Jan. 2, 1940. W. J. McLACHLAN ET AL 2,185,707

ELECTRIC CIRCUITS

Filed Jan. 25, 1939 4 Sheets-Sheet 1

Fig. 1.

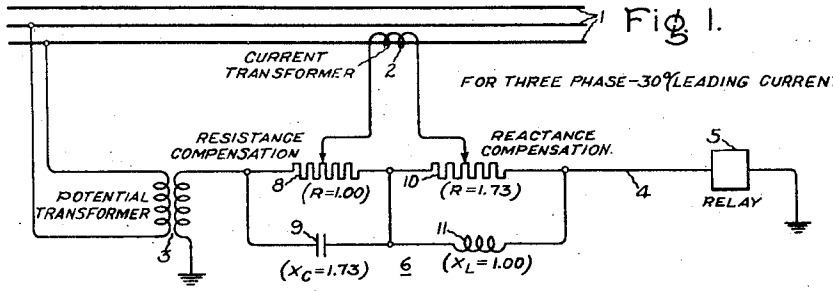


Fig. 4.

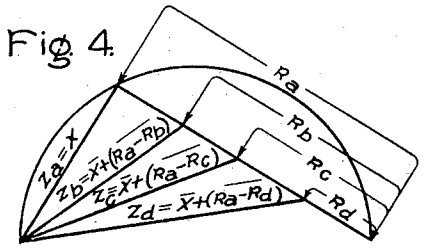


Fig. 5.

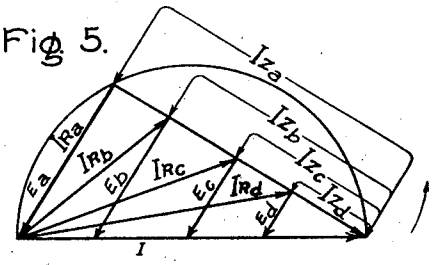


Fig. 2.

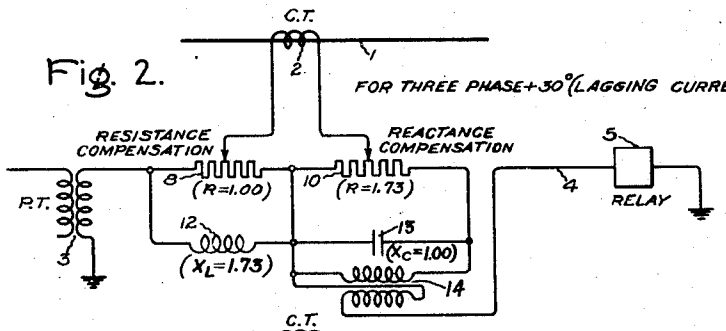
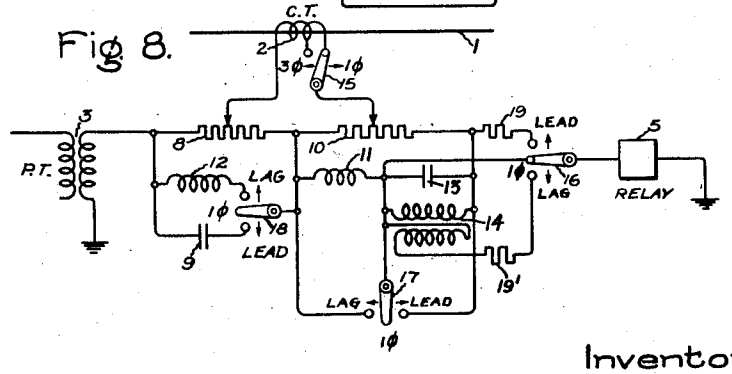


Fig. 8.



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Fig 3.

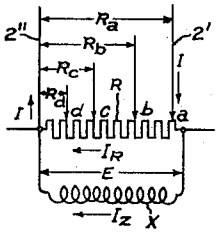


Fig 6.

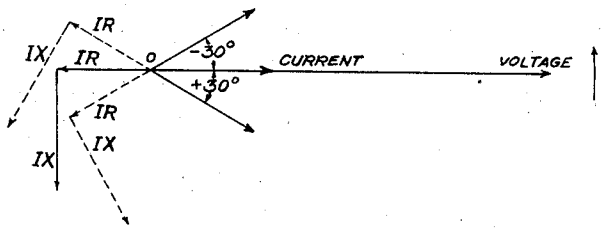


Fig 7.

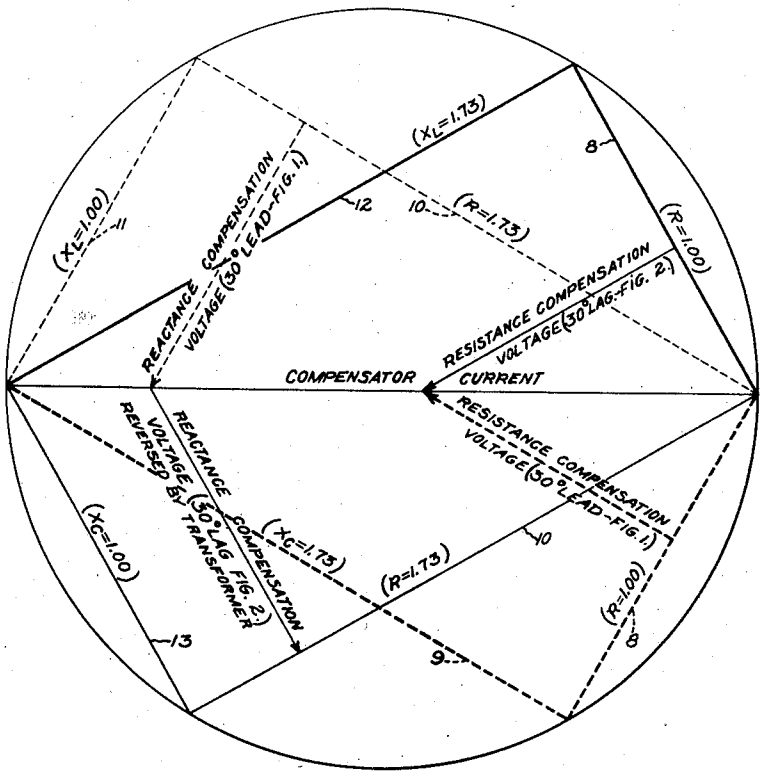
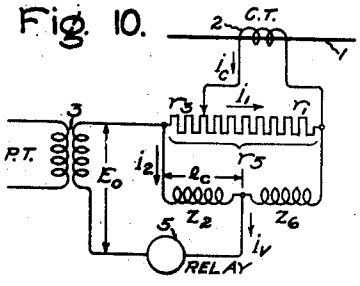


Fig. 10.



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ELECTRIC CIRCUITS

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Fig. 9.

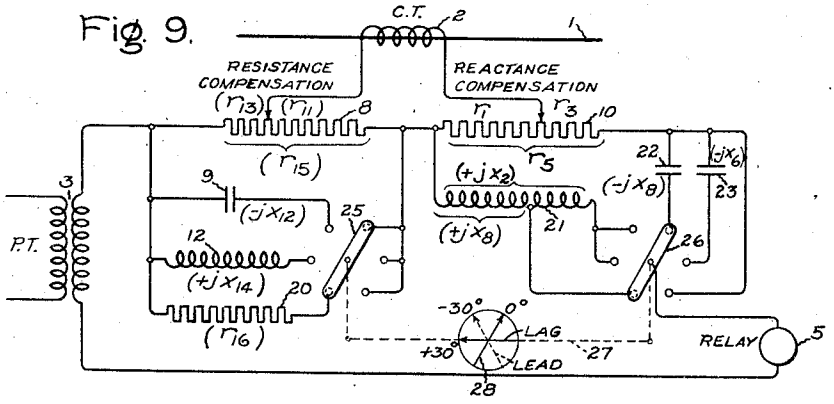


Fig. 11.

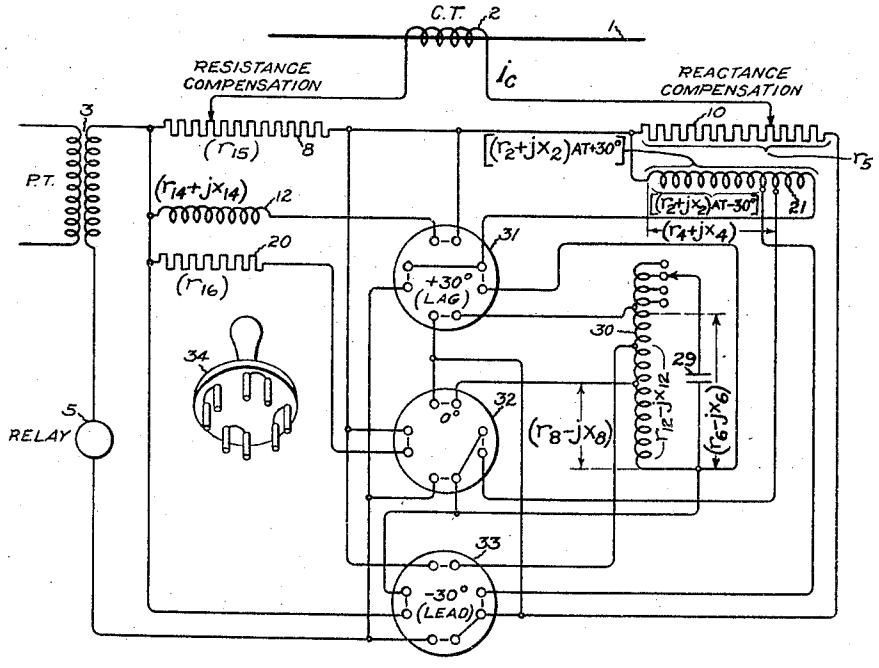


Fig. 12.

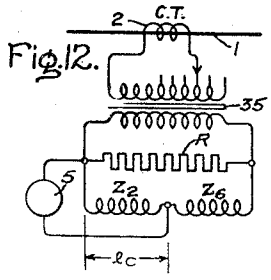
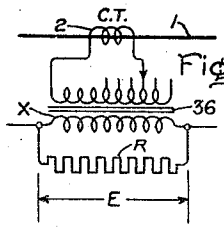


Fig. 13.



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ELECTRIC CIRCUITS

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Fig. 14.

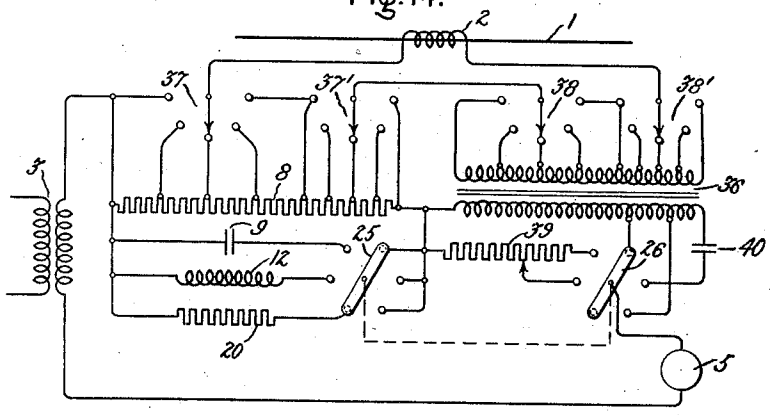
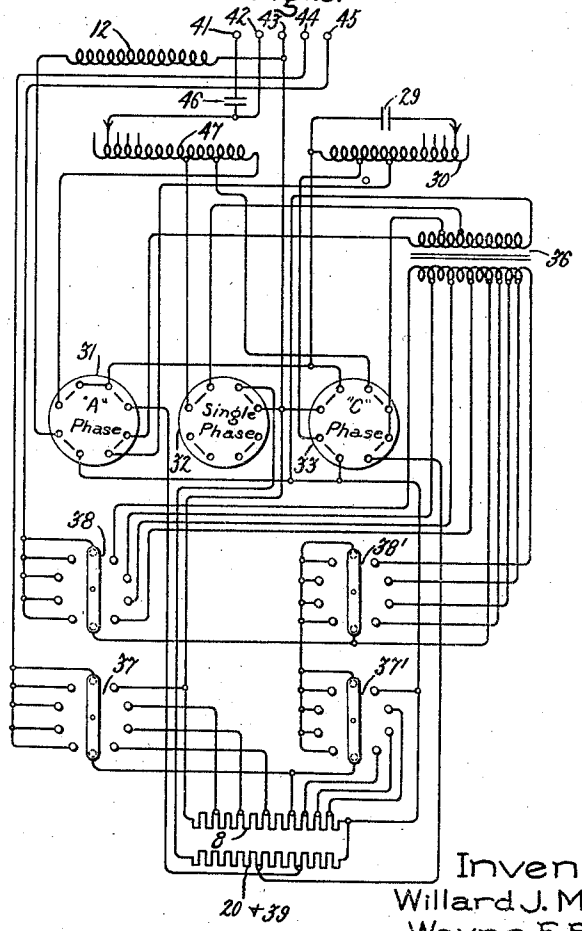


Fig. 15.



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Patented Jan. 2, 1940 2,185,707

UNITED STATES PATENT OFFICE

2,185,707

ELECTRIC CIRCUITS

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Application January 25, 1939, Serial No. 252,814

23 Claims. (Cl. 171—119)

This invention relates to electric circuits and more particularly to improvements in adjustable voltage phase shifting circuits for general use and particularly for use in line drop compensators for single phase automatic feeder voltage regulators adapted to be connected open-delta in three phase power lines.

This application is a continuation in part of our application Serial No. 188,492, filed February 3, 1938 and assigned to the assignee of this application.

As its name implies, a line drop compensator is a device which produces compensation for the voltage drop in an electric line. When used with an automatic voltage regulator, it permits the primary voltage sensitive device to measure, in effect, the voltage at a point farther out on the line than its actual point of connection, such as at a so-called center of distribution. By its use, regulators may be located in substations or at other points on a power system more or less remotely located from the loads connected to the system.

A common way of regulating the voltage of a 3-phase feeder circuit is by means of two single phase regulators connected respectively in two of the line conductors of the circuit. Such a connection is commonly referred to as an open-delta connection because only two of the three voltages of the circuit are regulated directly, the third voltage being regulated indirectly by means of the triangular relationship of the three voltages. Each single phase regulator has a series winding, which is connected in one of the lines of the circuit, and a shunt winding which is connected between the line in which its series winding is connected and one of the remaining lines. In other words, in connecting a single phase regulator to a 3-phase line, as far as the regulator proper is concerned, connections are made to only two of the three lines of the circuit. It is, therefore, desirable that the regulator auxiliaries and control circuits be energized from these same connections to the power circuit, as otherwise, the expense of installations may be considerably increased by having to make a connection to the third one of the circuit conductors. However, in a 3-phase circuit at unity power factor, the line to line voltage and the line current are displaced 30° in phase, this angle being an angle of lead or an angle of lag depending on the direction of phase rotation. Also, the resistance drop in the line at unity power factor is in phase opposition to the phase voltage and the reactance drop in the line is in quadrature lagging with respect to the phase voltage. Consequently, an ordinary line drop compensator adapted for simple single phase operation will not give true line drop compensation when the compensator current is displaced from the voltage of the voltage sensitive circuit.

In accordance with this invention there is provided a relatively simple and inexpensive compensator which corrects for the 30-degree shift and which does not require auxiliary current transformers or interconnections between regulators.

The invention is characterized by elements consisting of net works of parallel connected reactances and adjustable resistors or reactors wherein the adjustment of the resistors or reactors determines the magnitude of the compensation, and the ratio of the parallel impedances produces the desired phase shift in compensator voltage with respect to the compensator current.

An object of the invention is to provide a new and improved electric circuit.

A further object of the invention is to provide a new and improved line drop compensator.

Another object of the invention is to provide an inexpensive line drop compensator adapted for use with open-delta connected, single phase feeder voltage regulators.

The invention will be better understood from the following description taken in connection with the accompanying drawings and its scope will be pointed out in the appended claims.

In the drawings, Fig. 1 is a diagrammatic illustration of an embodiment of the invention adapted for use with compensator currents which lead the line voltage by 30° with unity power factor load, Fig. 2 is similar to Fig. 1 but is adapted for use with compensator currents which lag the line voltage by 30° with unity power factor load, Fig. 3 is a diagram of an element of the compensators of Figs. 1 and 2, Figs. 4, 5, 6 and 7 are vector diagrams for illustrating the operation of the invention, Fig. 8 illustrates diagrammatically what may be referred to as a universal com-

pensator which comprises the compensators of Figs. 1 and 2, and also may be used with single phase circuits, Fig. 9 is a modified universal compensator, Fig. 10 is a generalized diagram of a compensator element of Fig. 9, Fig. 11 is a modified form of the universal compensator shown in Fig. 9, Figs. 12 and 13 illustrate modified ways of adjusting the voltage or compensator setting and Figs. 14 and 15 illustrate modifications employing the adjusting means of Fig. 13.

Referring now to the drawings and more particularly to Fig. 1, there is shown therein a 3-phase power circuit 1 in the lowermost conductor of which there is connected a current transformer 2 and between whose center and lowermost conductors there is connected potential transformer 3. Potential transformer 3 energizes a relatively high impedance voltage sensitive circuit 4 containing any suitable voltage sensitive device 5 such, for example, as a primary relay, contact-making voltmeter or resonant circuit. Connected in the voltage responsive circuit is a line drop compensator 6 having a resistance compensation element consisting of a potentiometer or slide wire type adjustable resistor 8 connected in parallel with a capacitor 9 and having a reactance compensation element consisting of a slide wire type resistor 10 connected in parallel with a reactor 11. The ratio in ohms of resistor 8 to capacitor 9 is 1.00 : 1.73, while the ratio in ohms of resistor 10 to reactor 11 is 1.73 : 1.00.

Fig. 2 differs from Fig. 1 in that the capacitor 9 of the resistance compensation element of Fig. 1 is replaced by a reactor 12, while the reactor 11 of the reactance compensation element of Fig. 1 is replaced by a capacitor 13. In order vectorially to reverse the voltage drop of capacitor 13, for reasons which will be explained hereinafter, a transformer 14 is interposed between the capacitor 13 and the rest of the circuit. The ratio of resistance to reactance in both the resistance and reactance compensation elements of Fig. 2 is numerically the same as in Fig. 1.

The operation of Figs. 1 and 2 can best be understood by first referring to Fig. 3 which illustrates an element of one of the compensators. Specifically, it resembles most closely the reactance compensation element of Fig. 1 in that it consists of a slide wire resistor R paralleled by a reactor X. A current I enters this circuit through a conductor 2' and leaves it through a conductor 2''. In position *a* of the slide wire, wherein the resistance R and reactance X are directly in parallel, the current I divides part of it, I_R going through the resistance R and the remaining part of it, I_Z going through the reactance X. If the slide wire adjuster associated with the conductor 2' is now moved to the left successively to positions *b*, *c*, and *d*, I_R will progressively increase as it flows successively through less resistance, designated as R_b, R_c, and R_d, while at the same time I_Z will progressively decrease as it will have to flow successively through impedances consisting in position *b* of

$$[X+(R_a-R_b)]$$

in position *c* of

$$[X+(R_a-R_c)]$$

etc., it being understood, of course, that the indicated additions are vector additions. This change in the relative impedance values of the two branches of the circuit as the slide wire is moved is clearly shown in Fig. 4, this figure automatically making the vector addition of X plus the other varying values of resistance so as to give successively the impedance values Z_a, which equals X in position *a* of the slide wire, and Z_b, Z_c, and Z_d corresponding respectively to the positions *b*, *c*, and *d* of the slide wire. It will also be observed that in Fig. 4, if X has a value of unity, R has a value of approximately 1.73. This is the ratio of R and X given for the reactance compensation element of Fig. 1. The currents and voltages in Fig. 3 are shown vectorially in Fig. 5. This figure is essentially the same as Fig. 4 by reason of the fact that the current divides in such a manner that current in one parallel branch is proportional to the impedance of the other branch. Thus

$$I_{Z_a}$$

is proportional to

$$R_a,\ I_{Z_b} \text{ to } R_b, \text{ etc.}$$

while

$$I_{R_a},\ I_{R_b}, \text{ etc.}$$

are proportional respectively to Z_a, Z_b, etc. The voltage E produced by the compensator element is, of course, the voltage drop through the reactor X. In Fig. 5 this voltage will be proportional in magnitude to I_Z and will be lagging it 90 degrees in phase. It may, therefore, conveniently be represented by the vectors E_a, E_b, E_c and E_d corresponding respectively to the similarly lettered positions of the slide wire in Fig. 3.

From the above, it follows that Fig. 3 has the interesting property that the phase of the voltage E is independent of the position of the slide wire, while its magnitude is directly proportional to the position of the slide wire.

It will also be noted that the vector voltages E in Fig. 5 lag by about 30 degrees the voltage drop which would be produced in a reactor if it carried the current I. Therefore, Fig. 5 represents the vector relations in the reactance compensation element of Fig. 1 because if the total current I in Figs. 3 and 5 advanced 30 degrees, that is to say, if the entire vector diagram of Fig. 5 is rotated counter-clockwise 30 degrees, the voltages E will have the conventional vertically downward direction representing a quadrature lagging reactance drop.

This is better explained by reference to Fig. 6 in which the horizontal vectors to the right of the zero point are, respectively, the current and voltage of a unity power factor single phase circuit, while the horizontal and vertical downward vectors to the left of the zero point are the resistance and reactance drops respectively in the circuit. If now the current is shifted 30 degrees in either the lagging or the leading direction, the resistance and reactance drops are similarly shifted. The vector diagram of the voltage responsive circuit 4 of Figs. 1 and 2 is exactly the same as that of Fig. 6 except on a smaller scale, and the 30 degree shifted resistance and reactance drops indicated by the dashed lines represent the resistance and reactance compensation which would be secured by a conventional single phase line drop compensator if connected to a 3-phase circuit as in Fig. 1. The proper resistance and reactance compensation voltages are those shown by the continuous resistance and reactance drop vectors in Fig. 6 from which it will be seen that when the current lags the voltage by 30 degrees, the compensator

voltages should be shifted 30 degrees ahead in a leading direction in order to get true compensation, whereas if the current leads the voltage by 30 degrees, the compensator voltages should be shifted back 30 degrees in a lagging direction in order to secure correct compensation.

In Fig. 7, there are combined four diagrams similar to Fig. 5. Each of these diagrams represents conditions in a different one of the elements of Figs. 1 and 2. The heavy lines, both solid and dashed, denote resistance compensation, the light lines, both solid and dashed, denote reactance compensation, the solid lines denote compensation for use with 30 degree lagging current (Fig. 2) and the dashed lines denote compensation for use with 30 degree leading current (Fig. 1). For example, consider the rectangle composed of the heavy and light dashed lines. The vector $X_L=1.00$ corresponds to reactor 11, while the vector $R=1.73$ denotes resistor 10. The reactance compensation voltage is at right angles to the resistance vector 10, as in Fig. 5, and lags the correct reactance compensation voltage (as shown by IX in Fig. 6) by 30 degrees so that if the compensator current represented by the horizontal diameter in Fig. 7 is rotated 30 degrees in the leading direction, the entire vector diagram will rotate through a similar angle and the reactance compensation voltage will coincide in phase with the correct reactance compensation. Similarly, the heavy dashed vector $R=1.00$ denotes resistor 8 and the heavy dashed vector $X_c=1.73$ denotes the capacitor 9 in Fig. 1. The compensation voltage produced by the resistance compensation element of Fig. 1 will be at right angles to the vector 8 and, like the reactance compensation voltage, will be lagging the correct, or horizontal, phase angle by 30 degrees, so that if a compensator current of 30 degrees lead flows through the compensator, the resistance compensation voltage will be brought into the proper phase relation to secure true resistance compensation.

The rectangle composed of the continuous vectors represents conditions in Fig. 2 and with one exception the operation will be obvious from what has already been said. This exception relates to the reactance compensation voltage. Normally the voltage drop through a capacitor leads the current by 90 degrees. That would have produced a phase shift of the reactance compensation voltage in Fig. 2 of 150 degrees in the lagging direction instead of the desired 30° in the leading direction. Correction is secured by reversing the direction of the capacitor voltage drop by means of the transformer 14.

By adjusting the slide wires on resistors 8 and 10 in Figs. 1 and 2, the magnitude of the resistance and reactance compensation may be adjusted at will.

In Fig. 8, the compensators of Figs. 1 and 2 have been combined into a single compensator which, in addition, by means of the proper manipulation of four switches 15, 16, 17 and 18 may also be adapted for single phase operation. Thus, if switches 15 and 16 are moved to the positions labeled 1ϕ (single phase) and switches 17 and 18 are left in their mid-positions, the current transformer current will flow through adjustable portions of resistor 8 alone, and after leaving resistor 8 will divide, part of it flowing through the left hand portion of resistor 10 and the rest of it flowing through the reactor 11 and the capacitor 13 in series and back to the current transformer through the right hand part of the resistor 10. The reactor 11 and the capacitor 13 usually are equal in magnitude so that this branch of the circuit is series resonant and produces no phase shift of the compensator current. Consequently, there are inserted in series with the relay 5 a resistance compensation voltage corresponding to the voltage drop in resistance 8 and a reactance compensation voltage corresponding to the voltage drop in reactor 11, and this will give true compensation provided the potential transformer voltage and the current transformer current are in phase at unity power factor as they will be in a single phase circuit, and if reactor 11 has negligible resistance. If now switch 15 is thrown to the position labeled 3ϕ (3 phase) and switches 16, 17 and 18 are moved to their leading or lagging positions, the compensator connections produced thereby will respectively be the equivalent of Figs. 1 and 2.

Auxiliary resistors 19 and 19' are connected in series with the primary relay by the switch 16 in its 3-phase positions in order to compensate the voltmeter circuit for the change in compensator impedance when going from single phase to 3-phase operation. The switch 15 in going from its single phase to its 3-phase position changes the ratio of the current transformer in order to correct for the change in the compensator impedances when going from single phase to 3-phase operation. That is to say, in order that the same magnitude of line current will produce the same magnitude of compensation voltage, the current transformer ratio must be changed in order to correct for the change in compensator impedance.

If desired, the switches 15, 16, 17 and 18 may be interconnected by suitable mechanical means so that they may in effect form a compound 3-position switch, one position being for single phase phase operation and the other two positions being for plus and minus 30 degree, 3-phase operation, respectively.

The modification illustrated in Fig. 9 is fundamentally similar to the previously illustrated compensators. However, it differs therefrom in two important respects. The first is that the reversing transformer 14 for the capacitive reactance of the reactance compensation elements which gives correct compensation with 30 degrees lagging current is eliminated. The second is that taps are eliminated on the current transformer. Switching, which introduces the possibility of open-circuiting the secondary of a current transformer, is always undesirable because of the relatively high voltages involved.

Both of these changes are effected by the addition of a resistor 20, a tapped reactor 21 and two separate capacitors 22 and 23. The resistor 20 is arranged to be connected in parallel with the main slide wire resistance 8 of the resistance compensation element during single phase operation of the compensator by means of a switch 25, while various portions of the reactor 21 are connected respectively in series with the capacitors 22 and 23 during single phase and 3-phase operation of the compensator by means of a 3-position switch 26. As indicated schematically, these switches are mechanically interconnected by suitable means 27 and are provided with a common operating handle 28.

The general theory of this type of compensator can best be explained by means of Fig. 10 and the vector equations below. Fig. 10 represents a generalized element of the compensator of Fig. 9. The symbols which are used and which designate

the various elements in Fig. 10 are defined as follows:

r_5=total resistance of slide wire potentiometer-rheostat.
r_1=portion of r_5 in parallel with r_3, Z_1 and Z_6.
r_3=portion of r_5 in series with Z_2 and Z_6.
Z_2=a general impedance, containing resistance and inductance or capacitance.
Z_6=a general impedance.
i_c=compensation current, proportional to the load current of the regulator. (The very small component of i_c which flows through the contact-making voltmeter and potential transformer is neglected. Thus, i_c is confined to the compensator impedances.)
e_c=line drop compensation voltage added to E_o.
e_x=reactance compensation voltage.
i_v=contact-making voltmeter current.
E_o=voltage supplied by potential transformer, proportional to regulated line voltage at the regulator.
i_1=component of i_c through r_1.
i_2=component of i_c through Z_2.

The object is to determine e_c, the compensation voltage introduced into the contact-making voltmeter circuit by the compensation current, i_c. The impedance drops due to i_c are superposed upon those due to i_v, but for purposes of analysis and explanation i_v can be considered zero without error where the impedance elements are linear. For zero voltmeter current, i_v, Equations 1 and 2 are obviously true:

$$(1)\quad i_c=i_1+i_2$$

$$(2)\quad i_1r_1=i_2(r_3+Z_2+Z_6)$$

Solving these simultaneously for i_2, there is obtained,

$$(3)\quad i_2=\frac{i_cr_1}{r_1+r_3+Z_2+Z_6}=\frac{i_cr_1}{r_5+Z_2+Z_6}$$

The compensation voltage is, therefore,

$$(4)\quad e_c=i_2Z_2=i_cr_1\left(\frac{Z_2}{r_5+Z_2+Z_6}\right)$$

Equation 3 is the key to understanding why it is that adjusting the slide wire potentiometer does not affect the phase angle of the compensation voltage. It expresses the well known fact that current i_c divides between the two branches of a parallel circuit (branches r_1 and $r_3+Z_2+Z_6$) in such a manner that the current in one branch i_2 is directly proportional to the impedance of the other branch r_1 and inversely proportional to the vector sum of the impedances in both branches $(r_1+r_3+Z_2+Z_6)$. The sum of the impedances in the two branches has the same magnitude and angle for all positions of the slide wire, and the impedance angle of r_1 is zero for all positions. Therefore, the phase angle between i_2 and i_c is constant. Since the compensation voltage e_c is the impedance drop i_2Z_2, and since Z_2 has a fixed magnitude and angle, the phase angle between e_c and i_c must therefore be constant.

Three significant points should be noted in Equation 4. First, the compensation voltage e_c is directly proportional to the compensation current i_c as it should be. Second, the impedances in the parentheses are all constant and independent of the rheostat setting. They determine the phase angle between e_c and i_c, but permit a linear control of the magnitude of e_c as r_1 is varied from zero to its maximum value. The third point is that only Z_2 appears in the numerator of the expression, whereas the sum of Z_2 and Z_6 appears in the denominator. Thus the impedance angle of the numerator may be of opposite sign from that of the denominator permitting either positive or negative compensator impedance angles greater than 90 degrees. In practice, any angle between about −150° and +150° can be obtained. For the compensator we use −30°, 0°, +30°, +60°, +90° and +120°.

In Fig. 9, the same symbols used in Fig. 10 have been applied to the corresponding impedance elements and in addition, further symbols which are self-explanatory have been applied to the impedance elements present in Fig. 9 which are not present in Fig. 10.

With the switch handle **28** in the position shown, the resistance compensation element consists of the resistor **8** paralleled by the resistor **20**. The function of **20** is to balance the impedance of the resistance compensation element for single phase operation with respect to the impedance of the resistance compensation element for plus and minus 30°, 3-phase operation. In this way, the magnitude of the resistance compensation voltage for any given position of the slide wire will be the same for a given compensator current regardless of which position the switch handle **28** is in. The switch **26** connects the capacitor **22** in series with a tapped portion of the reactor **21** such that the capacitive and inductive reactance elements are equal. Thus, the reactance compensation element of Fig. 9, with the control switch in its single phase position, corresponds exactly to the reactance compensation element of Fig. 8 when it is connected for single phase operation.

If the control handle **28** is now moved to the −30° or 3-phase leading current position, the capacitor **9** is connected in parallel with the resistor **8** in the resistance compensation element and the whole reactor **21** is connected directly in parallel with the resistor **10** in the reactance compensation element. This corresponds to the arrangement shown in Fig. 1.

If now the handle is moved to the +30° or 3-phase lagging current position, the resistance compensation element consists of the slide wire resistor **8** which is paralleled by the reactor **12** and thus, the resistance compensation element corresponds to that of Fig. 2. However, the reactance compensation element consists of the capacitor **23** and the reactor **21** serially connected with each other and in parallel with the resistor **10**. By properly proportioning the values of the reactor **21** and the capacitor **23** the proper phase of the reactance compensation voltage is obtained without using the reversing transformer **14** as in Fig. 2.

The theory underlying this is as follows. The equation for the reactance compensation voltage when shifted 30° ahead of its normal phase angle is

$$(5)\quad e_x=\frac{ji_cr_1x_2}{r_5+j(x_2-x_6)}$$

if the resistances of the reactor and capacitor are neglected. Since e_x should be 90° ahead of i_c with no phase shift, the values of x_2 and x_6 should be such that it is 120° ahead of i_c with a positive 30 degree shift. Therefore, make

$$x_2=\frac{r_5}{\sqrt{3}},\quad x_6=\frac{2r_5}{\sqrt{3}}$$

and as seen from the drawings, $r_5=(r_1+r_3)$.

Substituting these values in Equation 5 we have

$$(6)\qquad e_x=i_c r_1\frac{j\frac{r_5}{\sqrt{3}}}{r_5+jr_5\left(\frac{1}{\sqrt{3}}-\frac{2}{\sqrt{3}}\right)}$$

$$e_x=i_c r_1\frac{\frac{1}{\sqrt{3}}\underline{/90^\circ}}{\frac{2}{\sqrt{3}}\underline{/30^\circ}}=\frac{i_c r_1}{2}\underline{/120^\circ}$$

Thus, the relative values of the impedance elements in Fig. 9, assuming ideal reactors and capacitors which have no resistance are as follows:

$$r_{15}=\frac{r_5}{\sqrt{3}}$$

$$r_{16}=\frac{r_5}{2-\sqrt{3}}$$

$$X_{14}=r_5=X_{12}$$

$$X_8=\frac{r_5}{2}$$

$$X_2=\frac{r_5}{\sqrt{3}}$$

$$X_6=\frac{2r_5}{\sqrt{3}}$$

However, for an economical design of compensator which will occupy a reasonably small space, the reactance elements must have appreciable resistance. The presence of this reactance makes necessary a proportioning of the various impedance values different from those with the theoretically "pure reactances." While there does not appear to be any simple rule for determining the impedance values for these conditions, nevertheless, it has been found by both cut and try calculations and by experiment that precise compensation can be obtained with relatively high resistance reactors provided that all resistances and reactances are chosen correctly.

The modification shown in Fig. 11 is fundamentally and theoretically the same as Fig. 9 but it represents a somewhat simplified and more practical arrangement. The most important simplification is that a single capacitor **29** has been substituted for the three capacitors **9**, **22** and **23** of Fig. 9. Capacitor **29** has associated therewith a tapped auto-transformer **30** which serves a number of purposes. The first purpose is to increase the voltage across the capacitor to an economical value and thus reduce the microfarad rating. Another purpose is readily and economically to adapt capacitors whose ratings vary according to commercial tolerances to the compensator circuit. This is done by means of taps on the high voltage output side of the transformer **30**. The remaining purpose of the transformer **30** is readily to permit adjustments to be made in the effective capacitance value of the capacitor so that the single capacitor **29** may successively have values corresponding to those of capacitors **9**, **22** and **23** of Fig. 9. This is done by means of the taps on the low voltage input side of the auto-transformer.

Another feature of Fig. 11 is the switching arrangement employed. This consists of three 8-pin sockets **31**, **32** and **33**, each of which is adapted to receive the 8-pin plug member **34**. These sockets may be standard 8-pin radio tube sockets, while the plug member **34** may be a standard 8-pin radio tube base with successive pairs of pins short circuited.

In the operation of Fig. 11, if single phase operation is desired, the plug **34** is placed in the socket labeled 0° (zero degrees) and by so doing the contacts in the plug **32** which are indicated as bridged by the short, heavy bars will be interconnected. The connections produced thereby will correspond to those produced in Fig. 9 when the handle **28** is in the position illustrated. Thus, the resistor **20** will be connected in parallel with the resistor **8** through the left hand contacts of the socket **32**. A portion of the reactor **21** will be connected in series with a portion of the primary of the auto-transformer **30** through the right hand contacts of the socket **32**. The topmost contacts will connect the serially related reactor and the transformer in parallel with the resistor **10**. The lowermost contacts will connect the relay **5** to the junction of the reactor **21** and the capacitor transformer **30**, thus, producing the reactance compensation connection corresponding to that produced in Fig. 9 with the handle **28** in the illustrated position.

Placing the plug **34** in the socket **31** or the socket **33** will produce connections equivalent respectively to those produced in Fig. 9 when the handle **28** is moved to the +30° and −30° positions.

There is, however, one exception to the above statement and that is that slightly different values of the reactor **21** are used for the 30° leading and 30° lagging connections, respectively. This is in order to compensate for the resistance of the reactance **21**, as well as for the resistance of the various other reactance of the circuit.

By way of example, but not by way of limitation, the following numerical values are given for a practical design of compensator of the type illustrated in Fig. 11. The compensator is designed to give a maximum of 24 volts, each of resistance and reactance compensation in a voltmeter circuit having a nominal current of 0.05 ampere. The subscripts used in the following table correspond to those used in Figs. 9 and 10. The two values of X_2 are obtained by different tap connections between the reactor **21** and the left hand contacts of the sockets **31** and **33**. Impedance values are effective, including for example, in the case of the capacitor, the effects of the auto-transformer. Resistances of reactors and capacitors have the same subscripts as to the corresponding reactances.

i_c	=0.20 amperes
r_{15}	=157.5 ohms
r_5	=315 ohms
r_{16}	=503 ohms
X_{14}	=230 ohms
X_{12}	=230 ohms
$X_2(+30°)$	=191 ohms
$X_2(-30°)$	=137 ohms
X_4	=143 ohms
X_6	=495 ohms
X_8	=193 ohms
r_{14}	=48 ohms
r_{12}	=48 ohms
$r_2(+30°)$	=24 ohms
$r_2(-30°)$	=19 ohms
r_4	=19 ohms
r_6	=64 ohms
r_8	=42 ohms

The use of a slide wire resistor or potentiometer type rheostat for adjusting the voltage is

not an essential part of the invention. Thus in Fig. 12 an adjustable ratio transformer 35 is interposed between the current transformer and the phase shifting circuit, while in Fig. 13 an adjustable reactance transformer 36 is substituted for the simple reactor X.

The modification shown in Fig. 14 differs from Fig. 9 principally in that the reactance compensation element contains an adjustable reactance transformer 36, as shown in Fig. 13, instead of a slide wire resistor. This requires a slight rearrangement of the parallel phase shifting impedances in the reactance compensation element. The arrangement is such that for single phase operation the switch 26 merely connects a portion of the secondary winding of the reactance transformer 36 in the circuit of the voltage relay 5 in series with the resistance compensation element. For three-phase operation the switch 26 connects a resistor 39 in parallel with a different amount of the secondary winding of the reactance transformer 36 for the 30 degree leading condition of operation and connects a part of the resistance 39 in series with a capacitor 40 across the secondary winding of the reactance transformer 36 for the 30 degree lagging other condition of operation. The resistance compensation element of Fig. 14 is substantially the same as the resistance compensation element of Fig. 9.

Instead of using slide wire adjusters, as in Fig. 9, Fig. 14 employs dial type tap switches 37 and 37' for the resistance compensation element and 38 and 38' for the reactance compensation element. Switches 37 and 38 provide for relatively coarse adjustment and switches 37' and 38' provide a relatively fine adjustment.

In general, Fig. 15 bears the same relation to Fig. 14 as Fig. 11 bears to Fig. 9. It shows diagrammatically the compensator as it is at present contemplated that it will be manufactured. It is provided with five terminals 41, 42, 43, 44 and 45. Terminals 41 and 42 are the ones to which the voltage measuring device or voltage regulating relay is connected, terminals 41 and 43 are the ones to which the secondary winding of the potential transformer 3 is connected, and terminals 44 and 45 are the ones to which the secondary winding of the current transformer 2 is connected.

Included in Fig. 15 is a special voltmeter circuit ballast of the type described and claimed in application S. N. 151,892, filed July 3, 1937, in the name of Wayne E. Birchard and assigned to the assignee of the present application. This ballast consists of a capacitor 46 and a reactor 47 so connected that the capacitor is across the terminals of the voltage measuring device and the reactor is in series in the circuit supplying both the capacitor and the voltage measuring device. These elements are proportioned in accordance with the teachings of the above-mentioned Birchard application with the result that the volt-ampere burden of the voltage measuring circuit on the potential transformer is very much less than when a conventional resistive ballast is employed and with the further result that the current in the voltage measuring device is substantially independent of reasonable variations in temperature, frequency and impedance of the voltage measuring device. Taps are provided on the reactor 47 and these are connected to the respective sockets 31, 32 and 33. The purpose of this is to change the value of the reactance 47 so as to compensate for changes in the effective reactance of the line drop compensator when the plug 34 is inserted in the different sockets. In this manner, the total effective series reactance which cooperates with the shunt capacitor 46 will remain constant for the various conditions of operation of the compensator and, therefor, the maximum effect of the capacitive and inductive ballast is secured.

While Figs. 3, 10, 12 and 13 have been referred to as compensator elements, that is to say either resistance compensator elements or reactance compensator elements, they are not limited to such use and any of them may be used alone as complete line drop compensators. For example, if Figs. 3 and 10 would produce the thirty-degree phase shift required for the resistance compensation voltage of three-phase circuits they would also produce complete impedance drop compensation for a single phase line having such resistance and reactance that its impedance angle was thirty degrees. Similarly, the reactance compensation elements shown in Figs. 12 and 13 would produce complete impedance drop compensation for a single phase circuit whose resistance and reactance has such relative values that the line had an impedance angle of sixty degrees. Furthermore, by varying the relative reactance and resistance values of the parallel branch circuits of these figures any desired phase shift can be secured so that line drop compensation of a line whose impedance has any given phase angle can be obtained. When used in this manner the magnitude adjustment consisting of the slide wire resistors in Figs. 3 and 10 and the taps on the transformers 35 and 36 in Figs. 12 and 13 would adjust the magnitude of the impedance compensation as a unit and it would be impossible to adjust separately the resistance and reactance compensation components of the total impedance compensation, as is done in Figs. 1, 2, 8, 9, 11, 14 and 15.

While there have been shown and described particular embodiments of this invention, it will be obvious to those skilled in the art that changes and modifications can be made therein without departing from the invention and therefore it is aimed in the appended claims to cover all such changes and modifications as fall within the true spirit and scope of the invention.

What we claim as new and desire to obtain by Letters Patent of the United States is:

1. In a line drop compensating system, a compensator element comprising, in combination, a resistor connected in a voltmeter circuit which measures the line to line voltage of a three-phase power line, adjustable means for selectively connecting to various points on said resistor a compensator current circuit which carries a current proportional in magnitude and similar in phase to the current in one of the lines of said power line between which said line to line voltage is measured, and means for shifting the phase of the compensation voltage of said element so as to correct for the unity power factor 30-degree phase displacement between the voltage of said voltmeter circuit and the compensator current comprising reactive means connected in parallel with said resistor.

2. In a line drop compensating system, a compensator element comprising, in combination, a reactance connected in a voltmeter circuit which measures the line to line voltage of a 3-phase power line, a serially-connected resistor and an opposite sign reactance connected in parallel circuit relation with said first-mentioned reactance,

adjustable means for selectively connecting to various points on said resistor a compensator current circuit which carries a current proportional in magnitude and similar in phase to the current in one of the lines of said power line between which said line to line voltage is measured, said reactances being so proportioned with respect to each other and with respect to said resistor as to shift the phase of the voltage across said first mentioned reactance element so as to correct for the unity power factor 30-degree phase displacement between the voltage of said voltmeter circuit and the compensator current.

3. A line drop compensator which is connected in a circuit for measuring the voltage between two conductors of a three-phase power line and which is energized by a current derived wholly from one of said two conductors comprising, in combination, a resistance compensator having a normally fixed reactance element and an adjustable potentiometer type resistor which is set directly in terms of power line resistance, and a reactance compensator having a normally fixed reactance element and an adjustable potentiometer type resistor which is set directly in terms of power line reactance.

4. A line drop compensator which is connected in a circuit for measuring the voltage between two conductors of a three-phase power line and which is energized by a current derived wholly from one of said two conductors comprising, in combination, a resistance compensator having a resistor connected in parallel with a reactance device, a reactance compensator comprising a second resistor connected in parallel circuit relation with a second reactance device, a potentiometer type adjuster on said first mentioned resistor which is set directly in terms of power line resistance, and a second potentiometer type adjuster on said resistor which is set directly in terms of power line reactance.

5. A line drop compensator for use with single phase and 3-phase power circuits comprising, in combination, a pair of fixed resistors, separate potentiometer type adjusters on each of said resistors which are set directly in terms of power line resistance and reactance respectively, means for shifting the phase of the compensator voltages comprising a plurality of impedance elements adapted selectively to be connected in parallel with said resistors, and 3-positioned switching means for selectively varying the parallel connections between said resistors and said impedance elements so as to provide the correct phase of the compensator voltages for single phase and plus and minus 30-degree 3-phase operation.

6. In combination, a relatively high impedance circuit, an impedance element connected in series circuit relation therewith, a branch circuit connected in parallel circuit relation with said impedance element, a different kind of impedance element serially connected in said branch circuit, and means for adjustably connecting an alternating current supply circuit to various points on the element in the branch circuit, the relative values of said elements being such as to shift the voltage drop in said first-mentioned element with respect to a current in said supply circuit through a predetermined acute angle.

7. In combination, a relatively high impedance circuit, a reactive element serially connected therein, a resistor connected in parallel circuit relation with said reactive element, and means for adjustably connecting an alternating current supply circuit to various points on said resistor, the relative values of said reactive element and resistor being such as to shift the voltage drop through said reactance element with respect to a current in said current supply circuit through a predetermined acute angle.

8. In combination, a relatively high impedance circuit, a reactance element serially connected therein, a branch circuit connected in parallel circuit relation with said reactance element, a second reactance element of different value and opposite sign and a resistor serially connected in said branch circuit, and means for adjustably connecting a current supply circuit to various points on said resistor for varying the magnitude at constant phase of the voltage drop in said first reactance element.

9. A line drop compensator comprising, in combination, a pair of serially connected resistors, a capacitive reactance connected in parallel with one of said resistors and having an ohmic value of 173 per cent of the ohmic value of its parallel resistor, an inductive reactance element connected in parallel with the other resistor which has an ohmic value of 173 per cent of the ohmic value of its parallel-connected reactive element and separate potentiometer type adjustors on each of said resistors adapted to be serially connected in an energizing circuit for said compensator.

10. A line drop compensator comprising, in combination, a pair of serially connected resistors, an inductive reactance element connected in parallel with one of said resistors and having an ohmic value of 173 per cent of the ohmic value of its parallel connected resistor, a capacitor connected in parallel with the other resistor, a reversing transformer for reversing the voltage of said capacitor, said capacitor and transformer having an effective capacitive reactance of substantially 58 per cent of the ohmic value of its parallel connected resistor, and separate potentiometer type adjusters on each of said resistors serially connected in an energizing circuit for said compensator.

11. In combination, a potential transformer having a primary winding connected between two conductors of a three-phase power line, a voltage measuring circuit connected to the secondary winding of said potential transformer, a pair of resistors serially connected in said voltage measuring circuit, a reactor, a capacitor, switching means for selectively connecting said reactor or said capacitor in parallel with one of said resistors, a second reactor and a second capacitor, a transformer for reversing the voltage of said second capacitor, said second reactor and said second capacitor being serially connected with each other in parallel with the other of said pair of resistors, switching means for selectively short circuiting said reactor or said reversing transformer, a pair of slidable contacts on said resistors, a current transformer connected in one of the conductors of the three-phase circuit between which the primary winding of said potential transformer is connected, a circuit containing the secondary winding of said current transformer and said slidable contacts in series, means for varying the ratio of said current transformer, a voltage sensitive device, a third resistor connected in series with the first-mentioned pair of resistors, and switching means for selectively connecting said voltage sensitive device to said third resistor or to a point be-

tween said second inductive reactance and said reversing transformer.

12. In a line drop compensator for single phase and plus and minus 30-degree 3-phase operation, a resistance compensator including a resistance, means for selectively connecting (1) a resistor in parallel with said resistance for single phase operation, (2) a reactor in parallel with said resistance for minus 30-degree 3-phase operation, and (3) capacitance in parallel with said resistance for plus 30-degree 3-phase operation, and a reactance compensator including a reactance connected in series with said resistance, and switching means for selectively connecting (1) in parallel circuit relation with a portion of said reactance, serially connected capacitance and a second resistor for single phase operation, (2) in parallel circuit relation with all of said reactance said second resistance for minus 30-degree 3-phase operation, and (3) in parallel circuit relation with all of said reactance serially connected different value of capacitance and said second resistance for plus 30-degree 3-phase operation.

13. A line drop compensator comprising, in combination, a first resistor and a second resistor serially connected with each other, a capacitor, a reactor, a third resistor, means for selectively connecting said capacitor, said reactor or said third resistor in parallel with the first resistor, a second reactor provided with taps, third and fourth capacitors having values different from each other and different from the first capacitor, switching means for selectively connecting said second reactor in parallel with said second resistor, connecting said second capacitor in series with a portion of said reactor across said second resistor and connecting said second reactor and said third capacitor in series with each other across said second resistor.

14. In a variable capacitive reactance device, a plurality of pairs of terminals between which it is desired to have different predetermined values of effective capacitive reactance, a capacitor, a transformer having a low voltage primary winding and a high voltage secondary winding, taps on said primary winding for connection to said terminals and electrically spaced on said winding according to the ratios of effective capacitive reactance desired, and taps on said secondary winding for connecting said capacitor across variable portions thereof so as to correct for manufacturing variations in capacity of said capacitor.

15. In a line drop compensator, a plurality of selectively operable circuits each adapted to contain a capacitor of different value, a single capacitor, switching means for selectively connecting said capacitor in said circuits, and an adapting step-up transformer interposed between said capacitor and said switching means, taps on the secondary side of said transformer for correcting for the effect of manufacturing tolerances on the value of said capacitor, and taps on the primary side of said transformer for changing the effective value of said capacitor.

16. A line drop compensator adapted for single phase and plus and minus 30-degree 3-phase operation comprising a first resistor and a second resistor each provided with potentiometer type adjusters, said adjusters being connected respectively to the out-put terminals of a current transformer, a simple reactor, a reactor provided with taps, a simple resistor, a capacitor provided with a tapped stepup transformer, and switching means for selectively connecting (1) said simple resistor in parallel with said first slidable contact resistor and said second slidable contact resistor and a portion of said step-up transformer in series with each other and in parallel with a portion of said tapped reactor, (2) said simple reactor in parallel with said first-mentioned resistor and said second slidable contact resistor in series with said stepup transformer across another portion of said tapped reactor and (3) a different portion of said stepup transformer in parallel with said first slidable contact resistor and said second slidable contact resistor in parallel with a different portion of said tapped reactor.

17. In combination, a main electric circuit, a pair of branch circuits connected in parallel circuit relation with each other and in series circuit relation with said main circuit, means for circulating an adjustable total current in said branch circuits so as to produce an adjustable voltage drop in said main circuit, and impedance elements of different kinds connected respectively in said branch circuits and being so correlated as to produce a predetermined phase angle relation between said voltage drop and said current.

18. In combination, a line drop compensator having an adjustable resistance compensation element and an adjustable reactance compensation element, said compensator being provided with a pair of output terminals connected in series with a voltametric device across two of the conductors of a polyphase circuit and being further provided with a pair of input terminals energized in accordance with the current in one of said two conductors, and means for causing the voltages of said elements to be in line and in quadrature respectively with the voltage between said two conductors at unity power factor on said circuit comprising a pair of impedance devices connected respectively in parallel circuit relation with said elements.

19. In combination, a line drop compensator having an adjustable resistance compensation element and an adjustable reactance compensation element, said compensator being provided with a pair of output terminals connected in series with a voltametric device across two of the conductors of an alternating current power circuit and being further provided with a pair of input terminals energized in accordance with the current in one of the conductors of said power circuit, and means for shifting the phase of the voltages of said elements so as to secure correct resistance and reactance compensation comprising a pair of impedance devices connected respectively in parallel circuit relation with said elements.

20. In combination, a plurality of impedance elements connected in parallel circuit relation in a relative high impedance circuit for measuring the voltage of a main alternating current circuit which has a resultant impedance consisting of resistance and reactance, and means for causing current derived from the current in said main circuit to flow in said elements, said elements having such resistive and reactance values as to cause the resultant voltage drop across them to bear the same relation in magnitude and phase to the voltage of said measuring circuit as exists between the resultant impedance voltage drop in said main circuit and the voltage of said main circuit.

21. In a line drop compensator for single phase and plus and minus thirty-degree three-

phase operation, a resistance compensator including a resistance, means for selectively connecting (1) a resistor in parallel with said resistance for single phase operation, (2) a reactor in parallel with said resistance for minus thirty-degree three-phase operation and (3) capacitance in parallel with said resistance for plus thirty-degree three-phase operation, a reactance compensator including a reactance transformer, and switching means for selectively connecting (1) a portion of the secondary winding of said reactance transformer in series with said resistance for single phase operation, (2) connecting a different value of resistance in parallel with a different portion of the secondary winding of said reactance transformer for minus thirty-degree three-phase operation and (3) connecting a third value of resistance and a second value of capacitance in series with each other and in shunt circuit relation with the secondary winding of said reactance transformer for plus thirty-degree three-phase operation.

22. A line drop compensator for use with single phase and three-phase power circuits comprising, in combination, a reactance element and a resistance element, each of said elements comprising an adjustable impedance and a plurality of additional impedances for selective connection in parallel therewith, and switching means for making and breaking the parallel connections of said elements comprising three multi-pin receiving sockets, and a common multi-pin plug for cooperating selectively with each of said sockets.

23. In a voltage measuring circuit, a ballast impedance and a line drop compensator connected in said circuit, said ballast impedance requiring substantially constant reactance in said circuit for best operation, switching means for shifting the phase of the voltage of said compensator, said switching means acting to vary the effective reactance of said compensator, and means controlled by said switching means for varying the reactance of said ballast impedance in such a manner as to maintain the combined reactance of said ballast impedance and said line drop compensator substantially independent of changes in the phase angle of the voltage of said compensator produced by said switching means.

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