Aug. 31, 1943. C. M. SUMMERS 2,328,037

VOLTAGE REGULATOR

Filed Aug. 14, 1940

Fig. 1.

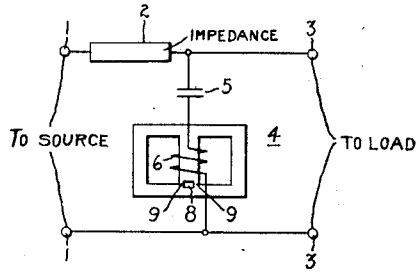


Fig. 2.

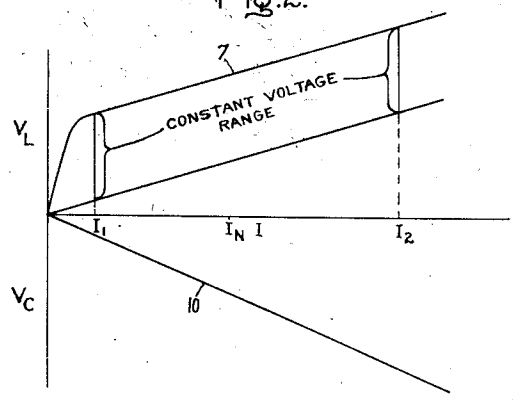


Fig. 4.

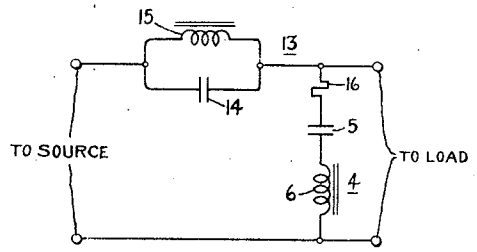


Fig. 3.

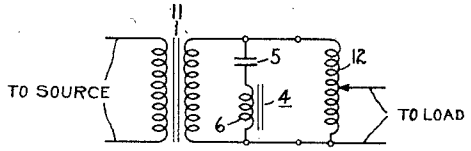
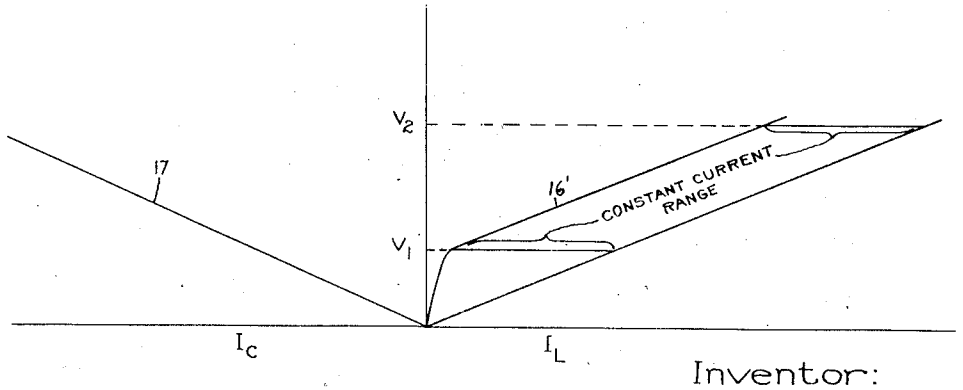


Fig. 5.



Inventor:
Claude M. Summers,
by Harry E. Dunham
His Attorney.

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VOLTAGE REGULATOR

Claude M. Summers, Fort Wayne, Ind., assignor to General Electric Company, a corporation of New York

Application August 14, 1940, Serial No. 352,569

11 Claims. (Cl. 171—242)

This invention relates to automatic voltage regulators and more particularly to improvements in static circuits for producing a constant output voltage over a wide range of variation of input voltage or of output current or both, the variation in output current being in magnitude or power factor or both.

An important feature of the invention comprises a very sensitive and accurate wide range impedance means which exhibits a constant voltage drop over a wide range of current variation. This impedance means is connected in parallel or shunt circuit relationship with a load whose voltage is to be maintained constant. In this manner variations in suppy voltage, or load magnitude, or load power factor or a combination thereof are automatically corrected for. Thus, if the supply voltage varies, my novel variable impedance means automatically adjusts itself so as to vary the current supplied by the source an amount sufficient to produce a change in voltage drop in either the inherent series internal impedance of the source or the conductors leading therefrom or a lumped series impedance, which change in voltage drop is sufficient exactly to counteract the change in supply voltage. Similarly, if the load current varies, the change in voltage drop in the supply circuit causes my novel variable impedance means to vary its impedance sufficiently to compensate for the change in impedance of the load. This compensation is characterized by maintaining the vector sum of the supply voltage and the series impedance voltage a constant in magnitude, but not necessarily a constant in phase angle. As the vector sum of these two voltages equals the load voltage and as the vector sum of all three voltages must equal zero, it will be seen that the magnitude of the load voltage is independent of the load current.

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

Another object of the invention is to provide a new and improved automatic voltage regulator circuit having no moving parts.

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

In the drawing Fig. 1 illustrates diagrammatically a simple form of my invention; Fig. 2 is a set of volt-ampere characteristics for illustrating the principle of operation of Fig. 1; Fig. 3 is a modification in which the series impedance is supplied by the leakage impedance of a supply transformer and in which the load voltage is made adjustable by means of a variable voltage auto-transformer; Fig. 4 is a further modification in which the series impedance means has constant current characteristics, and Fig. 5 is a set of volt-ampere characteristics for illustrating the principle of operation for the constant current portion of Fig. 4.

Referring now to the drawing and more particularly to Fig. 1, my circuit comprises a pair of input terminals 1 in series with which is an impedance 2, and a pair of output terminals 3 in parallel with which is an impedance means 4 comprising a serially-connected capacitor 5 and a reactor 6. The impedance 2 may be of any kind such as a resistor, a reactor, a capacitor or any combination thereof. Occasionally the inherent internal impedance of a source of current supply will be sufficient as in supply circuits or current sources which have unusually poor inherent regulation.

The reactor 6 has a special volt-ampere characteristic indicated by the curve 7 in Fig. 2. This curve has a sharp knee or bend near the origin and is practically a straight line over a relatively wide range of current. This characteristic may be obtained by providing the reactor with a core having an air gap 8 which is bridged by one or more restricted core sections 9. These restricted core sections saturate quickly and at relatively low values of current and thereafter the reactor acts like an air core reactor by reason of the air gap and thus has a substantially straight line volt-ampere characteristic. The initial saturated effect produced by the restricted sections serves to offset the straight line portion of the characteristic from the origin of coordinates. This is important as will now be explained.

The capacitor 5 has a volt-ampere characteristic 10 which in common with all capacitors is a straight line passing through the origin of coordinates. However, the capacitor 5 is so proportioned that the slope of its volt-ampere characteristic is made numerically equal but of course of opposite sign to the slope of the straight line portion of the reactor characteristic. By reason of the offset produced by saturation of the straight line portion of the reactor characteristic the numerical values of the voltage across the reactor and across the capacitor at any given current within the straight line range indicated by the currents I_1 and I_2 will be different. Furthermore, by reason of their signs being opposite, this difference which actually is the vector sum of the individual voltage is constant throughout the

current range I_1—I_2. This is clearly shown by rotating the capacitor characteristic into the quadrant occupied by the reactor characteristic. As the slopes of the characteristics are equal, they will be parallel when the capacitor characteristic is so rotated as indicated by the dotted line and consequently the numerical difference between their voltages being the vertical distance between two parallel lines will be equal over the current range.

In practice the capacitor and reactor are so proportioned that their resultant voltage corresponds to the desired constant load voltage. The circuit will then maintain constant load voltage regardless of relatively wide variations in source voltage and load current by automatically varying its resultant impedance in response to any change in resultant voltage or resultant current in such a manner as to change the current drawn through the impedance 2 by an amount sufficient to cause an impedance voltage drop which will automatically neutralize any variation in supply voltage or any variation in voltage drop caused by a variation in load current.

This regulation is independent of variations in load power factor so long as the current in the impedance means 4 stays within the range I_1—I_2 in Fig. 2. The worst condition for regulation so far as power factor is concerned is a lagging power factor. This is because the resultant impedance of the capacitor 5 and reactor 6 is inductive. This is clearly shown in Fig. 2 in which the voltage across the reactor always exceeds in magnitude the voltage across the capacitor. Consequently, the quadrature lagging component of load current adds or subtracts numerically from the current in the automatically variable impedance means 4 whereas with a resistance or unity power factor load the load current is in quadrature with the current through the impedance means 4 and with a leading power factor load the leading quadrature component is in phase opposition with the current through the impedance means 4.

For these reasons it is best to have the current through the impedance means 4 at some intermediate value I_n when the supply voltage is normal and the load value is normal and at unity power factor. Assuming that the supply voltage stays constant and that the power factor of the load is zero lagging, any change in load current will cause an equal and opposite change in current in the impedance means 4, whereas if the power factor is zero leading, the same changes in load current will cause equal changes in the same direction of the current in the impedance means 4. For all intermediate power factors the current change in the impedance means 4 will not be equal in magnitude to the load current change but it will be in the opposite direction or in the same direction depending upon the power factor.

In Fig. 3 the impedance 2 is replaced by a conventional supply transformer 11 whose inherent leakage impedance is all that is necessary to gain control of the voltage. For adjusting the magnitude of the load voltage to our predetermined value a simple variable ratio auto-transformer 12 is interposed between the output terminals of the circuit of Fig. 1 of the load.

In one modification shown in Fig. 4 the series impedance is made a constant current impedance means 13 consisting of a capacitor 14 and a reactor 15 connected in parallel with each other. The reactor 15 is provided with a core similar to the core of the reactor 6 of Fig. 1 and the volt-ampere characteristics of elements 14 and 15 are so proportioned that they have the same numerical slope over a predetermined range of voltage thereacross which is usually greater than the range of suppy voltage variations.

This relationship is shown in Fig. 5 in which the reactor characteristic is shown at 16' and the capacitor characteristic is shown by the straight line 17. When the characteristic 17 is rotated into the same quadrant with the reactor characteristic 16 for purposes of comparison it will be seen that they are parallel, thus showing that their slopes are numerically equal and it will also be seen that over the voltage range V_1—V_2 the numerical difference or vector sum of the currents of the individual elements is constant. Consequently, over this voltage range means 13 automatically regulates the current to a constant value in the supply circuit.

By reason of this, Fig. 4 has a substantially greater range of regulation than Fig. 1 because means 13 automatically compensates for variations in supply voltage so that means 4 is relieved of this duty and need only compensate for variations in load magnitude and power factor.

For simplicity and ease of manufacture the capacitors 5 and 14 may be made identical and the reactors 6 and 15 may be made identical. Usually, however, this does not make the most suitable circuit.

On a circuit having such identical elements which I have tested over a variation of supply voltage from 160 to 210 and with a variation of load volt-amperes from zero to 100 per cent with power factors varying from .6 lagging to .8 leading the maximum variation in load voltage was ±3% from a normal value of 110 volts. As previously explained, the worst conditions for regulation are at low power factor lagging so that if the lagging power factor range is limited to a value .8 the circuit maintains the voltage within ±2% or normal.

Under certain conditions, which at the present time are not fully understood, an unstable circuit condition occurs wherein the load voltage apparently oscillates from a low to a high amplitude as well as between two different phase angles. I have found, however, that this can be corrected by inserting a relatively small value of resistance in the impedance means 4 and I have found that it can also be controlled by constructing the reactor 6 so that it has appreciable losses. This unstable condition is not always encountered but when it does occur either of the above remedies is effective.

While there have been shown and described particular embodiments of this invention, it will be obvious to those skilled in the art that various 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 I claim as new and desire to secure by Letters Patent of the United States is:

1. An automatic voltage regulator for a load circuit comprising, in combination, a pair of impedance elements connected in series with each other and in parallel with said load circuit across the load end thereof, said elements having such volt-ampere characteristics that the vector sum of their respective voltages is a constant

over a current range which is of the order of magnitude of full load current.

2. An automatic voltage regulator for a load circuit comprising, in combination, a capacitor and a saturated core reactor connected in series with each other and in parallel with said load circuit across the load end thereof, said elements having such volt-ampere characteristics that the vector sum of their respective voltages is a constant over a current range which is of the order of magnitude of full load current.

3. In combination, a circuit having a variable voltage source end and a constant voltage load end, a series impedance connected in said circuit, and a voltage regulating circuit connected across said circuit on the load side of said impedance, said regulating circuit comprising a capacitor in series with a reactor, said reactor having a magnetic core provided with an air gap which is bridged by a restricted portion of said core, the volt-ampere characteristic of said reactor over a portion of its range being parallel to but displaced from the volt-ampere characteristic of said capacitor.

4. In combination, an electric circuit for interconnecting a source of alternating current and a load, and means for automatically maintaining substantially constant load voltage during substantial variations in source voltage and load magnitude including a capacitor and saturated core reactor connected in series with each other and in shunt with said load, the volt-ampere characteristics of said capacitor and reactor having numerically equal slopes over a predetermined current range.

5. In combination, means including a transformer for supplying alternating current at constant frequency and at a voltage which is subject to variation above and below a rated value, a variable load connected to be energized by said means, and voltage regulating means for said load connected in shunt therewith comprising a saturated core reactor and a capacitor connected in series, said reactor having a volt-ampere characteristic which is substantially a straight line above the knee thereof, said capacitor having a volt-ampere characteristic which has the same slope as said straight line portion of said reactor characteristic.

6. In combination, a source of variable voltage, a constant voltage variable load, constant current impedance means interconnecting said source and load, and constant voltage regulating means connected in shunt with said load, said regulating means comprising a pair of serially connected impedances the vector sum of whose voltages is constant over a predetermined range of current therethrough.

7. A voltage regulating system comprising in combination, variable voltage input terminals and constant voltage variable load current output terminals, a capacitor and a saturated core reactor connected in parallel with each other and in series with said input terminals, the vector sum of the currents in said capacitor and reactor being constant over a predetermined voltage range thereacross, a second capacitor and a second reactor connected in series across said load terminals, the vector sum of the voltages across said second capacitor and said second reactor being constant over a current range which is equal to the vector difference between the value of said constant current and the variable load current drawn from said output terminals.

8. A voltage regulating system comprising in combination, variable-voltage constant-frequency alternating-current input terminals and constant-voltage variable-load-current output terminals, a pair of identical capacitors and a pair of identical saturated core reactors, one of said capacitors and one of said reactors being connected in parallel with each other and in series with said input terminals, the vector sum of the currents in said parallel connected capacitor and reactor being constant throughout the range of voltage variation of said input terminals, the remaining capacitor and the remaining reactor being connected in series across said output terminals, the vector sum of the voltages of said remaining capacitor and remaining reactor being constant over a current range which is equal to the vector difference between the constant current value maintained by the parallel connected capacitor and reactor and the variable load current drawn from said output terminals over a wide range of power factor.

9. A voltage regulating system comprising, in combination, a pair of input terminals connected respectively to a pair of output terminals, a capacitor and reactor connected in parallel with each other between one of said input terminals and its associated output terminal, said capacitor and reactor having offset volt-ampere characteristics which have slopes of equal numerical value over a given voltage range thereacross, a second capacitor and a second reactor connected in series across said output terminals, said second capacitor and said second reactor having offset volt-ampere characteristics whose slopes are numerically equal over a predetermined range of current therethrough, and means for preventing unstable electrical oscillations in said system.

10. A voltage regulating system comprising, in combination, a pair of input terminals connected respectively to a pair of output terminals, a capacitor and reactor connected in parallel with each other between one of said input terminals and its associated output terminal, said capacitor and reactor having offset volt-ampere characteristics which have slopes of equal numerical value over a given voltage range thereacross, a second capacitor and a second reactor connected in series across said output terminals, said second capacitor and said second reactor having offset volt-ampere characteristics whose slopes are numerically equal over a predetermined range of current therethrough, and means for preventing unstable electrical oscillations in said system comprising a power consuming element in circuit with said second capacitor.

11. A voltage regulating system comprising, in combination, a pair of input terminals connected respectively to a pair of output terminals, a capacitor and a saturated reactor connected in parallel with each other between one of said input terminals and its associated output terminal, a second capacitor and a second saturated reactor connected in series across said output terminals, said second capacitor and said second reactor having volt-ampere characteristics whose slopes are numerically equal over a predetermined range of current therethrough.

CLAUDE M. SUMMERS.