May 26, 1936. R. E. POWERS ET AL **2,042,187**

NETWORK DISTRIBUTION SYSTEM

Filed Dec. 21, 1932 5 Sheets-Sheet 1

Fig. 1.

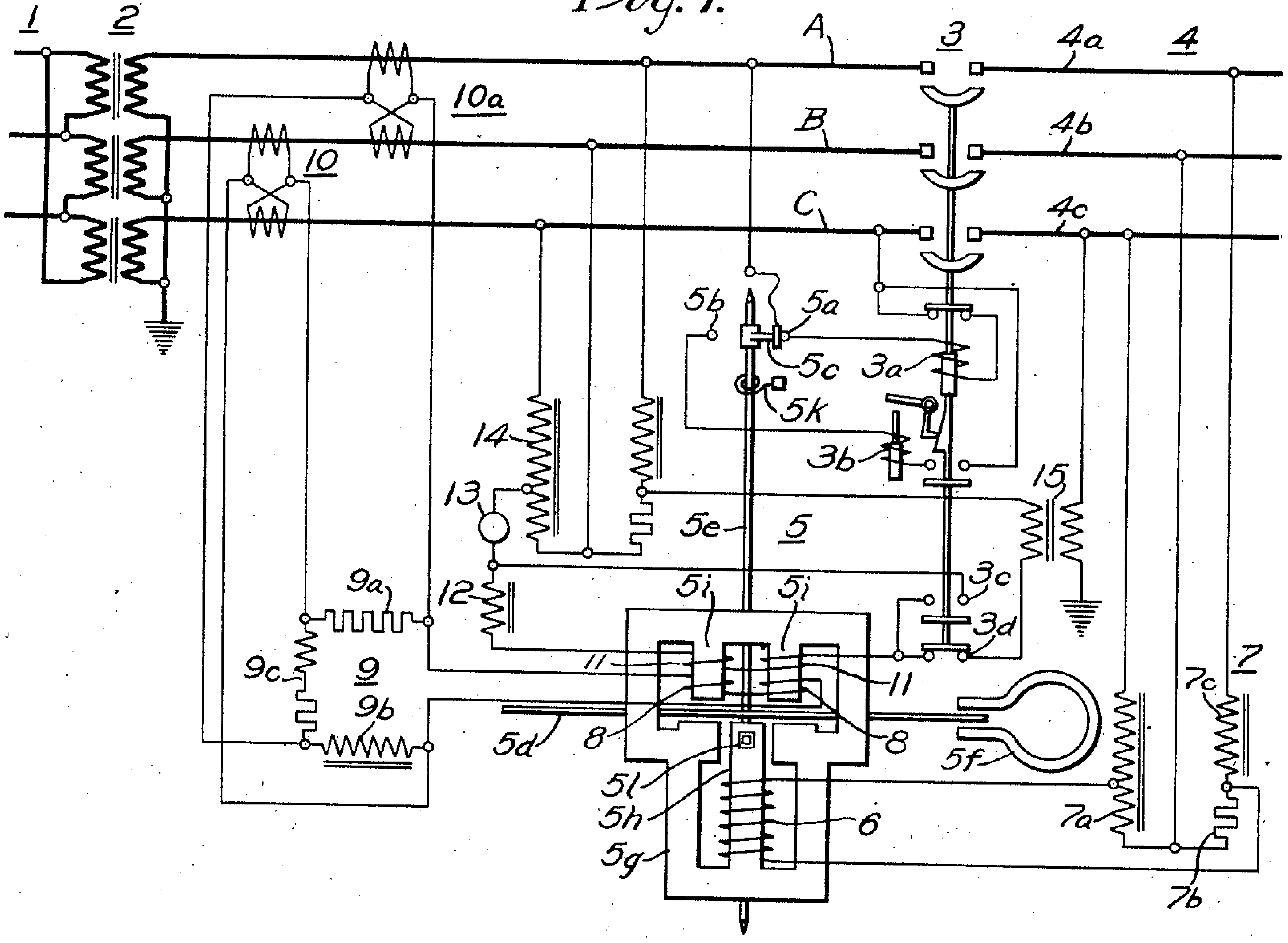


Fig. 2.

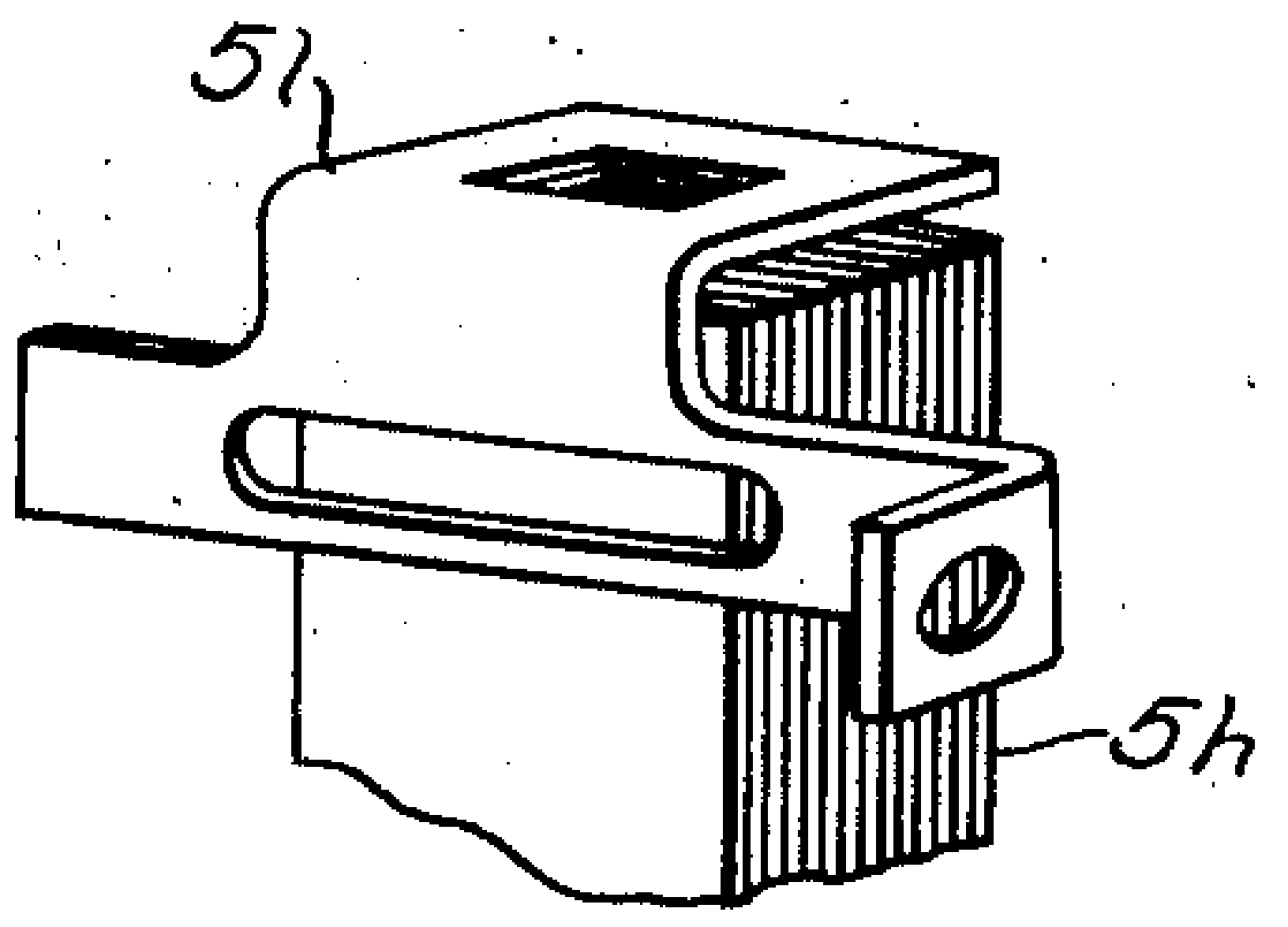
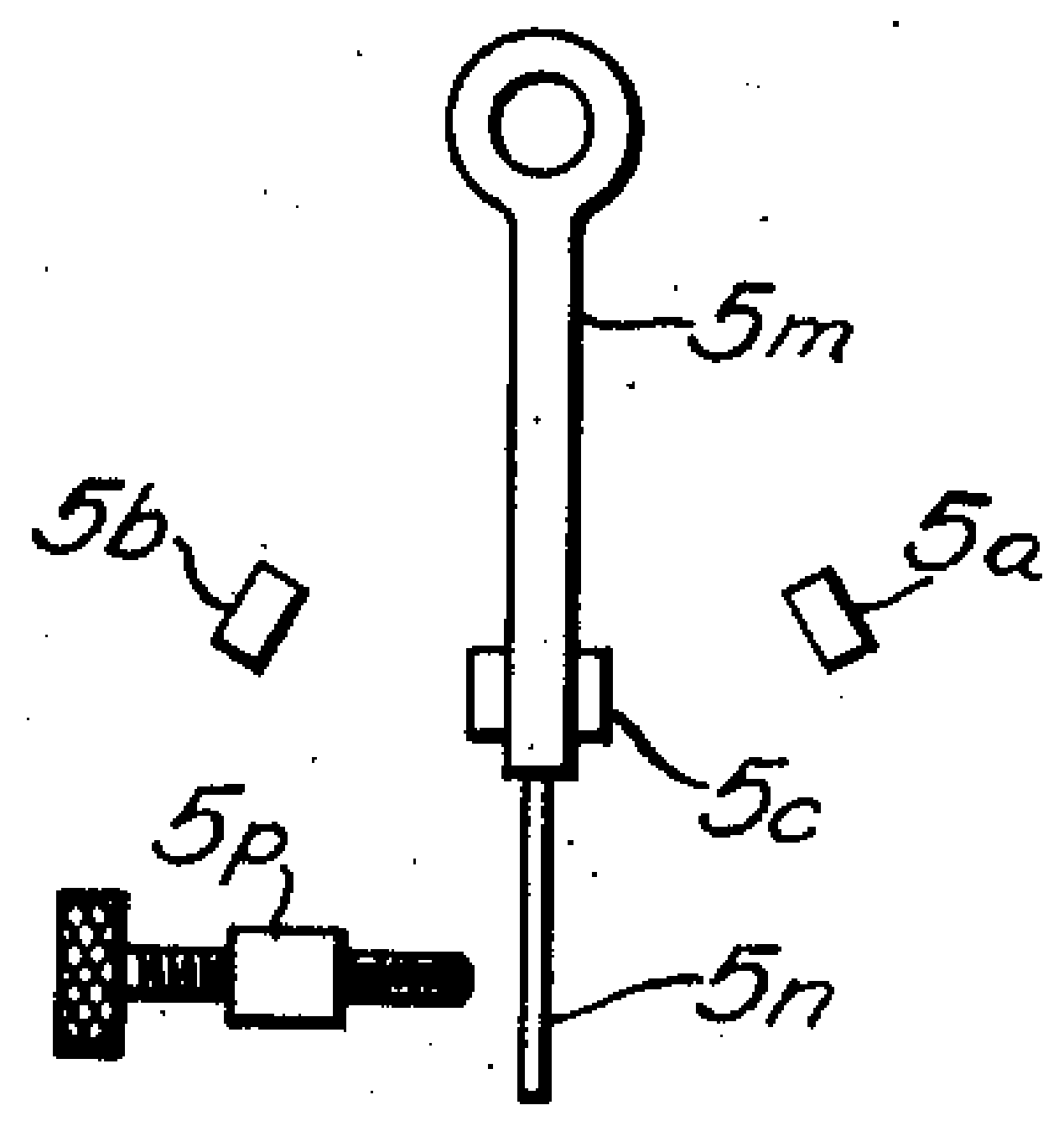


Fig. 3.



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NETWORK DISTRIBUTION SYSTEM

Filed Dec. 21, 1932 5 Sheets-Sheet 2

Fig. 4.

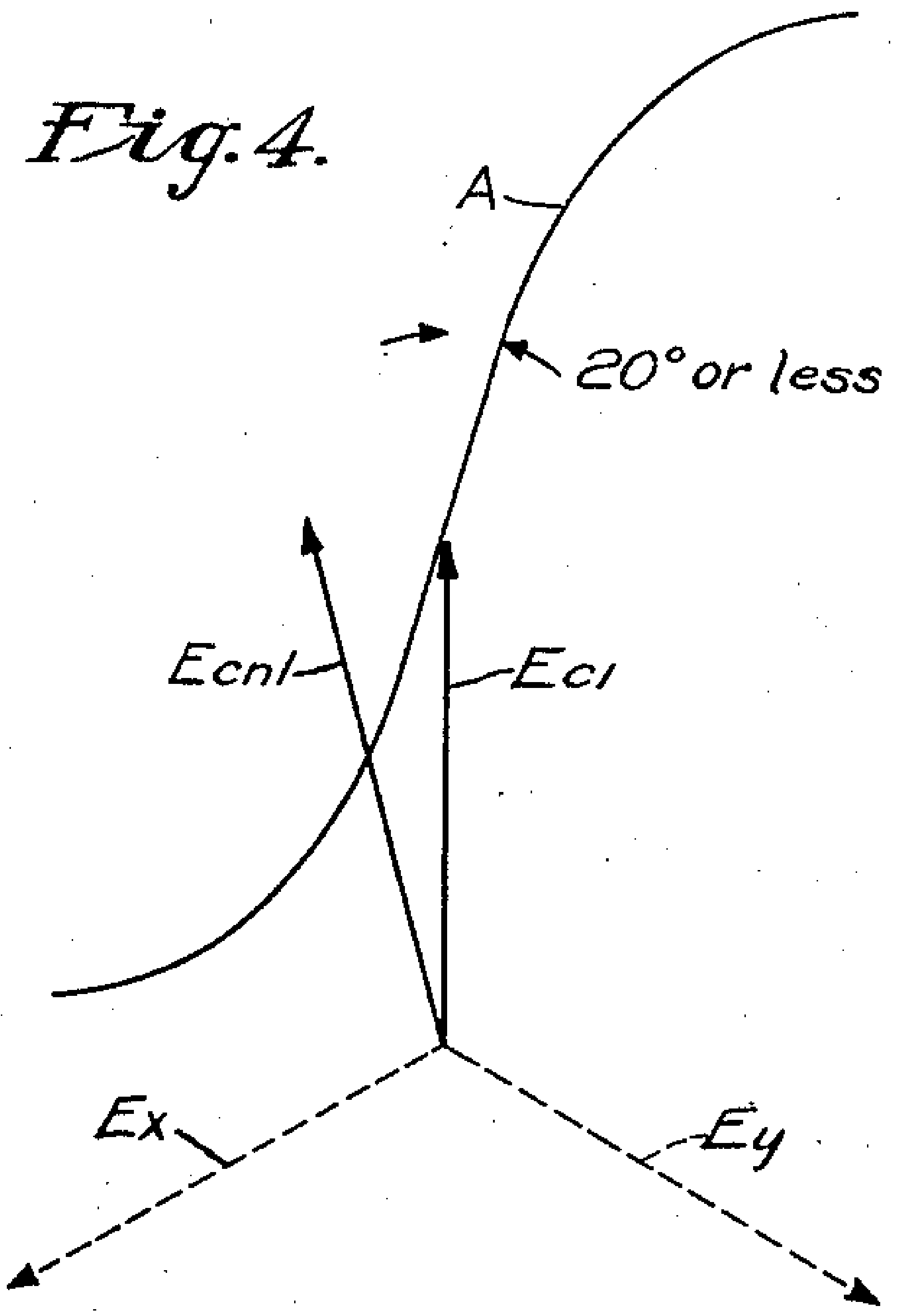
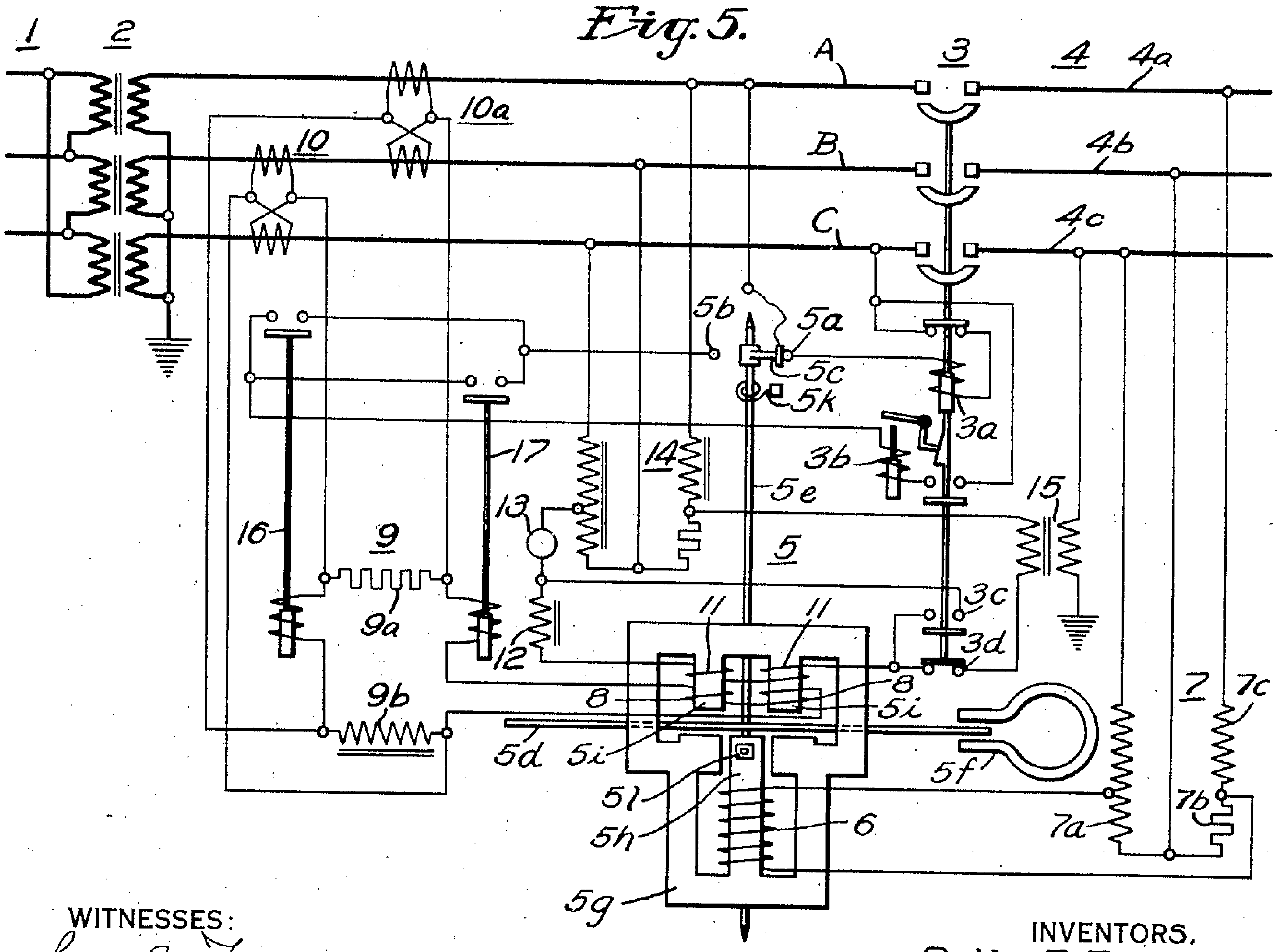


Fig. 5.



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NETWORK DISTRIBUTION SYSTEM

Filed Dec. 21, 1932 5 Sheets-Sheet 3

Fig. 6.

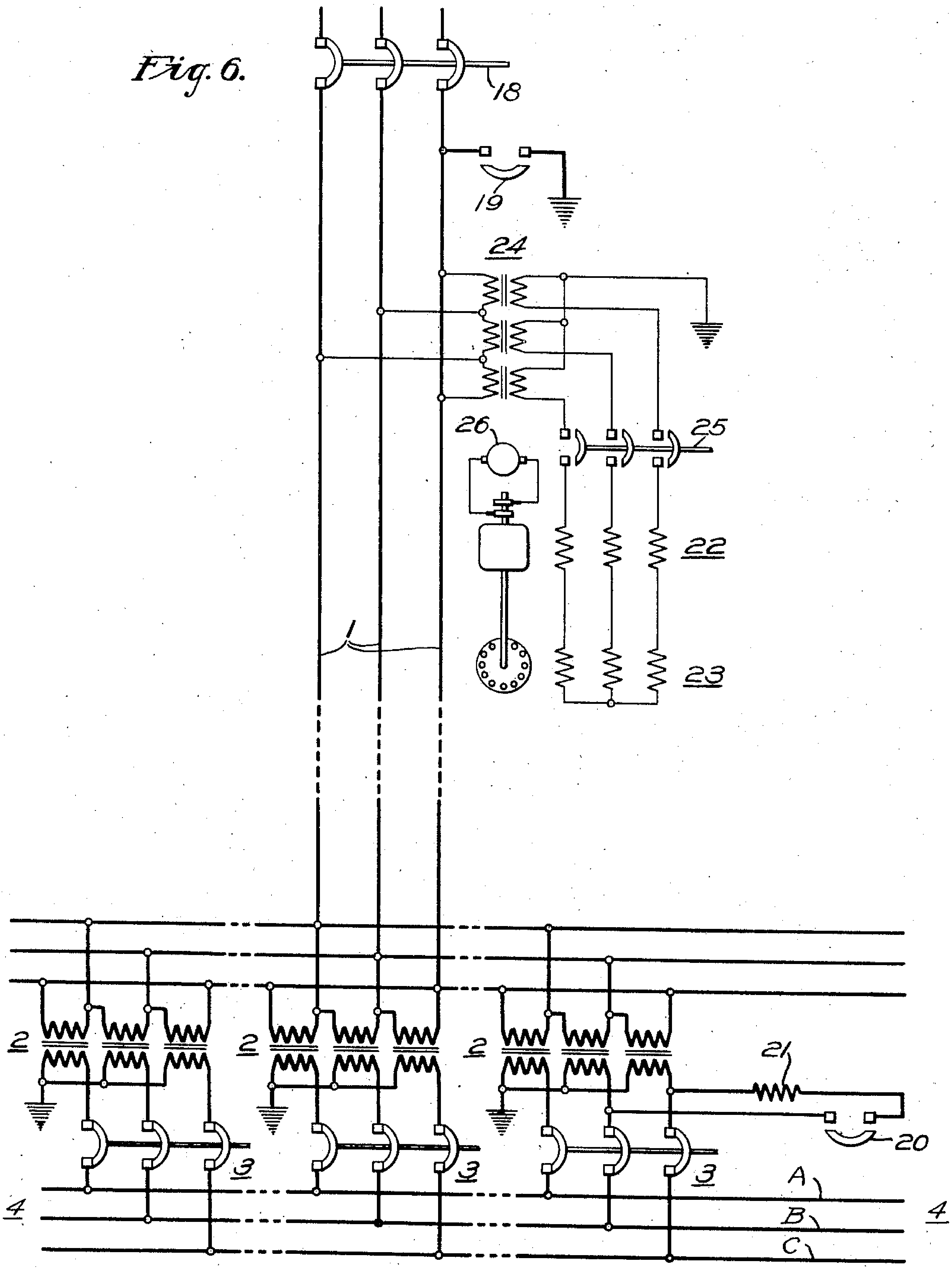

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Fig. 7.

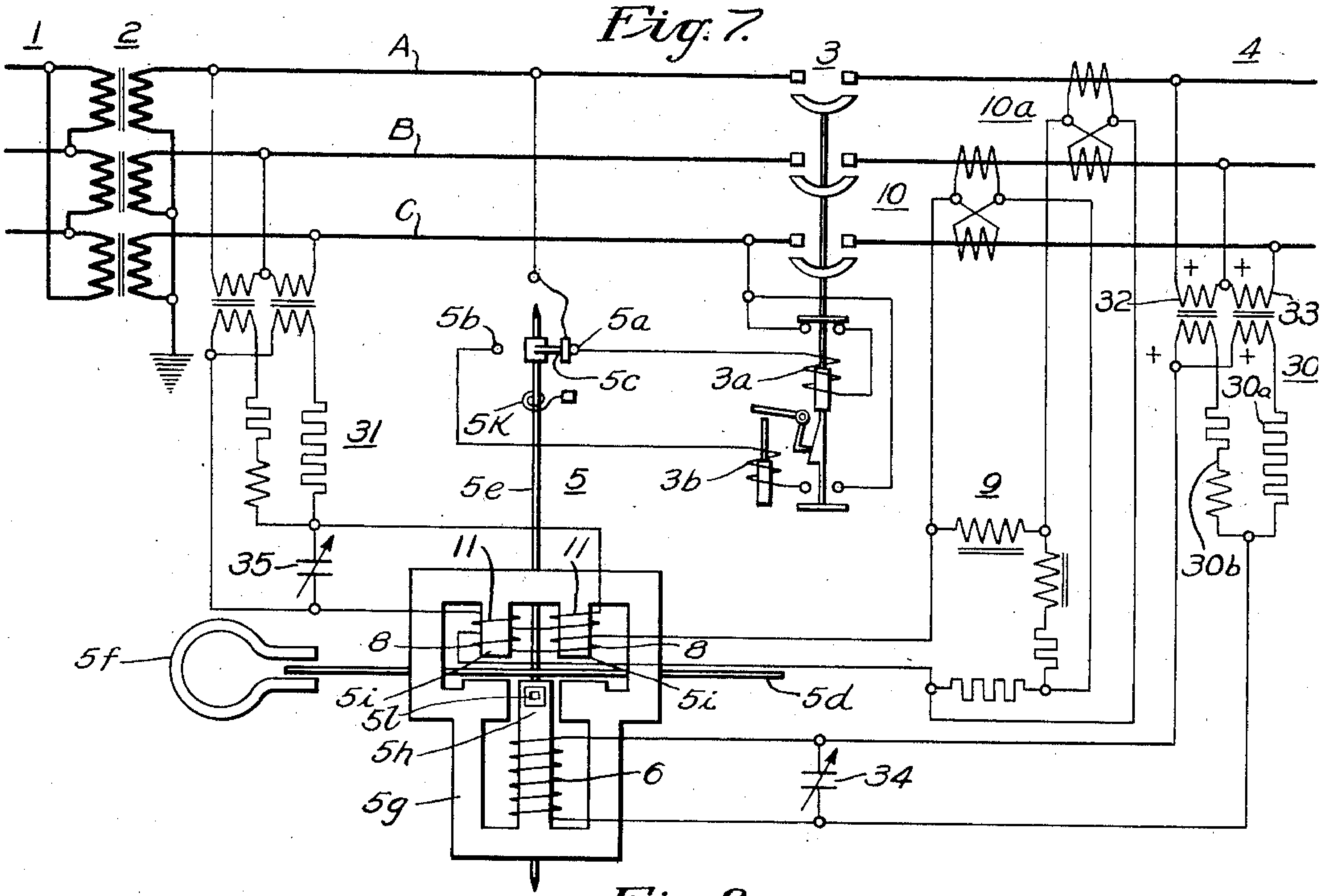
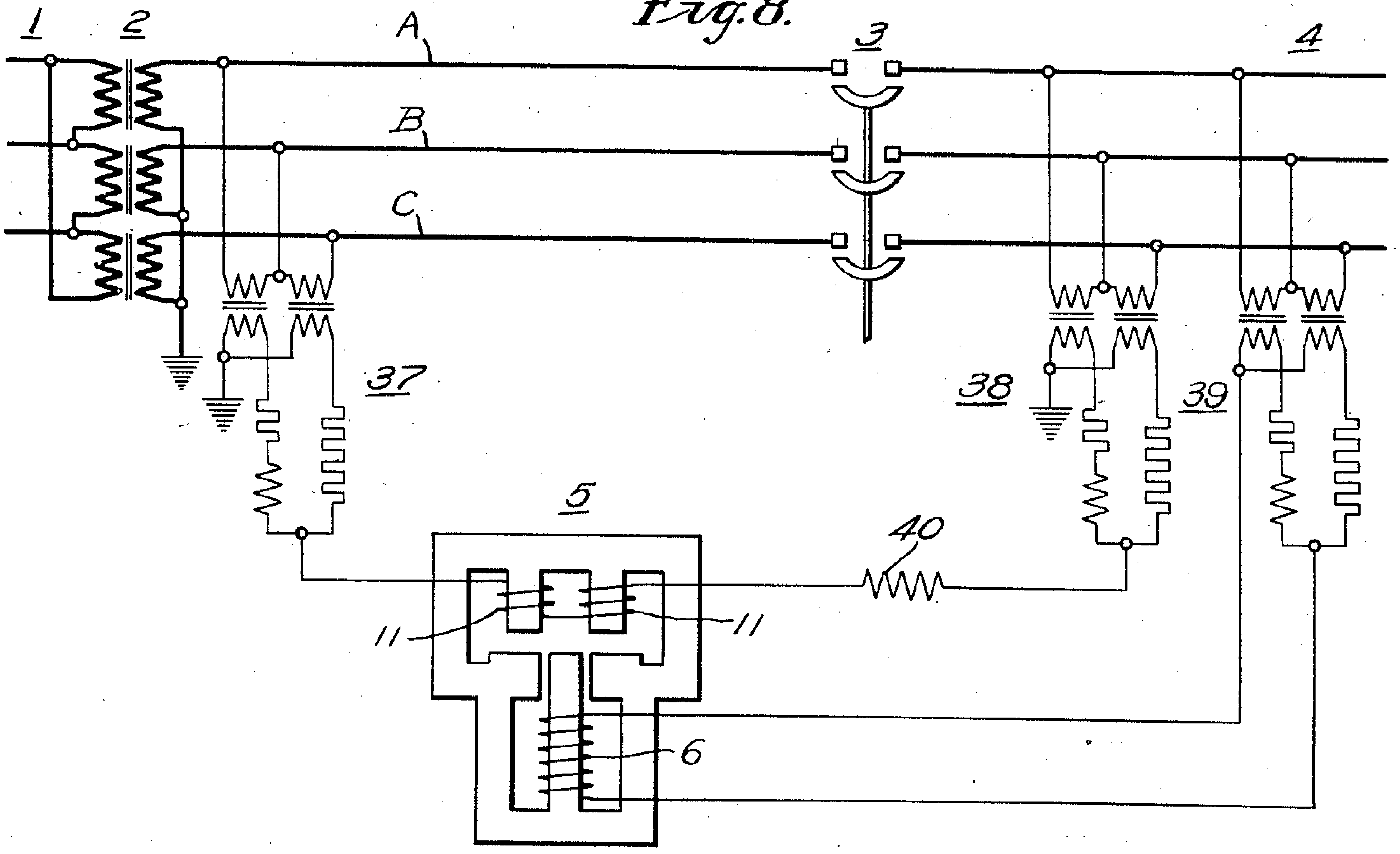


Fig. 8.



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NETWORK DISTRIBUTION SYSTEM

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Fig. 9.

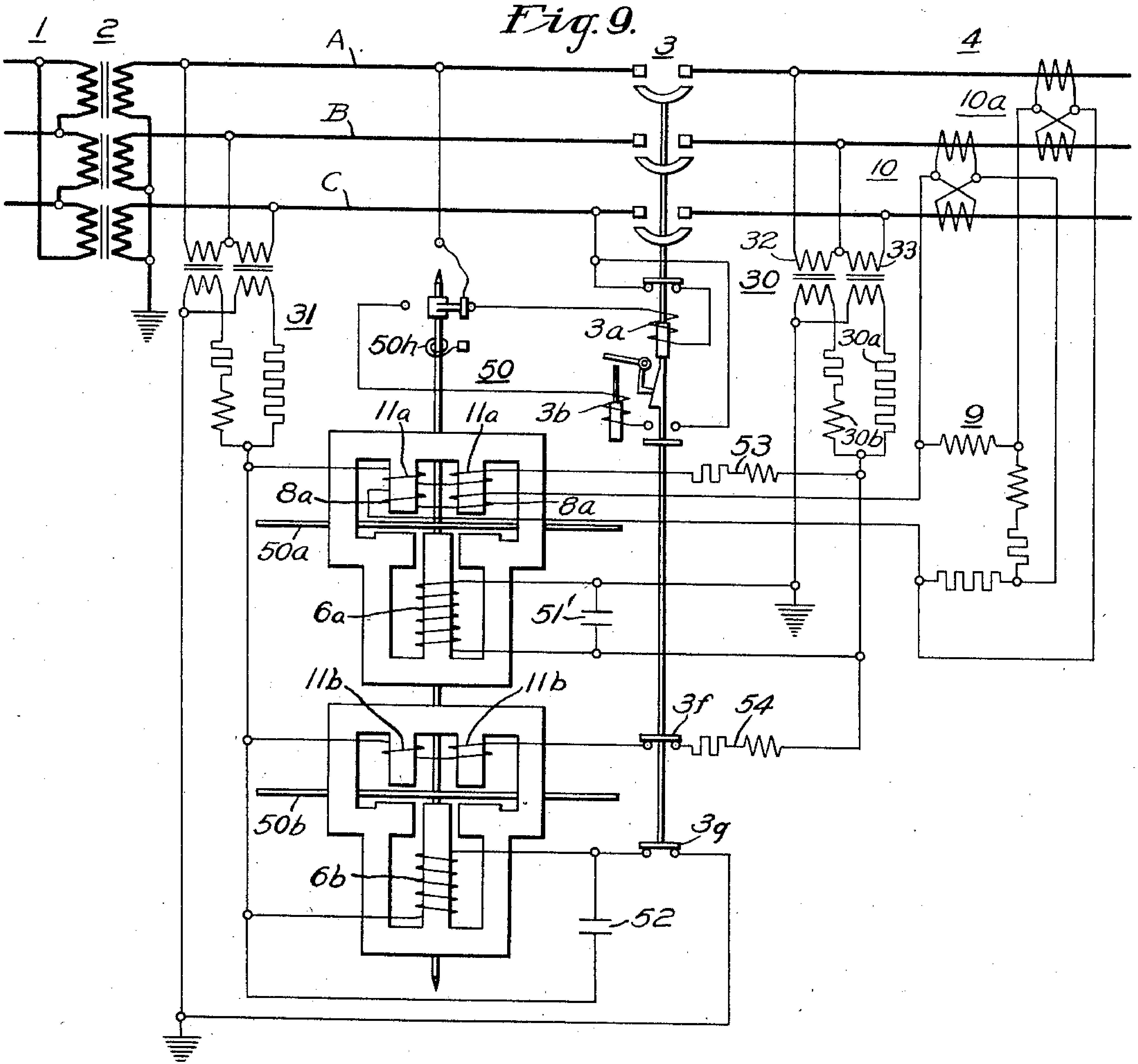
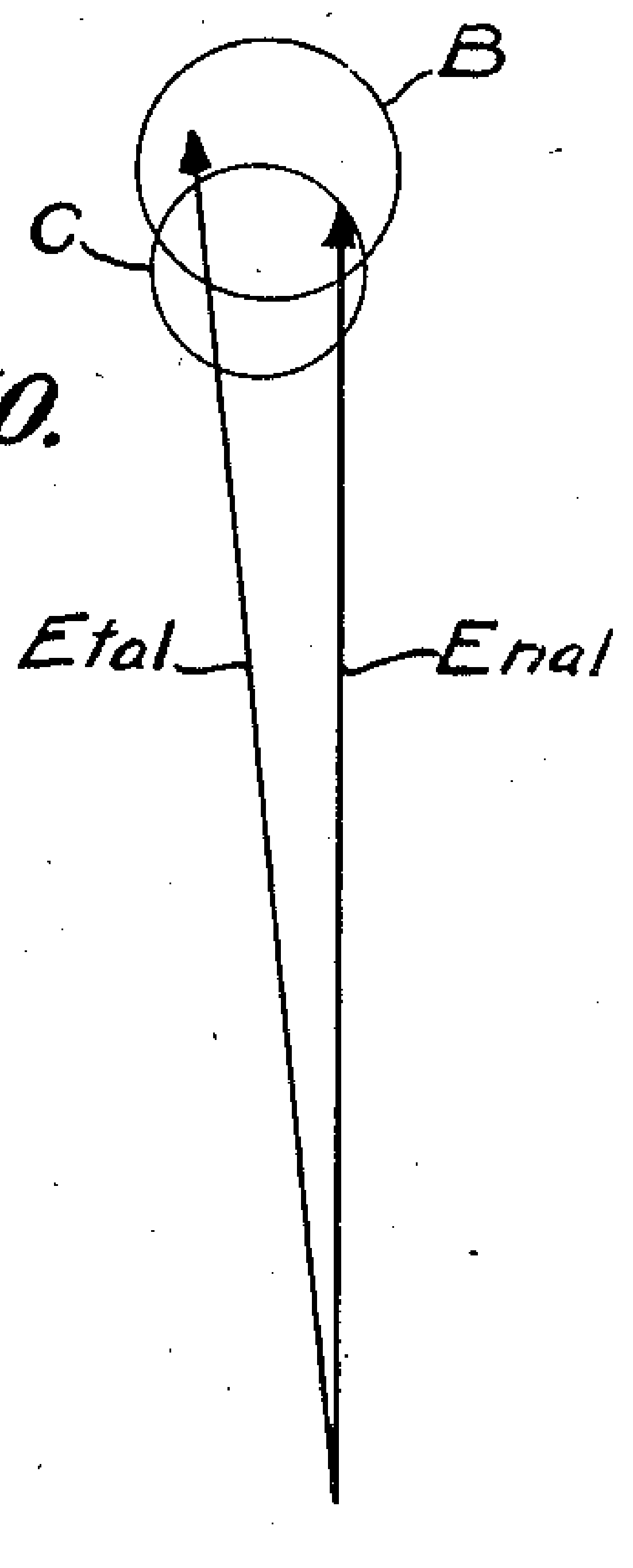


Fig. 10.



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UNITED STATES PATENT OFFICE

2,042,187

NETWORK DISTRIBUTION SYSTEM

Rolla E. Powers, Verona, Pa., and Hudson R. Searing, New York, N. Y., assignors to Westinghouse Electric & Manufacturing Company, East Pittsburgh, Pa., a corporation of Pennsylvania

Application December 21, 1932, Serial No. 648,207

29 Claims. (Cl. 175—294)

Our invention relates to protective apparatus for distribution systems, and particularly to automatic protectors for controlling the connection and disconnection of polyphase distribution systems in accordance with electrical conditions thereof.

Although not limited thereto, our invention is particularly applicable to automatic network protectors for controlling the connection and disconnection of distribution networks in systems of the so-called secondary network type. Our invention is also applicable to the control of any distribution circuits in which a sectionalizing action in response to polyphase directional power or to any vector product of polyphase voltages and currents is required. Similarly, the invention may be practiced in the automatic connection of any polyphase alternating-current circuits in response to a predetermined relationship of magnitude and phase angle of the voltages thereof.

In distribution systems of the secondary network type, a number of low voltage circuits from which the loads are directly supplied, are connected together to form a secondary grid or network, which is supplied by means of a plurality of feeders. The feeders may be energized from the same or different sources, and are usually of comparatively high voltage and connected to the network by a plurality of banks of step-down transformers. A network protector, consisting of a circuit breaker and one or more control relays, is interposed between the secondary side of each transformer bank and the network, to automatically control the connection of the feeders and the network.

The proper protection of a system of the type described above depends largely upon the characteristics and performance of the network protectors. For satisfactory operation, the network protectors must perform the following functions:

1. The network protector must close when the feeder with which it is associated is energized and the secondary network is deenergized.
2. If closed, the network protector must open and remain open, and if it is already open, it must remain open when the associated feeder is deenergized and the secondary network is energized.
3. When both the feeder and network are energized, the network protector must close only if the relative magnitude and phase relationship of the feeder and network voltages is such that the power flow immediately following closure will not cause the protector to reopen.
4. The protector must be capable of opening in response to reverse power occasioned by the magnetizing losses in its associated transformer bank or must be otherwise controllable so that all protectors connected to a feeder may be opened upon the opening of the feeder circuit breaker.
5. The characteristics of the protectors must be such that upon failure of a protector to open, because of a mechanical or electrical failure, the other protectors connected to the same feeder will not pump, that is repeatedly open and reclose.

Pumping of the protectors usually results from high feeder voltages which may occur when the feeder circuit breaker is open. If the resultant of feeder charging current and transformer magnetizing current is leading, as may be the case in a high voltage feeder, the sticking or failure to open of a protector causes a leading reverse current to flow from the network to the feeder. This leading current flowing through the inductive network impedance and transformer windings causes a rise of network voltage in the vicinity of the closed protector and a further rise of voltage in the feeder itself. If the characteristics of the open protectors are such that they reclose when the transformer secondary voltage exceeds the network voltage, the open protectors will reclose. However, as soon as a protector recloses, it carries part of the reverse current to the feeder, and the reverse power corresponding to transformer magnetizing losses causes it to reopen. The protectors will, therefore, open and reclose indefinitely unless means are provided for preventing reclosure under these conditions. As the rise of feeder voltage produced by the stuck protector results from impedance drops which lag the network voltage, the pumping action described above can be eliminated by preventing the reclosure of the network protectors when the feeder voltage is high and lagging.

The principal advantages of the secondary network system, as described above, lie in its economy of operation, reliability of service to consumer and that any faulty feeder can be completely disconnected for repairs without interruption of the supply of power to the network. As the feeders can be worked upon dead, there is no necessity for limiting feeder voltages to 4000 volts for safety to workmen. Substations for reducing generated voltages to 4000 volts are, therefore, unnecessary and the entire transformation of voltage can be effected in the transformer banks interconnecting the network and the feeders. Where such substations are already in existence, however, their apparatus can be economically used by connecting 4000 volt substation feeders through transformer banks and protectors to the network. A commercial secondary network system may, therefore, include 4000 volt feeders as well as feeders of higher voltages such as 6,600, 11,000, 13,800 and 27,600 volts.

Because of the diversified impedance characteristics of the feeders in such a system, the distribution of load between the feeders changes considerably with changes of total load and load location. Because of voltage and phase angle differences at various points in the network, large reverse power currents may flow, following the normal laws of energy interchange through a complicated network. Careful adjustment of the protectors at some locations is, accordingly, necessary to prevent excessive operations in response to reverse power currents.

If radial loads are drawn from substations from which feeders emanate to the network, part of the loads may flow through the network to the substation at periods of light load on the network, causing a reverse power flow in the substation feeders. For this reason an insensitive setting of the protectors connected to the substation feeders may be desirable to permit the flow of this reverse power without opening of the network protectors. Momentary power reversals may also occur because of synchronizing operations and regenerative operation of motors fed from the network. To avoid unnecessary protector operations from these causes, it is in many instances desirable to give the protectors a high reverse power setting of 20% to 100% of the rating of the associated transformer bank.

In order to meet the rather exacting protector requirements indicated above, it has heretofore been the practice to provide each network protector with a three-element power-directional induction-disc type relay which serves to open the protector breaker when the power flow from the network to the associated transformer bank exceeds a predetermined value. This value may correspond to transformer magnetizing losses or to a considerably higher reverse power flow depending upon the particular application of the protector. The power-directional relay also serves to reclose the protector circuit breaker when the component of transformer secondary voltage in phase with the network voltage exceeds the network voltage by a predetermined amount. In order to prevent pumping of the protector, a single-element phasing relay is in some cases provided for preventing closure of the protector circuit breaker when the transformer secondary voltage is high and lags the network voltage.

It is an object of our invention to provide a novel polyphase network protector in which a single-element power directional relay performs the function heretofore performed by a polyphase power directional master relay and a single phase phasing relay.

Another object of our invention is to provide a novel polyphase network protector in which the protector circuit breaker is opened in response to reverse positive phase-sequence power.

A further object of our invention is to provide a novel polyphase network protector in which the protector breaker is closed in response to a predetermined relationship of a symmetrical component of voltage on one side of the protector circuit breaker and a voltage derived from the other side of the protector circuit breaker.

In accordance with our invention, we provide phase sequence segregating filters to produce symmetrical components of polyphase voltages and currents, and utilize a single-element power-directional relay for controlling the opening of the network circuit breaker in accordance with a vector product of symmetrical current and voltage components. We also utilize the power directional relay to automatically reclose the network circuit breaker when the relationship of voltages on the transformer and network sides of the protector is such that power will flow from the feeder to the network upon closure of the breaker.

In order to produce a closing torque in the single-element power directional relay when voltage conditions are correct for closure of the protector, we may use any of a number of voltage combinations based upon the phase-sequence principle. In the preferred forms of our invention, the potential winding of the power directional relay is connected to a voltage phase-sequence segregating filter to be energized in accordance with a positive symmetrical component of polyphase network voltage. With the potential winding energized in this manner, the phasing windings of the relay may be energized in any of the following ways:

1. The phasing windings may be energized in accordance with the voltage difference between symmetrical components of the transformer secondary voltage and of the network voltage.

2. The phasing windings may be connected to a voltage phase-sequence filter to be energized in accordance with a positive symmetrical component of the polyphase voltage on the transformer side of the open protector.

3. The phasing windings may be energized in accordance with the voltage difference between a symmetrical component of transformer secondary voltage and a line-to-neutral or line-to-line voltage on the network side of the open protector.

Our invention may be better understood by reference to the accompanying drawings in which:

Figure 1 is a diagrammatic view of a network protector embodying our invention.

Figs. 2 and 3 are perspective and diagrammatic views, respectively, of details of the relay shown in Fig. 1.

Fig. 4 is a vector diagram showing the phasing characteristics of the protector shown in Fig. 1.

Fig. 5 is a diagrammatic view of a modification of the protector shown in Fig. 1.

Fig. 6 is a diagrammatic view showing part of a distribution system in which protectors of the type shown in Fig. 5 are used.

Fig. 7 is a diagrammatic view of a further modified form of protector embodying our invention.

Fig. 8 is a diagrammatic view of modified phasing circuits which may be used in the practice of our invention.

Fig. 9 is a diagrammatic view of a modification of our invention.

Fig. 10 is a vector diagram showing the phasing characteristics of the protector shown in Fig. 7.

Referring to Fig. 1 in detail, a polyphase feeder **1** is connected by means of a bank of transformers **2** to one side of a network circuit breaker **3**. The other side of the network circuit breaker **3** is connected to a distribution grid or network **4**, which is energized by other transformer banks (not shown), and which directly supplies part or all of the system load. Although we have shown the primary windings of the transformer bank **2** connected in delta to the feeder **1**, and the transformer secondary windings connected in star with neutral grounded, it will be understood that our invention may be practiced with other transformer connections known in the art.

The circuit breaker **3** is provided with a closing motor or coil **3***a*, and with any suitable tripping mechanism which we have illustrated as a shunt trip coil **3***b*. The closing coil **3***a* and the trip coil **3***b* are controlled in the usual manner by contact members of a power directional relay **5**, shown diagrammatically as a movable contact member **5***c*, a closing contact member **5***a* and a tripping contact member **5***b*.

The relay **5** is preferably of the induction-disc type and comprises an induction disc **5***d* rigidly secured to a rotatable spindle **5***e* in a position to rotate between the poles of a drag magnet **5***f* and a driving magnet **5***g* in the usual manner.

The driving magnet **5***g* may be of any suitable type having a potential pole **5***h* and a pair of current poles **5***i* symmetrically displaced from the potential pole. A potential winding **6** is mounted upon the potential pole **5***h* and is connected to a voltage-phase-sequence filter **7**, to be energized in accordance with a positive symmetrical component of the voltage of the distribution network **4**. The potential winding **6** has resistance and reactance of such ratio that the current through the winding at system frequency lags the voltage applied to the winding by a phase angle which will be assumed as 65°.

A pair of current windings **8** are mounted on the current poles **5***i* of the relay **5** and are connected to a current phase-sequence filter **9** to be energized in accordance with a positive symmetrical component of line current when the circuit breaker **3** is closed. The current phase-sequence filter **9** is energized by means of two pairs of current transformers **10** and **10***a* having their secondaries connected in opposition for a purpose which will be hereinafter more fully explained.

A pair of phasing windings **11** are mounted with the current windings **8** on the current poles **5***i*. The phasing windings **11** are controlled by two sets of auxiliary contact members **3***c* and **3***d* of the circuit breaker **3**, in such a manner that the phasing windings **11** are connected in a local circuit with a saturable reactor **12** when the circuit breaker **3** is closed, and are connected in series with the saturable reactor **12** and a phasing lamp **13** in a circuit which includes the output terminals of a voltage phase-sequence filter **14** and the secondary terminals of a transformer **15**, when the circuit breaker **3** is open. The voltage phase-sequence filter **14** is connected to the secondary terminals of the transformer bank **2**, and the primary winding of the transformer **15** is connected between the C-phase conductor of the network **4** and ground.

The power directional relay **5** is provided with a spring **5***k* for biasing the movable contact member **5***c* into engagement with the closing contact member **5***a*. An over-voltage adjusting loop, indicated diagrammatically at **51** is provided for biasing the movable contact member **5***c* away from the contact member **5***a* when the potential winding **6** is energized. The construction of the over-voltage adjusting loop **51** is shown in Fig. 2. As may be seen from the latter figure, the loop **51** comprises a stamping, preferably of copper, which is perforated and bent to form a short-circuited turn lying directly over the face of the potential pole **5***h*, between the pole **5***h* and the induction disc **5***d* (not shown in Fig. 2). An adjusting bolt (not shown) is provided for shifting the loop **51** tangential to the disc **5***d*, to thereby shade or lag part of the flux produced by the potential pole **5***h*. The adjusting loop **51** is so adjusted that the shifting component of flux produced by it in conjunction with the potential pole **5***h*, produces a relay torque in opposition to and slightly greater than the torque produced by the spring **5***k*. The spring **5***k* is therefore effective to maintain the movable contact member **5***c* in engagement with the closing contact member **5***a*, only as long as the potential winding **6** of the relay is deenergized. When the potential winding **6** is energized in response to normal balanced voltage of the network **4**, the torque produced by the action of the over-voltage adjusting loop **51** rotates the movable contact member **5***c* out of engagement with the closing contact member **5***a*, against the bias of the spring **5***k*.

Another detail of the relay **5** is shown diagrammatically in Fig. 3. The contact arm **5***m*, upon which the movable contact member **5***c* is mounted, is provided with a flat radial spring **5***n*. An adjustable stop member **5***p* is mounted in the path of travel of the spring **5***n* to produce a biasing torque tending to prevent the engagement of the contact member **5***c* and the tripping contact member **5***b*. It will be evident that by adjusting the stop member **5***p*, the reverse power setting of the relay **5** may be adjusted over a limited range of values.

Returning to Fig. 1, the voltage phase-sequence filters **7** and **14** are preferably of the type disclosed in the copending application of B. E. Lenehan, Serial No. 613,583, filed May 25, 1932 and assigned to the Westinghouse Electric and Manufacturing Company. The voltage phase sequence filter **7** consists of an auto-transformer **7***a* having a tap to provide a voltage less than half the total voltage impressed on the auto-transformer, for example, a 40% tap, a resistor **7***b* and a reactor **7***c*. The constants of the elements of the filter **7** are so related that the voltage drop across the resistor **7***b* is equal to the same percentage of the total voltage impressed on the resistor **7***b* and reactor **7***c* in series, as the ratio of the auto-transformer **7***a*, but lags the total voltage impressed on the resistor and reactor by a phase angle of 60°. Assuming that the phase sequence of voltages of the distribution network **4** is as indicated by the subscrips *a*, *b*, *c* of the network conductors, the voltage applied to the potential winding **6** is proportional to the positive symmetrical components of network voltage, as will be hereinafter more fully explained. The voltage phase-sequence filter **14** is similar to the filter **7** and produces an output voltage proportional to the positive symmetrical components of secondary voltage of the transformer bank **2**.

The current phase-sequence filter **9** consists of a Wheatstone bridge having a resistor **9***a*, a reactor **9***b*, the current windings **8** of the relay **5**, and a lagging impedance element **9***c* included in its four branches. The constants of these elements are related as follows: The resistance and reactance of the impedance element **9***c* are equal respectively to the resistance and reactance of the current windings **8**. The impedance of the reactor **9***b* and the current windings **8** in series is equal to the absolute value of the impedance of the resistor **9***a* and the current windings **8** in series, rotated through a phase angle of 60° in the positive or leading direction.

It was mentioned above that when the circuit breaker **3** is closed, the saturable reactor **12** is connected in a local circuit with the phasing windings **11**. The effect of this local circuit is to cause the flux produced by the current poles **5***i* to lag the current in the current windings **8**, in the same manner as a shading coil. The unsaturated reactance of the reactor **12** is so related to the remaining constants of this local circuit that the angle of lag of current pole flux behind the current in the current windings **8** is approximately 5°.

The phasing lamp **13** is preferably of the tungsten filament type and has a high temperature coefficient of resistance. The minimum resistance of the phasing lamp **13** and the maximum reactance of the saturable reactor **12** are so related that for low phasing voltages when the circuit breaker **3** is open, the current in the phasing windings **11** lags the output voltage of the voltage phase-sequence filter **14** by a phase angle of approximately 45°. It will be understood that the angular relationships of potential and phasing circuits given above are illustrative only and that in practice the actual relationship may be widely different from those given.

The operation of the above-described apparatus may be set forth as follows: It is assumed that initially the feeder **1** and the network **4** are deenergized, and the circuit breaker **3** and relay **5** are in the position shown in the figure.

If the feeder is first energized, the secondary windings of transformer bank **1** develop a polyphase voltage, and the voltage phase sequence filter **14** supplies a positive symmetrical component of this voltage, to the phasing windings **11**. As the circuit breaker **3** is open, no current flows through the current transformers **10** and **10***a*, and the current in the current windings **8** is zero. As the network **4** is dead, no voltage is applied to the potential winding **6** of the relay **5**. The relay **5** accordingly develops no torque and the spring **5***k* maintains the movable contact member **5***c* in engagement with the closing contact member **5***a*. Because of the engagement of contact members **5***c* and **5***a*, a circuit is completed for the closing coil **3***a* of the circuit breaker **3**, and the circuit breaker **3** closes and is latched in.

Upon closure of the circuit breaker **3**, the distribution network **4** is energized, and the voltage phase-sequence filter **7** supplies a positive symmetrical voltage component to the potential winding **6** of the relay **5**. Power now flows from left to right in the figure to supply the load of network **4**.

As the potential winding **6** is now energized through the voltage phase-sequence filter **7**, and the current-windings **8** are energized through the current phase-sequence filter **9**, the relay **5** now develops a torque dependent upon the magnitude and phase relationships of the currents in the windings **6** and **8**.

It may be shown that the output current of the current phase sequence filter **9**, because of the impedance relationships and connections described above, is

$$i_8=1.73e^{-j30°}\left(\frac{i_a+i_be^{j120°}+i_ce^{j240°}}{3}\right) \qquad (1)$$

where

i_8=current in the current winding 8

$\left.\begin{matrix}i_a\\ i_b\\ i_c\end{matrix}\right\}$=star currents of the network 4

e=the base of the natural logarithms

j=the imaginary $\sqrt{-1}$

In the above notation, $e^{j120°}$ and $e^{j240°}$ are operators which rotate their respective multipliers through 120° and 240°, respectively, in the counterclockwise or leading direction.

It may also be shown that the output voltage of the voltage phase sequence filter **7** is

$$E_6=3ke^{-j60°}\left(\frac{E_a+E_be^{j120°}+E_ce^{j240°}}{3}\right) \qquad (2)$$

where

E_6=voltage impressed on the potential winding 6

$\left.\begin{matrix}E_a\\ E_b\\ E_c\end{matrix}\right\}$=star voltages of the network 4

k=the turn ratio of the autotransformer 7a.

Let

i_6=current in the potential winding **6**

$Ze^{j65°}$=impedance of the potential winding **6**

Because of the 65° lagging impedance of the potential coil **6**,

$$E_6=i_6Ze^{j65°} \qquad (3)$$

Multiplying both sides of (3) by $e^{-j65°}$ and re-arranging

$$i_6=\frac{E_6}{Z}e^{-j65°} \qquad (4)$$

Substituting (2) in (4)

$$i_6=3ke^{j125°}\left(\frac{E_a+E_be^{j120°}+E_ce^{j240°}}{3}\right) \qquad (5)$$

Equation (5) gives the current in the potential winding **6** in terms of the network voltages E_a, E_b, and E_c.

By means of the symmetrical component relationships, explained in many engineering papers on the subject, any unbalanced system of polyphase vectors such as the star currents i_a, i_b, and i_c may be resolved into three systems of symmetrical polyphase components, called positive, negative and zero sequence components. Denoting the a-phase components of the positive, negative and zero phase-sequence systems by i_{a1}, i_{a2}, and i_{a0} respectively, the relationships are

$$i_{a0}=\frac{i_a+i_b+i_c}{3} \qquad (6)$$

$$i_{a1}=\frac{i_a+ai_b+a^2i_c}{3} \qquad (7)$$

$$i_{a2}=\frac{i_a+a^2i_b+ai_c}{3} \qquad (8)$$

where a is the 120° rotational operator $e^{j120°}$, and a^2 is the 240° rotational operator $e^{j240°}$.

Denoting the a-phase zero, positive and negative voltage components by E_{a0}, E_{a1}, and E_{a2} respectively, the system of network voltages E_a, E_b and E_c may be similarly represented by components:

$$E_{a0}=\frac{E_a+E_b+E_c}{3} \qquad (9)$$

$$E_{a1}=\frac{E_a+aE_b+a^2E_c}{3} \qquad (10)$$

$$E_{a2}=\frac{E_a+a^2E_b+aE_c}{3} \qquad (11)$$

Recalling that $a=e^{j120°}$ and $a^2=e^{j240°}$, Equation (7) may be substituted directly into Equation (1) giving

$$i_8=1.73e^{-j30°}i_{a1} \qquad (12)$$

From Equation (12) it may be seen that the current in the current windings **8** is proportional to the positive symmetrical components of line current and lags the a-phase positive component by 30°. However, the flux produced by the current i_0 lags the current i_{a1} by 30°+5° or 35°, because of the lagging effect of the local circuit through the phasing windings **11** and reactor **12**.

Similarly Equation (10) may be substituted into Equation (5) giving

$$i_6=3ke^{-j125^\circ}E_{a1} \qquad (13)$$

Equation (13) shows that the current in the potential winding **6** of the relay **5** is proportional to the positive symmetrical components of network voltage and lags the a-phase positive voltage component by a phase angle of 125°. As the flux produced by the potential winding **6** is in phase with the current i_6, the potential pole flux also lags E_{a1} by a phase angle of 125°.

It will be seen from Equations (12) and (13) that the torque of the relay **5** is a function of the power product $E_{a1}i_{a1}$ and is a maximum when i_{a1} is in phase with E_{a1}, as the fluxes produced by the windings **6** and **8** are, under these conditions, in quadrature. The relay **5** accordingly has watt tripping characteristics for the product $E_{a1}i_{a1}$, and its torque is proportional to $E_{a1}i_{a1}\cos\theta_1$, where θ_1 is the phase angle between E_{a1} and i_{a1}, neglecting current transformer phase angle and voltage errors.

The physical significance of the positive power product $E_{a1}i_{a1}$ may be explained as follows. The power in a polyphase circuit of any number of conductors may, as is well known, be measured by using any conductor of the circuit as a reference conductor, and measuring the voltages between the reference conductor and each of the remaining conductors, and the current in each conductor except the reference conductor. The total power then is the algebraic sum of the vector products of each voltage measured and the corresponding current

$$P=\Sigma E_n i_n \qquad (14)$$

If there are n circuits at a section of the polyphase system, $(n-1)$ voltages and $(n-1)$ currents or $2(n-1)$ independent parameters are necessary to completely determine the power flow at the section. In a three-phase four-wire system $2(n-1)=6$, and therefore six independent parameters are necessary to determine the power flow. In order to distribute the voltage stresses in relay or meter windings in a three-phase four-wire system, it is usually preferable to use the neutral conductor as reference and measure voltages and currents in the manner explained above. However, any other conductor may be used as reference conductor without affecting the result. The total power of the three-phase four-wire system, expressed in star voltages and currents is

$$p=E_a i_a+E_b i_b+E_c i_c \qquad (15)$$

The three power products on the right side of Equation (15) represent power flow in each of the three phases referred to the neutral conductor as reference. These products are equivalent to single-phase power flow in each of three separate circuits. By shifting the reference point to other conductors, such as the a-phase conductor, the total power could be represented by three power products having the same total value, but now corresponding to single-phase power flow in three fictitious circuits taken from the a-phase conductor as reference. By using the symmetrical component relationships, the total power can also be expressed in terms of power components representing polyphase power flow through all of the conductors together, as will be hereinafter more fully explained.

The equations given above are all based on the conception of alternating currents and voltages as stationary vectors having magnitude and angular position. Actually they are alternating scalar quantities, that is, products of scalar maximum values such as I and scalar time functions such as cos wt. A power quantity is accordingly a product of two scalar alternating quantities of line frequency.

$$\begin{aligned}
p&=\sqrt{2}E\cos wt\,\sqrt{2}I\cos(wt+\theta) && (16)\\
&=2\,EI\cos wt\cos(wt+\theta)\\
&=2EI\left(\frac{e^{iwt}+e^{-iwt}}{2}\right)\left(\frac{e^{i(wt+\theta)}+e^{-i(wt+\theta)}}{2}\right)\\
&=EI\left\{\left(\frac{e^{i\theta}+e^{-i\theta}}{2}\right)+\left(\frac{e^{i(2wt+\theta)}+e^{-i(2wt+\theta)}}{2}\right)\right\}\\
&=EI\cos\theta+EI\cos(2wt+\theta) && (17)
\end{aligned}$$

From Equation (17), it may be seen that the power product consists of a direct or zero frequency term EI cos θ and a term of double the line frequency EI cos $(2wt+\theta)$. The double frequency term disappears when integrated over a complete cycle, and hence represents a double frequency pulsation which does not change the average value of total power. In power-responsive meters or relays, the average power value EI cos θ produces the instrument deflection, and the double frequency term appears as a double frequency torque which produces no average deflection. The double frequency term may accordingly be neglected so far as its effect upon relays or meters is concerned.

As the power in a three-phase four-wire system is completely determined by six independent parameters, it may be expressed as a function of six independent phase sequence quantities such as E_{a0}, E_{a1}, E_{a2}, i_{a0}, i_{a1}, and i_{a2}. These six phase-sequence quantities are actually alternating scalar quantities of the general form indicated in connection with Equations (16) and (17).

However, any alternating scalar quantity may be represented as the sum of two oppositely rotating vectors of equal magnitude called principal and conjugate vectors. Employing the latter conception, the effective symmetrical components of star currents and voltages of the network **4** may be represented by

$$\left.\begin{aligned}
E_{a0}&=\frac{\check{E}_{a0}+\hat{E}_{a0}}{\sqrt{2}}\\
E_{a1}&=\frac{\check{E}_{a1}+\hat{E}_{a1}}{\sqrt{2}}\\
E_{a2}&=\frac{\check{E}_{a2}+\hat{E}_{a2}}{\sqrt{2}}\\
i_{a0}&=\frac{\check{I}_{a0}+\hat{I}_{a0}}{\sqrt{2}}\\
i_{a1}&=\frac{\check{I}_{a1}+\hat{I}_{a1}}{\sqrt{2}}\\
i_{a2}&=\frac{\check{I}_{a2}+\hat{I}_{a2}}{\sqrt{2}}
\end{aligned}\right\}\text{------------- (18)}$$

where

$$\left.\begin{aligned}
\check{E}_{a1}&=E_{a1}e^{iwt}\\
\hat{E}_{a1}&=E_{a1}e^{-iwt}\\
\check{I}_{a1}&=i_{a1}e^{i(wt+\theta_1)}\\
\check{I}_{a1}&=i_{a1}e^{-i(wt+\theta_1)}
\end{aligned}\right\}\text{etc., ------ (19)}$$

Using the notation of Equation (16) the zero frequency or average total power may be expressed as a complex quantity $P+jQ$, where P is real power and Q is reactive power

$$P+jQ=3(\check{E}_{a0}\hat{I}_{a0}+\check{E}_{a1}\hat{I}_{a1}+\check{E}_{a2}\hat{I}_{a2}) \qquad (20)$$

The proof of Equation (20) is not given here but may be found in a paper entitled "The Measurement of Power in Polyphase Circuits" by C. LeG. Fortescue in the Transactions of the A. I. E. E., 1923, volume 43, page 358.

Substituting,

$$P_0+jQ_0=3\check{E}_{a0}\hat{I}_{a0}=\text{zero sequence power}$$

$$P_1+jQ_1=3\check{E}_{a1}\hat{I}_{a1}=\text{positive sequence power} \qquad (21)$$

$$P_2+jQ_2=3\check{E}_{a2}\hat{I}_{a2}=\text{negative sequence power}$$

Equation (20) may be rewritten.

$$P+jQ=P_0+P_1+P_2+j(Q_0+Q_1+Q_2) \qquad (22)$$

Each of the quantities on the right side of Equation (22) represents symmetrical power flow through all three phases of the circuit, the P components representing real power and the Q components reactive power. These quantities are symmetrical in the sense that their component voltages and currents are equal and displaced by phase angles such that the sum of each set of phase angles is 360° or a multiple thereof. The positive components which produce P_1 and Q_1, are displaced from each other in the order ABC by +120°, the negative components which produce P_2 and Q_2 are displaced from each other by +240° or −120°, that is are of reversed phase sequence. The zero components which produce P_0 and Q_0 are displaced from each other by 360° or are in phase.

It will therefore be seen that only the positive and negative power components represent balanced three-phase power, the negative power components P_2 and Q_2 being of reversed phase sequence.

From (21), the positive power product is

$$P_1+jQ_1=3\check{E}_{a1}\hat{I}_{a1} \qquad (23)$$

Substituting values of $\check{E}_{a1}$ and $\hat{I}_{a1}$ from (19) in (23)

$$P_1+jQ_1=3E_{a1}e^{iwt}i_{a1}e^{-i(wt-\theta_1)}=3E_{a1}i_{a1}e^{-i\theta_1} \qquad (24)$$

However

$$e^{i\theta_1}=\cos\theta_1+j\sin\theta_1 \qquad (25)$$

Substituting (25) in (24)

$$P_1+jQ_1=3E_{a1}i_{a1}\cos\theta_1+j3E_{a1}i_{a1}\sin\theta_1 \qquad (26)$$

As the real components on both sides of Equation (26) must be equal,

$$P_1=3E_{a1}i_{a1}\cos\theta_1 \qquad (27)$$

It was shown above that the torque of relay **5** is proportional to the product $E_{a1}i_{a1}\cos\theta_1$, which from Equation (27) may be seen to be the real component of positive sequence power or P_1.

It will be noted from Equation (22) that the total real power of the system, P may be represented as the sum of three real sequence components P_0, P_1, and P_2, and that the total reactive power Q may be represented as the sum of three reactive sequence components Q_0, Q_1, and Q_2. It is shown in the paper of C. LeG. Fortescue, mentioned above, that a symmetrical generator can generate only positive sequence power, and that where negative sequence or zero sequence power exists, it is transformed from positive sequence power at the unbalanced loads. The direction of flow of negative and zero sequence power at a symmetrical generator is accordingly opposite to the direction of positive sequence power, that is, the negative and zero sequence power quantities flow into the generator and are absorbed in the generator negative and zero sequence admittances.

It follows that the total power output P of a symmetrical generator, as measured by a conventional wattmeter, cannot be greater than P_1, the positive symmetrical power component, and will be less than P_1 if the generator load is unbalanced.

As the negative sequence power is generated at unbalanced loads or faults and is absorbed by negative sequence admittances, a great deal of this power is absorbed in the network by induction motors and other polyphase apparatus having high negative sequence admittance and hence all does not return to the generator. We propose to use this phenomenon in connection with the circuit shown in Fig. 5, as will hereinafter be more fully explained.

Returning to the operation of the apparatus shown in Fig. 1, if a fault develops on the network **4**, the flow of positive sequence power remains from left to right in the figure, and the full capacity of transformer bank **2** as well as other transformer banks connected to the network **4** is available to burn the fault clear in the usual manner.

If an unbalanced fault develops on the feeder **1**, upon opening of the feeder breaker (not shown) the total power P flowing through the circuit breaker **3** reverses as usual. As the unbalanced fault generates a component of negative phase-sequence power, which flows into the network **4** from the fault, the direction of negative sequence power through the circuit breaker **3** also reverses, and negative sequence power flows from left to right in the figure. The reversal of both total power and negative sequence power requires that a positive sequence power component greater than the total power P flow from the network **4** to the feeder **1**. In response to this reversed positive sequence power flow, the torque of the relay **5** reverses and the movable contact member **5c** moves rapidly into engagement with the tripping contact member **5b**.

If the fault on feeder **1** is balanced rather than unbalanced, and the feeder breaker (not shown) is opened, no negative sequence power is generated at the fault, and positive sequence power flows from the network **4** to the fault. This causes a reversal of torque in the relay **5**, so that the contact member **5c** engages the contact member **5b**.

Upon engagement of the contact members **5c** and **5b**, a circuit for the trip coil **3b** is completed, and the circuit breaker **3** trips open. As soon as the circuit breaker **3** opens, the current phase-sequence filter **9** and the current windings **8** of the relay **5** becomes de-energized. As the feeder circuit breaker (not shown) is open, the voltage phase-sequence network **14** is deenergized. However, the secondary voltage of transformer **15** acts upon the phasing windings **11** to produce a torque which maintains the movable contact member **5c** in engagement with the tripping contact member **5b**. The over-voltage adjusting loop **51** acts in conjunction with the potential winding **6** to produce a torque which also tends to maintain the movable contact member **5c** in engagement with the tripping contact member **5b**, so that the contact member **5c** is held firmly in engagement with the tripping contact member **5b**.

When the fault on feeder **1** has been cleared and the feeder voltage has been restored, the voltage phase-sequence filter **14** becomes energized and supplies a voltage to the phasing circuit which includes the phasing winding **11**, saturable reactor **12**, phasing lamp **13** and the secondary winding of transformer **15**. It will be recalled from Equation (2) above, that the output voltage of the voltage phase-sequence filter **7** is proportional to the positive symmetrical components of network voltage and lags the *a*-phase positive component by 60°. As the voltage filter **14** is similar to the voltage filter **7**, its output voltage is proportional to the positive symmetrical components of transformer secondary voltage and lags the *a*-phase positive component by 60°. However, as a voltage lagging *a*-phase by 60° is 180° out of phase or opposite to *c*-phase, the output voltage of the network **14** is equal to the *c*-phase voltage produced by the transformer **15** when the secondary voltage of transformer bank **1** is in phase with the voltage of the network **4**.

The voltage applied to the phasing circuit accordingly is a difference voltage which becomes zero when the *c*-phase positive component of secondary voltage of the transformer bank **2** and the *c*-phase voltage of network **4** are equal and in phase. When the difference voltage acting in the phasing circuit is small, the current in the phasing winding **11** lags the difference voltage by approximately 45° as explained above. When the difference voltage is large the resistance of the phasing lamp **13** increases because of its positive temperature coefficient of resistance, and the reactance of the saturable reactor **12** decreases because of saturation. The angle of lag of current in the phasing winding **11** accordingly decreases with larger values of difference voltage.

It will be recalled from Equation (5) that the current in the potential winding **6** lags the *a*-phase positive component of voltage of network **4** by 125°. The maximum closing torque of the relay **5** occurs when the currents in the phasing windings **11** and the potential winding **6** are in quadrature, that is, when the current in the phasing windings **11** lags the *a*-phase positive components of voltage of the network **4** by 125°+90° or 215°.

However, when the difference voltage is small it must lead the current in the phasing winding **11** by 45° or must lag the *a*-phase positive component of network voltage by 215°−45° or 170° to produce maximum torque in the relay **5**. This is equivalent to leading the *c*-phase positive component of network by 240°−170° or 70°.

As the zero torque curve is in quadrature with the maximum torque curve, it lags the *c*-phase positive component of network voltage by 20°. This relationship is shown in Fig. 4, in which the *c*-phase symmetrical component of voltage of the network **1**, E_{c1}, is shown vertical for convenience and the zero torque characteristic of the relay **5** is indicated by characteristic curve A. It will be understood that if the *c*-phase positive symmetrical component of the secondary voltage of transformer bank **2**, denoted by the vector E_{cn1} terminates above the curve A, a closing operation of the relay **5** is indicated. It will be noted that if the secondary voltage of transformer bank **2** is high and lagging, the vector E_{cn1} will not intersect the curve A. This prevents pumping of the protector in the event of a stuck protector as discussed above. Although we prefer to practice our invention with the closing curve A rotated approximately 20° from the network voltage, we may practice it with the curve A in various other positions. By varying the constants of the phasing lamp **13** and reactor **12** or by varying other constants of the circuit various desirable closing characteristics may be obtained.

The bend of the closing curve A at its extremes results from the decrease of impedance angle in the phasing circuit with increasing difference voltages, as explained above. The purpose of this bend is to prevent the closing curve A from intersecting or approaching the voltage E_x shown in dotted lines.

It will be apparent that upon repairing a feeder fault, the ends of the feeder conductors may be incorrectly connected in several ways. The most frequently occurring incorrect connection is the reversal of two phase conductors giving a reversed phase sequence ACB at the terminals of the transformer bank **2**. With this connection, the positive symmetrical components of secondary voltage for the normal phase sequence ABC becomes zero. The output voltage of the phase-sequence filter **14** accordingly becomes zero, and the movable contact member **5c** is held in engagement with the tripping contact member **5b** as though the feeder **1** were deenergized. The circuit breaker **3** accordingly remains open under these conditions.

If in splicing the feeder cable, the ends of the cable are incorrectly connected to produce the sequence BCA or CAB at the terminals of transformer bank **1**, the direction of phase rotation remains the same and the phase-sequence filter **14** supplies a voltage of normal value to the phasing windings **11**, but displaced by +120° or +240° from the normal phase position. These voltages correspond to voltages E_x and E_y of Fig. 4. It will be seen that only the voltage E_x terminates in the neighborhood of the curve A. However because of the bend of curve A, the voltage E_x cannot intersect the curve and the circuit breaker **3** remains open.

By incorrectly connecting the transformers **2** and the phases of feeder **1**, various incorrect voltages different from E_x and E_y may be produced. However, as the voltages across the open circuit breaker contact members are always checked upon installing a new protector, any voltages which involve incorrect transformer connections may be disregarded as sources of faulty operation.

When the difference between the *c*-phase positive symmetrical component of the secondary voltage of transformer bank **2** and the *c*-phase voltage of the network **4** exceeds the positive symmetrical component of the voltage of network **4** by a predetermined amount corresponding to the adjustment of the over-voltage adjusting loop **51**, and terminates within the leading range of voltages determined by curve A of Fig. 4, the movable contact member **5c** of the relay **5** moves into engagement with the closing contact member **5a**.

Upon engagement of the contact members **5c** and **5a**, a circuit for the closing coil **3a** is completed, and the circuit breaker **3** closes. It will be observed that in the above operation, the relay **5** performs the functions of both the 3-element power directional relay and the single-element phasing relay ordinarily used in automatic protectors.

Fig. 5 shows a modification of the protector shown in Fig. 1. Referring to Fig. 5 in detail, the feeder **1**, transformer bank **2**, circuit breaker

3, network **4**, relay **5**, voltage phase sequence filters **7** and **14**, current transformers **10** and **10a**, saturable reactor **12**, the phasing lamp **13** and transformer **15** are similar to the corresponding elements of Fig. 1 and are connected in the same manner.

However, in Fig. 5, an over-current relay **16** is substituted for the impedance element **9c** of Fig. 1. A second over-current relay **17** is included in the circuit of the current windings **8**. The contact members of the relays **16** and **17** are connected in parallel in the circuit of the trip coil **3b**.

The relationship of impedances in the current phase-sequence filter **9** of Fig. 5 is as follows: The impedance of the relay **16** is equal in absolute value and in phase angle to the impedance of the relay **17** and phasing winding **11** in series. The impedance of the relay **16** and reactor **9b** in series is equal to the impedance of the resistor **9a** and the relay **16** in series rotated through an angle of 60° in the leading direction. It will be seen that the impedance relationships of the network **9** as a whole are the same in Fig. 5 as in Fig. 1.

Because of the impedance relationships in the phase sequence filter **9**, the current in the relay **16** is proportional to the negative symmetrical components of the star currents i_a, i_b, *and* i_c.

The reverse-power setting mechanism of Fig. 3 may be omitted from the relay **5** in the protector shown in Fig. 5. However, if the reverse power setting mechanism is used it should be set for such a low value of reverse power that the movable contact member **5c** will engage the tripping contact member **5b** in response to the reverse power flow corresponding to the magnetizing losses of the transformer bank **2**. The over-current relay **17** is designed to close when the positive sequence current flowing through the protector corresponds to a comparatively high percentage such as 20% to 100% of the rating of the transformer bank **2**. The over-current relay **16** is designed to remain open as long as the flow of negative sequence current through the protector is within the normal limits encountered during operation, and to close when negative phase-sequence currents of comparatively large value are forced through the protector.

The operation of the protector shown in Fig. 5 may be set forth as follows: The closing operations when the network **4** is dead and when both the feeder **1** and the network **4** are energized are the same as described above in connection with Fig. 1.

However, for a tripping operation to occur in the protector shown in Fig. 5, it is necessary that the negative symmetrical component of star currents supplied by the current phase sequence filter **9** exceeds the setting of relay **16** or that the positive symmetrical component exceeds the setting of relay **17** and that the direction of flow of positive sequence power is from the network **4** to the feeder **1**.

It was explained above that negative phase-sequence power is produced at unbalanced loads and is absorbed by negative phase sequence admittances either in the network or at the generator. As the negative phase-sequence admittances of induction motors and other polyphase apparatus connected to a network such as is indicated by the reference character **4** is very high, practically all of the negative phase-sequence power is absorbed in the network and very little flows in reverse direction through the protectors. We have found by tests on a representative 3-phase delta connected 13,200 volt underground cable feeder that the negative sequence current flowing at light loads and at heavy loads during normal operation was about one-tenth of that which could be produced by grounding one phase of the delta connected feeder.

Fig. 6 shows a feeder circuit equipped with various negative phase-sequence power sources for controlling a number of protectors of the type shown in Fig. 5. Referring to Fig. 6 in detail, the feeder **1** is connected by means of a circuit breaker **18** to a polyphase source (not shown). A plurality of transformer banks **2** and protectors, indicated diagrammatically at **3**, are interconnected between the feeder **2** and the distribution network **4**. It will be understood that the network **4** is also supplied from other feeders not shown. A switch **19** is provided for grounding one phase of the feeder **1**, and a second switch **20** is provided for connecting an impedance load **21** from phase to phase across a pair of secondary terminals of one of the transformer banks **2**.

A synchronous generator **22** and an induction motor **23** are connected in series to the secondary windings of a transformer bank **24**, energized from the feeder **1**, by means of a switch **25**. The windings of the generator **22** and induction motor **23** are connected in such relative directions that when the induction motor **23** rotates in the direction determined by the phase sequence of secondary voltage of transformer bank **24**, the generator **22** generates a voltage of opposite or negative phase sequence. An exciter **26** is provided for supplying direct current to the field winding of the generator **23**.

Assuming that the circuit breakers and switches shown in Fig. 6 are in the positions shown and that power is flowing through the feeder **1** into the network **4**, the protectors **3** may all be opened by opening the circuit breaker **18** and closing any of the switches **19**, **20** or **25**. Upon the opening of switch **18**, the power flow from the source (not shown) is interrupted and the magnetizing losses of the transformer banks **3** and the charging current of feeder **1** are supplied in reverse direction from the network **4**. The reverse positive sequence power which flows through the protectors **3** from his cause is sufficient to operate the power-directional relay **5** (Fig. 5) of each protector but not the over-current relay **17**. The protectors **3** accordingly remain closed.

If the switch **19** is now closed, the charging current of the feeder **1** becomes unbalanced, and, in response to the negative phase sequence current set up in his way, the negative phase sequence over-current relay **16** closes and the protectors **3** trip open.

If the switch **20** rather than the switch **19** is closed, a large negative sequence current flows from the impedance **21** through the right protector **3** to the negative sequence admittances of the polyphase load devices connected to the nework **4**. The protector **3** on the right immediately opens, causing the remaining closed protectors **3** to carry the negative sequence current. As each protector **3** opens, the negative sequence current carried by the others increases until all are opened.

If the switch **25** is closed rather than the switches **19** or **20**, the generator **22** produces a negative phase-sequence voltage and negative phase-sequence current flows from the generator **22**, through the protectors **3** to be absorbed in the negative phase-sequence admittances of the network **4**. The protectors **3** accordingly open in the manner previously described.

Fig. 7 shows a modified form of protector in which phasing is accomplished by a positive symmetrical component of transformer secondary voltage rather than a difference voltage as in Figs. 1 and 5. Referring to Fig. 7 in detail, the feeder **1**, transformer bank **2**, circuit breaker **3**, relay **5** and current phase sequence filter **9** are the same as the corresponding elements of Fig. 1.

A pair of voltage phase-sequence filters **30** and **31** of a different type from the filters **7** and **14** of Fig. 1 are provided for energizing the potential winding **6** and the phasing windings **11** of the relay **5**, respectively.

The filter **30** is energized by means of a pair of voltage transformers **32** and **33** having their primaries connected between the *a* and *b* phase conductors and the *b* and *c* phase conductors, respectively, of the distribution network **4**. The secondary windings of the transformers **32** and **33** are connected in parallel circuits which include a resistor **30***a* and an impedance element **30***b*. The polarities of the windings of transformers **32** and **33** are indicated by polarity marks on the figure. The impedance of the parallel branch circuit which includes the impedance element **30***b* and the secondary winding of transformer **32** is equal to the impedance of the parallel branch which includes the resistor **30***a* and the secondary winding of transformer **33**, rotated through a phase angle of 60° in the positive or leading direction. The phase sequence filter **31** is identical with the filter **30**.

A pair of impedance elements, which we have illustrated as adjustable condensers **34** and **35** are connected in parallel with the potential winding **6** and phasing windings **11**, respectively, for varying the phase angle of currents in the latter windings.

It may be shown by means of equations similar to those heretofore considered in connection with Fig. 1, that the voltage E_{30} impressed on the potential winding **6** is

$$E_{30}=\frac{Ea+Ebe^{j120°}+Ece^{j240°}}{1-e^{j60°}+\frac{Z_{33}}{Z_{34}}e^{j60°}} \qquad (28)$$

Where Z_{33}=the impedance of the parallel branch circuit which includes the resistor **30***a* and the secondary winding of transformer **33**.

$Z_{33}e^{j60°}$=the impedance of the parallel branch circuit which includes the impedance element **30***b* and the secondary winding of the transformer **32**.

Z_{34}=the impedance of the potential winding **11** and condenser **34** in parallel.

It will be apparent from inspection of Equation (23) that the voltage E_{30} is proportional to the positive symmetrical components of voltage of the network **4**. By varying the capacitance of the condenser **34**, the phase angle of the current in the potential winding **6** can be varied over a range of almost 180° with respect to the voltage E_{30}. Similarly, by adjusting the condenser **35** the phase angle of the current in the phasing windings **11** can be adjusted over a similar range.

It will be assumed the condenser **34** is adjusted to give watt tripping characteristics of the relay **5**, and the condenser **35** is adjusted so that the phasing torque of the relay will be a maximum when the *a*-phase positive symmetrical component of secondary voltage of the transformer bank **2** leads the *a*-phase positive symmetrical component of voltage of the network **4** by a large angle such as 70°. The over-voltage adjusting loop **51** of the relay **5** is now adjusted to produce a strong tripping torque, slightly less than the phasing torque corresponding to network and transformer secondary voltages in phase and of normal value. The reverse power setting mechanism (Fig. 3) is adjusted to prevent engagement of the contact members **5***c* and **5***b* from the biasing action of the loop **51**, and to give as high additional reverse power setting as desired.

The operation of the protector shown in Fig. 7 may be set forth as follows: The closing operation when the network **4** is deenergized and the tripping operation in response to reverse positive sequence power are the same as described above in connection with Fig. 1. The closing operation of the protector when both the feeder **1** and network **4** are energized, occurs when the torque corresponding to the product of the in-phase components of the positive phase sequence voltages of the transformer bank **2** and network **4** exceeds the biasing torque produced by the over-voltage adjusting loop **51**.

Fig. 8 shows a modified arrangement of phasing circuits which may be used in any of the protectors shown in Figs. 1, 5 or 7. In the modification shown in Fig. 8 the phasing windings **11** of the relay **5** are energized by means of two voltage phase-sequence networks **37** and **38** connected to the transformer side and network side, respectively of the circuit breaker **3**. The potential winding **6** of the relay **5** is energized in accordance with a positive symmetrical component of the voltage of the network **4**.

An impedance element **40** is included in series with the phasing windings **11**, to rotate the relay phasing characteristics in any desired manner. Although we have illustrated the voltage phase-sequence filters **37** to **39** as of the same type as networks **30** and **31** of Fig. 7, it will be understood that these networks may be of other types.

It will be apparent that with the phasing connections shown in Fig. 8, the phasing torque produced in the relay **5** will be proportional to the in-phase product of a positive component of network voltage and the difference between positive components of network voltage and transformer secondary voltage rotated through an angle corresponding to the constants of the impedance element **40**.

Fig. 9 shows an application of our invention to a protector having a two-element relay of the type disclosed in the copending application of William K. Sonnemann, Serial No. 552,673, filed July 23, 1931 and assigned to the Westinghouse Electric and Manufacturing Company. Referring to Fig. 9, the feeder **1**, transformer bank **2**, circuit breaker **3**, distribution network **4** and current phase sequence filter **9** are connected in the same manner as the corresponding elements of Fig. 7. A two-element induction disc relay **50**, of the type disclosed in the above-mentioned application of William K. Sonnemann is provided for controlling the circuit breaker **3**.

The relay **50** comprises two induction disc elements **50***a* and **50***b* rigidly coupled in any suitable manner so that the torque which produces movement of the relay contact members is the algebraic sum of the torque produced by both elements. The upper relay element **50***a* is provided with a potential winding **6***a*, a pair of current windings **8***a* and a pair of phasing windings **11***a*. The lower element **50***b* is provided with a potential winding **6***b* and a pair of phasing windings **11***b*.

A pair of voltage phase sequence filters **30** and **31**, similar to and energized in the same manner as the corresponding elements of Fig. 7, are provided for energizing the potential and phasing windings of the relay **50**. The potential windings **6***a* and **6***b* of the relay **50** are connected to the voltage phase-sequence filters **30** and **31** to be energized in accordance with positive symmetrical components of the voltage of network **4** and the secondary voltage of transformer bank **2**, respectively, and are connected in the proper directions to produce alternating fluxes of the same polarity when the symmetrical components of network and transformer secondary voltage are in phase.

The phasing windings **11***a* and **11***b* are connected in opposite directions to both the phase sequence filters **30** and **31**, to be energized in accordance with the difference of positive phase sequence voltages of the secondary windings of transformer bank **2** and the network **4**. It will be apparent that with the connections described, the phasing torques of elements **50***a* and **50***b* will act in opposite directions under most conditions.

An admittance element **51′** is shunted across the potential winding **6***a* to rotate the phase position of the current in the potential coil **6***a* through the necessary angle to produce watt tripping characteristics of the relay element **50***a*, as explained in connection with Fig. 7. A second admittance element **52** is connected in shunt to the potential winding **6***b* to produce an in-phase relationship of potential fluxes of elements **50***a* and **50***b* when the corresponding symmetrical voltage components are in phase.

A pair of impedance elements **53** and **54** are connected in series with the phasing windings **11***a* and **11***b*, respectively, to produce any desired rotation of the phasing characteristics of the elements **50***a* and **50***b*. The circuit breaker **3** is provided with back auxiliary contact members **3***f* and **3***g* for interrupting the connections of the phasing windings **11***b* and the potential winding **6**b when the circuit breaker **3** is closed.

The operation of the protector shown in Fig. 9 may be set forth as follows: The closure of the circuit breaker **3** when the feeder **1** is energized and the network **4** is deenergized is accomplished by the relay spring **50***h* as described above in connection with Fig. 1. The opening of the circuit breaker **3** in response to reverse positive sequence power is the same as that heretofore described.

Denoting the *a*-phase positive symmetrical component of secondary voltage by E_{ta1} and the *a*-phase positive symmetrical component of voltage of network **4** by E_{na1}, it will be apparent that when both the feeder **1** and network **4** are energized and the circuit breaker **3** is open, the torque of the relay element **50***a* is a function of E_{na1} and $E_{ta1}-E_{na1}$. Similarly the torque of element **50***b* is a function E_{ta1} and $E_{na1}-E_{ta1}$. As only two variables E_{na1} and E_{ta1} are involved, these two variables may be treated as single phase voltages. As explained in the copending application of William K. Sonnemann, mentioned above, when a two-element relay of the type under consideration is energized by single-phase voltages having the same relationship to the relay windings as the voltages E_{na1} and E_{ta1}, the closing characteristic of the relay is in the form of a circle such as shown at B in Fig. 10. By changing relay adjustments, as explained in the above-mentioned application of William K. Sonnemann, the diameter and position of the closing circle may be varied to suit the particular application of the protector. A second closing circle is denoted at C.

When the *a*-phase positive symmetrical component of secondary voltage of the transformer bank **2** is of proper magnitude and phase relationship as compared with the *a*-phase positive component of voltage of the network **4**, to terminate within the relay closing circle B or C, the relay **50** operates to close the circuit breaker **3**.

We do not intend that the present invention shall be restricted to the specific structural details, arrangement of parts or circuit connections herein set forth, as various modifications thereof may be effected without departing from the spirit and scope of our invention. We desire, therefore, that only such limitations shall be imposed as are indicated in the appended claims.

We claim as our invention:

1. In a network protector for controlling the connection and disconnection of a pair of polyphase alternating-current circuits, a circuit breaker, an electromagnetic device having a magnetic structure and a movable element responsive to a magnetic condition of said structure, means effective when said circuit breaker is open for energizing said structure in accordance with a magnetic condition dependent upon all phases of the polyphase voltage of one of said circuits and only a single voltage derived from the other of said circuits, and means including said movable element for causing said circuit breaker to close in response to a predetermined voltage relationship of said circuits.

2. In apparatus for controlling the connection of a pair of three-phase alternating-current circuits, a circuit breaker, impedance means for producing a resultant of at least two phase voltages of one of said circuits, and means for closing said circuit breaker in response to a predetermined relationship of said resultant and a voltage derived from the other of said circuits.

3. In apparatus for controlling the connection of a pair of grounded-neutral three-phase alternating-current circuits, a circuit breaker, impedance means for producing a resultant of at least two phase-to-ground voltages of one of said circuits, and means for closing said circuit breaker in response to a predetermined relationship of said resultant and a voltage derived from the other of said circuits.

4. In a network distribution system, a polyphase feeder circuit, a polyphase network circuit, transformer means connecting said feeder circuit to said network circuit, circuit-interrupting means for controlling the flow of power through said transformer means, means responsive to a fault on said feeder circuit for rendering said circuit-interrupting means effective to interrupt the flow of power through said transformer means, impedance means for producing a resultant of at least two phase voltages of one of said circuits, and means responsive to a predetermined relationship of said resultant and a voltage derived from the other of said circuits for rendering said circuit-interrupting means effective to establish power flow through said transformer means.

5. In an alternating-current network distribution system, a network distribution circuit, a plurality of feeders for supplying power to said network circuit, step-down transformer means connecting each of said feeders to said network circuit, each of said transformer means having ungrounded primary windings connected to the corresponding feeder, individual switching means for said transformer means, means responsive to

an abnormal ground condition of one of said feeders for causing the corresponding switching means to open, and means for selectively producing said abnormal ground condition of said one of said feeders, whereby said one of said feeders may be removed from service without substantially disturbing the electrical condition of said network circuit.

6. In an alternating-current network distribution system, a network distribution circuit, a plurality of feeders for supplying power to said network circuit, step-down transformer means connecting each of said feeders to said network circuit, each of said transformer means having ungrounded primary windings connected to the corresponding feeder, individual switch means for said transformer means, means responsive to a ground fault on one of said feeders for causing the corresponding switching means to open, and means for selectively producing a ground fault on said one of said feeders.

7. In a polyphase alternating-current network distribution system, a network distribution circuit, a plurality of polyphase feeders for supplying power to said network circuit, step-down transformer means connecting each of said feeders to said network circuit, each of said transformer means having ungrounded delta-connected windings connected to the corresponding feeder, individual switching means for said transformer means, means responsive to an abnormal ground condition of one of said feeders for causing the corresponding switching means to open, and means for selectively producing said abnormal ground condition of said one of said feeders.

8. In a polyphase alternating-current network distribution system, a network distribution circuit, a plurality of polyphase feeders for supplying power to said network circuit, step-down transformer means connecting each of said feeders to said network circuit, each of said transformer means having ungrounded delta-connected windings connected to the corresponding feeder, individual switching means for said transformer means, means responsive to a ground fault on one of said feeders for causing the corresponding switching means to open, and means for selectively grounding said one of said feeders.

9. In an alternating-current network distribution system, a network distribution circuit, a plurality of feeders for supplying power to said network circuit, a feeder circuit breaker in each of said feeders adjacent the source end thereof, step-down transformer means connecting each of said feeders to said network circuit, each of said transformer means having ungrounded primary windings connected to the corresponding one of said feeders, individual switching means for said transformer means, means responsive to an abnormal ground condition of one of said feeder circuits for causing the corresponding switching means to open, and means effective when the corresponding one of said feeder circuit breakers is open for producing said abnormal ground condition of the said one of said feeders.

10. In a polyphase alternating-current network distribution system, a network distribution circuit, a plurality of feeders for supplying power to said network circuit, a feeder circuit breaker in each of said feeders adjacent the source end thereof, step-down transformer means connecting each of said feeders to said network circuit, each of said transformer means having ungrounded delta-connected primary windings connected to the corresponding one of said feeders, individual switching means for said transformer means, means responsive to a ground fault on a selected one of said feeders for causing the corresponding switching means to open, and means effective when the corresponding one of said feeder breakers is open for producing a ground fault on said selected one of said feeders.

11. In apparatus for controlling the connection and disconnection of a pair of polyphase alternating-current circuits, a circuit breaker, a relay for controlling said circuit breaker, said relay having a pair of windings and a movable element operable in response to a predetermined value of the vector product of currents in said windings, means effective when said circuit breaker is open for energizing one of said windings in accordance with a voltage resultant dependent upon a plurality of phases of the polyphase voltage of one of said circuits, means for energizing the other of said windings in accordance with a voltage derived at least partially from the other of said circuits such that the vector product of said resultant and said last-mentioned voltage is a function of the magnitude and phase relationship of the polyphase voltages of said circuits, and means including said movable element for causing said circuit breaker to close in response to a predetermined value of the vector product of currents in said windings.

12. In apparatus for controlling the connection and disconnection of a pair of grounded-neutral polyphase alternating-current circuits, a circuit breaker, a relay for controlling said circuit breaker, said relay having a pair of windings and a movable element operable in response to a predetermined value of the vector product of currents in said windings, means effective when said circuit breaker is open for energizing one of said windings in accordance with a positive symmetrical component of the polyphase voltage of one of said circuits, means for energizing the other of said windings in accordance with the difference between said component and the corresponding phase voltage of the other of said circuits, and means including said movable element for causing said circuit breaker to close when said positive component and said corresponding phase voltage are in a predetermined relationship of magnitude and phase position.

13. In apparatus for controlling the connection and disconnection of a pair of grounded-neutral polyphase alternating-current circuits, a circuit breaker, a relay for controlling said circuit breaker, said relay having a pair of windings and a movable element operable in response to a predetermined value of the vector product of currents in said windings, means effective when said circuit breaker is open for energizing one of said windings in accordance with a positive symmetrical component of the polyphase voltage of one of said circuits, means for energizing the other of said windings in accordance with the difference between said component and a corresponding positive symmetrical component of the polyphase voltage of the other of said circuits, and means including said movable element for causing said circuit breaker to close when said positive components are in a predetermined relationship of magnitude and phase position.

14. In a network protector for controlling the connection and disconnection of a pair of polyphase alternating-current circuits, a circuit breaker, means including a power-directional relay for controlling said circuit breaker, means

effective when said circuit breaker is open for energizing said relay in accordance with a vector product of a positive symmetrical component of the polyphase voltage of one of said circuits and a phasing voltage derived at least partially from the other of said circuits, said vector product being a function of the magnitude and phase relationship of the polyphase voltages of said circuits and means for preventing closure of said circuit breaker except when said phasing voltage is within a predetermined range of phase relationships with reference to said positive component.

15. In a network protector for controlling the connection and disconnection of a pair of polyphase alternating-current circuits, a circuit breaker, means including a power-directional relay for controlling said circuit breaker, means effective when said circuit breaker is open for energizing said relay in accordance with a vector product of a positive symmetrical component of the polyphase voltage of one of said circuits and a phasing voltage derived at least partially from the other of said circuits, said vector product being a function of the magnitude and phase relationship of the polyphase voltages of said circuits, and means for modifying the operation of said relay to prevent closure of said circuit breaker except when said phasing voltage is within a predetermined range of phase relationships with reference to said positive component.

16. In a network protector for controlling the connection and disconnection of a pair of grounded-neutral polyphase alternating-current circuits, a circuit breaker, means including a power-directional relay for controlling said circuit breaker, means effective when said circuit breaker is open for energizing said relay in accordance with a vector product of a positive symmetrical component of the polyphase voltage of one of said circuits and the difference between a positive symmetrical component of the polyphase voltage of one of said circuits and a voltage of corresponding phase derived from the other of said circuits, said vector product being a function of the magnitude and phase relationship of the polyphase voltages of said circuits, and means for modifying the operation of said relay to prevent closure of said circuit breaker except when said difference voltage is within a predetermined range of phase relationships with reference to one of said positive components.

17. In a network protector for controlling the connection and disconnection of a pair of grounded-neutral polyphase alternating-current circuits, a circuit breaker, means including a power-directional relay for controlling said circuit breaker, means effective when said circuit breaker is open for energizing said relay in accordance with a vector product of a positive symmetrical component of the polyphase voltage of one of said circuits and the difference between said positive symmetrical component and the corresponding positive symmetrical component of the polyphase voltage of the other of said circuits, and means for modifying the operation of said relay to prevent closure of said circuit breaker except when said positive symmetrical components are within a predetermined range of phase relationships to each other.

18. In a network protector for controlling the connection and disconnection of a transformer and a polyphase network circuit, a circuit breaker, a power-directional relay, means effective when said circuit breaker is closed for energizing said relay in accordance with a power quantity of said circuits, a second relay, means for energizing said second relay in accordance with a negative symmetrical component of a polyphase electrical quantity of said circuits, and means responsive to operation of both said relays for causing said circuit breaker to open when said power quantity flows from said network circuit to said transformer to supply the magnetizing losses thereof and said polyphase quantity is unbalanced to a predetermined degree.

19. In a network protector for controlling the connection and disconnection of a transformer and a polyphase network circuit, a circuit breaker, a power directional relay, means effective when said circuit breaker is closed for energizing said relay in accordance with a power quantity flowing through said circuit breaker, a second relay and energizing means therefor effective to produce operation thereof in response to a predetermined unbalanced condition of the phase currents flowing through the said circuit breaker, and means responsive to operation of both of said relays for causing said circuit breaker to open when said power quantity flows through said circuit breaker in a predetermined direction and said phase currents are unbalanced to a predetermined degree.

20. In a network protector for controlling the connection and disconnection of a pair of polyphase alternating current circuits, a circuit breaker, a power-directional relay, means effective when said circuit breaker is closed for energizing said relay in accordance with a power quantity of said circuits, an over-current relay, means for energizing said over-current relay in accordance with a positive symmetrical component of the polyphase current of said circuits, and means responsive to operation of both of said relays for causing said circuit breaker to open when said power quantity is in a predetermined direction and an over-current condition of said circuits exists.

21. In a network protector for controlling the connection and disconnection of a pair of polyphase alternating current circuits, a circuit breaker, a power-directional relay, means effective when said circuit breaker is closed for energizing said relay in accordance with the vector product of a positive symmetrical component of the polyphase current of said circuits and a positive symmetrical component of the polyphase voltage of one of said circuits, an over-current relay, means for energizing said over-current relay in accordance with a positive symmetrical component of the polyphase current of said circuits, and means responsive to operation of both of said relays for causing said circuit breaker to open when said vector product is of a predetermined direction and said positive symmetrical component of current is of predetermined value.

22. In apparatus for controlling the connection and disconnection of a pair of polyphase alternating-current circuits, a circuit breaker, a power-directional relay, means effective when said circuit breaker is closed for energizing said relay in accordance with a positive component of power of said circuits, an over-current relay, means for energizing said over-current relay in accordance with a positive symmetrical component of the polyphase current of said circuits, and means responsive to operation of both of said relays for causing said circuit breaker to open when said positive component of power is in a predetermined direction and said positive

symmetrical component of current is of predetermined value.

23. In a network protector for controlling the connection and disconnection of a pair of polyphase alternating-current circuits, a circuit breaker, a power-directional relay, means effective when said circuit breaker is closed for energizing said relay in accordance with a positive component of power of said circuits, a pair of over-current relays, means for energizing one of said over-current relays in accordance with a positive symmetrical component of the polyphase current of said circuits and for energizing the other of said over-current relays in accordance with a negative symmetrical component of the polyphase current of said circuits, and means responsive to the operation of said power-directional relay and either of said over-current relays for causing said circuit breaker to open when said positive component of power is in a predetermined direction and said positive symmetrical component of current is of predetermined value or said negative symmetrical component of current is of predetermined value.

24. In a network protector for controlling the connection and disconnection of a polyphase alternating-current network circuit and a polyphase alternating-current supply circuit, a circuit breaker, a single-element power-directional relay for controlling said circuit breaker, said relay having a potential winding, a current winding and a phasing winding, means for energizing said potential winding in accordance with a positive symmetrical component of the polyphase voltage of said network circuit, means effective when said circuit breaker is closed for energizing said current winding in accordance with a positive symmetrical component of the polyphase current of said circuits to cause operation of said relay in response to a vector product of positive symmetrical voltage and current components and means effective when said circuit breaker is open for energizing said phasing winding in accordance with the difference between a positive symmetrical component of the polyphase voltage of one of said circuits and a voltage of corresponding phase derived from the other of said circuits to cause the operation of said relay to be dependent upon the magnitudes and phase relationship of the polyphase voltages of said circuits.

25. In a network protector for controlling the connection and disconnection of a polyphase alternating-current network circuit and a polyphase alternating-current supply circuit, a circuit breaker, a single-element power directional relay for controlling said circuit breaker, said relay having a potential winding, a current winding and a phasing winding, means for energizing said potential winding in accordance with a positive symmetrical component of the polyphase voltage of said network circuit, means effective when said circuit breaker is closed for energizing said current winding in accordance with a positive symmetrical component of the polyphase currents of said circuits to cause operation of said relay in accordance with a vector product of positive symmetrical voltage and current components, means effective when said circuit breaker is open for energizing said phasing winding in accordance with the difference between a positive symmetrical component of the polyphase voltage of one of said circuits and a voltage of corresponding phase derived from the other of said circuits, and impedance means connected to one of said windings when said circuit breaker is open for rotating the closing characteristic of said relay to prevent closure of said circuit breaker except when said difference voltage is within a predetermined range of phase relationships with reference to said first-mentioned voltage component.

26. In an alternating-current distribution system of the type in which power is transmitted to a polyphase network by means of a plurality of feeder circuits, a polyphase feeder for transmitting power to said network, a feeder circuit breaker for controlling the power flow through said feeder, a plurality of transformer banks interconnecting said feeder and said network, a network protector connected between said network and each of said transformer banks, each of said network protectors comprising a network circuit breaker and relay means for causing said network circuit breaker to open when the magnetizing losses of the corresponding transformer bank are supplied from said network and a negative phase sequence current of predetermined value flows through the protector, and means effective when said feeder circuit breaker is open to establish a negative phase sequence current higher than said predetermined value through each of said protectors to thereby cause said network circuit breakers to open.

27. In an alternating-current distribution system of the type in which power is transmitted to a polyphase network by means of a plurality of feeder circuits, a polyphase feeder for transmitting power to said network, a feeder circuit breaker for controlling the power flow through said feeder, a plurality of transformer banks interconnecting said feeder and said network, a network protector connected between said network and each of said transformer banks, each of said network protectors comprising a network circuit breaker and relay means for causing said network circuit breaker to open when the magnetizing losses of the corresponding transformer bank are supplied from said network and a negative phase-sequence current of predetermined value higher than normal average value flows through the protector, or the reverse power flow from the network through the protector exceeds a predetermined power value corresponding to an insensitive setting of the protector, and means effective when said feeder circuit breaker is open for establishing a negative phase sequence current higher than said predetermined current value through each of said protectors, whereby said network protectors operate with insensitive setting while said feeder circuit breaker is closed but may be opened in response to reverse transformer magnetizing losses and negative phase sequence current when said feeder circuit breaker is open.

28. In apparatus responsive to the condition of synchronism of a pair of polyphase alternating-current circuits, a pair of induction disc operators and a movable element responsive to the algebraic sum of the torques of said operators, each of said operators having a pair of windings relatively positioned to produce a torque proportional to the vector product of currents in said windings, phase-sequence means for energizing a winding of one of said operators in accordance with a positive symmetrical component of the polyphase voltage of one of said circuits, phase sequence means for energizing a winding of the other of said operators in accordance with a positive symmetrical component of the polyphase voltage of the other of said circuits, and conductors connecting the remaining windings of said operators to both of

said sequence means to respond to the difference of said components, the relative directions of said windings being such that the torques of said operators normally oppose, whereby the torque applied to said movable element is dependent upon the condition of synchronism of said circuits.

29. In a network protector for controlling the connection and disconnection of a pair of polyphase alternating current circuits, a circuit breaker, a relay having a pair of induction disc operators and a movable element responsive to the algebraic sum of the torques of said operators, each of said operators having a pair of windings positioned to produce a torque proportional to the vector product of currents in said windings, phase sequence means for energizing a winding of one of said operators in accordance with a positive symmetrical component of the polyphase voltage of one of said circuits, phase-sequence means for energizing a winding of the other of said operators in accordance with a positive symmetrical component of the polyphase voltage of the other of said circuits, conductors connecting the remaining windings of said operators to both of said phase sequence means to respond to the difference of said components, said windings being connected in such relative directions that the torques of said operators are normally opposed, and means including said movable element for causing said circuit breaker to close when said polyphase voltages are in a predetermined relationship of magnitude and phase position.

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