K. S. JOHNSON.

SIGNALING CIRCUITS.

APPLICATION FILED JAN. 4, 1918.

1,396,760.

Patented Nov. 15, 1921.

Fig. 1.

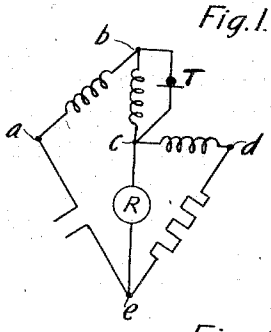


Fig. 5.

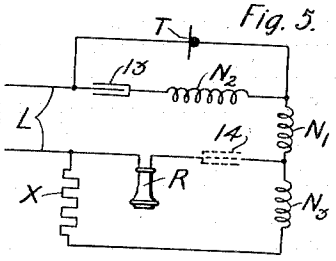


Fig. 2.

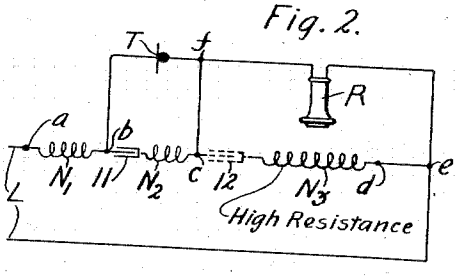


Fig. 6.

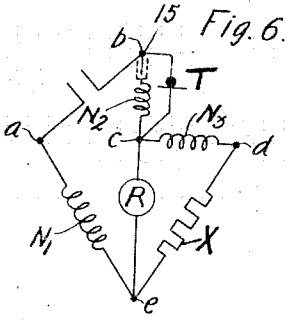


Fig. 3

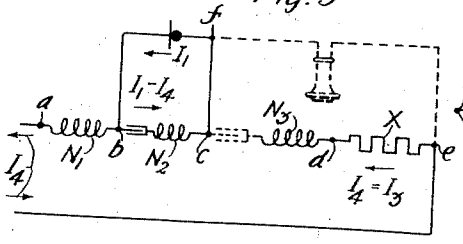


Fig. 7.

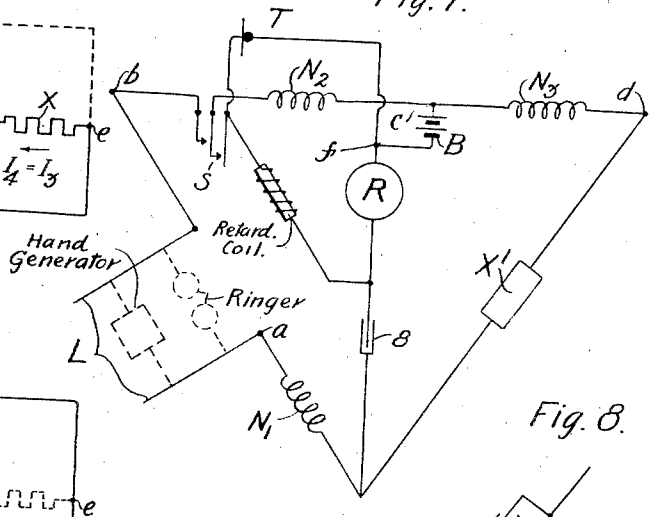


Fig. 4.

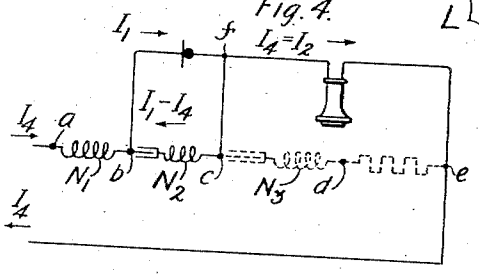
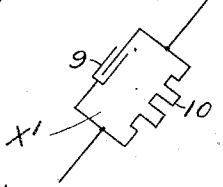


Fig. 8.



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UNITED STATES PATENT OFFICE.

KENNETH S. JOHNSON, OF JERSEY CITY, NEW JERSEY, ASSIGNOR TO WESTERN ELECTRIC COMPANY, INCORPORATED, OF NEW YORK, N. Y., A CORPORATION OF NEW YORK.

SIGNALING-CIRCUIT.

1,396,760. Specification of Letters Patent. Patented Nov. 15, 1921.

Application filed January 4, 1918. Serial No. 210,265.

To all whom it may concern:

Be it known that I, KENNETH S. JOHNSON, a citizen of the United States, residing at Jersey City, in the county of Hudson, State of New Jersey, have invented certain new and useful Improvements in Signaling-Circuits, of which the following is a full, clear, concise, and exact description.

This invention relates to circuit arrangements for signaling systems wherein signals may be either transmitted from or received at the same station. In its more specific aspects, this invention is embodied in a subscriber's telephone station, hereinafter termed, in accordance with common usage, a substation, and more particularly in the combination of a substation and a telephone line. Its object is to provide a signaling circuit arrangement which, in coöperative combination with a similar and equal communicating arrangement or station, shall deliver the maximum amount of energy to the receiving apparatus of said communicating station or arrangement. A further object is to provide an arrangement such that the receiving apparatus is protected from interference by the transmission energy originating at the same station.

The particular substations herein illustrated are modifications of a general type described in a U. S. patent of George A. Campbell, No. 1,254,472, dated January 22, 1918, and are closely related to the form shown in Fig. 1 (a) of the said patent.

The object of the invention is attained, in its specific aspect, by providing a substation consisting of transmitter, receiver, a balancing network consisting in the simplest form of an auxiliary resistance, and a transformer having a plurality of windings which, in combination with a telephone line, shall satisfy the following fundamental requirement: Given two identical substations designed for invariable two-way communication, and connected by a line of given impedance, the amount of energy absorbed by the receiver at the receiving station shall be the maximum part of the total telephonic energy developed by the transmitter at the transmitting station consisent with invariable two-way communication, and as hereinafter explained, consistent with a desirable amount of discrimination against disturbing line noise. This fundamental requirement may be stated in terms of the following subordinate requirements which are necessary for its satisfaction: (1) the transmitter and receiver shall be conjugate, that is, there shall be negligible side tone in the receiver in consequence of the actuation of the transmitter by sound waves; (2) the line and auxiliary resistance shall be conjugate in order that a negligible amount of the energy absorbed by the substation from the line shall be wasted in said auxiliary resistance; (3) for a given line having a definite impedance, the telephonic energy delivered by the transmitter shall be a maximum; (4) the amount of energy delivered by the line to the substation shall be a maximum, in other words, the impedance of the substation as seen from the line shall be numerically equal to the impedance of the line; (5) at a small sacrifice of efficiency it shall be possible to discriminate effectively against disturbing line noise as distinguished from the telephonic signals from the communicating station.

A substation satisfying the above-mentioned requirements is ideal in that its over-all efficiency from transmitter of one substation to receiver of the communicating substation is a theoretical maximum which cannot be exceeded by any two similar invariable substations whether satisfying the requirement of transmitter and receiver conjugacy or not. It is further ideal in the sense that a minimum number of elements is employed, since at least one auxiliary element is necessary to secure freedom from side tone.

It might be inferred that the addition of an auxiliary resistance element, necessary as it is to secure freedom from side tone, would at the same time necessarily reduce the efficiency of the substation since energy is unavoidably wasted in said auxiliary resistance. That this is not the case and that the efficiency of the substation of my invention is a theoretical maximum which cannot be exceeded by any two-way substation whether with or without side tone, the following considerations will show.

The simplest form of substation for invariable two-way communication is that in which the receiver and transmitter are connected in series with each other across the line. In such an arrangement, the over-all efficiency is a maximum when the resistances of the receiver and transmitter are each equal to one-half the resistance of the line, assuming that the total reactances in

the circuit are negligible. When this condition is satisfied, obviously, on receiving, fifty percentum of the energy delivered by the line to the substation enters the receiver, and on transmitting an amount of energy equivalent to fifty percentum of the maximum energy which can be delivered by the transmitter, enters the line. However, such an arrangement labors under the disadvantage of full side tone. In the substation of this invention, fifty percentum of the energy delivered by the line to the substation enters the receiver when no discrimination against line noise is made, and none enters the auxiliary resistance, since the said auxiliary resistance and said line are conjugate; hence ,the receiving efficiency is as great as that of the simple series substation. When transmitting, fifty percentum of the energy delivered by the transmitter, now delivering its maximum power, enters the line. The remainder of the energy is wasted in the auxiliary resistance since none is lost in the receiver. The transmitting efficiency is therefore also a theoretical maximum and neither transmitting nor receiving efficiency is reduced by the addition of the auxiliary resistance which is necessary to secure freedom from side tone. The foregoing consideration will serve to explain the desirability of having the line and auxiliary resistance conjugate as well as the transmitter and receiver.

In my present invention, I provide a substation comprising transmitter, receiver, auxiliary resistance and transformer, and so proportion said component elements and so relate them to a telephone line and to each other that, in combination with said telephone line, said substation satisfies all of the foregoing requirements.

This invention is illustrated in the accompanying drawings, in which Figure 1 is a schematic diagram of the invention in its fundamental form; Fig. 2 shows the circuit of Fig. 1 in greater detail; Figs. 3 and 4 are diagrams showing the relative direction of current flow during transmission and reception, respectively; Figs. 5 and 6 are forms of the invention which are assumed by it upon mechanical rearrangement of the elements for practical reasons; Fig. 7 is an arrangement of a substation fundamentally like that of Fig. 6 but modified for practical reasons; and Fig. 8 is a diagram of the elements of the balancing network used in the substation of Fig. 7 when that substation is used on an unloaded line having considerable distributed capacity.

It will be clear from an inspection of the design formulæ hereinafter set forth that the winding ratios r and r' may, in general, be either positive or negative, depending upon the values of the line and transmitter resistances. If, therefore, one or both of the winding ratios results in a negative value, it is to be interpreted as meaning that the relative direction of winding of the coils whose winding ratio is negative must be the reverse of that shown in the diagram. Positive values should in general be used in practice.

In order to illustrate the scope of my invention and elucidate the principles on which all specific embodiments rest, a general theoretical discussion will now be given which applies to all substations satisfying the requirements heretofore stated in this specification. In this discussion and the equations and formulæ included in this specification, the subscripts 1, 2, 3 and 4 will refer to transmitter, receiver, auxiliary resistance and line, respectively. Thus I_1, I_2, I_3, I_4 will denote the currents flowing in transmitter, receiver, auxiliary resistance and line respectively, while R_1 will denote the resistance of the transmitter, R_2, the resistance of the receiver, etc.

Consider a substation consisting of transmitter, receiver, auxiliary resistance and appropriate transformer windings, connected to a line of given impedance. The line usually connects two similar and equal substations between which communication is established. It is a well-known principle that if a terminal impedance is connected to a source of electromotive force through a line of impedance $Z=R_4+iR'_4$, where R_4 is the resistance and R'_4, the reactance component of the impedance, the terminal impedance must be $R_4-iR'_4$ for maximum absorption of energy. In particular, if the line impedance has no reactance component, the impedance of the terminal arrangement as seen from the line should be equal to the resistance of the line. The condition, then, that the substation shall have maximum energy absorption from the line is that its impedance, as seen from the line, shall be numerically equal to the effective line impedance. The significance of the foregoing statement may be explained by reference to Fig. 2, as follows: Let the substation be disconnected from the line and let the impedance of the substation be measured across the terminals a and e. Then the impedance so measured shall be equal to the impedance of the line. With the line terminated at each end by a substation satisfying this condition, the line may be replaced, as regards transmission from either substation, by an element of resistance equal to that of the line. Any reactance effect which is in practice small, may be eliminated by neutralizing reactance, and may be ignored in this theoretical discussion. The condition, then, that the substation have maximum energy absorption from the line is that its impedance as seen from the line be a pure resistance of value equal to the effective resistance of the

line. This condition is evidently equivalent to the following requirement; let an electromotive force be impressed on the substation terminals through a resistance equal to the impedance of the line; then the energy consumed in the substation shall be equal to the energy consumed in said resistance.

Further, line and auxiliary resistance are conjugate by requirement (2) as hereinbefore stated, or in other words, the auxiliary resistance is connected to points of equal potential with respect to an electromotive force applied to the line terminals. Moreover, the impedance of the substation as seen from the line should be equal to the impedance of the line to the signaling impulses. Let, then, an electromotive force E_4 be impressed through a resistance R_4 on a substation whose transmitter and receiver resistances are R_1 and R_2 respectively, and let the resultant currents in line, transmitter and receiver be I_4, I_1 and I_2 respectively; the impedance across the substation terminals must be R_4 as seen from the line and the total resistance in series with E_4 is $2R_4$, and since the current in the line is I_4, it follows that

$$\frac{E_4}{2R_4}=I_4$$

The total energy consumed may then be expressed by the formula

$$(I_4)^2R_4+(I_1)^2R_1+(I_2)^2R_2=I_4E_4=\frac{(E_4)^2}{2R_4}$$

Since the energy consumed by the substation is equal to that consumed by the resistance R_4 and is therefore one-half of the total energy consumed, it follows that requirement (4) may be formulated by the following:

$$R_4(I_4)^2=(I_2)^2R_2+(I_1)^2R_1=\frac{(E_4)^2}{4R_4} \quad (1)$$

This equation states that the energy consumption in the resistance R_4 is equal to that in the substation, and that the substation is equivalent, as seen from the line, to a resistance of value R_4.

Similarly, if transmitter and receiver are conjugate the condition that the transmitter shall have its maximum output to line and auxiliary resistance may be formulated as follows: Let an electromotive force E_1 in the transmitter produce currents I_1, I_4, and I_3 in transmitter, line and auxiliary resistance. Then, for maximum output, it follows that

$$(I_1)^2R_1=(I_4)^2R_4+(I_3)^2R_3=\frac{(E_1)^2}{4R_1} \quad (2)$$

Equation (2) is the analogue of equation (1) and may be interpreted as follows by reference to Fig. 2. Let the transmitter be disconnected from the terminals b and c and let the impedance be measured across said terminals. Then if equation (2) is satisfied, the impedance so measured is equal to the impedance of the transmitter itself. In other words, the impedance of the combination as seen from the transmitter is equal to that of the transmitter itself.

As hereinafter shown for the particular embodiments of my invention equation (2) follows as a consequence of the conditions of double conjugacy and equation (1). Therefore, the foregoing four requirements impose but three restrictions on the substation.

To complete the general discussion it remains to consider the energy division between receiver and transmitter when receiving, and between line and auxiliary resistance when transmitting. Let W_o be the total amount of telephonic energy developed by the transmitter at the transmitting substation; then, by equation (2) $\frac{1}{2}W_o$ is the amount of energy delivered to line and auxiliary resistance. Let the amount of energy taken by the auxiliary resistance be x times that taken by the line, then the amount of energy taken by the line is

$$\tfrac{1}{2}W_o\frac{1}{(1+x)}$$

so that the transmitting efficiency is measured by

$$\frac{1}{(1+x)} \quad (3)$$

Of the total energy delivered to the receiving substation, let the transmitter absorb y times that absorbed by the receiver; then, the receiving efficiency is measured by

$$\frac{1}{(1+y)} \quad (4)$$

The over-all efficiency from transmitter of one station to receiver of communicating station is clearly proportional to the product of the transmitting efficiency and receiving efficiency; therefore, the over-all efficiency is by formulæ (3) and (4)

$$\left(\frac{1}{1+x}\right)\left(\frac{1}{1+y}\right)$$

If x and y were independent, clearly the over-all efficiency would be a maximum for $x=y=o$. For all substations embodying the principles of my invention it may be readily shown, however, that x and y are connected by the relation $xy=1$. Eliminating x from the above formula by means of this relation, the expression for the over-all efficiency becomes

$$\frac{y}{(1+y)^2} \quad (5)$$

In order to demonstrate the above state-

ment, namely that $xy=1$, designate the elements or branches T, R, X and L by 1, 2, 3 and 4, respectively, and let 1 and 2 be conjugate and also 3 and 4 be conjugate. Further it will be assumed for an electromotive force in branch 4, equation (1) is satisfied, while for an electromotive force in branch 1, equation (2) is satisfied. Let S_{11} denote the current produced in branch or element 1 by a unit electromotive force in branch 1, S_{12} the current produced in branch 2 by a unit electromotive force in branch 1, etc. Then, by the conjugacy of branches 1 and 2 and branches 3 and 4, it follows that

$$S_{12}=S_{34}=o$$

Also by equation (1)

$$(S_{44})^2R_4=(S_{42})^2R_2+(S_{41})^2R_1=\frac{1}{4R_4} \quad (1')$$

and by equation (2)

$$(S_{11})^2R_1=(S_{13})^2R_3+(S_{14})^2R_4=\frac{1}{4R_1} \quad (2')$$

Now it is a fundamental principle which is deducible from elementary algebra, that $S_{41}=S_{14}$. That is, the current set up in branch 1 by a unit electromotive force in branch 4, is equal to the current set up in branch 4 by a unit electromotive force in branch 1. Multiplying equation (1') by R_4 and equation (2') by R_1 and subtracting it follows that:

$$(S_{42})^2R_2R_4=(S_{13})^2R_1R_3 \quad (a)$$

Now in accordance with the notation adopted in this specification, the energy consumed in branch 3 is x times that consumed in branch 4 when an electromotive force acts in branch 1; therefore

$$(S_{13})^2R_3=x(S_{14})^2R_4 \quad (b)$$

Also the energy consumed in branch 1 is y times that consumed in branch 2 when an electromotive force acts in branch 4; whence

$$(S_{14})^2R_1=y(S_{24})^2R_2 \quad (c)$$

Multiplying (b) and (c)

$$(S_{13})^2R_1R_3=xy(S_{24})^2R_2R_4 \quad (d)$$

From (a) and (d) it follows at once that $xy=1$.

Obviously the expression given by formula (5) is a maximum when $y=1$. This means that for a given amount of telephonic energy developed in the transmitter at the transmitting substation a maximum amount is usefully delivered to the receiver at the receiving substation connected by the line, when $y=1$. Since the maximum amount of energy in the receiver is the prime desideratum of telephony, it would appear that the substation should be designed to make $y=1$. Another consideration, however, modifies this conclusion somewhat, namely, the effect of line noise. Since the line noise originates in the line the amount delivered to the receiver is proportional to

$$\frac{1}{1+y}$$

(see equation 4) while the amount of energy delivered from the transmitter of the communicating station is proportional to

$$\frac{y}{(1+y)^2}$$

(see equation 5). The ratio of the latter to the former is

$$\frac{y}{1+y},$$

and this increases as y increases beyond unity. It will be clear, then, that if y is made greater than unity, the substation discriminates against line noise as compared with the signals it is desired to receive. The amount of discrimination desired depends of course on the amount of line noise present. For conditions occurring in practice it has been found by experiment that a desirable value for y is 1.4. With this value of y, the over-all efficiency is reduced 2.8% below the maximum for $y=1$, while the receiving efficiency alone is reduced 16.6%. It is thus seen that a good degree of discrimination against line noise is obtained with a small loss in over-all efficiency.

The above considerations as to over-all efficiency and discrimination against line noise may be formulated as

$$R_1(I_1)^2=yR_2(I_2)^2 \quad (6)$$

for an electromotive force inserted in the line. In this equation y is to have a value lying between 1 and 1.5 preferably.

Proceeding now to a description of the specific circuits, one form of my invention is illustrated in Fig. 2, in which L represents a telephone line terminating in a substation comprising a transmitter T, a receiver R, and an induction coil comprising windings N_1, N_2, and N_3. Windings N_1 and N_2 are of negligible resistance, but winding N_3 is of high resistance in order to balance the line L. The windings N_1, N_2 and N_3 are connected in series with the line L, while the transmitter T is connected to terminals b and c so as to shunt the winding N_2 and receiver R is connected to terminals c and a so as to shunt the high resistance winding N_3. If desired, the high resistance winding N_3 may be replaced by a winding N_3 of negligible resistance and a separate resistance element X as shown in Figs. 3 and 4. Condensers 11 and 12 may be inserted as indicated in order to determine the path of the direct current through the substation. Condenser 11 will cause direct current to

flow through the transmitter T, and the condenser 12, if used, will also cause all the direct current to flow through the receiver. Direct current from the line will flow through the winding N_1 to terminal b, through the transmitter T, receiver R, terminal e and back over the line.

The operation during transmission is indicated in Fig. 3, in which the arrows represent the direction of current flow at any given instant. When the transmitter T is operated, variations in the current flow are produced, the effect being equivalent to applying a variable electromotive force to the transmitter. At a given instant, a current I_1 flows from the terminal c through the transmitter to terminal b. At terminal b, the current divides and a current I_4 equal to I_3 flows through the winding N_1 over the line L, through the resistance X and winding N_3 to terminal c, while a current $I_1—I_4$ flows in parallel therewith through the winding N_2. Potentials are induced in the windings of the transformer of such value and direction that terminals c and e are brought to the same potential, so that no current flows through the receiver during transmission and consequently the substation is anti-side tone.

The action during reception is indicated in Fig. 4 and is as follows: Upon the application of a receiving potential to the line terminals, since no current flows through the auxiliary resistance, the line and receiver are in a series circuit and a current I_2 equal to I_4 flows from terminal f, through the receiver to terminal e, over the line L and through the winding N_1 to terminal b. From terminal b a current I_1 flows through the transmitter to terminal f. The transmitter current is greater than the line current and consequently a current $I_1—I_4$ flows from terminal c, through the winding N_2 to terminal b. Potentials are induced in the transformer windings of such value and direction that terminals d and e are brought to the same potential, so that no energy is wasted in the auxiliary resistance during reception.

The proportioning of the arrangement of Fig. 2, to satisfy the fundamental requirements of the substation of the invention will now be given. In deriving the design formulæ, the resistances of the transformer windings will be ignored. It will be assumed further that there is no magnetic leakage between the transformer windings and that the self-impedances are very large compared with the impedances of any of the component elements of the substation or the impedance of the line. Experience has shown that these simplifying assumptions are justified and that the assumed conditions may be closely realized in practice by careful design.

To formulate the condition of conjugacy of transmitter T and receiver R, assume an electromotive force in the transmitter circuit and assume that the required condition of conjugacy is satisfied. In other words, assume that the terminals of the receiver are at points of equal potential with respect to an electromotive force applied to the transmitter. Let I_1, I_2, I_3 and I_4 denote the currents flowing in the transmitter, the receiver, auxiliary resistance and line, respectively, and R_1, R_2, R_3 and R_4 denote the resistances of the corresponding elements. The condition of conjugacy of the receiver with respect to the transmitter requires that no current flow through the receiver during transmission and hence $I_2=o$. It is also clear from Fig. 3 that $I_3=I_4$. Since the auxiliary resistance, line and the three transformer windings are in a series circuit, the algebraic sum of the drops through the transformer windings and the IR drop of the line and auxiliary resistance is equal to zero. Remembering that $I_3=I_4$, this condition may be expressed as follows:

$$K(n_1+n_2+n_3)=(R_3+R_4)I_4$$

where K represents the drop per turn of the transformer windings. Furthermore, since terminals c and e are at the same potential, the algebraic sum of the drop through the winding N_3 and the IR drop through resistance X must equal zero. Whence

$$Kn_3=R_3I_3=R_3I_4$$

Solving these equations we have

$$\frac{R_3+R_4}{R_3}=\frac{n_1+n_2+n_3}{n_3}$$

which may be expressed

$$1+\frac{R_4}{R_3}=1+\frac{n_1+n_2}{n_3}$$

whence

$$R_3=\frac{n_3}{n_1+n_2}R_4 \quad (7)$$

Also the alegbraic sum of the ampere turns of the transformer windings must equal zero, so that

$$n_2(I_1—I_4)=(n_1+n_3)I_4$$

or

$$n_2I_1=(n_1+n_2+n_3)I_4$$

which reduces to

$$I_1=\left(\frac{n_1+n_2+n_3}{n_2}\right)I_4 \quad (8)$$

Referring now to Fig. 4 which shows the condition when receiving, since the transmitter and winding N_2 are in a series circuit, the algebraic sum of the IR drop through

the transmitter and the drop through the winding N_2 is equal to zero, so that

$$Kn_2=R_1I_1$$

Furthermore, since terminals d and e are at the same potential, the algebraic sum of the drop through the winding N_3 and the IR drop through the receiver equals zero. Remembering that $I_4=I_2$ during reception, the above condition may be expressed.

$$Kn_3=R_2I_2=R_2I_4$$

Also the algebraic sum of the ampere turns of the transformer windings equals zero, so that

$$n_1I_4=n_2(I_1-I_4)$$

From the above equations we get the following:

$$\left.\begin{aligned}&\frac{R_2}{R_1}\frac{I_4}{I_1}=\frac{n_3}{n_2}\\&n_2I_1=(n_1+n_2)I_4\\&\frac{R_2}{R_1}=\frac{n_3}{n_2}\frac{n_1+n_2}{n_2}\\&=\frac{n_3(n_1+n_2)}{n_2^2}\end{aligned}\right\}$$

whence

$$R_2=\frac{n_3(n_1+n_2)}{n_2^2}R_1 \quad (9)$$

$$I_2=I_4=\frac{n_2}{(n_1+n_2)}I_1 \quad (10)$$

Substituting the values given by equation (8) in equation (2), we have

$$\left(\frac{n_1+n_2+n_3}{n_2}\right)^2R_1=R_3+R_4 \quad (12)$$

Also substituting the values given by equation (10) in equation (6), we have

$$R_1=y\left(\frac{n_2}{n_1+n_2}\right)^2R_2 \quad (13)$$

Collecting formulæ we get

$$\left.\begin{aligned}&R_3=\left(\frac{n_3}{n_1+n_2}\right)R_4 \quad (a)\\&R_2=\frac{n_3(n_1+n_2)}{n_2^2}R_1 \quad (b)\\&\left(\frac{n_1+n_2+n_3}{n_2}\right)^2R_1=R_3+R_4 \quad (c)\\&R_1=y\left(\frac{n_2}{n_1+n_2}\right)^2R_2 \quad (d)\end{aligned}\right\}$$

From formulæ (b) and (d) it follows that

$$R_2=\frac{n_3(n_1+n_2)}{n_2^2}R_1=\frac{1}{y}\left(\frac{n_1+n_2}{n_2}\right)^2R_1$$

whence

$$n_3=\frac{1}{y}(n_1+n_2) \quad (14)$$

Also from equations (a) and (c) it follows that

$$R_3=\left(\frac{n_3}{n_1+n_2}\right)R_4=\left(\frac{n_1+n_2+n_3}{n_2}\right)^2R_1-R_4$$

whence

$$\frac{n_1+n_2+n_3}{n_1+n_2}R_4=\left(\frac{n_1+n_2+n_3}{n_2}\right)^2R_1$$

or

$$\frac{n_2^2}{(n_1+n_2)\,(n_1+n_2+n_3)}=\frac{R_1}{R_4} \quad (15)$$

Designating the ratios $\frac{n}{n_3}$ and $\frac{n_2}{n_3}$ as r and r' respectively, equations (14) and (15) may be written

$$\left.\begin{aligned}&r+r'=y\\&\frac{r'^2}{(r+r')\,(r+r'+1)}=\frac{R_1}{R_4}\end{aligned}\right\} \quad (16)$$

Solving equations (16) we have

$$\frac{r'^2}{y(y+1)}=\frac{R_1}{R_4}$$

or

$$r'=\pm\sqrt{\frac{R_1}{R_4}(1+y)y} \quad (17)$$

and

$$r=y\mp\sqrt{\frac{R_1}{R_4}(1+y)y} \quad (18)$$

Substituting r and r' in equation (d) we get the following:

$$\begin{aligned}R_2&=\frac{1}{y}\left(\frac{r+r'}{r'}\right)^2R_1\\&=\frac{1}{y}\,\frac{y^2}{\frac{R_1}{R_4}(1+y)y}R_1\\&=\frac{1}{1+y}R_4 \quad (19)\end{aligned}$$

Also substituting r and r' in equation (a)

$$R_3=\frac{1}{r+r'}R_4=\frac{1}{y}R_4 \quad (20)$$

The design formulæ for the substation of Fig. 2 then become

$$\left.\begin{aligned}&R_2=\frac{1}{1+y}R_4\\&R_3=\frac{1}{y}R_4\\&r=y\mp\sqrt{\frac{R_1}{R_4}y(1+y)}\\&r'=\pm\sqrt{\frac{R_1}{R_4}y(1+y)}\end{aligned}\right\} \quad (A)$$

It will be seen from the above formulæ that the impedances of the receiver and

auxiliary resistance are given in terms of the impedance of the line and ratio y. Also the transformer ratios r and r' are given in terms of the ratio y and the impedances of the line and transmitter. Consequently, the impedance of the line being known and having selected a suitable value for the impedance of the transmitter and the ratio y, the remaining elements of the substation may be readily computed.

Inspection of Figs. 1 to 4 inclusive, shows that there is a series arrangement of four components consisting of (1) line L, (2) winding N_1, (3) the mesh consisting of transmitter T and winding N_2 and (4) the mesh consisting of receiver R in parallel with winding N_3 and resistance X. Any rearrangement of parts which keeps those four components in series will be electrically equivalent. Fig. 5 is one example of rearrangement in which winding N_1 is placed between the two meshes, and Fig. 6 is another example in which the line L and winding N_1 are merely interchanged. Figs. 2 and 5 are particularly adapted for common battery substations and Fig. 6 is a suitable arrangement for a local battery substation, but may also be used as a common battery substation. The design formulæ above given are equally applicable to all of these several arrangements.

In Fig. 5, the condenser 13 will cause direct current from a common battery to pass through transmitter T. The condenser 14 may be used, if desired, to cause direct current to be shunted around the receiver R in case a permanent magnet receiver is used. If condenser 14 is not used, a part only of the direct current will pass through the receiver R. This will serve to magnetize the receiver in case a neutral receiver is used. A neutral receiver is one whose core consists of a soft iron core which is only magnetized while current is being supplied to the receiver. If the arrangement of Fig. 6 is used with a common battery system, the condenser 15 may be used.

The assumptions upon which the theory for the forms of substation above discussed is based, are that the impedances of the line and substation elements consist of pure resistance. In cases where greater exactness is required correction must be made for such departures from the assumed conditions as would reduce the operating efficiency below that required. Assuming a line of considerable distributed capacity or inductive reactance, then it becomes advisable to substitute for the pure resistance X, a balancing network, other than a non-inductive resistance, of such nature that its ratio of resistance and reactance components closely approximates, over the required range of voice current or signaling frequencies, the resistance and reactance components of the line in question. The manner of constructing many such networks is known in the art and reference is made for examples to the United States Patents of Hoyt 1,167,693; 1,167,694; 1,240,213. Necessarily, however, a substation which at one time is connected to a line of one length and at another to a line of another length, should be designed for the average sort of line with which it is to be used.

The substation in Fig. 7 is designed for use with a local battery. This circuit is identical in respect to the five fundamental properties mentioned in the beginning of this specification with that of Fig. 6. For securing greater efficiency, the inductive reactance of the receiver R is balanced by a condenser 8 in series therewith. X′ represents a balancing impedance means or network. Network X′ may be a resistance or have different forms depending upon the nature of the line, the maximum cost allowable, and the degree of exactness required. For a line having considerable distributed capacity such as submarine cable, a suitable form is shown in Fig. 8 and consists of a capacity 9 in parallel with a resistance 10. The elements are of such values that the characteristic impedance of the line is approximately simulated. In other words, if a voltage of signaling frequency be impressed upon the line and a similar voltage upon the network X′, the current will lead the voltage by an equal angle in the two cases while the ratio of the numerical values of the impedance of the line and the network depends upon the value of the energy ratio y, as expressed by the second of equations (A).

Certain auxiliary elements are used, which are battery B, a retardation coil, a three-point switchhook contact S, a ringer and a hand generator. The battery B supplies current to the transmitter T and receiver R. The retardation coil has a very large impedance to alternating current of voice frequency but allows the direct current to pass through to the receiver R. The effect of the retardation coil in shunting voice current is negligible. The usual three-point contact switchhook S is arranged to open the circuit of the battery B and also to cut off the substation from the line. The usual high impedance ringer and normally open circuit hand generator are bridged across the line as shown. Consideration will show that this circuit is fundamentally identical with that of Fig. 6. By eliminating the generator, ringer, switchhook contacts, retardation coil, battery B and condensers 8 and 9, the circuit reduces to the form of Fig. 6. Fig. 7 shows one only of many possible adaptations and modifications of the circuits of Figs. 1, 5 and 6 for practical application.

The type of substation disclosed above and illustrated in the accompanying drawings is but one of a number employing only one

transformer and one auxiliary resistance, and all of them are ideal in the sense that they satisfy the fundamental requirements for an ideal substation, as stated heretofore in this specification. The substations herein are of a type related to that of Figs. 1, 2, 3, 4 and 1 (*a*) of U. S. patent to George A. Campbell, No. 1,254,472, dated January 22, 1918, and to those substations disclosed in U. S. patent to George A. Campbell, No. 1,254,117, dated January 22, 1918.

The circuits disclosed in both of the said applications are hereby disclaimed as a part of this invention, which is an improvement on and extension of the work of Campbell. However, as there are a large number of possible substations of this general type which are not disclosed in the said applications, it will be understood that this invention is not limited to the specific embodiments herein illustrated, but is intended to include such equivalent arrangements as come within the scope of the appended claims. Furthermore, it is not desired to limit the design of the substations herein disclosed and illustrated to the accompanying design formulæ. These formulæ are derived on the assumption that ideal transformers are employed and that the component elements of the substation have no reactance, assumptions which are only approximately justified in practice. The formulæ may be modified when greater precision is desired by taking into account the fact that the transformer is not physically perfect and that the line and the various substation elements may in general have some characteristic reactance. The accompanying formulæ, however, give quite satisfactory results, and the methods by which they are derived will enable one skilled in the art to compute more precisely the substation constants when desired.

It will be understood that in the appended claims, where certain elements are said to be conjugate, or certain impedance relations are said to exist, since in practice these conditions can in general only be approximated, these expressions will be satisfied by structures substantially conforming thereto, especially where some compromise with respect to the rigid requirements is necessary in order to discriminate against line noise. It will also be understood that while my invention has been specifically illustrated and described as embodied in a telephone substation, it is capable of many and varied embodiments which render it applicable in other kinds of signaling systems and consequently the invention is not to be limited to the particular form and use herein disclosed. It will be further understood that in this specification the word "substation" is employed in its generic sense and that consequently its significance is not limited to a subscriber's telephone station but embraces broadly any telephone station including a repeater station for relaying telephonic signals.

What is claimed is:

1. A signaling circuit comprising a transformer, a path for the transmission and reception of signals, a path including a transmitting apparatus, a path of high resistance, and a receiver, said first and last mentioned paths and a winding of said transformer being included in a series circuit, said receiver being included in a path shunted about said high resistance path, said second mentioned path being included in a circuit shunted about said transformer winding, said last mentioned circuit, said receiver path and said high resistance path having a common terminal with respect to alternating signaling current.

2. A signaling circuit comprising a transformer, a path for the transmission and reception of signals, a path including a transmitting apparatus, a path of high resistance, and a receiver, said first and last mentioned paths and a winding of said transformer being included in a series circuit, said receiver being included in a path shunted about said high resistance path, said second mentioned path being included in a circuit shunted about said transformer winding; said last mentioned circuit, said receiver path and said high resistance path having a common terminal with respect to alternating signaling current, said elements being so proportioned and related that the impedance of the combination comprising said transformer, said first and third mentioned paths and said receiver, as seen from said second mentioned path, is equal to the impedance of said second mentioned path.

3. A signaling circuit comprising a transformer, a path for the transmission and reception of signals, a path including a transmitting apparatus, a path of high resistance, and a receiver, said first and last mentioned paths and a winding of said transformer being included in a series circuit, said receiver being included in a path shunted about said high resistance path, said second mentioned path being included in a circuit shunted about said transformer winding, said last mentioned circuit, said receiver path and said high resistance path having a common terminal with respect to alternating signaling current, said elements being so proportioned and related that the impedance of the combination comprising said transformer, said second and third mentioned paths and said receiver, as seen from said first mentioned path, is equal to the impedance of said first mentioned path.

4. A signaling circuit comprising a transformer, a path for the transmission and reception of signals, a path including a trans-

mitting apparatus, a path of high resistance, and a receiver, said first and last mentioned paths and a winding of said transformer being included in a series circuit, said receiver being included in a path shunted about said high resistance path, said second mentioned path being included in a circuit shunted about said transformer winding, said last mentioned circuit, said receiver path and said high resistance path having a common terminal with respect to alternating signaling current, said elements being so proportioned and related that said receiver and said second mentioned path are conjugate.

5. A signaling circuit comprising a transformer, a path for the transmission and reception of signals, a path including a transmitting apparatus, a path of high resistance, and a receiver, said first and last mentioned paths and a winding of said transformer being included in a series circuit, said receiver being included in a path shunted about said high resistance path, said second mentioned path being included in a circuit shunted about said transformer winding, said last mentioned circuit, said receiver path and said high resistance path having a common terminal with respect to alternating signaling current, said elements being so proportioned and related that said third and first mentioned paths are conjugate.

6. A signaling circuit comprising a transformer, a path for the transmission and reception of signals, a path including a transmitting apparatus, a path of high resistance, and a receiver, said first and last mentioned paths and a winding of said transformer being included in a series circuit, said receiver being included in a path shunted about said high resistance path, said second mentioned path being included in a circuit shunted about said transformer winding; said last mentioned circuit, said receiver path and said high resistance path having a common terminal with respect to alternating signaling current, said elements being so proportioned and related that the impedance of the combination comprising said transformer, said first and third mentioned paths and said receiver, as seen from said second mentioned path, is equal to the impedance of said second mentioned path, the impedance of the combination comprising said transformer, said second and third mentioned paths and said receiver, as seen from said first mentioned path, is equal to the impedance of said first mentioned path, said receiver and said second mentioned path are conjugate and said third and first mentioned paths are conjugate.

7. A signaling circuit including in series four components, the first of said components including a line, the second of said components including a transformer winding, the third of said components including a transformer winding and a source of transmitting voltage in parallel, and the fourth of said components including a receiving instrument in parallel with a balancing impedance means and a transformer winding in series, said windings having a common magnetic field.

8. A signaling circuit including in series four components, the first of said components including a line, the second of said components including a winding of a transformer, the third of said components including a second winding of said transformer and a transmitter in parallel, and the fourth of said components including a receiver in parallel with a series arrangement of balancing impedance means whose reactance approximately simulates the reactance of the line over the range of voice current frequencies, and a third winding of said transformer.

9. A telephone system adapted for use with a common battery system including in series four components, the first of said components including a line; the second of said components including a winding of a transformer; the third of said components including a transmitter in parallel with a path containing a second winding of said transformer; the fourth of said components including a receiver in parallel with a series arrangement of a balancing resistance means and a third winding of said transformer.

10. A signaling circuit including in series four components, the first of said components including a line; the second of said components including a winding of a transformer; the third of said components including a second winding of said transformer and a transmitter in parallel; and the fourth of said components including a receiver in parallel with a series arrangement of balancing impedance means and a third winding of said transformer, said elements being so proportioned that the impedance of said combination comprising said transformer, said line, said receiver and said impedance means, as seen from said transmitter, is equal to the impedance of said transmitter.

11. A signaling circuit including in series four components, the first of said components including a line; the second of said components including a winding of a transformer; the third of said components including a second winding of said transformer and a transmitter in parallel; and the fourth of said components including a receiver in parallel with a series arrangement of balancing impedance means and a third winding of said transformer, said elements being so proportioned that the impedance of the combination comprising said receiver, said transmitter, said transformer and said

impedance means when seen from the terminals of said line is equal to the effective impedance of said line.

12. A signaling circuit including in series four components, the first of said components including a line; the second of said components including a winding of a transformer; the third of said components including a second winding of said transformer and a transmitter in parallel; and the fourth of said components including a receiver in parallel with a series arrangement of balancing impedance means and a third winding of said transformer, said elements being so proportioned that said receiver and said transmitter are in conjugate branches of said circuit.

13. A signaling circuit including in series four components, the first of said components including a line, the second of said components including a winding of a transformer; the third of said components including a second winding of said transformer and a transmitter in parallel; and the fourth of said components including a receiver in parallel with a series arrangement of balancing impedance means and a third winding of said transformer, said elements being so proportioned that said line and said impedance means are in conjugate branches of said circuit.

14. A signaling circuit including in series four components, the first of said components including a line; the second of said components including a winding of a transformer; the third of said components including a second winding of said transformer and a transmitter in parallel; and the fourth of said components including a receiver in parallel with a series arrangement of balancing impedance means and a third winding of said transformer, said elements being so proportioned that the impedance of said combination comprising said transformer, said line, said receiver and said impedance means, as seen from said transmitter, is equal to the impedance of said transmitter; and the impedance of the combination comprising said receiver, said transmitter, said transformer and said impedance means when measured from the terminals of said line is equal to the effective impedance of said line; said receiver and said transmitter being in conjugate branches of said circuit; and said line and impedance means being in conjugate branches of said circuit.

15. A telephone circuit including in series four components, the first of said components including a line; the second of said components including a winding of a transformer; the third of said components including a second winding of said transformer and a transmitter in parallel; and a fourth of said components including a receiver in parallel with a series arrangement of balancing impedance means and a third winding of said transformer; a source of direct current, and means for directing a suitable current therefrom through each of said receiver and transmitter.

16. A telephone substation comprising a neutral receiver and a transmitter, said receiver and transmitter being located in conducting paths in parallel with each other with respect to a local source of direct electromotive force for energizing said instruments, said receiver and transmitter being effectively connected in series with respect to received telephonic currents.

17. A telephone substation including a neutral receiver and a transmitter which are in substantially conjugate branches, said substation having two points to which a local source of direct electromotive force may be connected, a complete conducting path from one of said points through said transmitter to the other of said points and another such path through said receiver, and a coil of large self inductance located in at least one of said paths.

18. A telephone substation including a neutral receiver and a transmitter, conducting paths in said substation through which a local source of direct electromotive force may propel current through each of said receiver and transmitter, one of said paths comprising means for retarding the flow of alternating current therethrough.

19. In a signaling system, a transmission circuit, a transmitting circuit, a receiving circuit, a balancing circuit, and a transformer having three windings, one of said windings being included in said transmission circuit, another of said windings being included in said balancing circuit, and the third winding being included between said transmission and balancing circuits; a terminal of said transmission circuit, said receiving circuit and said balancing circuit being joined together, the other terminal of said receiving circuit being connected between said third winding and the circuit including one of the other two windings; said transmitting circuit being connected in shunt with said third winding, and a source of direct current so connected as to supply current to both said transmitting and said receiving circuits.

20. In a signaling system, a transmission circuit, a transmitting circuit, a receiving circuit, a balancing circuit, and a transformer having three windings, one of said windings being included in said transmission circuit, another of said windings being included in said balancing circuit, and the third winding being included between said transmission and balancing circuits; a terminal of said transmission circuit, said receiving circuit and said balancing circuit being joined together, the other terminal

of said receiving circuit being connected between said third winding and the circuit including one of the other two windings; said transmitting circuit being connected in shunt with said third winding, and a source of direct current included in series with said third winding.

21. In a signaling system, a transmission circuit, a transmitting circuit, a receiving circuit, a balancing circuit, and a transformer having three windings, one of said windings being included in said transmission circuit, another of said windings being included in said balancing circuit, and the third winding being included between said transmission and balancing circuits; a terminal of said transmission circuit, said receiving circuit and said balancing circuit being joined together, the other terminal of said receiving circuit being connected between said third winding and the circuit including one of the other two windings; said transmitting circuit being connected in shunt with said third winding; and a source of direct current so connected as to supply current to both said transmitting and said receiving circuits, one terminal of said source being connected to said receiving circuit through a path of high impedance and low resistance.

22. In a signaling system, a transmission circuit, a transmitting circuit, a receiving circuit, a balancing circuit, and a transformer having three windings, one of said windings being included in said transmission circuit, another of said windings being included in said balancing circuit, and the third winding being included between said transmission and balancing circuits; a terminal of said transmission circuit, said receiving circuit and said balancing circuit being joined together, the other terminal of said receiving circuit being connected between said third winding and the circuit including one of the other two windings; said transmitting circuit being connected in shunt with said third winding; and a source of direct current included in series with said third winding, one terminal of said source being connected to said receiving circuit through a path of high impedance and low resistance.

23. In a signaling system, a transmission circuit, a transmitting circuit, a receiving circuit, a balancing circuit, and a transformer having three windings, one of said windings being included in said transmission circuit, another of said windings being included in said balancing circuit, and the third winding being included between said transmission and balancing circuit; a terminal of said transmission circuit, said receiving circuit and said balancing circuit being joined together, the other terminal of said receiving circuit being connected between said third winding and the circuit including one of the other two windings; said transmitting circuit being connected in shunt with said third winding; and a source of direct current so connected as to supply current to both said transmitting and said receiving circuits, one terminal of said source being connected to said receiving circuit at a point adjacent its junction with said transmission and balancing circuits through a path of high impedance and low resistance.

24. In a signaling system, a transmission circuit, a transmitting circuit, a receiving circuit, a balancing circuit, and a transformer having three windings, one of said windings being included in said transmission circuit, another of said windings being included in said balancing circuit, and the third winding being included between said transmission and balancing circuits; a terminal of said transmission circuit, said receiving circuit and said balancing circuit being joined together, the other terminal of said receiving circuit being connected between said third winding and the circuit including one of the other of two windings; said transmitting circuit being connected in shunt with said third winding; and a source of direct current included in series with said third winding, one terminal of said source being connected to said receiving circuit at a point adjacent its junction with said transmission and balancing circuits through a path of high impedance and low resistance.

25. In a signaling system, a transmission circuit, a transmitting circuit, a receiving circuit, a balancing circuit, and a transformer having three windings, one of said windings being included in said transmission circuit, another of said windings being included in said balancing circuit, and the third winding being included between said transmission and balancing circuits; a terminal of said transmission circuit, said receiving circuit and said balancing circuit being joined together, the other terminal of said receiving circuit being connected to the junction point between said third winding and said balancing circuit; said transmitting circuit being connected in shunt with said third winding, and a source of direct current so connected as to supply current to both said transmitting and receiving circuits.

26. In a signaling system, a transmission circuit, a transmitting circuit, a receiving circuit, a balancing circuit, and a transformer having three windings, one of said windings being included in said transmission circuit, another of said windings being included in said balancing circuit, and the third winding being included between said transmission and balancing circuits; a terminal of said transmission circuit, said receiv-

ing circuit and said balancing circuit being joined together, the other terminal of said receiving circuit being connected to the junction point between said third winding and said balancing circuit; said transmitting circuit being connected in shunt with said third winding, and a source of direct current included in series with said third winding.

27. In a signaling system, a transmission circuit, a transmitting circuit, a receiving circuit, a balancing circuit, and a transformer having three windings, one of said windings being included in said transmission circuit, another of said windings being included in said balancing circuit, and the third winding being included between said transmission and balancing circuits; a terminal of said transmission circuit, said receiving circuit and said balancing circuit being joined together, the other terminal of said receiving circuit being connected to the junction point between said third winding and said balancing circuit; said transmitting circuit being connected in shunt with said third winding; and a source of direct current so connected as to supply current to both said transmitting and receiving circuits, one terminal of said source being connected to said receiving circuit through a path having high impedance and low resistance.

28. In a signaling system, a transmission circuit, a transmitting circuit, a receiving circuit, a balancing circuit, and a transformer having three windings, one of said windings being included in said transmission circuit, another of said windings being included in said balancing circuit, and the third winding being included between said transmission and balancing circuits; a terminal of said transmission circuit, said receiving circuit and said balancing circuit being joined together, the other terminal of said receiving circuit being connected to the junction point between said third winding and said balancing circuit; said transmitting circuit being connected in shunt with said third winding; and a source of direct current included in series with said third winding, one terminal of said source being connected to said receiving circuit through said third winding and an inductance circuit.

29. In a signaling system, a transmission circuit, a transmitting circuit, a receiving circuit, a balancing circuit and a transformer having three windings, one of said windings being included in said transmission circuit, another of said windings being included in said balancing circuit, and the third winding being included between said transmission and balancing circuits; a terminal of said transmission circuit, said receiving circuit and said balancing circuit being joined together, the other terminal of said receiving circuit being connected to the junction point between said third winding and said balancing circuit; said transmitting circuit being connected in shunt with said third winding; a source of direct current so connected as to supply current to both said transmitting and receiving circuits; an inductance element through which said direct current may be supplied to the receiving circuit, said inductance element being connected in shunt with a circuit including said balancing circuit, and its inductance being sufficiently high to substantially prevent the transmission of alternating talking currents through the inductance element while its resistance is so proportioned as to supply the optimum value of direct current to the receiver.

In witness whereof, I hereunto subscribe my name this 29th day of December, A. D. 1917.

KENNETH S. JOHNSON.