

May 4, 1937.

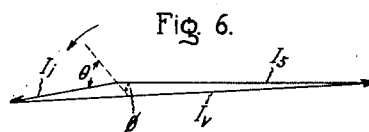
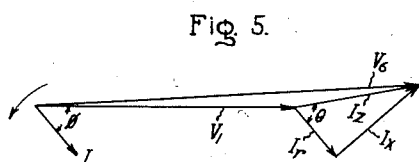
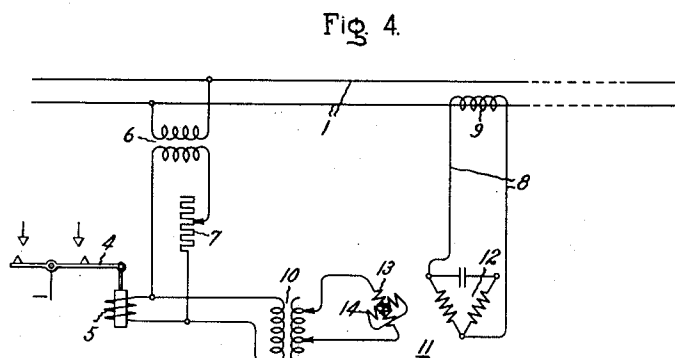
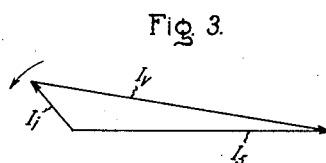
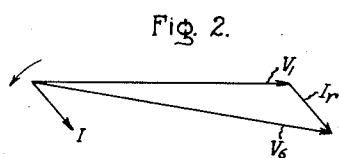
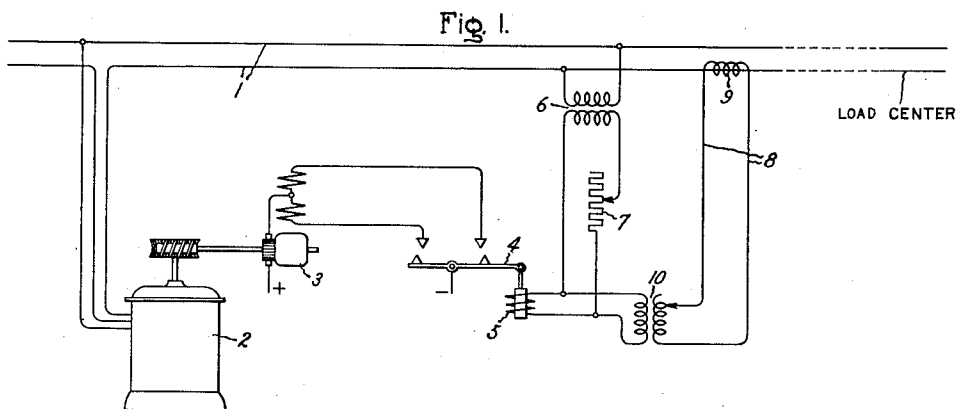
F. J. CHAMPLIN

2,079,488

VOLTAGE REGULATION

Filed Oct. 23, 1935

3 Sheets-Sheet 1



Inventor:
Franklin J. Champlin,
by *Harry E. Dunham*
His Attorney.

May 4, 1937.

F. J. CHAMPLIN

2,079,488

VOLTAGE REGULATION

Filed Oct. 23, 1935

3 Sheets-Sheet 2

Fig. 7.

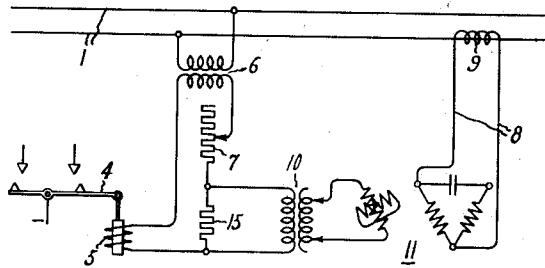


Fig. 8.

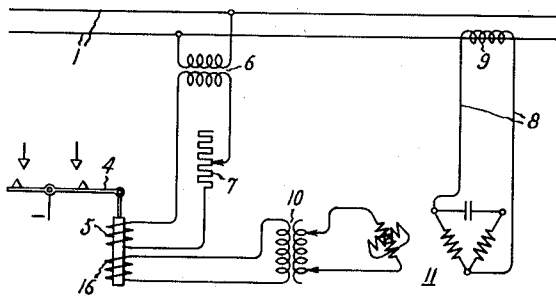


Fig. 9.

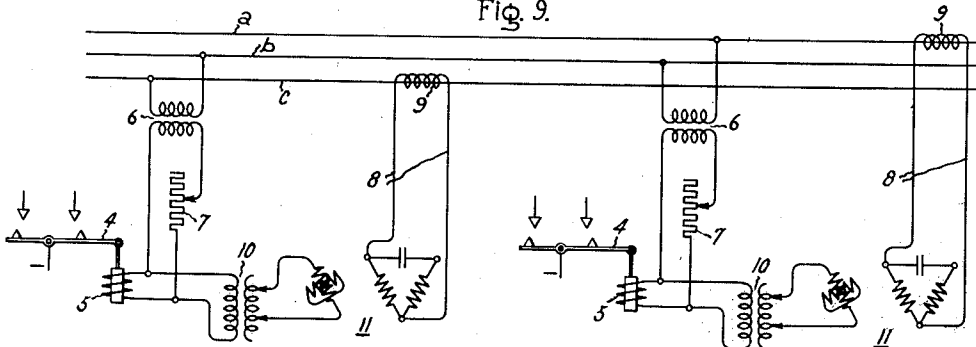


Fig. 10.

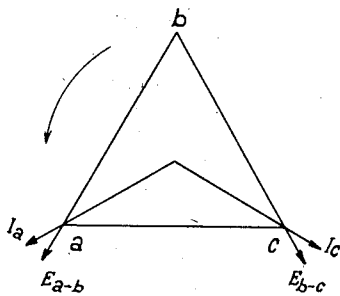
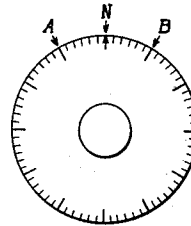


Fig. 11.



Inventor:
Franklin J. Champlin,
by *Harry E. Dunham*
His Attorney.

May 4, 1937.

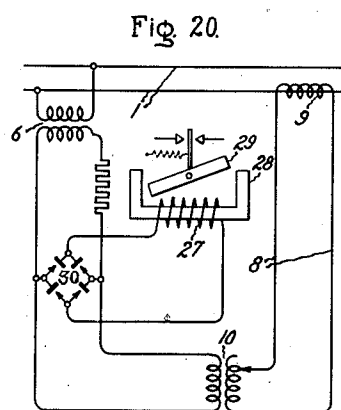
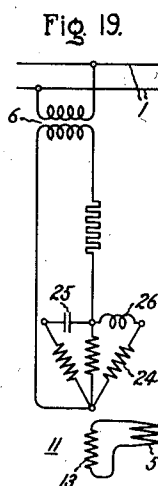
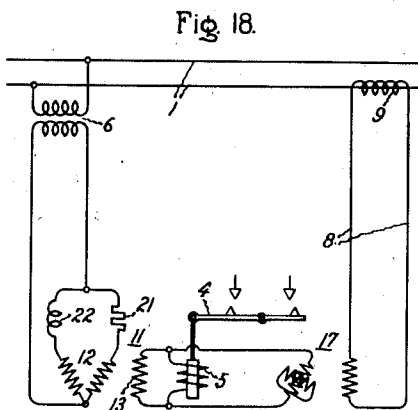
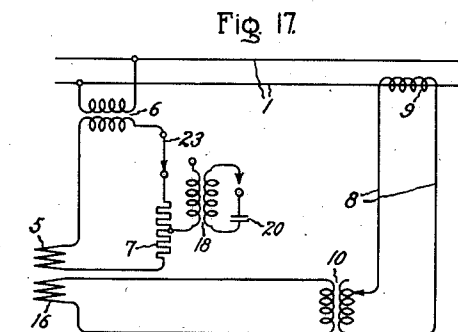
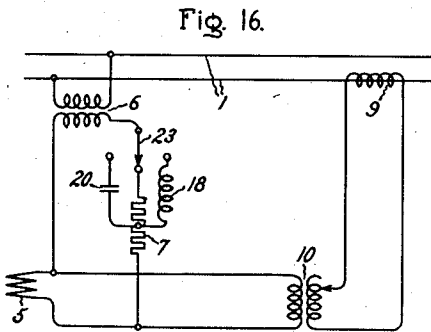
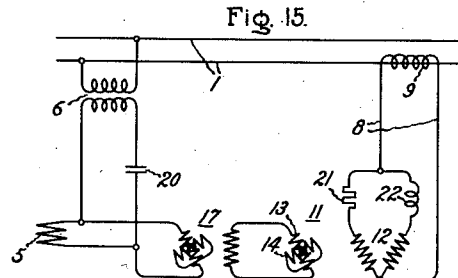
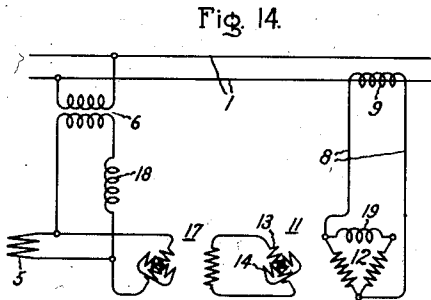
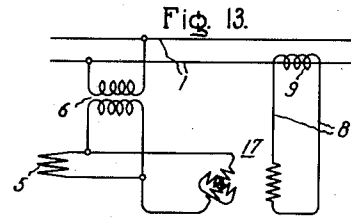
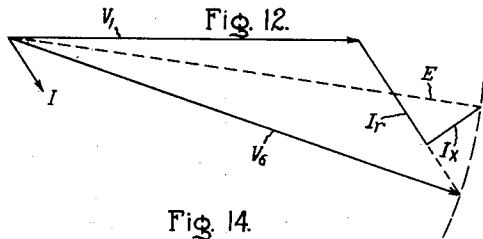
F. J. CHAMPLIN

2,079,488

VOLTAGE REGULATION

Filed Oct. 23, 1935

3 Sheets—Sheet 3



Inventor:
Franklin J. Champlin,
by *Harry E. Dunbar*
His Attorney.

UNITED STATES PATENT OFFICE

2,079,488

VOLTAGE REGULATION

Franklin J. Champlin, Dalton, Mass., assignor to
General Electric Company, a corporation of
New York

Application October 23, 1935, Serial No. 46,321

24 Claims. (Cl. 171-119)

My invention relates to voltage regulation and more particularly to improvements in line drop compensating means for automatic voltage regulating systems.

Most voltage regulating systems have a control device, such as a contact making voltmeter, connected to respond to the voltage at a particular point on the circuit or system. The system then acts to maintain the voltage at this point substantially constant. However, this point is not always the point at which it is actually desired to maintain substantially constant voltage. Theoretically it is always possible to connect the voltage responsive control device to respond directly to the voltage at the point where it is really desired to maintain substantially constant voltage but some times the distance between this point and the point where the regulating apparatus must be located is so great that the cost of such a direct connection renders it impractical. In such cases line drop compensating means are resorted to. Such means may be defined as means for compensating the regulating system for the voltage drop produced by the impedance of a circuit between the point to which the voltage responsive control device is connected and the point at which substantially constant voltage is to be maintained. As the voltage drop is proportional to the current in the circuit, one way of energizing the line drop compensator is by means of a current proportional to the current in the circuit. It is this type of line drop compensation with which my invention is concerned.

Heretofore, line drop compensation of the above type has generally been secured by producing a voltage drop in the energizing circuit for the voltage responsive control device of the regulating system which corresponds in magnitude and phase with the voltage drop to be compensated for.

In accordance with one feature of my invention I secure line drop compensation by circulating in the main voltage responsive operating winding of the control device an auxiliary current which is proportional to the current in the main circuit. Such an arrangement utilizes fewer parts than previous line drop compensators and has lower losses than such previous compensators. This will be explained more in detail hereinafter.

In accordance with another feature of my invention I employ variable phase shifting means for selectively controlling the relative phase angle between the potential responsive current and the current responsive auxiliary line drop compensat-

ing current. This is done in order to take account of the difference in the ratio of resistance to reactance of various lines. The phase shifting means may be applied either to the potential responsive current or to the current responsive auxiliary line drop compensating current or to both and the auxiliary line drop compensating current may either be circulated in the main potential responsive control winding or it may be circulated in an auxiliary winding whose flux cooperates with the flux produced by the main potential responsive control winding.

An object of my invention is to provide new and improved line drop compensating means.

Another object of my invention is to provide novel and simple resistance line drop compensating means.

An additional object of my invention is to provide novel and simple line drop compensating means employing variable current phase shifting means.

My 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 showing of an embodiment of my invention for securing resistance line drop compensation only, Figs. 2 and 3 are vector diagrams for illustrating the principle of operation of Fig. 1, Fig. 4 illustrates a modification of Fig. 1 adapted for complete line drop compensation by means of the addition of a phase shifting transformer, Figs. 5 and 6 are vector diagrams for illustrating the principle of operation of Fig. 4, Figs. 7 and 8 illustrate modifications of Fig. 4, Fig. 9 illustrates how the circuit of Fig. 4 can be utilized for securing voltage regulation in an improved manner of three phase circuits by means of two single phase regulators, Fig. 10 is a vector diagram illustrating the operation of Fig. 9, Fig. 11 illustrates a control dial for the phase shifting transformers adapted for use with the circuit of Fig. 9, Fig. 12 is a vector diagram illustrating how the circuit of Fig. 1 may be adjusted to produce resistance over-compensation corresponding to complete compensation at any particular power factor, Fig. 13 illustrates a modification in which the series impedance in the circuit of the potential transformer is omitted and in which a miniature induction regulator has been utilized as a variable ratio adjusting transformer for the line drop compensating auxiliary current, Fig. 14 is a modification of Fig. 4 in which an inductive reactance is substituted for the series resistance in the potential transformer cir-

cuit and in which a small induction regulator is substituted for the variable ratio current adjusting transformer and in which phase splitting is secured by a reactor instead of by a capacitor, Fig. 15 is similar to Fig. 14 except that a series capacitor is utilized in the potential circuit instead of the series inductance as in Fig. 14 and in which phase splitting is secured by a combination of resistance and inductance, Fig. 16 is a modification in which phase shifting means is inserted in the potential circuit instead of the current circuit, Fig. 17 is similar to Fig. 16 except that the auxiliary current is circulated in an auxiliary winding instead of in the main winding, Fig. 18 is a further modification showing another type of phase shifter in the potential circuit, Fig. 19 shows an additional type of phase shifting transformer of the three phase type and Fig. 20 illustrates an application of my invention to a direct current electro-responsive control device through the use of a full wave rectifier.

Referring now to Fig. 1 of the accompanying drawings, there is shown therein by way of example a single phase alternating current circuit 1 whose voltage is to be regulated. The regulating means may be of any suitable type and is shown by way of example as a conventional induction voltage regulator 2 which is adjusted by means of a conventional reversible servomotor 3 under the control of a suitable voltage responsive device which is illustrated, by way of example, as a contact making voltmeter 4. Contact making voltmeter 4 is provided with a control winding 5 connected to be responsive to the voltage of a point on the circuit 1 by means of a potential transformer 6. Connected in series with the operating coil 5 is a relatively high impedance in the form of a resistance 7 which may or may not be adjustable. This resistance is provided for controlling the setting of the voltage regulating system and also for minimizing temperature and frequency errors in the contact making voltmeter. Ordinarily the voltage drop across resistance 7 is roughly about 90% of the voltage across the secondary winding of transformer 6 and the voltage across the control winding 5 is about 10% of the secondary winding voltage of transformer 6.

The line drop compensating means consists of an auxiliary circuit 8 for circulating directly in the control winding 5 an auxiliary current which is proportional to the current in the circuit 1. This compensating circuit may consist of a current transformer 9 for energizing a suitable variable ratio transformer 10 whose secondary winding is connected across the control winding 5. The ratio of the transformer 10 is adjustable so that the value of the auxiliary current may be adjusted in order that the proper degree of line drop compensation may be secured.

The operation of the arrangement illustrated in Fig. 1 is as follows: If no current flows in the main regulated circuit 1 there will of course be no auxiliary current circulated in the winding 5 by the line drop compensating circuit 8. Under these conditions contact making voltmeter 4 is controlled entirely in accordance with the voltage at the point on circuit 1 to which the potential transformer 6 is connected. If the voltage exceeds a predetermined normal value the winding 5 will be energized sufficiently to cause the contact making voltmeter to close one set of contacts thereby energizing the motor 3 for operation in such direction as to cause the regulator to lower the voltage until the contact making voltmeter opens its contacts thereby stopping the motor,

Similarly if the circuit voltage at the point where transformer 6 is connected to circuit 1 falls below the predetermined normal value the other set of contacts on the contact making voltmeter close causing reverse operation of the motor 3 whereby the regulator 2 raises the voltage of circuit 1 until the voltage is again restored to normal when the contacts separate and the motor stops. As there is no current flow there is no voltage drop in the circuit and the voltage will be the same throughout the circuit.

If now a load which draws a current should be placed upon the circuit a voltage drop will be produced in the circuit between the point where transformer 6 is connected thereto and the load center, which is indicated at the right-hand end of circuit 1, at which it is desired to maintain substantially constant voltage regardless of load changes. By properly selecting the way the transformers 9 and 10 are connected, the auxiliary current produced by the line drop compensating circuit 8 can be made 180° out of phase with the main current in the winding 5 so that this auxiliary current in effect subtracts from the main current. Consequently, the effect will be to decrease the net energization or electromagnetic effect of the winding 5 as the current in the circuit 1 increases which is the equivalent of a reduction in voltage at the point where transformer 6 is connected in the circuit. Consequently the regulating system will act as though the voltage is too low and will increase the voltage at the point where transformer 6 is connected to the circuit. By properly adjusting the ratio of transformer 10 the voltage at the point where potential transformer 6 is connected to circuit 1 may be made higher than the voltage at the load center by an amount which is exactly equal to the resistance voltage drop in the circuit 1 between these two points. In this way resistance line drop compensation is secured.

A better understanding of this line drop compensating action may be had by reference to the vector diagrams of Figs. 2 and 3. In Fig. 2 the voltage V_1 represents the voltage at the load center which is to be maintained constant. The vector I represents the current flow in the circuit 1. The vector I_r represents the resistance voltage drop which is shown in phase with the current vector I , as it should be. The vector V_c represents the voltage which must be maintained at the point where the potential transformer 6 is connected to the circuit in order that V_1 will remain constant for the given resistance voltage drop I_r . In other words, V_c must always equal the vector sum of the substantially constant V_1 and the variable resistance voltage drop I_r which varies in magnitude in direct proportion to the magnitude of the current and which also varies in phase in accordance with the phase angle of the load current I .

In Fig. 3 the diagram is of the currents in the control winding 5. The horizontal vector I_s represents the net or total current in the winding 5 which the automatic regulator system inherently acts to maintain substantially constant for only at one particular value will the contacts of the contact making voltmeter be open and for any other value one of the other of the contacts will be closed causing the regulator to operate in such a direction as to cause that pair of contacts to again separate. The vector I_1 represents the auxiliary current in the winding 5 produced by the line drop compensating circuit 8 while the vector I_v represents the main current in the

winding 5 which is produced in accordance to the voltage of the circuit. As will be seen, the current produced component I_1 of the total current I_2 is reversed in phase with respect to the current vector I of Fig. 2 and it ordinarily subtracts from the voltage produced current vector I_v . The vector sum of these two current components is the resultant, or net total, current I_2 in the winding 5.

It should, of course, be understood that diagram of Fig. 3 is not exact because some of the current from line drop compensating circuit 8 may tend to flow through the resistor 7 and the potential transformer 6. However, it serves to illustrate the principle of the operation. At unity power factor on circuit 1, that is to say when the current and voltage are in phase, the voltage drop I_r in Fig. 2 subtracts arithmetically from the voltage V_0 to give the voltage V_1 and similarly in Fig. 3 the current component I_1 subtracts arithmetically from the voltage component of current I_v to give the resultant current I_2 in the control winding 5.

The above described circuit has the advantage over conventional line drop compensating circuits that no auxiliary series resistor is required with which to produce a line drop compensating voltage drop. In addition its losses are lower than the losses of the conventional system using a series resistor for producing the compensating voltage drop. This may be illustrated as follows: Assume that 24 volts compensation is required, that is to say, a compensating effect is desired which is the equivalent of a 24-volt change in the secondary winding potential of transformer 6, and that the normal voltage drop across the winding 5 is approximately 12 volts and the current through this winding is .5 of an ampere. Assume also that the potential on the secondary side of the transformer 6 is 120 volts. As 24 volts is one-fifth of 120 volts the current differential in the winding 5 will be one-fifth of .5 of an ampere, or one-tenth of an ampere. Consequently, the volt-ampere burden on the secondary side of the current transformer 9 will be one-tenth of an ampere times 12 volts equaling 1.2 volt-amperes plus the losses in the transformer 10.

Assume now that this same compensation is to be obtained across 120 ohms resistance, which may be considered a part of the resistance 7. In order to obtain a voltage drop of 24 volts across a resistance of 120 ohms, .2 of an ampere will be required to be passed through the resistance. The normal current through this resistance, however, is .5 of an ampere and the corresponding voltage across the resistance will be 60 volts. Consequently the volt-ampere burden on a current transformer for the circuit of this type of line drop compensation will be 60 volts times .2 of an ampere equals 12 volt-amperes. This is ten times the volt-ampere burden required by my circuit illustrated in Fig. 1.

The circuit in Fig. 1 has the advantage over the type of line drop compensation secured by means of an additional winding or windings on the operating magnet of the contact making voltmeter that no such additional windings are required and an ordinary standard contact making voltmeter may be employed.

In many cases, for example, in relatively widely variable power factor circuits, the reactance voltage drop in the main circuit cannot be neglected so that the simple resistance line drop compensating circuit of Fig. 1 will not give sufficiently good voltage regulation. In the circuit

of Fig. 4 means in the form of a current phase shifting element 11 has been added so that true and complete line drop compensation can be secured. The current phase shifting means need not be of any particular type so long as it can readily shift the phase of the current through an angle whose tangent is the ratio of the reactance to the resistance of the circuit whose line drop is to be compensated for. As many voltage regulating systems are applied to single phase circuits it is desirable to have a phase shifter which will operate for such circuits. The phase shifter shown in Fig. 4 at 11 consists of a transformer whose primary winding 12 is a V winding having an electrical condenser or capacitor connected to close the V. Such a winding corresponds to the stator of the conventional alternating current single phase capacitor motor and is well known to those skilled in the art. Such a winding, due to the phase shift produced by the capacitor, produces a rotating magnetic field. Mounted for relative rotation with respect to the primary winding is the secondary winding 13 which has currents induced in it by the rotating field produced by the primary winding 12. By rotating the winding 13 through any given angle the phase of the current output of this winding can be shifted with respect to the phase of the current in the circuit 1, which current energizes the primary winding 12 through the current transformer 9. An auxiliary winding 14 is shown mounted at right angles to the secondary winding 13 and this winding is short circuited upon itself. The purpose of this winding is to equalize the load on the primary winding produced by shifting the angular position of the secondary winding 13. Without the winding 14, shifting the angular position of the winding 13 would affect the load balance between the two parts of the V winding of the primary but by means of the right angle auxiliary winding 14, whose impedance should be substantially the same as the impedance of the circuit of winding 13, the load on the two halves of the V of the primary winding will remain balanced regardless of the angular position of the secondary structure. Winding 14, however, is not essential and the circuit of Fig. 4 is operative without it.

The operation of the phase shifting means of Fig. 4 to give true line drop compensation can best be understood by reference to the vector diagrams comprising Figs. 5 and 6. In Fig. 5 the horizontal vector V_1 represents the voltage of the load center which is to be maintained substantially constant regardless of load changes. The vector I is the current which is shown lagging the voltage by the power factor angle ϕ . The resistance drop I_r is shown in phase with the current as it should be and the reactance drop I_x is shown at right angles to the resistance drop and to the current vector which is as it should be. The resultant of these two voltage drops is the impedance drop I_z . The impedance drop I_z makes an angle θ with the resistance voltage drop I_r , this angle θ being the angle whose tangent is the ratio of the reactance x of the circuit to the resistance r of this circuit. As the resistance voltage drop I_r and the current I are in phase the impedance drop I_z also makes the angle θ with the current in the circuit. Consequently in order to secure true line drop compensation it will be necessary to insert an auxiliary current in the winding 5 which exactly subtracts arithmetically from the main current in the circuit 5 when the angle of lag between the

current and the voltage in the circuit corresponds to the angle θ for with this power factor angle the impedance drop in the circuit will subtract arithmetically from the generated voltage of the circuit 1.

This phase shift is represented in Fig. 6 where I_s represents the resultant current in the winding 5 which is to be maintained constant by the regulating system, I_1 represents the auxiliary line drop compensating current in the winding 5 and I_v represents the voltage produced main current in the winding 5. The angle θ in Fig. 6 represents the phase shift angle through which the line drop compensating auxiliary current is shifted by the phase shifting transformer 11. This angle corresponds with the angle θ in Fig. 5 and represents the difference in angles between the current I_1 in Fig. 3 for obtaining simple resistance line drop compensation and the current I_1 in Fig. 6 for securing complete or total impedance line drop compensation.

In the modification shown in Fig. 7 complete line drop compensation is secured by passing the auxiliary current from phase shifting transformer 11 through an auxiliary impedance 15 in series with the operating winding 5 of the contact making voltmeter 4. This circuit corresponds in principle to the conventional line drop compensating circuit in that compensation is secured by inserting an auxiliary voltage drop in the energizing circuit for the control winding of the contact making voltmeter. In other words, line drop compensation is secured by voltage variation instead of by current combination as in Figs. 1 and 4. However, by the use of the phase shifting transformer 11 it is possible to eliminate either the resistance or the reactance elements of conventional line drop compensators for securing complete line drop compensation. Consequently, all that is needed is a single impedance element 15.

In the modification shown in Fig. 8 the line drop compensation from the phase shifting transformer 11 is secured by a combination of magnetomotive forces or fluxes by the addition of the auxiliary line drop compensating coil 16 on the core of the operating solenoid for the contact making voltmeter 4. The principle is similar to the principle of Fig. 4 except that instead of combining the currents directly in one winding the currents are in separate windings which produce separate fluxes which combine in the core vectorially in a manner similar to the way the currents combine in the single winding 5 of Fig. 4.

Fig. 9 illustrates a further modification of my invention for the case when two single phase regulators are connected in V or open delta for regulating the voltage of a three phase circuit. The two separate control circuits for the two single phase regulators (not shown) are each similar to the circuit of Fig. 4.

Heretofore when regulating the voltage of a three phase circuit by means of two single phase regulators it was necessary to utilize auxiliary cross connections between the regulators in order to secure true line drop compensation. This was because the line voltage was out of phase with the line current by 30° . This can be seen more readily by reference to Fig. 10 wherein, if the three lines of the three phase circuit of Fig. 9 are lettered a , b and c from top to bottom, the vector E_{a-b} representing the voltage between the lines a and b is 30° out of phase with the current I_a representing the current in line a , while similarly the vector E_{b-c} representing the voltage between the lines b and c is 30° out of phase with

the current vector I_c representing the current in the line c . The vector diagram of Fig. 10 represents, of course, conditions at unity power factor on the three phase circuit of Fig. 9.

By means of the phase shifting transformers 11 this 30° phase angle difference between the voltage and current vectors may be corrected for independently in each line drop compensator so that auxiliary phase shifting interconnections may be dispensed with, thus increasing the flexibility of the system. The phase shifters, in addition to eliminating an auxiliary interconnection also eliminate the additional current transformers required in the interconnection. In setting the phase shifting transformers 11 of Fig. 9 all that is necessary over the setting for Fig. 4 is that a 30° shift be added or subtracted from the angle θ depending upon with which of the two regulators the particular transformer 11 is associated. This will be seen also in Fig. 10 wherein the voltage vector E_{a-b} leads (phase rotation $a-b-c$) the current vector I_a by 30° whereas the current vector I_c leads the voltage vector E_{b-c} . Thus in the left-hand line drop compensator of Fig. 9 for the regulator which controls the voltage of line c the phase shift angle should be the angle θ minus 30° whereas for the right-hand compensator for the regulator controlling the voltage of line a the phase shift produced in phase shifting transformer 11 should be the angle θ plus 30° .

In Fig. 11 is shown a suitably calibrated dial for the phase shifting transformer 11 for use in circuits such as shown in Fig. 9. In this figure the reference mark N corresponds to no phase shift whereas the reference mark A corresponds to a phase shift of 30° lead and the mark B corresponds to a phase shift of 30° lag. Consequently depending upon with which one of the two compensators the transformer 11 is used the phase shifter will be shifted to point A or point B in order to make up the necessary plus or minus 30° shift and then the shifter is rotated further in order to obtain the shift corresponding to the angle θ .

There is another type of resistance line drop compensation than that which has already been described in connection with Fig. 1. This may be termed resistance over-compensation and is useful in cases where the power factor of the main regulated circuit is substantially constant. Resistance over-compensation means that the resistance compensation is changed by such an amount that it becomes the equivalent of complete impedance compensation at any given power factor. This may be understood better by reference to Fig. 12 wherein V_1 represents the voltage which is to be maintained constant at the center of distribution, I represents the current in the main circuit, I_r represents the resistance voltage drop and I_x represents the reactance drop. The dashed vector E represents the voltage which must be maintained by the regulator in order to compensate for the combined resistance and reactance drops I_r and I_x so as to give the voltage V_1 . If now the voltage vector E is rotated so that its outer end produces an arc and the resistance drop I_r is extended until it intersects this arc, the distance between this intersection point and the arc corresponds to the vector V_2 in Fig. 2. V_2 of course equals vector E so that if the voltage V_2 is held by the regulator the desired voltage V_1 will be maintained at the center of distribution. It will thus be seen that by over-compensating for the resistance drop by the amount indicated by the dashed extension of the resist-

ance drop I_r complete compensation is secured. It should be understood, however, that this holds true only at the particular power factor shown and that if the power factor shifts the voltage V_s will no longer equal the voltage E . In adjusting the circuit of Fig. 1 for resistance over-compensation all that is necessary is that the transformer 10 be adjusted so that enough additional auxiliary current is passed through the winding 5 to just make up for the reactance voltage drop in the circuit at the given power factor for which the setting is made.

It is not always necessary to have a series impedance in the voltage responsive circuit for energizing the control winding 5. Thus, in Fig. 13 there is shown a modification in which the winding 5 is constructed for direct connection to the secondary winding of potential transformer 6. It is also unnecessary to utilize a variable ratio transformer of the type shown at 10 in the previous figures. If desired, such transformers may be replaced by any equivalent form of variable ratio transformer, such for example, as a miniature induction regulator. Such a miniature regulator is shown at 17 in Fig. 13.

In some cases where a series impedance in the voltage responsive energizing circuit of the control winding is necessary, it is desirable to use a reactance instead of the resistance 7. In Fig. 14 there is shown an inductive reactance 18 connected in this manner. Such a reactance has lower losses than the resistance 7 although it renders the circuit more subject to frequency error than does the resistance 7. It is also unnecessary to utilize a capacitor for phase splitting as in Figs. 4, 7, 8 and 9. For example, a relatively high inductive reactance can also be utilized for phase splitting. This is illustrated by the inductive reactance 19 for producing a split phase primary winding 12 of the phase shifting transformer 11 in Fig. 14.

Fig. 15 is illustrative of another modification wherein a capacitor 20 is utilized as a series impedance in the voltage responsive energizing circuit for the main control winding 5. In this figure there is also illustrated an alternative arrangement for phase splitting consisting of a resistor 21 in series with one of the halves of the primary winding 12 of the phase shifting transformer 11 and an inductive reactance 22 in series with the other half of the winding 12.

It should be understood that the matter of phase shift is a relative relationship between the potential in the potential transformer secondary circuit and the current in the current transformer circuit and that therefore the phase shift may be made either in the current or potential circuit or partly in both and is not limited to the current circuit as in the circuits which have been described up to this point. For instance, in Fig. 16 there is illustrated a circuit similar to Fig. 1 for producing resistance compensation or resistance over-compensation but in addition to the series resistance 7, there are provided an inductive reactance 18 and a capacitor 20 branched off from the resistance and all three elements terminating in taps with which an adjustable contact member 23 may be selectively placed in contact. When the contact 23 is on the center tap no phase shift at all is produced because the current merely flows through the resistance 7. By properly proportioning the inductance 18 and the capacitor 20 a resultant 30° lead or lag phase shift may be produced by shifting the contact 23 to the left-hand tap in contact with the capa-

citor or to the right-hand tap in contact with the inductance. Such a circuit would be useful when two single phase regulators are used on three-phase circuits, such as is illustrated in Fig. 9. For example, if the circuit of Fig. 16 were substituted for either one of the two regulator control circuits shown in Fig. 9 and the contact 23 adjusted to the proper tap the necessary 30° phase shift is secured in the potential circuit instead of in the current circuit as in Fig. 9.

Fig. 17 differs from Fig. 16 in two respects. One is that the resistance line drop compensation is secured by means of an auxiliary winding 16 as in Fig. 8. The other is in the arrangement of the phase shifting circuit. This arrangement which is as follows, can also be used in Fig. 16. I find that the capacitor 20 in Fig. 16 is sometimes comparatively large and costly. In order to overcome this difficulty, I build reactor 18 as a transformer by adding a secondary winding to step up the voltage for a capacitor. With this arrangement, the exciting winding of 18 will be used as a reactor and when phase splitting in the leading direction is required, I will close the circuit through the capacitor from the secondary winding of this reactor transformer to effect this phase shift. In this case, the volt ampere capacity of the capacitor in the reactor transformer secondary will be double that required when shown as in Figure 16 because it must neutralize the exciting current of this transformer and in addition provide a leading current equal to that exciting current.

It should, of course, be understood that in Figs. 16 and 17 phase shifting transformers 11 in the compensating circuits may also be utilized if desired and the conventional variable ratio transformer 10 may also be replaced by a miniature regulator 17 if desired.

In Fig. 18 is shown a circuit in which the phase shifting transformer 11 for securing complete line drop compensation is inserted in the potential circuit instead of in the current circuit. This transformer 11 utilizes the resistor-reactor phase splitting arrangement shown in Fig. 15. For the following reason the short circuited quadrature winding on the secondary of the phase shifting transformer has been omitted. When the phase shifter is installed in the current transformer circuit, it is most desirable to maintain a uniform impedance in that circuit regardless of the position of the phase shifter for which reason the short circuit winding is employed. In the potential circuit, this winding is not so necessary, however, because the impedance of the phase shifter is only a small part of the total impedance of the circuit and the small overall change in impedance which will occur when the phase shifter is turned to different positions would not have any appreciable effect upon the contact making voltmeter setting.

In the operation of Fig. 18 the auxiliary current produced by the compensating circuit 8 will tend to be in phase or in phase opposition with the current in the main circuit 1 and the necessary line drop compensating phase angle or phase shift between this current and the potential produced current is secured by rotating the secondary winding 13 with respect to the primary winding 12 of the phase shifting transformer 11.

Fig. 19 is similar to Fig. 18 except that a three-phase primary winding 24 is provided on the phase shifting transformer 11 and phase splitting is secured by means of a capacitor 25 and

an inductance 26. The secondary winding 13 may be the same and is rotated relatively to the three-phase primary to produce the necessary phase shifting. Such a three-phase phase shifting transformer may also be employed in the current as well as the potential circuit if desired.

Instead of utilizing a contact making voltmeter a direct current electro-responsive control device such as is sometimes used on automatic voltage regulators of other types may be employed. For example, in Fig. 20 such a device is illustrated as having a main control winding 27 for energizing a core 28 which operates an armature 29 carrying contacts for cooperation with fixed contacts. The winding 27 is connected to the direct current terminals of a rectifier 30 to whose alternating current terminals are connected in parallel the potential responsive and current responsive circuits as in the previous figures. The rectifier acts like a resistance so that broadly speaking the action will be somewhat similar to the action of Fig. 7 where the current from the line drop compensating circuit 8 will produce an auxiliary current or voltage which will act to produce a line drop compensating action in the winding 27. The arrangement shown in Fig. 20 will of course only give resistance compensation or over compensation but obviously suitable phase shifting means, such as have already been shown and described, may be inserted in either the current responsive circuit 8 or in the potential transformer circuit so as to give complete compensation.

While I have shown and described particular embodiments of my invention, it will be obvious to those skilled in the art that changes may be made without departing from my invention and I therefore aim in the appended claims to cover all such changes and modifications as fall within the true spirit and scope of my invention.

What I claim as new and desire to secure by Letters Patent of the United States, is:

1. In combination, a main electric circuit whose voltage at a relatively remote point is to be maintained constant, voltage regulating means for said circuit including a single solenoid winding, and two parallel circuits the current in each of which passes through said winding, one of said circuits being energized in accordance with the voltage of said main circuit and the other of said circuits being energized in accordance with the current in said main circuit.

2. In combination, an alternating current circuit whose voltage is to be regulated, voltage regulating means therefor including a contact making voltmeter having an operating winding whose net ampere turns are to be kept substantially constant, means including a potential transformer and a relatively high series impedance for circulating a current in said winding which varies in magnitude and phase with the voltage of said circuit, and line drop compensating means including a current transformer for circulating in said winding a current which varies in magnitude and phase with the current in said circuit, said two currents in said winding being in phase opposition when the voltage and current of said circuit are in phase.

3. In combination, an alternating current circuit whose voltage is to be regulated, voltage regulating means therefor including a contact making voltmeter having an operating winding whose net ampere turns are to be kept substantially constant, means including a potential transformer and a relatively high series impedance for

circulating a current in said winding which varies in magnitude and phase with the voltage of said circuit, line drop compensating means including a current transformer for circulating in said winding a current which varies in magnitude and phase with the current in said circuit, said two currents in said winding being in phase opposition when the voltage and current of said circuit are in phase, and a variable ratio transformer interposed between said winding and said current transformer.

4. In a voltage regulating system for an alternating current circuit, a voltage responsive control device, line drop compensating means for said device, and adjustable means for selectively varying the relative phase relation of the voltage applied to said device and the current in the line drop compensating means.

5. In a system for regulating the voltage of an alternating current circuit, an electroresponsive control device, means for applying an operating current to said device which varies in accordance with the magnitude and phase of the potential of said circuit, means for applying a second current to said device which varies in accordance with the magnitude and phase of the current in said circuit, and means for varying the relative phase of said currents.

6. In a system for regulating the voltage of an alternating current circuit, a control winding, means for circulating in said winding a current which varies in accordance with the magnitude and phase of the potential of said circuit, means for circulating in said winding a second current which varies in accordance with the magnitude and phase of the current in said circuit, and means for varying the relative phase angle between the currents in said winding.

7. In a system for regulating the voltage of an alternating current circuit, an electroresponsive control device having a pair of cooperating windings, means for circulating in one of said windings a current which varies in accordance with the magnitude and phase of the potential of said circuit, means for circulating in the other winding a current which varies in accordance with the magnitude and phase of the current in said circuit, and means for varying the relative phase of said currents.

8. In a voltage regulating system for an alternating current circuit, a control winding connected to respond to the voltage of said circuit, and line drop compensating means for said system, said line drop compensating means including apparatus for producing a current which is proportional to the current in said circuit and which is selectively variable in phase with respect to the current in said circuit.

9. In a voltage regulating system for an alternating current circuit, a control winding connected to respond to the voltage of said circuit, and line drop compensating means for said system, said line drop compensating means including apparatus for producing a current which is directly proportional to the current in said circuit but which is selectively variable in magnitude and phase with respect to the current in said circuit.

10. In a voltage regulating system for an alternating current circuit, a control winding connected to respond to the voltage of said circuit, and line drop compensating means for said system, said line drop compensating means including a phase shifting transformer having relatively rotatable primary and secondary windings.

11. In a voltage regulating system for an alternating current circuit, a control winding connected to respond to the voltage of said circuit, means for circulating in said winding an auxiliary current which is proportional to the current in said circuit, and means for selectively adjusting the phase of said auxiliary current.

12. In a voltage regulating system for an alternating current circuit, a control winding connected to respond to the voltage of said circuit, means for circulating in said winding an auxiliary current which is proportional to the current in said circuit, and means for adjusting the magnitude and phase of said auxiliary current.

13. In a voltage regulating system for an alternating current circuit, a control winding, means including a relatively high series impedance for energizing said winding in accordance with the voltage of said circuit, and line drop compensating means for circulating an auxiliary current in said winding which varies in magnitude and phase with the current in said circuit, said compensating means including current phase shifting means for shifting the phase of said auxiliary current from the phase of the current in said circuit through an angle whose tangent is the ratio of the reactance to the resistance of said circuit.

14. In a system for regulating the voltage of an alternating current circuit, an electroresponsive control device, means for applying an operating current to said device which varies in accordance with the magnitude and phase of the potential of said circuit, means for applying a second current to said device which varies in accordance with the magnitude and phase of the current in said circuit, and means for varying the phase of the potential responsive operating current.

15. In a system for regulating the voltage of an alternating current circuit, a control winding, means for circulating in said winding a current which varies in accordance with the magnitude and phase of the potential of said circuit, means for circulating in said winding a second current which varies in accordance with the magnitude and phase of the current in said circuit, and means for varying the phase of the current which varies in accordance with the potential of said circuit.

16. In a system for regulating the voltage of an alternating current circuit, an electroresponsive control device having a pair of cooperating windings, means for circulating in one of said windings a current which varies in accordance with the magnitude and phase of the potential of said circuit, means for circulating in the other winding a current which varies in accordance with the magnitude and phase of the current in said circuit, and means for varying the phase of the current which varies in accordance with the potential of said circuit.

17. In a system for regulating the voltage of an alternating current circuit, a control device, separate circuits responsive to the voltage and current of said circuit for energizing said device, and variable phase shifting means in said voltage responsive circuit.

18. A single-phase phase shifting transformer adapted for use in line drop compensators comprising in combination, a V-connected primary winding having a reactance connected to close the V, a secondary winding mounted for relative rotation with respect to said primary winding, and an

auxiliary short circuited winding arranged at right angles to said secondary winding.

19. In a voltage regulating system for three-phase alternating current circuits, means for obtaining correct line drop compensation when two single phase regulators are used without the necessity for auxiliary inter-connections between the regulators comprising a pair of adjustable phase shifting transformers having their primary and secondary windings interposed in the line drop compensating energizing circuits for their respective regulators.

20. In a system for regulating the voltage of an alternating current circuit, a direct current electroresponsive control device having an operating winding, a rectifier having a pair of alternating current input terminals and a pair of direct current output terminals, said output terminals being connected to said winding, and separate circuits carrying currents which vary in accordance with the phase and magnitude of the voltage and current respectively of said alternating current circuit connected to said alternating current terminals.

21. In a phase shifting circuit, a resistor, a reactor, means for selectively connecting either the resistor or the reactor in said circuit, a winding inductively coupled to said reactor, a capacitor, means for selectively connecting said capacitor across said winding, said capacitor having such a volt-ampere capacity that when it is connected across said winding its capacitive effect when referred to the reactor will correspond to the inductive effect of said reactor alone.

22. In a compensated voltage sensitive control system for use with alternating current power lines, in combination, a voltage sensitive main control circuit and a current sensitive line drop compensating circuit, means for adjusting for the magnitude of the line impedance having the drop to be compensated comprising means for varying the magnitude of the current in said current sensitive circuit, and means for adjusting for the impedance angle of the line having the drop to be compensated comprising means for varying the relative phase of current in said voltage and current sensitive circuits.

23. In combination, an alternating current circuit, a line drop compensated voltage sensitive device, means for energizing said device with a voltage which varies in accordance with the magnitude and phase of the voltage of said circuit, means for energizing said device with a current which varies in accordance with the magnitude and phase of the current in said circuit, means for adjustably varying the phase of the energizing voltage of said device, and means for adjustably varying the magnitude of the energizing current of said device.

24. In combination, a poly-phase alternating current circuit, a voltage measuring device adapted to be connected between two of the conductors of said circuit by means of a single potential transformer, and line drop compensating means for said device adapted to be connected by means of a single current transformer to respond to the current in one of the two conductors of said circuit between which said potential transformer is connected, said line drop compensating means including two separately operable elements for adjusting respectively for the magnitude of the impedance of said circuit and for the ratio of the resistance to the reactance of said circuit.

FRANKLIN J. CHAMPLIN.