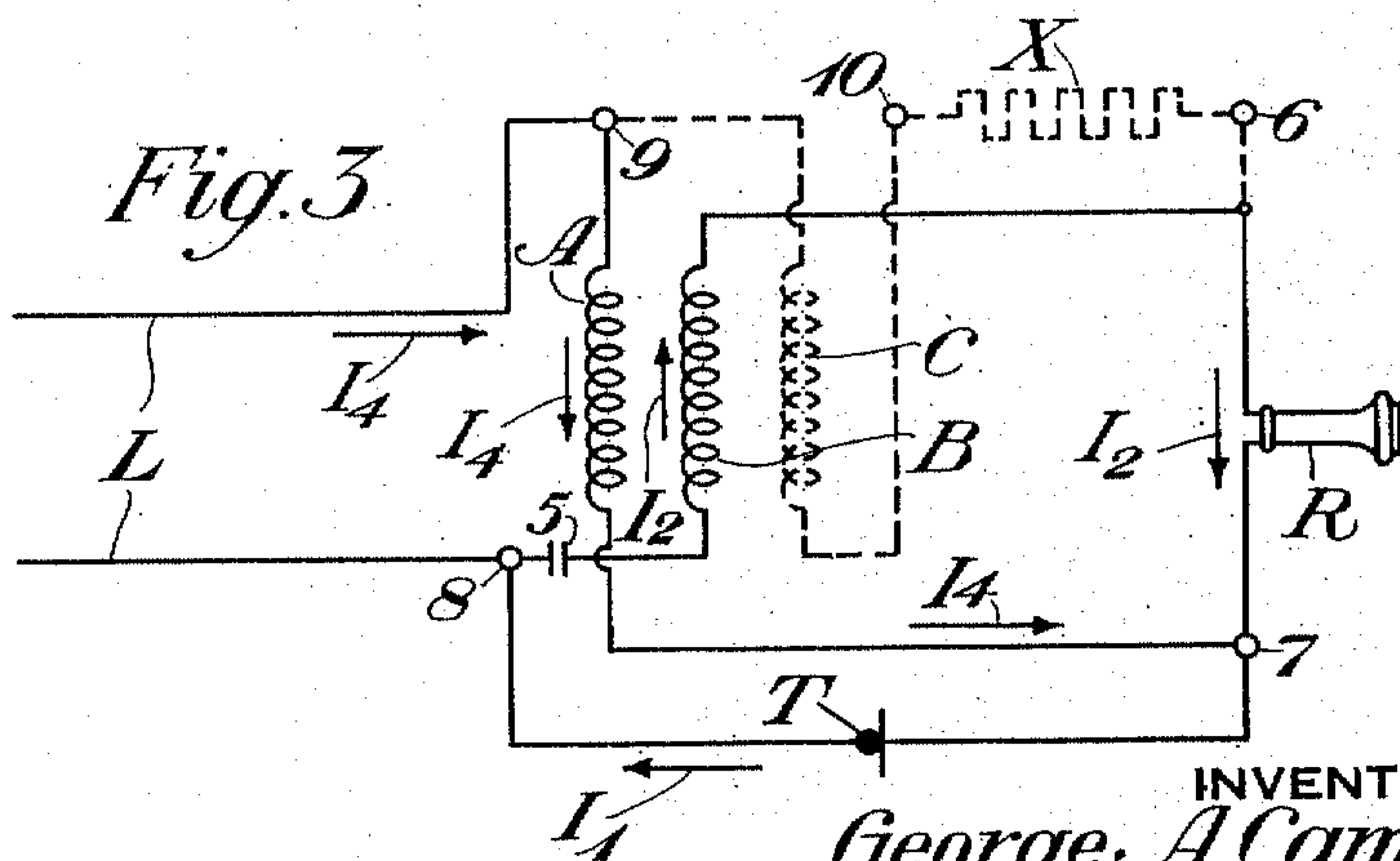
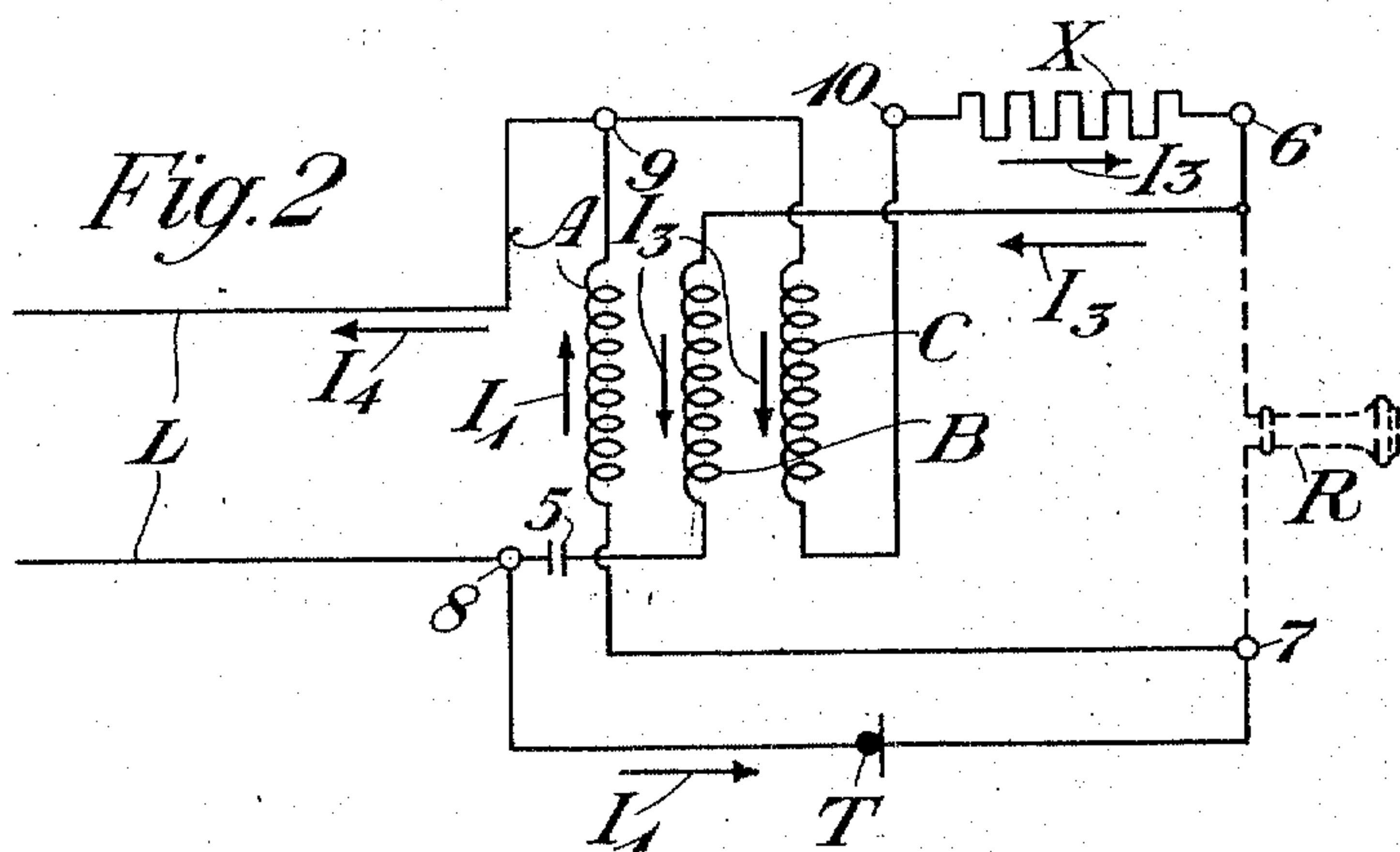
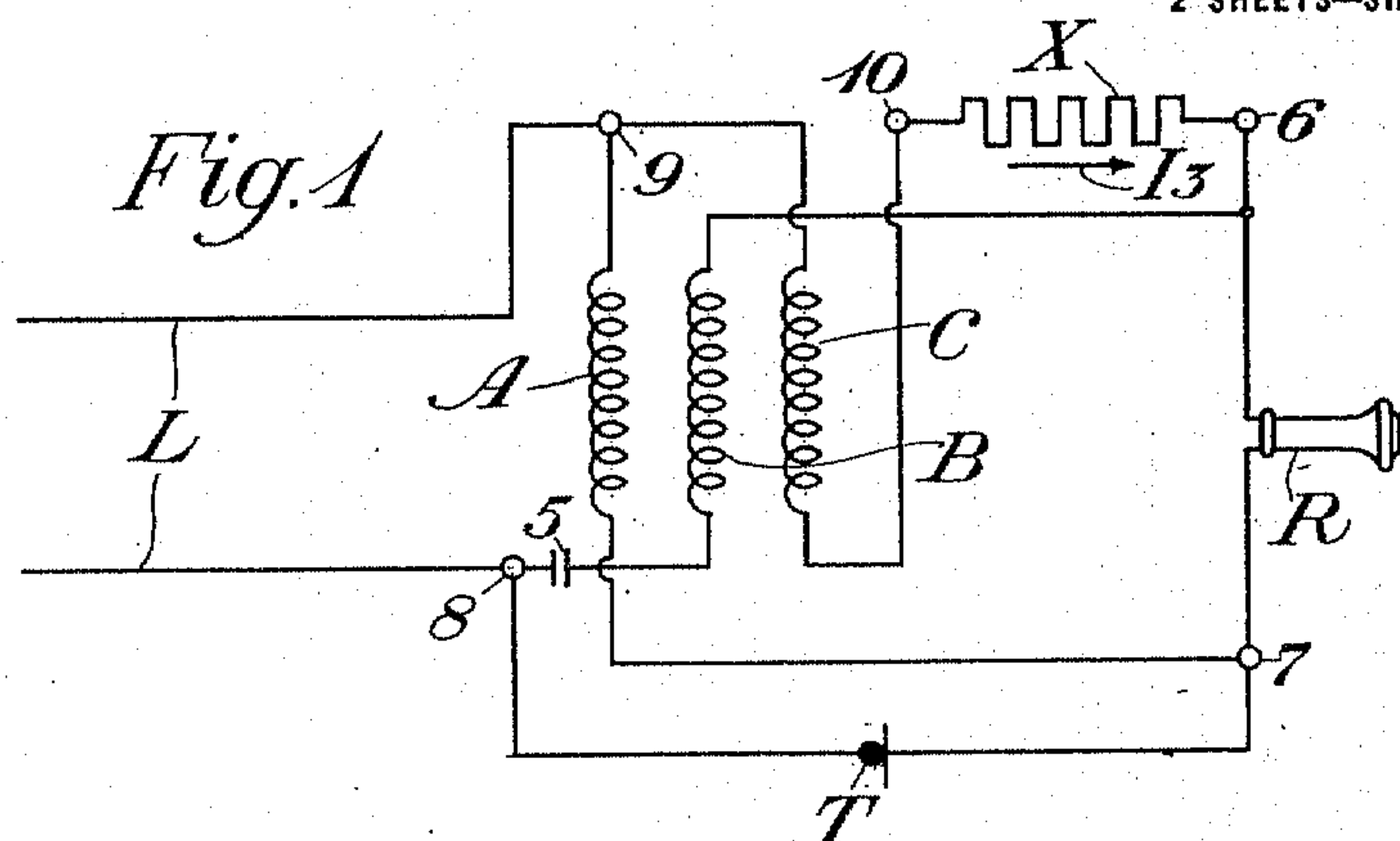


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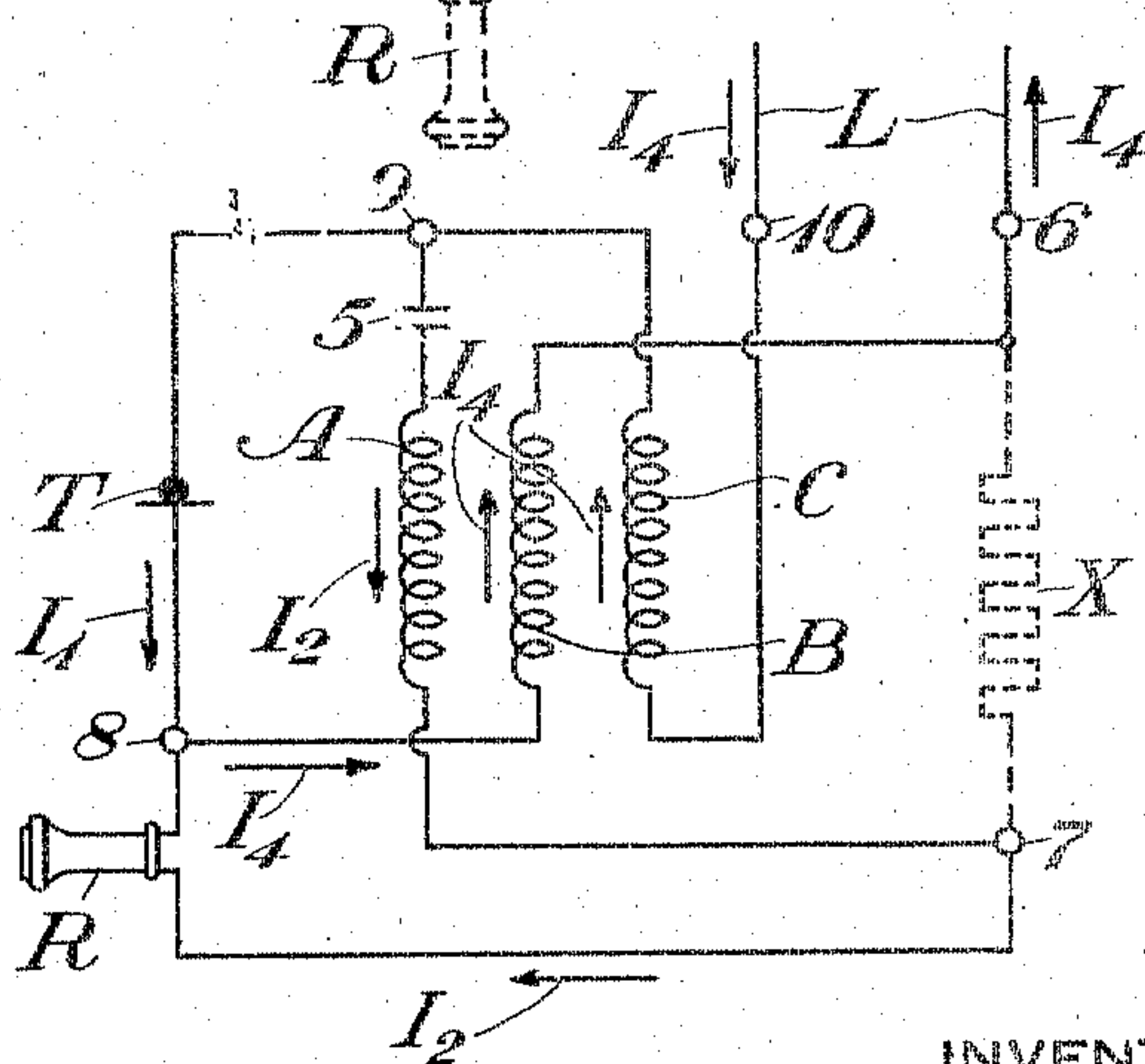
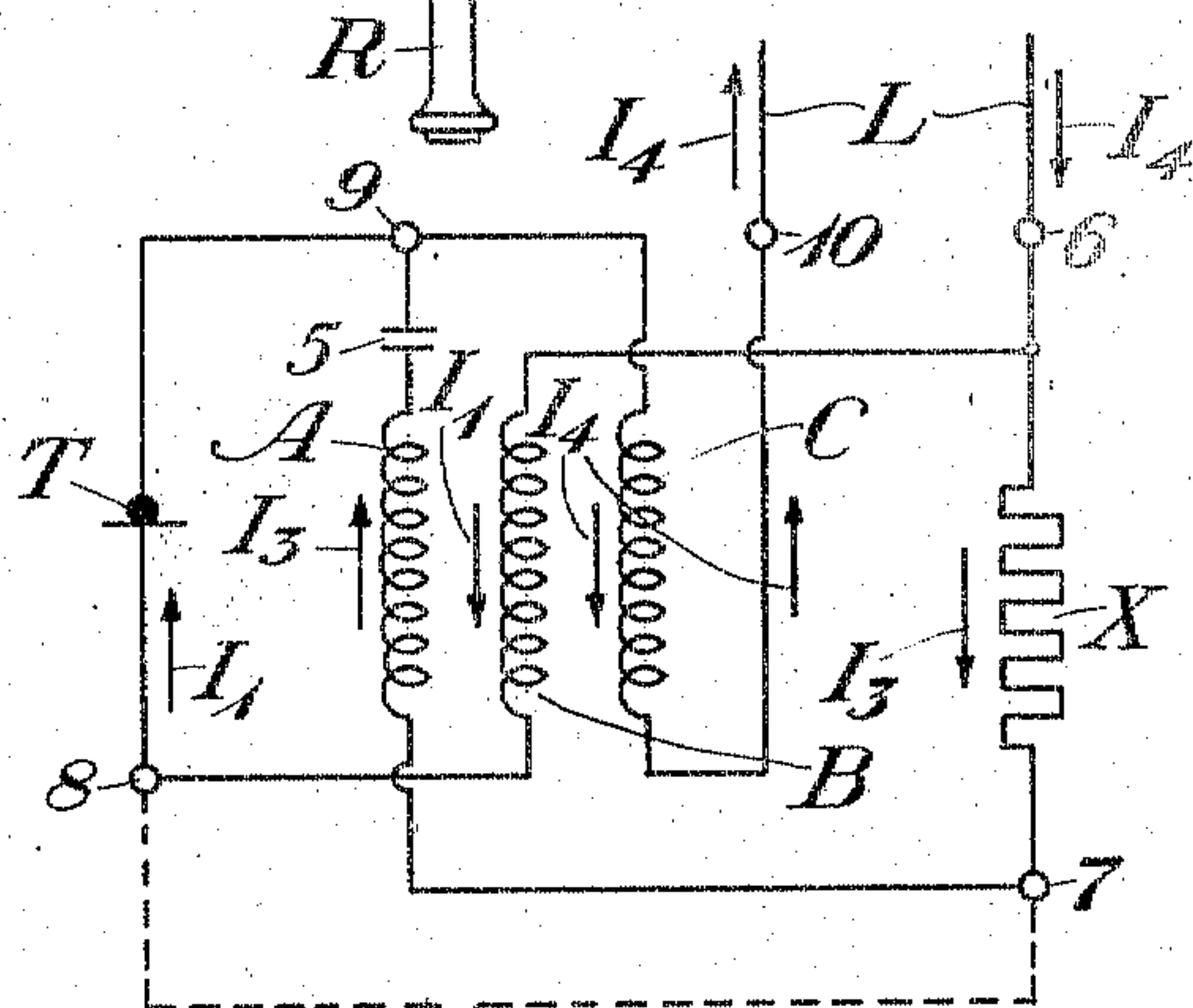
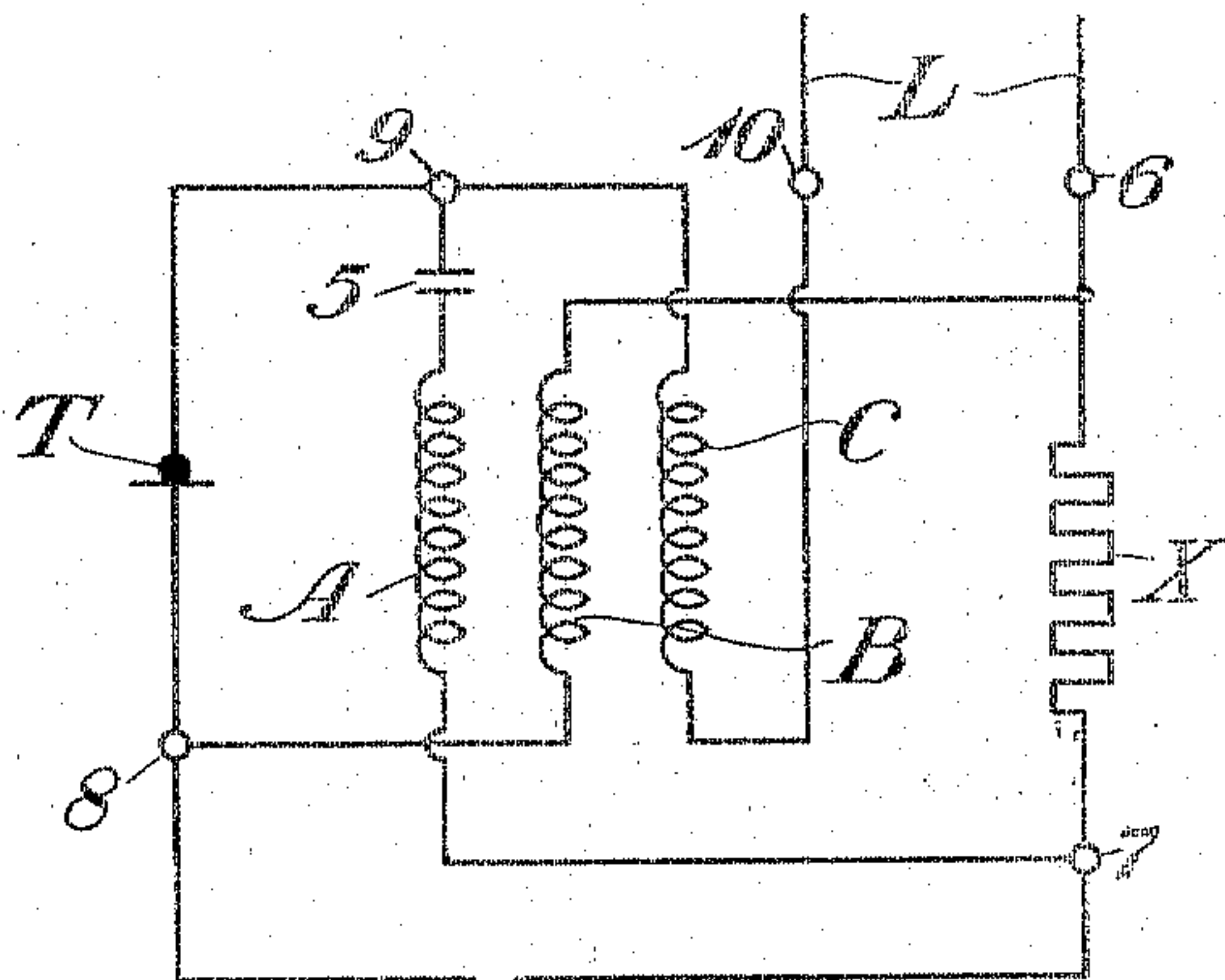
Patented Jan. 22, 1918.
 2 SHEETS—SHEET 1.



INVENTOR
George A. Campbell
 BY *Thomas D. Lockwood*
 ATTORNEY

1,254,476.

2 SHEETS—SHEET 2.



2
INVENTOR
George A. Campbell
BY *Thomas D. Lockwood*
ATTORNEY

UNITED STATES PATENT OFFICE.

GEORGE A. CAMPBELL, OF UPPER MONTCLAIR, NEW JERSEY, ASSIGNOR TO AMERICAN TELEPHONE AND TELEGRAPH COMPANY, A CORPORATION OF NEW YORK.

SIGNALING CIRCUIT.

1,254,476.

Specification of Letter Patent.

Patented Jan. 22, 1918.

Application filed May 14, 1917. Serial No. 149,443.

To all whom it may concern:

Be it known that I, GEORGE A. CAMPBELL, residing at Upper Montclair, in the county of Essex and State of New Jersey, have invented certain Improvements in Signaling Circuits, of which the following is a specification.

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 cooperative 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. In other words, its object is to provide signaling means characterized by the maximum possible ratio of received and transmitted energy and further characterized by the absence of side tone.

The object of the invention is attained, in its specific aspect, by providing a substation consisting of transmitter, receiver, 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 and length, 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 consistent with invariable two-way communication, and, as hereinafter explained, consistent with a desirable amount of discrimination against disturbing line noise. This fundamental re-

quirement 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 none 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 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 overall efficiency from transmitter of one substation to receiver of the communicating substation is a theoretical maximum which cannot be exceeded by any invariable substation 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 resistance of the receiver is equal to that of the transmitter. When this condition is satisfied, obviously fifty per cent. of the energy delivered by the line to the substation is wasted in the transmitter and fifty per cent. of the energy delivered by the transmitter is wasted in the receiver. Further, such an arrangement labors under the disadvantage of full side tone. In the substation of my invention fifty per cent. of the energy delivered by the line to the substation is wasted in the transmitter but none in the auxiliary resistance if said auxiliary resistance and said line are conjugate; hence the efficiency of receiving is as great as that of the simple series substation. When transmitting no energy is wasted in the receiver but fifty per cent. of the energy delivered by the transmitter is wasted in the auxiliary resistance. 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.

I have discovered that the above-mentioned requirements may be satisfied by a large number of arrangements employing the minimum number of elements and all equally efficient and without side tone. While theoretically all these arrangements are equally good, practical considerations make certain arrangements preferable.

My invention is best understood by reference to the accompanying drawing in which Figure 1 is a diagram illustrating one form of my invention; Fig. 2 is a diagram illustrating the operation of the substation of Fig. 1 during transmission; Fig. 3 is a similar diagram illustrating the operation during the reception of signals; Fig. 4 is a diagram illustrating a modification of my invention; while Figs. 5 and 6 are diagrams illustrating the operation of the substation of Fig. 4 during transmission and reception respectively.

Referring to Fig. 1, a telephone line L terminates in a substation comprising a transmitter T, a receiver R, an auxiliary resistance X, preferably non-inductive, and a transformer having windings A, B and C.

Said transformer is preferably of very high impedance and very closely coupled, conditions, it is well known, which may be very approximately satisfied in telephone transformers. It is also desirable that the resistance of said windings be negligibly small. When direct current is supplied to transmitter T from line L, a condenser may be inserted in series with winding B in order to confine the direct current to the transmitter. Said condenser may be, so large as to offer very small reactance to currents of telephonic frequency, or its capacity reactance may be substantially neutralized by the inductive reactance of the winding B. In either case the capacity effect may be rendered negligible as regards telephonic currents. As shown in the drawing, line L, winding C, auxiliary resistance X, receiver R and transmitter T, are serially connected. Winding B is bridged across the junction points of the line L and the transmitter T on the one hand, and the receiver R and the auxiliary resistance X on the other hand, at terminals 8 and 6 respectively. The winding A is similarly bridged across the junction points of the transmitter T and the receiver R, and of the line L and winding C at terminals 7 and 9 respectively.

Referring now to Fig. 2 the arrows indicate the direction of current flow during transmission and the dotted lines indicate elements through which no current flows.

In said diagram, as well as in the diagrams of Figs. 3, 5 and 6 and in the equations and formulæ hereinafter given, the subscripts 1, 2, 3 and 4 refer to transmitter, receiver, auxiliary resistance and line, respectively; thus I_1 , I_2 , I_3 and I_4 denote the currents flowing in the transmitter, receiver, auxiliary resistance and line, respectively. In interpreting said diagrams it should be understood that the direct battery supply current which is preferably supplied over the line from a central source of energy is not indicated since said current merely serves to energize the transmitter. Further it will be understood that the flow of telephonic current as indicated by the arrows is conditioned by the proper proportioning of the component elements of the substation in accordance with the design formulæ hereinafter derived and set forth.

The operation during transmission is indicated in Fig. 2 and is as follows: The actuation of the transmitter T sets up variations in the resistance thereof which are equivalent in their action to an alternating electromotive force in said transmitter. An alternating current of telephonic frequency is therefore superimposed on the direct current (not indicated), the path and relative direction of said alternating current being indicated by the arrows. Since the substation is without side tone no current flows

through the receiver, but the total alternating current in the transmitter, denoted by I_1 , flows from terminal 7 through winding A to terminal 9. Here the current divides, a portion I_2 flowing out over line L and back to terminal 8 of the transmitter; while a portion I_3 flows through winding C, auxiliary resistance X and winding B to terminal 8 where it joins the returning line current I_4 . It will be clear that the transmitter current I_1 is equal to the sum of the line current I_2 and the current I_3 which flows through the auxiliary resistance X. Said current I_3 is wasted in the resistance X, but, as herein shown, such waste is unavoidable in two-way communication. If the auxiliary resistance were omitted, an equivalent waste of energy would be necessitated in the receiver with the further disadvantage of side tone. It will be observed that no current flows through receiver R and consequently terminals 6 and 7 must be at the same potential as regards the transmission current. This is made possible by a proper proportioning of the relative impedances of line and auxiliary resistance with reference to the relative number of turns on windings of the transformer. The windings, when properly proportioned, interact in such manner that potentials are induced in the windings B and C in a direction tending to increase the potential of terminal 6 to a value equal to that of terminal 7.

Referring to Fig. 3, which is a diagram illustrating the relative directions of flow of telephonic current during the operation of receiving, a potential applied to the line causes a current I_2 to flow over the line L to terminal 9. This current then flows through the winding A to terminal 7, thereby inducing a current I_3 in winding B which flows in the opposite direction, said current flowing from terminal 8 through winding B and receiver R to terminal 7 where it unites with current I_4 so that a current I_1 equal to the combined currents I_3 and I_4 flows through the transmitter T to terminal 8. At this point the current divides, the portion I_2 flowing back over the line while the portion I_3 flows through the winding B as already described. No current flows through the auxiliary resistance X when the elements of the substation are properly proportioned as the potentials induced in windings B and C are in such direction and of such values as to raise the potential of terminal 6 to a value equal to that of terminal 10.

Before proceeding to the description of the modification shown in Fig. 4, a general theoretical discussion will now be given which applies to all substations satisfying the requirements heretofore stated in this specification.

This discussion, which illustrates the scope

of my invention and elucidates the principles upon which all specific embodiments rest, will be followed by a theoretical consideration of the manner in which the arrangement of Fig. 1 is proportioned, together with a derivation of the design formulae applicable to said arrangement. In this discussion and the equations and formulae included in this specification, the subscripts 1, 2, 3 and 4 will, as hereinbefore stated, 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. In practice the line 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 component of the impedance of the line. The condition, that the substation shall have maximum energy absorption from the line is that its impedance, as seen from the line, shall be equal to the line impedance. The significance of the foregoing statement may be explained by reference to Fig. 1 as follows: Let the substation be disconnected from the line and let the impedance of the substation be measured across terminals 8 and 9. 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 impedance element of resistance equal to the impedance of the line. Any reactance effect, which is in practice small, may be eliminated by neutralizing reactance and, therefore, need not be considered. 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 impedance 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 con-

summed 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 that of the line. 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; then 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

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

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 equation:

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

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:

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

Equation (2) is the analogue of equation (1), and may be interpreted as follows by reference to Fig. 1. Let the conductor which connects transmitter T to terminal 7 be opened and let the impedance be measured across terminals 7 and 8. 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_0 be the total amount of telephonic energy developed by the transmitter at the transmitting substation; then, by equation (2), $1/2 W_0$ 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

$$1/2 W_0 \frac{1}{(1+x)} \quad 90$$

so that the transmitting efficiency is measured by

$$\frac{1}{(1+x)} \quad (3) \quad 95$$

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

$$\frac{1}{(1+y)} \quad (4) \quad 105$$

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

$$\left(\frac{1}{1+x} \right) \left(\frac{1}{1+y} \right) \quad 110$$

If x and y were independent, clearly the over-all efficiency would be a maximum for $x=y=0$. 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

$$\frac{y}{(1+y)^2} \quad (5) \quad 125$$

In order to demonstrate the above statement, namely that $xy=1$, designate the elements or branches T, R, X and L by 1, 2, 3 and 4

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

$$S_{12}=S_{34}=0.$$

Also by equation (1)

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

and by equation (2)

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

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:

$$(S_{42})^2 R_2 R_4 = (S_{13})^2 R_1 R_3 \quad (a).$$

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

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

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

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

Multiplying (b) and (c)

$$(S_{13})^2 R_1 R_3 = xy (S_{24})^2 R_2 R_4 \quad (d)$$

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 origin

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 discrimination 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 I have found by experiment that a desirable value for y is 1.4. With this value of y the overall efficiency is reduced 2.8% below the maximum for $y=1$, while the receiving efficiency alone is reduced 16.6%. However under certain conditions it may be desirable to substantially increase the value of y beyond unity. It will be therefore understood that, when the value of y is referred to as approximately unity, its actual value may considerably exceed the theoretical optimum.

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

$$R_1 (I_1)^2 = y R_2 (I_2)^2 \quad (6)$$

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

The proportioning of the arrangement of Fig. 1, in order to satisfy the fundamental requirements, will now be given. The condition that the receiver R shall be conjugate with respect to transmitter T is satisfied if no current flows in said receiver in consequence of an electromotive force of telephonic frequency inserted in series with the transmitter between terminals 7 and 8. If receiver R is to be conjugate to said transmitter then points 6 and 7 must be at the same potential as regards the effect of said electromotive force. Further if the windings of the transformer have very high self impedances, the algebraic sum of the products of the currents flowing in said windings, by the number of turns of said windings, will equal zero. Bearing these considerations in mind, the condition of conjugacy of transmitter and receiver is derivable as follows:—

Assume an electromotive force in the

transmitter branch of Fig. 2, and let I , I_2 , I_3 and I_4 denote the currents flowing in transmitter, receiver, auxiliary resistance and line respectively. Then since no current

5 flows through the receiver

$$I_2=0 \text{ and } I_1=I_3+I_4 \quad (7)$$

Also if the self impedance of the transformer is very high, representing the number of turns of windings, A, B and C as a , b , and c respectively

$$aI_1-(b+c)I_3=0$$

whence

$$I_3=\left(\frac{a}{b+c}\right)I_1$$

Since $I_3=I_1-I_4$ this equation becomes

$$I_1-I_4=\left(\frac{a}{b+c}\right)I_1$$

or

$$I_4=\left(\frac{b+c-a}{b+c}\right)I_1 \quad (8)$$

If K denotes the voltage drop per turn in the transformer windings, V the potential difference across the terminals of the transmitter, and R_1 , R_2 , R_3 and R_4 the resistances of transmitter, receiver, auxiliary resistance and line, respectively, it follows that since points 6 and 7 are at the same potential;

$$V=KR_1 \quad (9)$$

Also, since the impressed potential is equal to the algebraic sum of the $I R$ drop through the line and the drop through winding A,

$$V=-Ka+I_4R_4 \quad (10)$$

The negative sign indicates that the induced drop through winding A is in the opposite direction to the current flow therethrough.

Furthermore since points 6 and 7 are at the same potential, the drop between each of said points and point 9 must be equal so that

$$I_3R_3+Kc=Ka$$

or

$$I_3R_3+K(c-a)=0 \quad (11)$$

The several equations just derived from Fig. 2 reduce to the following relation which must be satisfied for conjugacy of transmitter and receiver;

$$R_3=-\left(\frac{c-a}{b+a}\right)\left(\frac{b+c-a}{a}\right)R_4 \quad (12)$$

where R_3 and R_4 are the resistance of auxiliary resistance and telephone line respectively.

Similarly, referring to Fig. 3, the condition of conjugacy of line and auxiliary resistance may be derived as follows:

Assuming an electromotive force V applied across the terminals of the line, since

no current flows through the auxiliary resistance

$$I_3=0 \text{ and } I_1=I_2+I_4 \quad (13)$$

Since the algebraic sum of the products of the currents flowing through the transformer windings by their number of turns is zero

$$aI_4-bI_2=0$$

Combining this equation with the preceding we get

$$I_1=\left(\frac{a+b}{b}\right)I_4 \quad (14)$$

Further, since the applied voltage equals the algebraic sum of the induced drop through the winding A and the $I R$ drop through the transmitter,

$$V=Ka+I_1R_1 \quad (15)$$

In a similar manner it will be seen that

$$V=Kb+I_2R_2+Kc \quad (16)$$

Since no current I_3 is flowing $I_3 R_3$ becomes zero and this expression reduces to

$$V=K(b+c) \quad (17)$$

Finally, since points 10 and 6 are at the same potential, the algebraic sum of the drop through the windings C and A and $I R$ drop through the receiver is zero. Hence

$$I_2R_2-Ka+Kc=0$$

or

$$I_2R_2+K(c-a)=0 \quad (18)$$

The several expressions derived from Fig. 3 may be reduced to the following expression satisfying the requirement of conjugacy of the auxiliary resistance with respect to the line;

$$R_2=-R_1\left(\frac{a+b}{a}\right)\left(\frac{c-a}{b+c-a}\right) \quad (19)$$

where R_2 and R_1 are the resistance of receiver and transmitter respectively.

From equation (8) it is apparent that during transmission I_3 and I_4 are proportional to $b+c-a$ and $b+c$ respectively, and since from equation (7) above $I_3=I_1-I_4$, it is evident that I_3 is proportional to a . Substituting these values in equation (2) the condition of maximum output of the transmitter is satisfied by the following expression

$$R_1(b+c)^2=R_3(a)^2+R_4(b+c-a)^2 \quad (20)$$

which reduces to

$$R_1=R_3\left(\frac{a}{b+c}\right)^2+R_4\left(\frac{b+c-a}{b+c}\right)^2$$

Similarly, during reception it is apparent from equation (14) that I_1 and I_4 are proportional to $a+b$ and b and since from equation (13) $I_2=I_1-I_4$, it follows that I_2 is proportional to a . Substituting these values

in equation (1) the condition that the receiver shall have maximum energy absorption from the line may be expressed:

$$R_1(b)^2 = R_1(a)^2 + R_1(a+b)^2 \quad (21)$$

So also by substituting these values in equation (6) we have as the expression for maximum over-all efficiency

$$R_1(a+b)^2 = yR_1(a)^2$$

Denoting $\frac{b}{a}$ and $\frac{c}{a}$ by r and r' respectively equations (19) and (22) give

$$y = -\left(\frac{a+b}{a}\right)^2 \left(\frac{a}{a+b}\right) \left(\frac{b+c-a}{c-a}\right) = -(r+1) \left(\frac{r+r'-1}{r'-1}\right) = \frac{(r+1)(r+r'-1)}{1-r'} \quad (23)$$

Eliminating R_2 from (19) and (21) we get:

$$R_1 = \left[\frac{1}{r^2} (1+r) \left(\frac{1-r'}{r+r'-1} \right) + \left(\frac{r+1}{r} \right)^2 \right] R_1 = \frac{1+r}{r^2} \left[\frac{1-r'}{r+r'-1} + r+1 \right] R_1 = \frac{1+r}{r^2} \left[\frac{r(r+r'-1)}{r+r'-1} \right] R_1$$

$$\frac{R_1}{R_4} = \frac{(r)(r+r'-1)}{(1+r)(r+r')} \quad (24)$$

Equation (23) by simple algebraic transformation becomes

$$\frac{1+y}{y} = \frac{r(r+r')}{(1+r)(r+r'-1)} \quad (25)$$

Dividing equation (25) by equation (24) we have

$$\frac{R_1(1+y)}{R_1 \left(\frac{r}{1+y} \right)} = \frac{(r+r')^2}{(r+r'-1)^2} \quad (26)$$

Multiplying equation (24) and equation (25) we have

$$\frac{R_1}{R_1} \left(\frac{y}{1+y} \right) = \left(\frac{1+r}{r} \right)^2 \quad (27)$$

By substituting r and r' in equation (12) said equation may be rewritten

$$R_1 = -\left(\frac{r'-1}{r+1} \right) (r+r'-1) R_4 = -\left(\frac{1-r'}{r+1} \right) (r+r'-1) R_4 \quad (28)$$

Multiplying equations (23) and (28) we have

$$R_2 = \frac{(r+r'-1)^2}{y} R_4 \quad (29)$$

By substituting r and r' for $\frac{b}{a}$ and $\frac{c}{a}$ in equations (21) and (22), and eliminating R_1 from said equations we have

$$R_2 = \frac{r^2}{(1+y)} R_4 \quad (30)$$

If now in equations 26, 27, 29 and 30

$$\pm \sqrt{\frac{R_4}{R_1}}$$

be written as F and

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

be written as h , then said equations may be written as follows:

$$\left. \begin{aligned} \frac{1}{r+r'-1} &= Fh-1 \\ \frac{1}{r} &= \frac{F}{h}-1 \\ R_2 &= \frac{R_4}{y(Fh-1)^2} \\ R_2 &= \frac{R_4}{(1+y) \left(\frac{F}{h}-1 \right)^2} \end{aligned} \right\} (G)$$

The above group of formulæ are the formulæ appropriate to the substitution of Fig. 1. It will be observed that, in the above design formulæ the winding ratios r and r' and the values of the receiver resistance R_2 and the auxiliary resistance R_3 are determined in terms of the assigned values of the line resistance R_4 , the ratio y , and the term F , which is a function of the ratio of the line resistance to the transmitter resistance. Consequently any desired value of F^2 or $\frac{R_4}{R_1}$ may be assigned; that is, the value of R_1 (the transmitter resistance) is at our disposal.

Another specific embodiment of the invention is shown in Fig. 4. Referring to said figure and comparing the arrangement there shown with that illustrated in Fig. 1 it will be seen that they are identical except for the interchange of certain component elements. Thus in Fig. 4 the transmitter T replaces the line of Fig. 1, the receiver of Fig. 4 replaces the transmitter of Fig. 1, the auxiliary resistance X of Fig. 4 replaces the receiver of Fig. 1 and the line of Fig. 4 replaces the auxiliary resistance of Fig. 1.

The operation of the substitution shown in Fig. 4 during transmission is indicated in Fig. 5 and is as follows: the actuation of the transmitter T sets up variations in the resistance thereof which are equivalent in their

action to an alternating electromotive force in said transmitter. An alternating current of telephonic frequency is thereby set up, whose relative direction at any given instant is indicated by the arrows in Fig. 5. A current I_1 therefore flows from terminal 3 through winding B and through transmitter T to terminal 9. A potential is thereby induced in winding A so that a current I_2 flows from terminal 6 through resistance X and winding A to terminal 9. At said terminal the currents I_1 and I_2 join so that a current I_3 flows from terminal 9, through winding C and over line L to terminal 6, at which point it divides so that currents I_1 and I_2 flow through the transmitter and auxiliary resistance X as already stated. No current flows through the receiver R, this result being effected by the interaction of the transformer windings, potential of such value and direction being induced in windings A and B as to bring points 7 and 8 to the same potential.

The action during reception is indicated in Fig. 6. Assuming a source of current variation applied to the line terminals, at a given instant a current I_1 flows from terminal 10 through winding C to terminal 9 where it divides, a current I_2 flowing through transmitter T to terminal 8, and a current I_3 flowing through winding A and receiver R to terminal 8. At this point the currents I_2 and I_3 merge, and a current I_4 flows from the terminal 8 through the winding B back to the line. No current flows through the auxiliary resistance X as the windings of the induction coil are so proportioned with respect to the resistances of the line, transmitter and receiver, that potentials will be induced in windings A and B of such value and direction as to bring points 6 and 7 to the same potential.

The design formulæ in accordance with which the elements of the substation of Fig. 4 may be proportioned to secure the results herein set forth may be derived in a manner analogous to that described in connection with Fig. 1. Said design formulæ are as follows:

$$\left. \begin{aligned} 1+r &= \frac{F}{h+1} \\ r+r' &= \frac{F}{h+1} \\ R_3 &= R_4 \frac{1}{y(Fh+1)^2} \\ R_2 &= R_4 \frac{1}{(1+y)\left(\frac{F}{h}+1\right)^2} \end{aligned} \right\} \text{(II)}$$

The substations disclosed above and illustrated in the accompanying drawing are but two of a large number employing only one

transformer and one auxiliary resistance and all of these are ideal in the sense that they satisfy the fundamental requirements for an ideal substation, as stated heretofore in this specification. It will be understood therefore, that my invention is not limited to the specific embodiments herein illustrated, but is broadly directed to providing a substation comprising a single transformer and only one auxiliary element, which is so proportioned with reference to the line with which it is to be coöperatively combined, that it is ideally efficient and substantially without side tone. Furthermore, I do not desire 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 have no reactance, assumptions which are only approximately justified in practice. When particularly high precision is desired, I may, therefore, proportion the substation more precisely by taking into account the fact that the transformer impedances are finite, and that the line and the various substation elements may have in general some 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 regard to the rigid requirements is necessary in order to discriminate against line noise.

It will be further understood that while I have specifically illustrated and described my invention 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 my invention is not to be limited to the particular form and use herein disclosed.

What I claim is:—

1. In combination with a telephone line, a substation, said substation comprising a transmitter, receiver, auxiliary resistance and a transformer having three windings, said line, transmitter, receiver, auxiliary resistance and one winding of the transformer being connected in a series circuit, and the other two windings of said transformer being bridged across said series circuit.

2. In a two way signaling system, a circuit for the transmission and reception of signals, a transmitting circuit proper, a receiving circuit proper, a balancing circuit,

and a transformer having three windings, all of said circuits and one of said windings being serially related, and the other windings being in bridge relation with respect to said circuits.

3. In combination with a telephone line, a substation, said substation comprising a transmitter, receiver, auxiliary resistance and a transformer having three windings, said line, transmitter, receiver, auxiliary resistance and one winding of the transformer being connected in a series circuit, another of said winding being in shunt of said line and transmitter, and the third winding being in shunt of said receiver and transmitter.

4. In combination with a telephone line, a substation, said substation comprising a transmitter, receiver, auxiliary resistance and a transformer having three windings, said line, transmitter, receiver, auxiliary resistance and one winding of the transformer being connected in a series circuit, another of said windings being bridged across said circuit in shunt of said receiver and transmitter and the third winding being also bridged across said circuit.

5. A signaling system comprising a transformer and four fundamental elements consisting of a path for the transmission and reception of signals, a transmitting element, a receiving element, and a balancing element, said fundamental elements and one winding of said transformer being in a series circuit.

6. A signaling system comprising a transformer and four fundamental elements consisting of a path for the transmission and reception of signals, a transmitting element, a receiving element, and a balancing element, said fundamental elements and one winding of said transformer being in a series circuit, said transformer and said fundamental elements being so proportioned and related that said transmitting element and said receiving element are conjugate.

7. A signaling system comprising a transformer and four fundamental elements consisting of a path for the transmission and reception of signals, a transmitting element, a receiving element, and a balancing element, said fundamental elements and one winding of said transformer being in a series circuit, said transformer and said fundamental elements being so proportioned and related that said balancing element and said path are conjugate.

8. A signaling system comprising a transformer and four fundamental elements consisting of a path for the transmission and reception of signals, a transmitting element, a receiving element, and a balancing element, said fundamental elements and one winding of said transformer being in a series circuit, said transformer and said fundamental elements being so proportioned and related that the impedance of the combination comprising the transmitting element, the receiving element, the balancing element, and the transformer, as seen from said path, is equal to the impedance of said path.

9. A signaling system comprising a transformer and four fundamental elements consisting of a path for the transmission and reception of signals, a transmitting element, a receiving element, and a balancing element, said fundamental elements and one winding of said transformer being in a series circuit, said transformer and said fundamental elements being so proportioned and related that the impedance of the combination comprising said path, receiving element, balancing element and transformer, as seen from the transmitting element, is equal to the impedance of the transmitting element.

10. A signaling system comprising a transformer and four fundamental elements consisting of a path for the transmission and reception of signals, a transmitting element, a receiving element, and a balancing element, said fundamental elements and one winding of said transformer being in a series circuit, said transformer and said fundamental elements being so proportioned and related that said transmitting and receiving elements are conjugate; said path and said balancing element are conjugate; the impedance of the combination comprising said transmitting, receiving and balancing elements and said transformer, as seen from said path, is equal to the impedance of said path; and the impedance of the combination comprising said path, said receiving and balancing elements, and said transformer, as seen from the transmitting element, is equal to the impedance of said transmitting element.

In testimony whereof, I have signed my name to this specification this fourteenth day of May, 1917.

GEORGE A. CAMPBELL.