Nov. 12, 1940. G. H. POHM ET AL 2,221,456

ELECTRICAL REGULATOR

Filed June 16, 1938 4 Sheets-Sheet 1

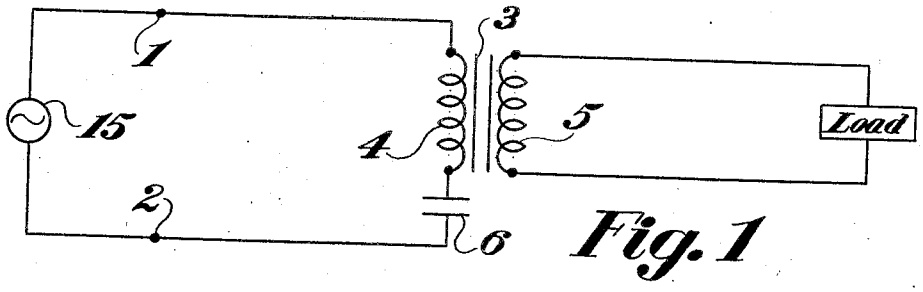


Fig. 1

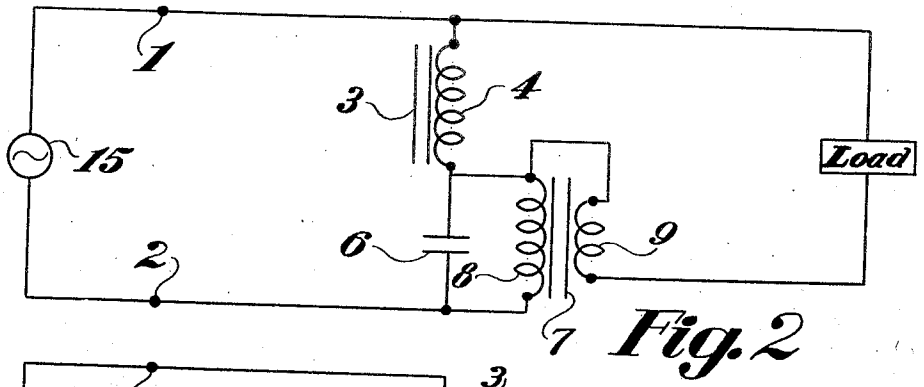


Fig. 2

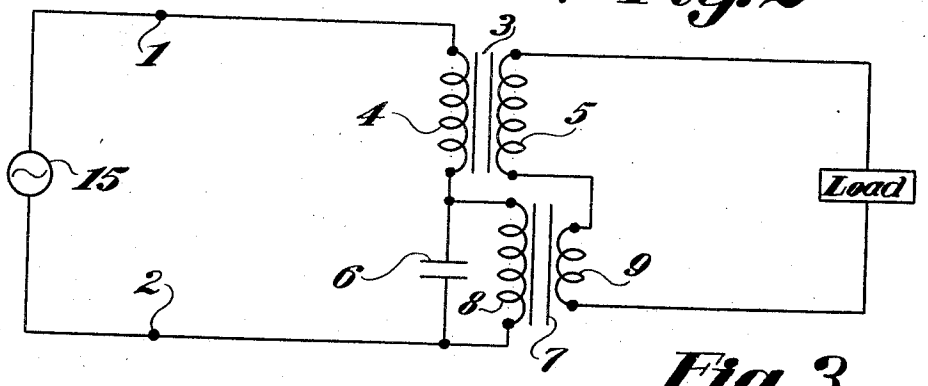


Fig. 3

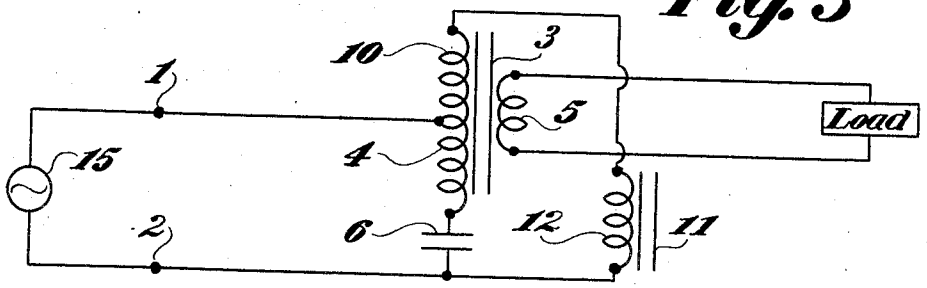


Fig. 4

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Nov. 12, 1940. G. H. POHM ET AL 2,221,456

ELECTRICAL REGULATOR

Filed June 16, 1938 4 Sheets-Sheet 2

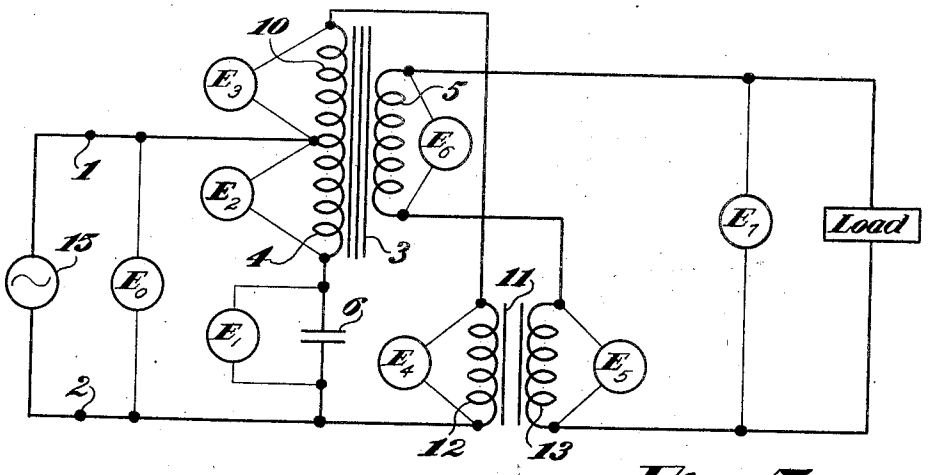


Fig. 5

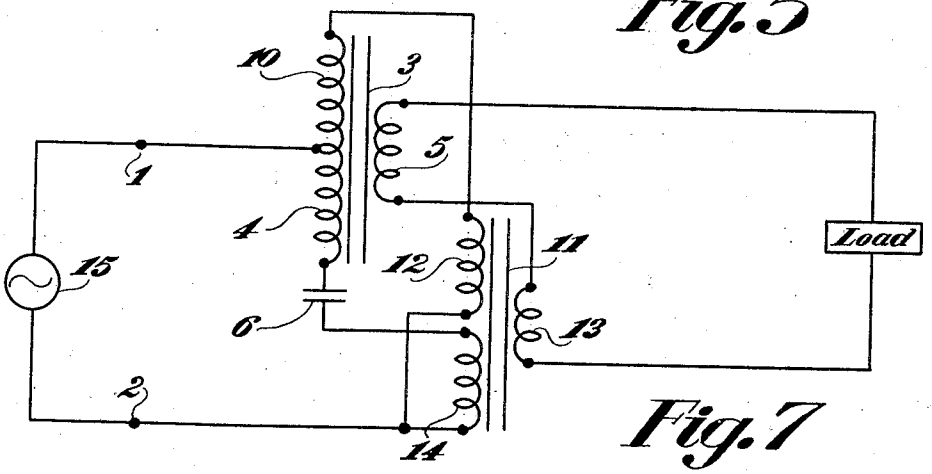


Fig. 7

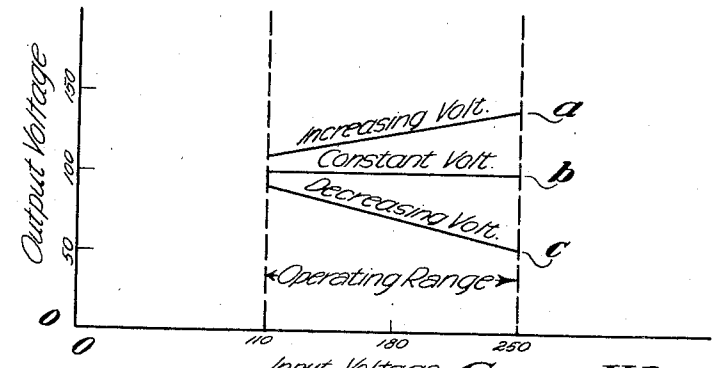


Fig. 8

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Nov. 12, 1940. G. H. POHM ET AL 2,221,456

ELECTRICAL REGULATOR

Filed June 16, 1938 4 Sheets-Sheet 3

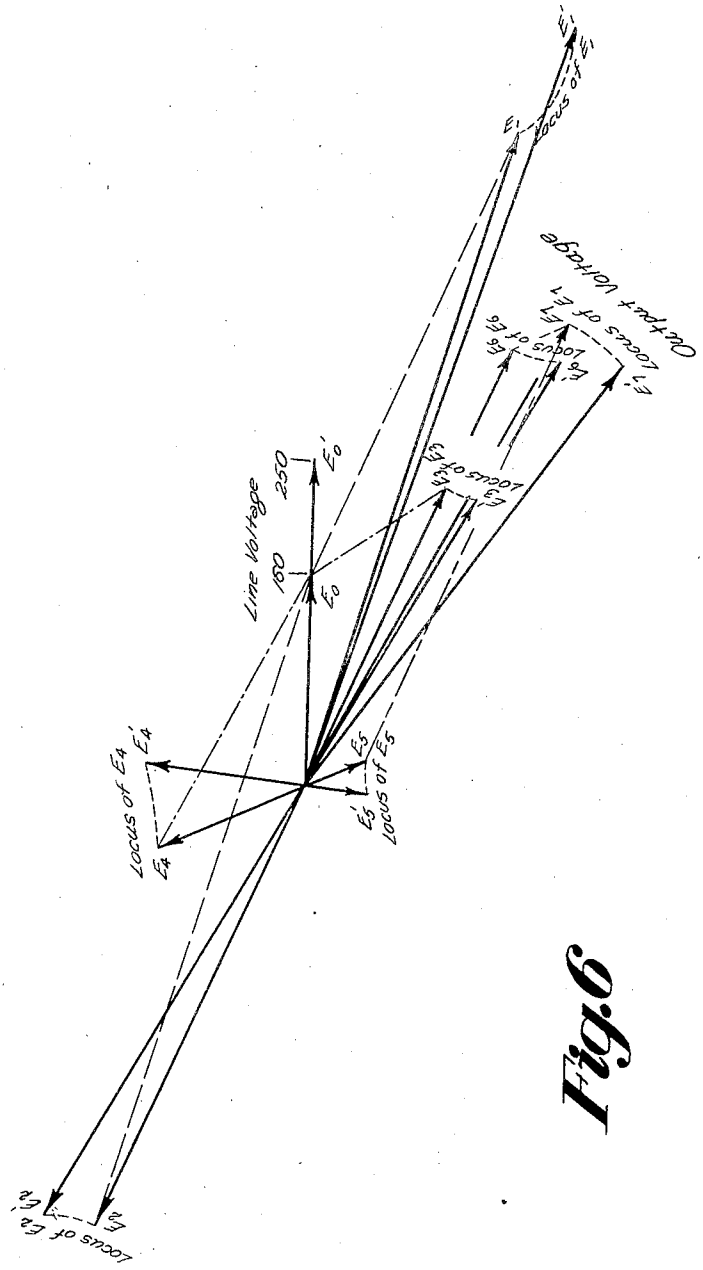


Fig. 6

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Nov. 12, 1940. G. H. POHM ET AL 2,221,456

ELECTRICAL REGULATOR

Filed June 16, 1938 4 Sheets-Sheet 4

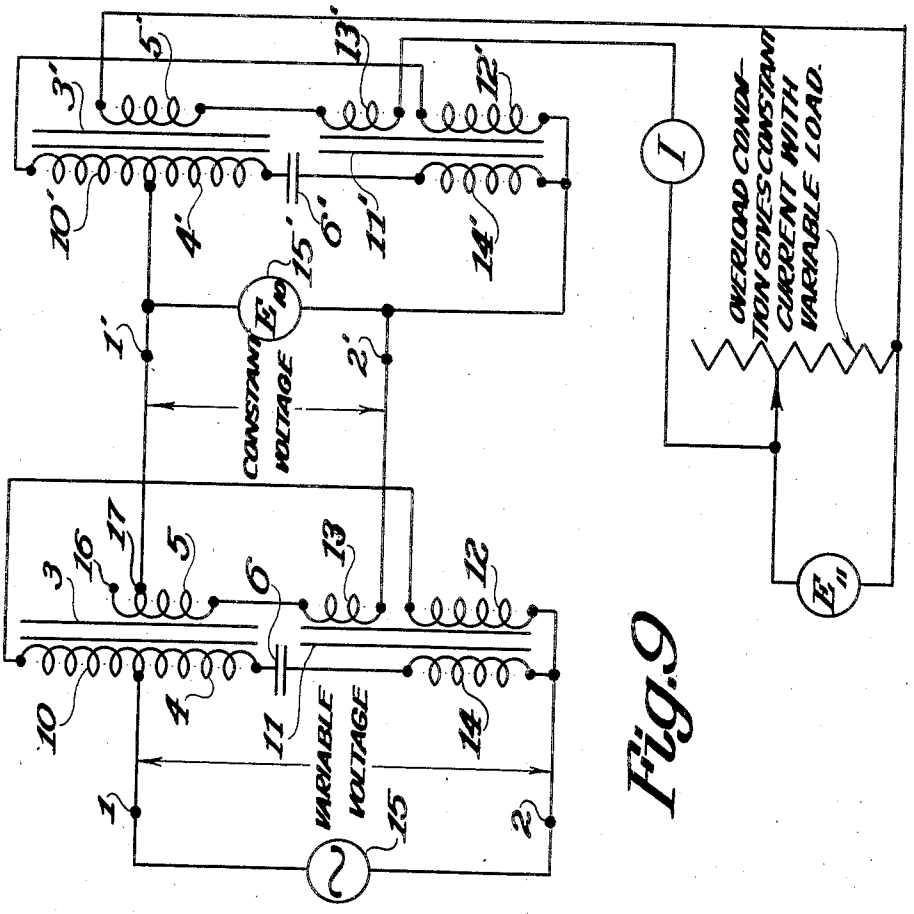


Fig. 9

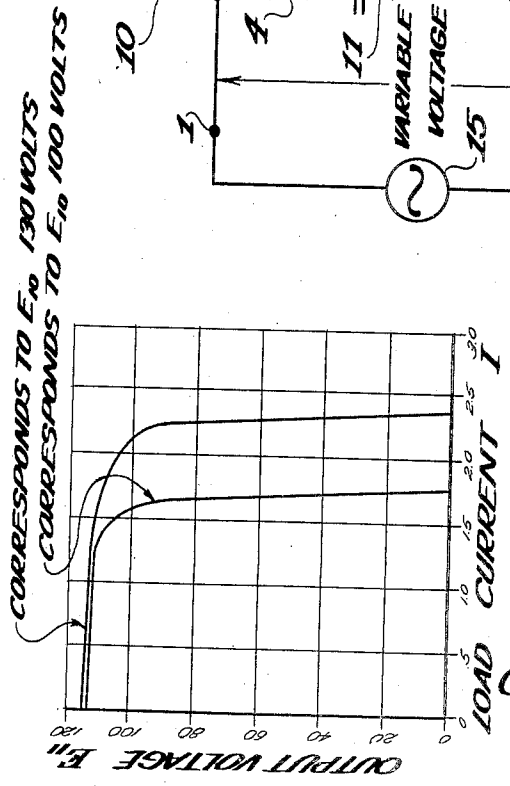


Fig. 10

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Patented Nov. 12, 1940 2,221,456

UNITED STATES PATENT OFFICE

2,221,456

ELECTRICAL REGULATOR

George H. Pohm, Olmsted Falls, and Closman P. Stocker, Lorain, Ohio, assignors, by mesne assignments, of one-half to said Closman P. Stocker, and one-half to E. M. Heavens, Lorain, Ohio

Application June 16, 1938, Serial No. 214,076

19 Claims. (Cl. 171—119)

Our invention relates to electrical regulators of the static type and more particularly to improvements in electrical regulators depending upon magnetic saturation and ferro-resonance as disclosed by Dr. Ing, Gr. Keinath in Elektrotechnik Und Maschinenbau XXXIV Jahrgang Heft 24, Wien 11 Juni 1916, Pages 282 to 286.

Heretofore, electrical regulators depending upon magnetic saturation have required relatively large exciting currents at no load with a resulting low power factor with load. Also, prior art regulators have been incapable of supplying appreciable power without the use of excessively heavy and expensive construction. Particularly in regulators using series ferro-resonance, it has been impossible to withdraw any appreciable power because of detuning caused by the load.

An object of our invention is to provide a means for stabilizing the operation of series ferro-resonant circuits.

Another object of our invention is to provide means for starting series ferro-resonant circuits at a lower supply voltage.

Another object of our invention is to provide a static type voltage regulator with an improved power factor.

A further object of our invention is to provide a voltage regulator more economical to build.

Another object of our invention is to provide a regulated voltage in such a way as to increase or decrease at a predetermined rate of change with respect to variations of the power supply.

Another object of our invention is to provide for coupling the load circuit to both the inductance of the series ferro-resonant circuit and the stabilizer inductance.

Another object of our invention is to minimize the effect of load upon the tuning inductance of the ferro-resonant circuits.

Another object of our invention is to reduce the no-load input current for a given size regulator.

Another object of our invention is to provide a substantially constant current to a variable load when supplied with a variable voltage.

Another object of our invention is to provide a substantially constant current to a variable load when supplied with a constant voltage.

Another object of our invention is to provide a constant voltage until a certain maximum value of load is reached, after which, if the load impedance is further decreased, a substantially constant current is delivered to the load.

A further object of our invention is to provide a substantially constant voltage to a regulator capable of supplying a substantially constant current to a varying load.

Other objects and a fuller understanding of our invention may be had by referring to the following description when read with reference to the accompanying drawings in which like parts are designated by like reference characters and in which:

Figure 1 shows a voltage regulator circuit of the series ferro-resonant type.

Figure 2 shows a voltage regulator of the series ferro-resonant type in which a portion of the condenser voltage is used to obtain a more constant output voltage.

Figure 3 is the same as Fig. 2 except that a separate winding is used on each inductance to insulate the load circuit from the supply circuit.

Figures 1, 2 and 3 are known in the art of voltage regulators as will be described later.

Figure 4 shows a voltage regulator of the series ferro-resonant type having our improved method of stabilization.

Figure 5 shows our invention with the load circuit coupled to the series tuning inductance of the ferro-resonant circuit and also to the stabilizing inductance. Figure 5 also shows voltmeters which will be used in explaining the vector diagram of Figure 6.

Figure 6 shows the vector diagram of our improved voltage regulator circuit as operated at no load and as shown in Figure 5.

Figure 7 shows an additional compensation winding added in series with the condenser for obtaining better regulation between no load and full load.

Figure 8 shows how our voltage regulator can be made to give not only a constant voltage output, but either an increasing or decreasing output voltage with variation in input voltage. The regulator in Figure 8 may also be used for obtaining a substantially constant current under varying load conditions.

Figure 9 shows how two of our energy regulating devices may be connected in series to obtain a substantially constant current from a source of variable input voltage.

Figure 10 shows characteristics obtained by operation of our invention as shown in Figure 9.

The present invention relates to voltage regulators of the static type and more particularly to voltage regulators using magnetic saturation. The prior art is crowded and discloses voltage regulators using magnetic saturation as early as U. S. Patent 907,931 issued in 1908 to W. J. Williams. Other patents such as German Patents

231,938, 313,300 and 338,677 all disclose voltage regulators using an impedance in series with a saturable core. None of these patents show the use of a condenser in this type of voltage regulator circuit. In 1916 Dr. Ing. Gr. Keinath added a condenser in series with a saturable core and obtained remarkable voltage regulation by means of a series ferro-resonant circuit which he used in connection with a frequency meter. This voltage regulator is shown and described in Elektrotechnik und Maschinenbau XXXIV Jahrgang Heft 24, Wien 11 Juni 1916, Pages 282 to 286. A further description of this regulator is found in G. Keinath Techn. Messg³., Munchen 1928 II, S 137.

Our invention is an improvement upon the series ferro-resonant circuit as described by Dr. Keinath in these two articles. A further investigation of the prior art shows a most comprehensive study of voltage regulators entitled, "Selbsttatige Strom- und Spannungs Regler", Wilhelm Geyger, Archiv fur Technisches Messer, Nov. and Dec. 1934, P. T147 and T162. The bibliography given at the end of this article is especially valuable in disclosing prior art.

Another bibliography which shows numerous references to the prior art will be found at the end of the article in July 1937 Electronics, P. 14–16 entitled "Voltage Regulator Using Magnetic Saturation" by K. J. Way of Bell Telephone Laboratories.

In making our invention, we have also been aware of German Patent 578,321 and voltage regulator systems shown and disclosed in U. S. Patents to W. K. Fleming, Nos. 1,985,634 and 1,985,635 along with the patent to C. F. Cairns, U. S. Patent No. 1,942,535, but the prior art referred to above does not teach our invention.

Our invention has been made after making comprehensive tests upon voltage regulators as described in the prior art. As previously mentioned, our invention is an improvement upon the Keinath voltage regulator containing a series ferro-resonant circuit, various modifications of which are shown in Figures 1, 2 and 3. In the voltage regulator shown in Figure 1, inductance 4 wound upon saturable core 3 is in series with condenser 6. Inductance 4 and condenser 6 are substantially tuned to resonate at the frequency of generator 15. Under this condition, sufficient current flows through inductance 4 to saturate core 3. After core 3 is brought up to saturation, a change in the voltage supplied to terminals 1 and 2 will cause a much smaller variation in voltage across inductance 4. Under this condition, the circuit acts as a voltage regulator and the voltage delivered by winding 5 to the load increases at about the same rate of increase as the magnetization curve of the iron. While the output voltage from such a regulator shows much less variation than the supply voltage, nevertheless the fluctuation is appreciable unless some method is used to reduce this variation. Figure 2 shows how another form of the Keinath regulator accomplishes this result. Again we have the series resonant-circuit comprising inductance 4 and condenser 6. Most of the load is taken directly from across inductance 4. However, transformer 7 with winding 8 bridged across condenser 6 serves to introduce by means of winding 9, sufficient voltage substantially 180° out of phase with the voltage across inductance 4 to cause the resultant voltage supplied to the load to remain substantially constant over wide fluctuations of supply voltage.

It will be readily seen that Figure 3 differs from Figure 2 only by the addition of winding 5 on core 3. This does not alter the operation of the circuit except to insulate the load circuit from the supply source.

Experiments indicate that while the Keinath regulator gives excellent voltage regulation over wide variations of input voltage, it will not sustain any appreciable load. In this type of regulator, the load shunts the saturable inductance wound upon core 3. As load is applied, saturation in core 3 is decreased by the shunting action of the load. As a result, core 3 tends to become demagnetized and the circuit becomes detuned. The Keinath type of regulator is therefore, particularly well suited for very light loads and fixed loads. However, when the load is variable or is in excess of 25 to 50 watts, this type of regulator becomes uneconomical and inefficient due to the limitations explained above. It will be evident from the above explanation that if some method is used to prevent the demagnetization of core 3 as load is applied, the voltage regulator would be satisfactory for a great variety of applications.

Our invention tends to prevent detuning of the series ferro-resonant circuit and therefore, accomplishes this desired result. At the same time, our invention provides a new means for starting the series ferro-resonant circuit upon a relatively low supply voltage. Other features of our invention will be explained later.

Figure 4 shows one embodiment of our invention in which the series ferro-resonant circuit comprises saturable inductance 4 and condenser 6. By coupling inductance 12 to saturable inductance 4 by means of winding 10 on core 3, we are able to stabilize the operation of the ferro-resonant circuit.

While we are unable to fully understand the theory of operation of the circuit, we believe that one possible or probable manner of operation is as follows: In Figure 4 under no-load condition, the series ferro-resonant circuit comprising saturable inductance 4 and condenser 6 will resonate at substantially the frequency of generator 15. Under this condition, stabilizing inductance 12 may be connected or disconnected with no appreciable change in voltage across the output winding 5. Tests disclose that under no-load condition, the voltage across capacitor 6 is substantially the same whether stabilizing inductance 12 is connected or disconnected. Also with stabilizing inductance 12 disconnected the voltage regulator circuit of Figure 4 reverts to the Keinath regulator circuit shown in Figure 1. However, it should be pointed out that stabilizing inductance 12 causes the regulator circuit to go into ferro-resonance on lower supply voltages.

The stabilizing inductance 12 becomes increasingly energized when load is applied to the regulator shown in Figure 4. As load is applied to winding 5, the series ferro-resonant circuit tends to become detuned due to the change of impedance of winding 4 on core 3. This change of impedance causes a phase shift in voltage between the voltage across winding 10 and the supply voltage. This phase shift causes a higher voltage to be impressed upon winding 12. The result is an increasing current flow through winding 10 in the proper direction to tend to maintain the flux condition of core 3. This prevents the detuning of the series ferro-resonant circuit.

With our improved voltage regulator, the regulation under no load and full load is better than that of the regulator shown in Figure 1. This is

due to the magnetization current which passes through winding 10 and inductance 12. By adjusting inductance 12 so that the condition of core 11 will operate at different points on its magnetization curve, the voltage across winding 5 can be made substantially constant with respect to a given range of the supply voltage applied to terminals 1 and 2. We have discovered that if core 11 is operated near the knee of the magnetization curve, the output voltage will have a tendency to rise when load is applied to winding 5 and the supply voltage remains constant.

With the voltage regulator shown in Figure 4, we have been able to maintain a regulated output voltage between the limits plus or minus 5% from no load to full load under wide variations of supply voltage.

As previously stated, stabilizing inductance 12 also causes the regulator circuit to operate at lower supply voltages. The starting condition is controlled by inductance 12 and the number of turns on winding 10. If stabilizing inductance 12 were disconnected, it would be necessary to increase the supply voltage applied to terminals 1 and 2 to cause the ferro-resonant circuit to give reliable starting, for instance, if the circuit normally operates on 110 volts, 60 cycles with the inductance 12 disconnected, it may be necessary to increase this voltage to 200 volts to insure reliable starting. It should be pointed out that under certain transient conditions, the circuit can be made to start on the same supply voltage at which it will normally operate with stabilizing inductance 12 connected.

The starting condition for the regulator as shown in Figure 4 is as follows: Current from generator 15 initially flows through winding 10 on core 3 and stabilizing inductance 12. This in turn, charges condenser 6 to a high voltage due to the fact that there is a step-up ratio between the turns in winding 10 and winding 4. Therefore on the start, the primary circuit would include winding 10 and stabilizing inductance 12. When sufficient current from generator 15 flows through capacitor 6 to reduce the impedance of saturable inductance 4, the circuit including winding 4 and capacitor 6 jumps into ferro-resonance. When this occurs, the voltage across winding 10 is greatly increased because of the high flux density in core 3. This increase in voltage on winding 10 is in opposition to the voltage supplied to stabilizing inductance 12 by generator 15. Therefore, after the series ferro-resonant circuit starts, the voltage on winding 12 is decreased and this results in a decrease in current flowing through stabilizing inductance 12 and winding 10. After the starting condition is passed, the ferro-resonant circuit at no-load is substantially the same as Figure 1. This can be illustrated by allowing circuit shown in Figure 4 to start and then disconnecting stabilizer inductance 12. Under no-load condition and with a suitable choice of condenser 12, there is substantially no change in the voltage on winding 4 when stabilizing inductance 12 is connected or disconnected. It might be said that the primary or principal circuit is different for the starting condition as compared to the operating condition. As explained above, the primary circuit during starting, comprises windings 10 and 12 in series with generator 15. After passing the starting condition, the operating condition is transferred to the series ferro-resonant circuit, comprising winding 4 and capacitor 6 in series with generator 15. Therefore during operation at no-load, the primary circuit consists of the series ferro-resonant circuit including inductance 4 and capacitor 6.

With the series ferro-resonant circuit started, stabilizing inductance 12 does not appreciably further effect the operation of the regulator at no load. It should be pointed out that at no load there is a current through stabilizing inductance 12 which depends upon the input voltage. That is to say with the minimum input voltage supplied to the regulator, the current through stabilizing inductance 12 will be at a minimum and the addition of load will increase this current. As load is applied to winding 5 of Figure 4, the load impedance is reflected into winding 4 of the saturable inductance in the ferro-resonant circuit. Load, therefore, changes the phase angle of the voltage across winding 4 of the series ferro-resonant circuit with respect to the voltage of generator 15. This change in phase angle of the voltage is in such a direction as to impress a higher voltage upon inductance 12. This causes an increase in current flowing through winding 10 and inductance 12 in such a direction as to tend to restore the flux condition of core 3 to its initial condition. As load is applied, the increment increase in voltage across inductance 12 (when linear) is substantially proportional to the increase in load.

By this method of operation, we obtain much better power factors than have hitherto been possible with voltage regulators using magnetic saturation. Probably the reason for the better power factors obtained with our improved regulator is due to the fact that the input currents are substantially lower than the input currents in typical voltage regulators of the prior art. For example, in typical voltage regulators of the prior art, a regulator having an output of 500 watts may have an input of 8.2 amperes at no load with an input voltage of 130 volts, 60 cycles. While we have not made tests upon a 500-watt unit, we have obtained more than 400 watts output from an experimental set-up. With this regulator built according to our invention, the no-load input current was 3.2 amperes, when worked under the same input voltage conditions. Under conditions of full load, our regulator operates at a much higher power factor than has hitherto been possible.

Figure 5 differs from Figure 4 by the addition of winding 13 on core 11. If a substantially constant output voltage is desired, winding 13 would consist of a few turns as compared to winding 5 on core 3. The voltage across winding 13 is in opposition to the voltage across winding 5 to obtain this condition. Most of the load is carried by winding 5 and winding 13 is used as a compensating winding. By correctly proportioning windings 13 and 5 and adjusting core 11, it is possible to narrow the output voltage variation to approximately plus or minus 2% when the input voltage applied to terminals 1 and 2 is varied over wide limits.

In the operation of our invention, we prefer to adjust the ratio of copper and iron of coil 12 and core 11 in conjunction with winding 10 and core 3 so that substantially the minimum input current flows to the regulator when the minimum voltage to be regulated is supplied to terminals 1 and 2. After such an adjustment, it is necessary to check the operation of the circuit upon full load and if operation at full load is not entirely satisfactory, some slight adjustment between the two elements may be neces-

sary. Also, we prefer to operate the ferro-resonant circuit comprising winding 4 and capacitor 6 with slightly more capacity than is necessary to exactly resonate the circuit at no load.

Figure 6 shows the vector diagram for the no-load condition of Figure 5. The vectors E_3, E_3', E_4, E_4', E_5, E_5', E_6 E_6', E_7 and E_7' have been elongated to more clearly illustrate their relative positions.

The vector diagram represents the action of an experimental circuit and is taken from the no-load data when operated within the particular voltage input range E_0 to E_0' which we have shown to vary from 160 to 250 volts. The locus of E_1 represents the voltage across condenser 6. According to the vector diagram, this voltage lags the line voltage by approximately 30° and is greater than E_2, which leads it by approximately 180°. E_2 is the voltage across winding 4 in the ferro-resonant circuit consisting of winding 4 and condenser 6. The voltages E_3 and E_6 are substantially 180° out of phase with voltage E_2. Since the vector sum of the voltages on windings 10 and 12 must equal the line voltage, the vector E_4 can be determined by knowing the locus of E_3 and E_0. By knowing the vector E_4, which is the voltage across winding 12, vector E_5 can be determined. By adding vectors E_5 and E_6 which represents the vector sum of the voltages of windings 5 and 13, which is the voltage applied to the output or utilization circuit, the locus of the output voltage can be determined. From the vector diagram, it can be shown that this locus is approximately the locus of a circle about the point "0" which tends to show that the output voltage is constant. The vector diagram shows the regulation of the voltages when the supply voltage varies from 160 to 250 volts input. Under load, the entire diagram rotates with respect to E_0 but does not change the output voltage. By changing the ratio of the vector E_6 with respect to the vector E_5, the output voltage E_7 can be made to deviate from a constant voltage output. For example, E_7 may rise as the supply voltage increases or it may decrease as the supply voltage increases. This relation also holds true under load.

Within portions of the operating range, the output voltage of this regulator can be made substantially constant with variations of supply voltage, or the output voltage may be made to increase or to decrease with a given change of supply voltage. By this we mean that the output voltage may be made to vary with a substantially constant rate of change with respect to an increasing supply voltage. This is shown graphically by Figure 8. In Figure 8 it will be noted that curves *a*, *b* and *c* represent a constant rate of change of output voltage with respect to supply voltage. Curve *a*, represents an increasing output voltage and curve *c* represents a decreasing output voltage with respect to an increasing supply voltage. In order to obtain curve *c*, the ratio is decreased between the voltages supplied by windings 5 and 13 when compared with the ratios used to obtain curve *b*. If this decrease in ratio is carried to the extreme so that winding 13 supplies most of the voltage to the load, we find that the output voltage tends to become a direct function of the input current. To obtain curve *a*, we prefer to reverse either winding 13 or winding 5, but not both. However, where only a slight increase in output voltage is desired, we prefer to obtain it by increasing the ratio between windings 5 and 13. While we have shown the operating range in Figure 8 between 110 volts and 250 volts, it will be understood that this can be shifted to any other operating voltage range.

Figure 7 differs from Figure 5 by the addition of winding 14 on core 11. We have found that the addition of winding 14 in series with condenser 6 of the series ferro-resonant circuit tends to reduce the input current.

Also, the addition of winding 14 enables us to get much closer regulation in commercial applications. The regulation is in the order of plus or minus 1%, while in special cases, a much closer output voltage tolerance can be obtained over wide variations of supply voltage. Also, we have found that winding 14 gives a more nearly linear output voltage characteristic than can be obtained by Figure 5.

In the working of our invention, we prefer to have winding 14 connected in such relation with winding 12 that the voltage as measured across winding 12 is decreased by the addition of winding 14.

In order to more fully explain the action of winding 14, it must be remembered that in connection with the explanation of Figure 4, it was mentioned that the current through stabilizing inductance 12 increased with an increase of the supply voltage. When the supply voltage increases there is also a tendency for the current to increase through capacitor 6. The object of winding 14, therefore, is to modify the effect of variation in input voltage upon capacitor 6. By connecting winding 14 in series with capacitor 6, we are able to introduce a voltage in opposition to the increasing supply voltage. By this means we are able to hold the voltage on capacitor 6 substantially constant over wide variations of input voltage. If winding 14 is increased so as to supply more than enough voltage to exactly compensate the increase due to the supply voltage variation, we are able to obtain a decreasing voltage on capacitor 6 as the supply voltage increases.

The action of the winding 14 under load is not fully understood. However, we believe that due to the phase shift in the voltages under load, the action of this winding does not materially reduce the condenser voltage. We have found that when load is applied the voltage on winding 14 increases, but this increase does not affect the voltage of capacitor 6 because of the change of phase relation.

By way of example, in an experimental set-up capable of supplying 400 watts to the load circuit, we have an input current of approximately 4.5 amperes having a circuit as shown in Figure 5. By the addition of winding 14 in which winding 12 has approximately twice as many turns as winding 14, the no-load input current is reduced to approximately 3.5 amperes for the same supply voltage condition. Considerable change can be effected in the input current by increasing winding 14. For instance, if winding 14 contains approximately twice as many turns as winding 12, the no-load current is further reduced and is approximately 2.5 amperes for the same supply voltage condition. As previously mentioned, the prior art indicates that a 500-watt voltage regulator of the magnetic type takes approximately 8.2 amperes at no-load high voltage input.

Our regulator, capable of delivering 400 watts,

may be made to have a no-load input current of 2.5 amperes under the same input supply voltage condition.

We have also discovered that it is possible to obtain a substantially constant current from our invention if a substantially constant voltage is supplied to input terminals 1 and 2. To obtain a substantially constant current with a variable load, we work our regulator on an overload condition. That is to say that up to a certain point, with a given input voltage, the regulator will maintain a substantially constant voltage. After passing this point, the regulator voltage drops rapidly with a decreasing load impedance. Figure 10 is a graphical representation of data obtained on our energy regulating device when supplied with two different input voltages.

We will explain the action of our regulator on overload by referring to Figure 4. An overload condition on winding 5 will tend to detune saturated core 3. Under the overload condition, detuning of core 3 causes series ferro-resonant circuit, comprising inductance 4 and capacitor 6 to approach a non-resonant condition. The rate at which the series ferro-resonant circuit approaches the non-resonant condition is determined by the rate of decrease of flux in core 3. It will be seen that this may be controlled by condenser 6, windings 4 or 10, or inductance 12. An easy way to control this condition is by varying the number of turns in winding 10.

It will be recognized that the rapid drop in voltage on an overload condition is a highly desirable characteristic from the standpoint of protection. If it is desired to have the substantially constant current vary along a predetermined characteristic, we prefer to have the input voltage to our energy regulating device held constant. This will hold the cut-off characteristic constant for a variable load. However, where it is not necessary to have the cut-off occur at any particular point, it is then possible to use only one of our regulators, such for example as shown in either the Figures 4, 5, or 7, to obtain a substantially constant voltage when supplied with a variable input voltage. Under this condition the cut-off point will vary with the input voltage similar to the two characteristics shown in Figure 10.

By using two of our regulating devices connected in cascade as shown in Figure 9, we are able to operate the first regulator to obtain a constant voltage from a source of variable voltage. The constant voltage obtained from the first regulator is then introduced into the second regulator which may be worked as a constant current device. Figure 9 shows this arrangement with the parts of the second regulator indicated by the same numbers as in the first regulator except prime marks are used. By this means we are able to obtain a substantially constant current through a variable load when supplied by a source of variable voltage. With such an arrangement, the current through the variable load may be predetermined.

Referring to Figure 9, if input terminal 1' is connected to terminal 17, we obtain the characteristic shown in Figure 10 corresponding to E_{10} at 100 volts. If terminal 1' is connected to terminal 16, we may then obtain the characteristic represented in Figure 10 by E_{10} at 130 volts.

Our regulator as shown in Figure 9 has the same type of characteristic as is obtained by rotating types of battery charging equipment. In the rotating type of equipment it is often desirable to have a cut-off point at 125% overload for protection purposes. We are, therefore, able to duplicate these results without moving parts, and also to avoid the disadvantage of the rotating type due to the motor slipping. In the rotating type of equipment just mentioned, where the charging generator is driven by an induction motor, the motor tends to slip as the supply voltage is decreased. This in turn causes the charging voltage to vary. When our regulating device is used for battery charging, this disadvantage is eliminated.

As is well known, it is desirable to have some sort of an overload protection when using the dry-disc type of rectifier. Our invention is particularly well adapted for use with dry-disc rectifiers because of the automatic overload protection. We, therefore, feel that the use of our regulator in conjunction with the dry-disc type of rectifier will provide a battery charging unit having many advantages.

To those skilled in the art, it will be evident that while we have shown separate windings in our diagrams for ease of explanation, it may be possible to substitute autotransformers having common windings. Also, while we refer to ferro-resonance, we do not wish to be limited to the use of iron to obtain our results. For instance, many of the nickel iron alloys would be suitable for the working of our invention. In the description of our invention, we have referred to the various circuits as voltage regulator circuits. It will be understood by those skilled in the art that our invention may be used as a non-linear impedance matching device or as an energy regulating device.

Although we have described our invention with a certain degree of particularity, it is understood that the present disclosure has been made only by way of example and that numerous changes in the details of construction and the combination of arrangement of parts may be resorted to without departing from the spirit and scope of the invention as hereinafter claimed.

We claim as our invention:

1. A voltage regulator adapted to be energized by a variable voltage source of alternating current, comprising in combination, a saturable inductive element and a capacitor arranged to form a series ferro-resonant circuit, a second saturable inductance inductively and conductively coupled to the inductive element to cause a lagging current to flow in the first inductive element for increasing the effective voltage upon the capacitor and enabling the series ferro-resonant circuit to start at the lower values of the fluctuations of the supply voltage than would be possible without second said inductance, said saturable inductance having output terminal means connected thereacross and giving a substantially constant voltage.

2. An electrical system adapted to be energized by a source of alternating current comprising in combination, a saturable inductive element and a capacitor arranged to form a series ferro-resonant circuit, said saturable inductive element, and a second inductance having output terminal means connected thereacross and giving a substantially constant voltage coupled to the first said inductive element to cause a lagging current to flow in the first inductive element to minimize de-tuning of the ferro-resonant circuit as load is applied to said outlet terminal means.

3. An electrical energy regulating device hav-

ing a series ferro-resonant circuit, comprising a saturable inductance and a capacitor, a second inductance, input means for connecting said ferro-resonant circuit to a source of alternating current supply voltage, a winding magnetically coupled to the first said inductance, said winding being in series with the second inductance and with the input means, and output means connected across said saturable inductance and giving a substantially constant voltage.

4. A non-linear impedance matching system for coupling a utilization circuit to a source of variable alternating current supply voltage, comprising a saturable inductance and a capacitor arranged to form a series ferro-resonant circuit when connected directly to the voltage supply source, a second inductance, a winding magnetically coupled with first said inductance, and in series with the second inductance, and a utilization circuit including terminal means connected across both the first and second said inductances and giving a substantially constant voltage.

5. An electrical energy regulating device having a series ferro-resonant circuit, comprising a saturable first inductance and a capacitor, input means for connecting said series ferro-resonant circuit to a source of alternating current supply voltage, a second inductance, a winding magnetically coupled to said saturable inductance, said winding being in series with said second inductance and in series with the input means, and output means including terminal means connected across the first and second said inductances and arranged to be connected in series with a load to give a substantially constant voltage.

6. An electrical energy regulating device having a series ferro-resonant circuit arranged to be connected to a load and give a substantially constant output voltage for wide fluctuations in the voltage of the supply source, comprising a saturable first inductance and a capacitor, input means for connecting said series ferro-resonant circuit to a source of variable alternating current supply voltage, a second inductance, a winding magnetically coupled to said second inductance and in series with the capacitor, a winding coupled to said first inductance, said winding being in series with said second inductance and with the input means, output means magnetically coupled to first and second said inductances.

7. In combination, a saturable first inductance and a capacitor arranged to form a series ferro-resonant circuit and adapted to be energized by a source of alternating current, a second inductance coupled to said first inductance to cause a lagging current to flow in the first inductance and minimizing the flux changes in the first said inductance under varying load conditions, output means including terminal means connected across both the first and second inductances to cause the first said inductance to supply most of the load voltage and the second inductance to control the rate of change of voltage variation of the output means with respect to variation in the supply voltage when energized within the operating range.

8. An electrical energy regulating device having a series ferro-resonant circuit, comprising a saturable first inductance and a capacitor, input means for connecting said ferro-resonant circuit to a source of alternating current supply voltage, a second inductance having a first and second winding, a winding magnetically coupled to first said inductance, said winding being in series with said first winding of the second inductance and with the input means, said second winding of the second inductance being connected in series with the saturable inductance and capacitor forming the ferro-resonant circuit, and output means coupled to both the said first and second inductances.

9. An electrical energy regulating device adapted to be energized by a source of variable alternating current supply voltage comprising a condenser and two transformers, each transformer having a winding in series with each other and with the condenser to form a series ferro-resonant circuit, input means for connecting said ferro-resonant circuit to a source of alternating current supply voltage, an additional winding on each of two said transformers being connected in series with each other and with the input means, and a utilization circuit coupled to both the first and second transformers.

10. An electrical energy regulating device adapted to be energized by a source of variable alternating current supply voltage, comprising a condenser, two transformers each having a winding connected in series, at least one winding on one of the transformers being connected in series with the condenser and arranged to form a series ferro-resonant circuit when connected to the supply voltage, a utilization circuit coupled to both the first and second transformers, said coupled utilization circuit controlling the rate of change of the voltage delivered with respect to variation in the supply voltage when energized within the operating range.

11. An electrical energy regulating device having a series ferro-resonant circuit, comprising a saturable inductance and a capacitor, input means for connecting said ferro-resonant circuit to a source of alternating current supply voltage, a second inductance, a winding magnetically coupled to first said inductance, said winding being in series with the second inductance and with input means, winding means on second inductance for introducing a voltage in series with said ferro-resonant circuit, and winding means on both first and second inductances, connected in series to form a utilization circuit.

12. An electrical energy regulating device having a series ferro-resonant circuit, comprising a saturable inductance and a capacitor, input means for connecting said ferro-resonant circuit to a source of alternating current supply voltage, a second inductance, a winding magnetically coupled to first said inductance, said winding being in series with the second inductance and with input means, winding means on second inductance in series with said ferro-resonant circuit to cause a decrease in voltage across said second inductance and winding means on both first and second inductances connected in series to form a utilization circuit.

13. An electrical energy regulating device having a series ferro-resonant circuit, comprising a saturable inductance and a capacitor, input means for connecting said ferro-resonant circuit to a source of alternating current supply voltage, a second inductance, a winding magnetically coupled to first said inductance, said winding being in series with a second inductance and with input means, winding means on second inductance for introducing a voltage in series with said ferro-resonant circuit greater than, equal to, or less than the voltage on second said inductance,

and winding means on both first and second inductances connected in series to form a utilization circuit.

14. An electrical system adapted to supply a substantially constant current to a variable load when said system is supplied with a constant alternating current voltage, comprising in combination, a saturable inductive element and a capacitor connected to form a series ferro-resonant circuit, utilization means including terminal means connected across said saturable inductive element to give a substantially constant current, a second inductance inductively and conductively coupled to the saturable inductive element to control detuning of the series ferro-resonant circuit as the impedance of the load, applied to the utilization means, is decreased.

15. An alternating current controlling circuit, comprising a capacitor, an inductance and a saturable transformer, said capacitor and transformer connected to form a series ferro-resonant circuit, means for inductively and conductively connecting said inductance to the transformer and to the condenser to cause a current flow through the inductance for stabilizing the ferro-resonant circuit, and output means including terminal means connected across said saturable transformer.

16. A voltage regulator adapted to be energized by a source of alternating current comprising, in combination, a saturable transformer having at least two winding portions connected in series, a capacitor connected to one of said winding portions and adapted to cause a leading current in the said winding portion, an inductance inductively and conductively coupled to the other winding portion to cause a lagging current in the said other winding portion for increasing the voltage upon the capacitor and enabling the series ferro-resonant circuit to start at a lower supply voltage than would be possible without the second inductance, and output means including terminal means connected across the saturable transformer.

17. An electrical system adapted to be energized by a source of alternating current comprising in combination, a saturable inductance and a capacitor arranged to form a series ferro-resonant circuit, said saturable inductance having output terminal means connected thereacross and giving a substantial constant voltage, and a linear inductance inductively and conductively coupled to the saturable inductance to minimize de-tuning of the ferro-resonant circuit as load is applied to said output terminal.

18. An electrical system adapted to be energized by a source of alternating current comprising in combination, a saturable inductance and a capacitor arranged to form a series ferro-resonant circuit, said saturable inductance having output terminal means connected thereacross and giving a substantial constant voltage, and a non-linear inductance inductively and conductively coupled to the saturable inductance to minimize de-tuning of the ferro-resonant circuit as load is applied to said output terminal.

19. A voltage regulator adapted to be energized by a variable voltage source of alternating current comprising, in combination, a first saturable inductance having two winding portions in series, a capacitor connected to one end of one of said winding portions, said capacitor and said one of said winding portions being adapted for connection to the variable voltage source of alternating current and forming a series ferro-resonant circuit, a second inductance having a winding connected in parallel with the capacitor and both windings of the first saturable inductance and enabling the ferro-resonant circuit to start at the lower values of the fluctuations of the variable voltage source of alternating current, said first saturable inductance having output terminal means connected thereacross and giving a substantially constant voltage.

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