = H_2 \sqrt{1 - H_1/H_2} \quad (24)$$

or, what are equivalent,

$$Y_1 = \frac{H_1}{\sqrt{1 - H_1/H_2}} = H_1 \sqrt{\frac{H_2}{H_2 - H_1}} \quad (25)$$

$$Z_2 = \frac{K_2}{\sqrt{1 - K_2/K_1}} = K_2 \sqrt{\frac{K_1}{K_1 - K_2}} \quad (26)$$

The design equations are written in these several different forms for use below in the further exposition of the design theory.

The design formulas (23) and (26) show that when the line impedances  $K_1$  and  $K_2$  approach equality, the requisite values for  $Z_1$  and  $Z_2$  approach zero and infinity respectively—a fact which is evident from physical considerations also. On the other hand, for the extreme case where  $K_2$  is very small compared to  $K_1$  the formulas show that  $Z_1$  and

$Z_2$  are approximately equal to  $K_1$  and  $K_2$  respectively and hence can be physically constituted by networks such as those described in my above cited article in the Bell System Technical Journal; that those networks are adequate also for other than this extreme case will be shown a little later herein, after the next paragraph wherein the design procedure is illustrated for the simple case of two smooth lines whose impedances are nearly constant resistances; the more general case, which is less simple, being considered thereafter.

Thus, consider now the case of two smooth lines whose impedances are nearly constant resistances. Certain instances of this case possess some practical importance: one instance, holding even at fairly low frequencies, is that of two smooth lines constructed of large wires, so as to be nearly non-dissipative; another instance is that of any two smooth lines, even highly dissipative lines, when employed at high frequencies—such as carrier frequencies. The proportioning of the compensator is very simple whenever the effect of dissipation on the line impedance is negligible over the frequency range contemplated; for then the two line impedances  $K_1$  and  $K_2$  are (approximately) pure resistances and independent of frequency, their values being

$$K_1 = \sqrt{L_1/C_1} \text{ and } K_2 = \sqrt{L_2/C_2},$$

the  $L$ 's and  $C$ 's denoting the inductances and the capacities of the lines per unit length. Thence the compensator impedances  $Z_1$  and  $Z_2$  are pure resistances having, by (23) and (26), the values

$$Z_1 = \sqrt{\left(\frac{L_1}{C_1} - \sqrt{\frac{L_1 L_2}{C_1 C_2}}\right)} \quad (27)$$

$$Z_2 = 1/\sqrt{\left(\frac{C_2}{L_2} - \sqrt{\frac{C_2 C_1}{L_2 L_1}}\right)} \quad (28)$$

(Evidently the line having the larger ratio  $L/C$  must be designated as line 1). Identically the same design is applicable in case either or both of the lines are replaced by any constant resistance devices; for instance, a constant resistance repeater, or a constant resistance substation set.

In many cases it will be advantageous to interpose a transformer or transformers on one or both sides of the compensator (as shown for example, with the line 3 in Fig 5); for by adopting suitable transformer ratios the design of the compensator may be facilitated, the presence of a transformer or of transformers effectively changing the ratio of the two line impedances by an approximately constant factor which can be given any desired value by suitable choice of the transformer ratio or ratios. For, when transformers having impedance-ratios  $\lambda_1$  and



$\lambda_2$  are interposed between the compensator and  $K_2$  to  $\lambda_1 K_1$  and  $\lambda_2 K_2$  respectively, the and lines 1 and 2 respectively their effect on design equations (23) and (26) thus be- the design-formulas is merely to change  $K_1$  coming

$$Z_1 = \sqrt{\lambda_1 K_1 (\lambda_1 K_1 - \lambda_2 K_2)} = \lambda_1 K_1 \sqrt{1 - \frac{\lambda_2}{\lambda_1} \frac{K_2}{K_1}} \quad (27)$$

$$Z_2 = \lambda_2 K_2 \sqrt{\frac{\lambda_1 K_1}{\lambda_1 K_1 - \lambda_2 K_2}} = \lambda_2 K_2 / \sqrt{1 - \frac{\lambda_2}{\lambda_1} \frac{K_2}{K_1}} \quad (28)$$

10 In passing, it should be noted, from (27) and (28), that  $Z_1$  and  $Z_2$  are related to each other in the simple manner expressed by the equation

$$15 \quad Z_1 Z_2 = \lambda_1 \lambda_2 K_1 K_2 \quad (29)$$

This relation is useful in showing how the design of either branch of the compensator fixes the design of the remaining branch. The equations (27) and (28) show by their second forms that two transformers will accomplish no more than one, in facilitating the design; but the use of two imparts greater symmetry to the system and to the design equations and hence may be advantageously assumed in an exposition of the design theory. The omission of either transformer is equivalent to retaining it but with its ratio chosen equal to unity. Thus the design work for the two branches is somewhat tentative in its nature and is most advantageously carried on for them simultaneously or at least by short alternate stages; for any tentative choice of the transformer ratios  $\lambda_1$  and  $\lambda_2$  fixes immediately the corresponding tentative values of  $Z_1$  and  $Z_2$ .

To indicate the design procedure we shall outline first the design of the series branch of the compensator. The design of this branch must be such that its impedance  $Z_1$  will have approximately the value expressed by the general design formula (27). A little consideration shows that in most instances the networks described in my above cited article in the Bell System Technical Journal will admit of the requisite proportioning, at least when supplemented by transformers having suitably chosen ratios. For  $\lambda_1 K_1 - \lambda_2 K_2$ , in the first form of equation (27), can be made to vary with frequency in at least roughly the same way as the impedance of a smooth line; and then the geometric means of  $\lambda_1 K_1$  and  $\lambda_1 K_1 - \lambda_2 K_2$  will likewise vary in about that manner. This may be further explained in connection with Fig. 8: Here the resistance components  $D_1$  and  $D_2$  and the reactance components  $X_1$  and  $X_2$  of  $K_1$  and  $K_2$  are plotted as functions of the frequency,  $K_1$  and  $K_2$  being the characteristic impedances of two smooth lines such as may be regarded as fairly representative. Likewise the components of  $K_1 - K_2$  are plotted in the curves marked  $D_1 - D_2$  and  $X_1 - X_2$ . It will be seen that the curve of  $D_1 - D_2$  is of the same character as the curves of  $D_1$  and

$D_2$ , and that the curve of  $X_1 - X_2$  is of the same character as the curves of  $X_1$  and  $X_2$ ; and hence the same general type of networks shown in the Bell System Technical Journal article for simulating the impedance or the excess impedance of smooth lines can simulate the difference of the impedance of two smooth lines. In a case where the difference curves  $D_1 - D_2$  and  $X_1 - X_2$  are not of suitable form and relation they can usually be made so by the interposition of transformers having suitably chosen ratios  $\lambda_1$  and  $\lambda_2$ , the difference curves then being drawn to represent  $\lambda_1 D_1 - \lambda_2 D_2$  and  $\lambda_1 X_1 - \lambda_2 X_2$ . From these considerations it follows that the same general type of networks will serve for simulating

$$\sqrt{\lambda_1 K_1 (\lambda_1 K_1 - \lambda_2 K_2)},$$

in equation (27); in other words  $Z_1$  can be realized as a combination like that shown in Fig. 9, where  $F_1$  is a resistance and  $J_1$  is an excess simulator for which the principles of design are given in my above cited article in the Bell System Technical Journal.

Consider next the shunt branch of the compensator. The requisite value for its impedance  $Z_2$  corresponding to the design of the impedance  $Z_1$  is fixed by  $Z_1$  in accordance with equation (29)—or, what is equivalent, by equation (28), since  $\lambda_1$  and  $\lambda_2$  have been fixed in the design of  $Z_1$ . If this requisite value of  $Z_2$  cannot be realized it will be necessary to choose somewhat different values for  $\lambda_1$  and  $\lambda_2$  and repeat the design procedure.

In any case where none of the networks in my above cited article in the Bell System Technical Journal admits of the requisite proportioning, the design-formulas (27) and (28) will still serve as the basis for arriving at suitable forms and designs of networks for constituting the series and shunt branches of the compensator. The design-formulas may also lead to alternative forms and designs of networks, thereby admitting transformers having other ratios or even obviating a need for transformers.

For the case where no transformers are employed equations (23) and (26) show that  $Z_1$  and  $Z_2$  will vary at least roughly in the same way as the impedances of smooth lines provided that  $K_1 - K_2$  varies at least roughly as  $K_1$  or as  $K_2$ ; or as some intermediate value, such as the average of  $K_1$  and  $K_2$  for example.



In certain cases, if no transformers are used,  $K_1 - K_2$  may have such large negative values that the angle of  $Z_2$  will be positive over a considerable frequency range; for certain of such cases it will suffice to employ for  $Z_2$  a 6-element network consisting of the series combination of a resistance  $R_3$ , inductance  $L_3$ , capacity  $C_3$  placed in series with the parallel combination of a resistance  $R_4$ , inductance  $L_4$ , capacity  $C_4$ —as represented by Fig. 10. However, by the use of a transformer the need for any such special network can usually be obviated.

The lines 1' and 2 in Fig. 5 are compensated both ways. Connecting them together and looking into the compensator ( $Z_1, Z_2$ ) on the side of line 1, the impedance is  $K_1$ , the same as of the line on that side; and looking into the compensator on the side of the line 2, the impedance is  $K_2$ , the same as of the line on that side. It is assumed that the relative magnitudes of  $K_1$  and  $K_2$  are such that the series element  $Z_1$  will properly go on that side of the shunt element  $Z_2$  toward line 1, but in some cases  $Z_1$  will properly go on the side of  $Z_2$  toward line 2.

In some cases it will not be necessary to compensate the impedance both ways, one-way compensation sufficing. This is so, for example, when there is no repeater in one of the lines, or when the repeater, if any, in that line is electrically remote from the junction of the two lines. For example, in Fig. 5 the line 4 may be compensated to the line 1' by means of a transformer, and an excess impedance simulator  $J_4$ , it being assumed that the line 4 has relatively small excess impedance compared to the line 1'. The line 1' will not be compensated thereby to the line 4, and hence incoming currents on the line 4 will be partially reflected at  $J_4$ ; but if the distance out to the first repeater on line 4 is great the attenuation of the reflected wave may be sufficient so that the disturbance caused thereby to the repeater will not be serious. In almost any extensive system one-way compensation suffices at many of the junction points. In particular, at the junction of a line and a substation set, one-way compensation usually suffices (though for antiside tone sets two-way compensation is desirable).

It appears desirable to outline here the limitations and the possibilities of one-way impedance compensators:

In general, a series branch  $Z_1$  alone or a shunt branch  $Y_2$  alone can accomplish only one-way compensation; and, indeed, it increases the irregularity for the other direction. These facts are most readily seen in the case of two smooth lines,  $K_1$  and  $K_2$ . For instance, if a series impedance

$$Z = K_1 - K_2$$

is connected between them line No. 1 will

be properly terminated, with the impedance  $Z + K_2 = K_1$ ; but line No. 2 will be terminated with the impedance  $Z + K_1 = 2K_1 - K_2$ , instead of with the proper impedance  $K_2$ , and hence will be afflicted with an impedance-irregularity

$$(Z + K_1) - K_2 = 2(K_1 - K_2) -$$

which is twice what the irregularity in that direction would have been if  $Z = K_1 - K_2$  had not been inserted at all. Thus the series impedance  $Z = K_1 - K_2$  leave the difference between the two impedance-departures unchanged, while eliminating one of them. For the shunt type of compensator the statements are the same, if expressed in terms of admittances instead of impedances. Thus, if the admittances of lines No. 1 and No. 2 are  $H_1$  and  $H_2$  respectively, and if a shunt admittance  $Y = H_1 - H_2$  is connected between them, line No. 1 will be properly terminated, but line No. 2 will be afflicted with an admittance departure equal to  $2(H_1 - H_2)$ .

As to whether the series type or the shunt type of one-way compensator would be chosen depends, in any particular case, on the relative magnitudes of the two line-impedances  $K_1$  and  $K_2$ , and on the direction chosen for the compensation. The series type enables the line of larger impedance to be properly terminated; the shunt type, the line of smaller impedance, that is, larger admittance. (Since the line-impedances are, in general, complex, these statements are only roughly indicative, for evidently they can have a precise significance only when the two line-impedances have the same phase-angle.) The interposition of a transformer, of suitable ratio, between either line and the compensator will enable either the series type or the shunt type of compensator to be chosen, as may be desired; moreover the employment of the transformer may facilitate the design of the compensator.

When regarded from a sufficiently fundamental viewpoint, a one-way compensator can logically be regarded as a limiting form of the two-way compensator. This is so if we go back to the fundamental implicit equations (1) and (2), whose solution yielded the explicit design equations (16), (17), (23), (24), (25), (26); for it is seen that equations (1) and (2) include the two types of one-way compensators, namely series impedance  $Z_1$  and shunt admittance  $Y_2$  (or impedance  $Z_2$ ), by setting  $Y_2 = 0$  and  $Z_1 = 0$  respectively. For instance, by setting  $Y_2 = 0$  in (1) and (2) we get the equations of the series type of one-way compensator, namely—

$$S_1 = Z_1 + K_2 \text{ and } S_2 = Z_1 + K_1$$

Clearly it is impossible to choose  $Z_1$ , so as to satisfy both of these equations simultaneously for arbitrary preassigned values of  $S_1$  and  $S_2$ . In particular if we set  $S_1 = K_1$  and



assign to  $Z_1$  the value  $K_1 - K_2$  so as to satisfy the first equation, namely  $S_1 = Z_1 + K_2$ , then the second equation shows that  $S_2 = 2K_1 - K_2$  whence the departure  $S_2 - K_2$  is equal not to zero but to  $2(K_1 - K_2)$  which moreover is twice what it would be if the compensator ( $Z_1$ ) were not present at all. These conclusions reached from regarding the one-way compensator as a limiting case of a two-way

are seen to agree with those reached otherwise above. Similarly the one-way compensator consisting of the shunt admittance  $Y_2$  can logically be regarded as a limiting case of the two-way compensator ( $Z_1, Y_2$ ).

Line 5 of Fig. 5 is a loaded line entering the station at midsection in accordance with the common practice, which is to bring a loaded line into the station either with a half section next the station, or an entire section, in the latter case a half load being placed at the station end of the section (as shown for line 6).

In accordance with the principles disclosed in my U. S. Patent No. 1,243,066, granted October 16, 1917, the loaded line 5 is built out by means of a condenser  $C_5$ , so that the terminal half section and the condenser together are equivalent to about 0.8 section, while a reactance neutralizer  $XN_5$  is placed in series, as shown in the drawing, and with its design fixed according to the principles of the patent just referred to. Looking into the loaded line through the reactance neutralizer  $XN_5$ , the impedance is approximately that of a smooth line, over the available useful frequency range of the loaded line; and looking the opposite way into an appropriate smooth line through the reactance neutralizer (now functioning as a supplemental reactance) the impedance would be approximately equal to that of a loaded line terminating at 0.2-section; thus the reactance neutralizer is a two-way compensator, but functioning mainly at the higher frequencies. Next, to complete the two-way equalization, the series-shunt type of two-way compensator  $W_5$  is introduced, whose design is determined by the principles heretofore pointed out in this specification. A transformer  $T_5$  may be advantageous in certain instances.

In case the loaded line ends at mid-load, as for line 6 in Fig. 5, the coil  $L_6$  is added in series to build the load out to approximately 0.8 load and then a susceptance neutralizer  $SN_6$  is placed in shunt, as shown in the drawing. This procedure is in accordance with my Patent No. 1,475,997, granted December 4, 1923, in which is set forth the procedure for the design of susceptance neutralizers. Looking into the line 6 through the susceptance neutralizer  $SN_6$ , the impedance is substantially that of a smooth line over the variable frequency

range for the loaded line; looking the other way, the susceptance neutralizer functions as a supplemental susceptance. As for line 5, the two-way equalization is completed by means of the two-way compensator  $W_6$ . A transformer  $T_6$  may be advantageous in certain instances.

Several repeaters are shown at the left in Fig. 5. The first of these, designated  $P_1$ , is a 22-type repeater designed and built initially to fit between two lines, each having the characteristic impedance  $K_1$ . Evidently, its balancing networks should be designed to have the same impedance value  $K_1$  and accordingly in the drawing they are marked with that symbol.

The repeater  $P_2$ , looking in at its immediate terminals, has the passive impedance  $Q$ . To prevent reflection effects for currents coming to this repeater over the standard line a one-way compensator  $N_2$  is interposed, so that the impedance looking into the terminals of the compensator is  $K_1$ .

Obviously, the balancing networks for this repeater may be composite, each consisting of a part  $K_1$  to match the standard line and a part  $N_2$  to match the like designated one-way compensator that is introduced next to the outside terminals of the repeater.

In the case of the repeater designated  $P_3$ , the same passive impedance for the repeater per se is assumed, namely, the value  $Q$ . Recognizing the condition for efficiency that, external and internal impedance should be substantially conjugate, a two-way compensator  $N_3$  is introduced, designed to make the impedance looking into it toward the repeater the same as of the standard line, namely,  $K_1$ ; whereas, looking out from the repeater through the compensator  $N_3$ , the impedance is  $\bar{Q}$ , the conjugate of that looking the opposite way from the same point into the repeater.

Obviously, each of the balancing networks for the repeater  $P_3$  may be made in two parts, one part having the impedance  $K_1$  and the other part being a duplicate of the network  $N_3$ .

As shown for the repeater designated  $P_4$ , a two-way compensator  $N_4$  is introduced such that the impedance looking through it in opposite directions on each side is  $K_1$  in both cases. Accordingly, the balancing network is made to have the impedance value  $K_1$ .

The repeater  $P_5$  is assumed to have a balancing network designed for some other line than the standard line whose impedance is  $K_1$ . Let the impedance of this balancing network be represented by the character  $U$ , as shown. Interposing a suitable one-way impedance condenser  $N_5$ , it will be seen that the repeater networks are now properly



balanced against the standard line, and thereby the repeater  $P_5$  is reduced to the case presented by the repeater  $P_1$  already considered.

5 The repeater  $P_6$  is also supposed to have the same balancing network of impedance value  $U$ , and in this case the compensation is effected by means of the two-way compensators  $N_6$ , each on the line side of the re-  
 10 spective transformer, and giving the impedance value  $K_1$  looking through the compensator into the repeater and the impedance value  $U$  when looking through the compensator into the standard line.

15  $P_7$  is a 21-type repeater. As is well known, the first condition for proper operation of a 21-type repeater having unity impedance-ratio is that it shall be connected between lines of equal characteristic im-  
 20 pedance. Since all the lines entering the station are equalized to a certain standard line, it is obvious that this condition has been met and that the 21-type repeater  $P_7$  may suitably be connected between any two of the  
 25 lines. However, for some reason, perhaps for more efficient operation, it may be desirable to interpose compensators  $N_7$  and in that case it may be desirable to design them so that the impedance looking into the re-  
 30 peater through a compensator will be the same as of the standard line, that is,  $K_1$ . If it seems desirable, these compensators may be one-way compensators or they may be two-way compensators and in the latter  
 35 case they may be constructed to give any suitable desired value for the impedance looking through them into the standard line.

This impedance may be  $Q$ , the conjugate to the impedance of the repeater per se on the  
 40 same principle as discussed for repeater  $P_3$ .

The line 7, shown at the lower right-hand part of Fig. 5, is a four-wire line entering the station, one of its transmission pairs being for signals one way and the other for  
 45 signals the other way. The usual three-winding transformer is shown at the station end. As is well understood, a four-wire system is equivalent to a 22-type repeater with its symmetrical parts drawn wide apart  
 50 in a geographical sense, and it will be evident from the drawings that the line 7 and the associated parts correspond closely to one-half of the repeater  $P_2$  or  $P_3$ . The networks shown correspond, each to each, with  
 55 those shown for repeater  $P_2$  or  $P_3$ , according as one-way compensation or two-way compensation is desired.

It will be seen that for a plurality of lines of a wide variety of kinds and for a plural-  
 60 ity of repeaters of widely different character I have shown how to equalize all the lines and all the repeaters to a single definite impedance value, so that any line can be connected with any other line or any two  
 65 lines can be connected through any repeater

without introducing objectionable reflection effects due to impedance inequalities at the junction points.

I claim:

1. A plurality of lines of diverse characteristic impedance extending from a common station, and respective means for equalizing, the impedances to a definite function of frequency over the useful frequency range of the line. 70 75

2. A plurality of lines of diverse impedance extending from a station, some of them being loaded lines, means to equalize the loaded lines to smooth lines, means further to equalize all the lines to a standard smooth  
 80 line, a plurality of repeaters at said station and means to equalize said repeaters to said standard smooth line whereby any two lines can be connected directly or through any re-  
 85 peater without reflection effects.

3. A plurality of lines of diverse characteristic impedance extending from a common station, interposed impedance compensators at the station, and interposed transformers at the station, all designed to equalize the  
 90 lines to a certain standard line.

4. A plurality of lines of diverse impedance extending from a common station, respective means for equalizing their impedances to that of a standard smooth line, a  
 95 plurality of repeaters at said station, and impedance compensators interposed in the terminals of said repeaters, whereby all the repeaters have their impedance equalized to the said standard and therefore to the said  
 100 lines that extend from the station.

5. In combination, two impedance constituents and an interposed impedance compensator between them, said compensator having  
 105 respective impedances looking into it on each side which are complementary to the impedances of the constituents looking away from the compensator.

6. In combination, two impedance constituents and an impedance compensator interposed between them, said compensator comprising a series impedance and a shunt im-  
 110 pedance and said compensator having pre-assigned impedance values respectively when looking into the compensator on both sides  
 115 thereof.

7. In combination, a transmission line, an impedance compensator of series-shunt type, a transformer connecting them, and an impedance constituent connected on the  
 120 other side of the compensator, the transformer ratio being so chosen as to facilitate the design of said impedance compensator, and said compensator being designed to  
 125 equalize the impedances looking both ways on each side thereof.

8. In combination, a plurality of transmission lines and respective impedance compensators connected therewith, a standard line, the impedances looking both ways at a  
 130



point between each compensator and its line being equalized and the impedances looking both ways at a point on the other side of each compensator being equalized to  
 5 said certain standard line.

9. In combination, two lines of respective characteristic impedances  $K_1$  and  $K_2$  and an impedance compensator between them comprising a series element of impedance  $Z_1$   
 10 and a shunt element of impedance  $Z_2$ , subject to the relations expressed in the equations

$$Z_1 = \sqrt{K_1(K_1 - K_2)} = K_1 \sqrt{1 - K_2/K_1}$$

15 and

$$Z_2 = \frac{K_2}{\sqrt{1 - K_2/K_1}} = K_2 \sqrt{\frac{K_1}{K_1 - K_2}}$$

10. In combination, two impedance constituents respectively of impedance  $K_1$  and  
 20 admittance  $H_2$  and an impedance compensator between them comprising a series ele-

ment of impedance  $Z_1$  and a shunt element of admittance  $Y_2$ , subject to the relations

$$Z_1/K_1 = A_1 - 1 + A_1 \sqrt{1 - r/A_1 B_2}$$

25

and

$$Y_2/H_2 = B_2 - 1 + B_2 \sqrt{1 - r/A_1 B_2}$$

so that the impedances looking into the com- 30  
 pensator on each side shall have respective preassigned values  $S_1$  and  $1/T_2$ , and with the understanding that

$$\begin{aligned} A_1 &= (S_1 + K_1)/2K_1 \\ B_2 &= (T_2 + H_2)/2H_2 \\ S_1 &= Z_1 + 1/(Y_2 + H_2) \\ T_2 &= Y_2 + 1/(Z_1 + K_1) \end{aligned}$$

35

and

$$r = K_1 H_2.$$

In testimony whereof, I have signed my 40  
 name to this specification this 29th day of  
 January, 1924.

RAY S. HOYT.