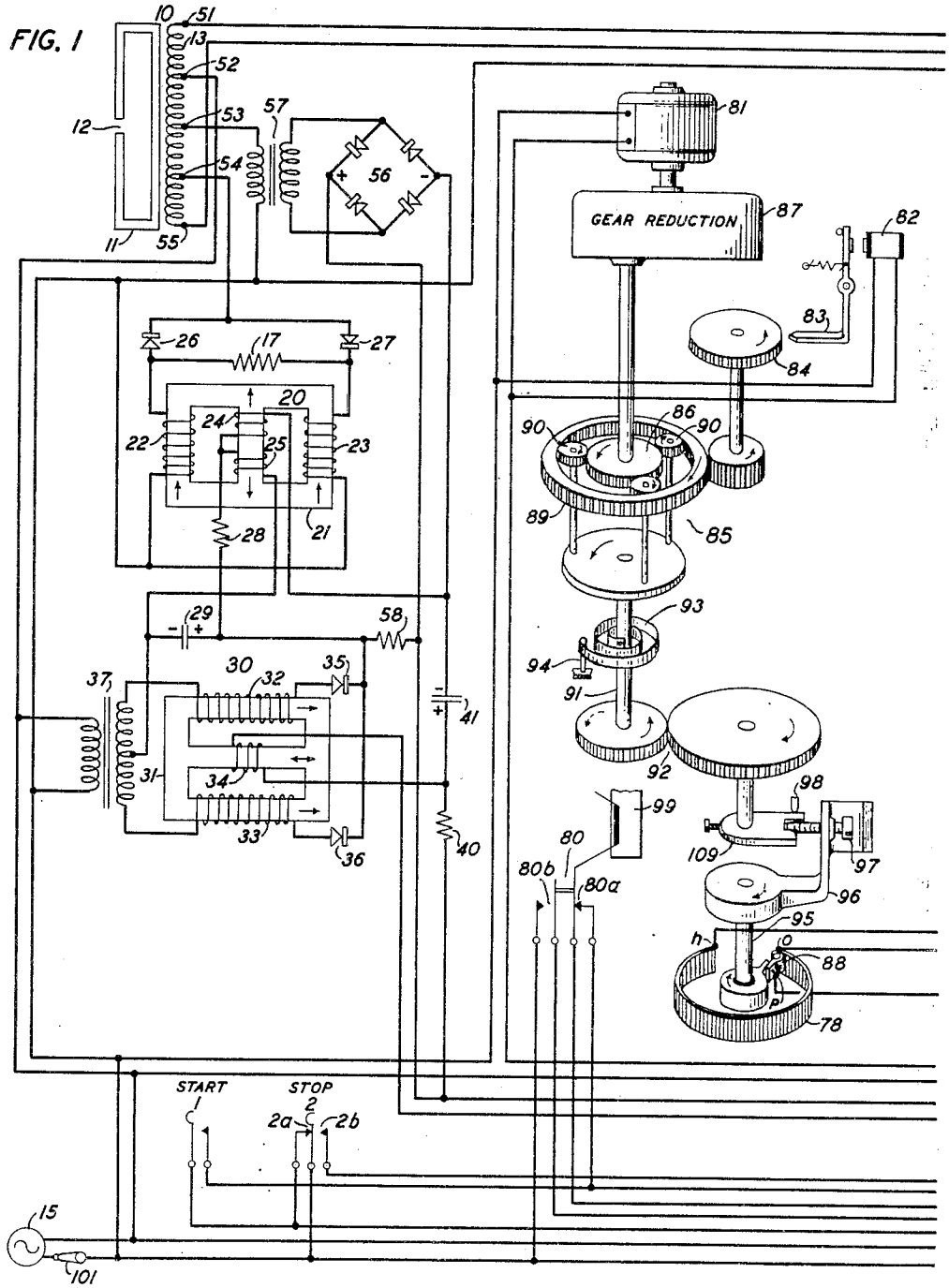
May 31, 1955 W. H. BIXBY 2,709,778

CURRENT SUPPLY APPARATUS

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FIG. 1



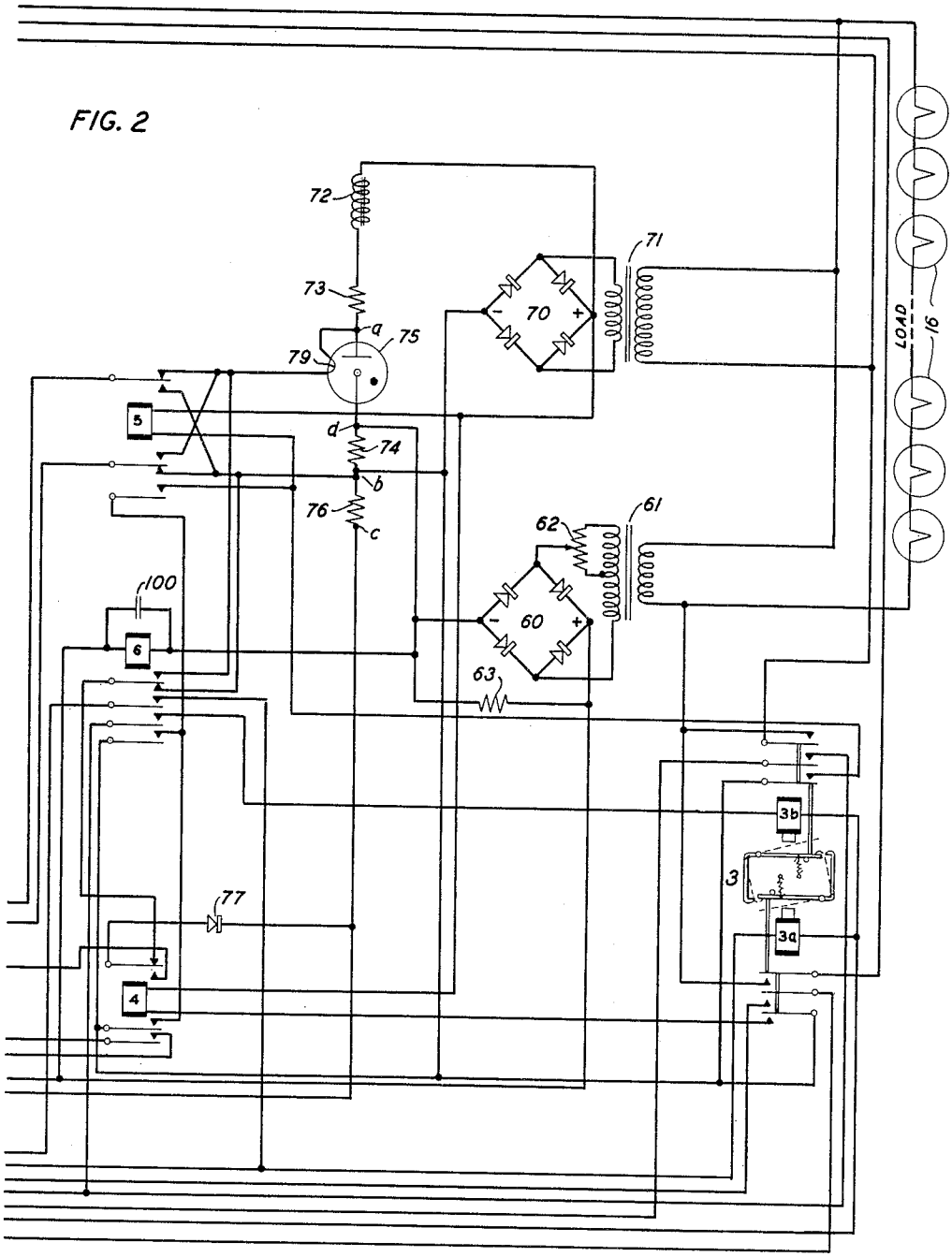
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CURRENT SUPPLY APPARATUS

Filed July 13, 1954 2 Sheets-Sheet 2

FIG. 2



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2,709,778

CURRENT SUPPLY APPARATUS

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Application July 13, 1954, Serial No. 443,021

10 Claims. (Cl. 323—45)

This invention relates to current supply apparatus and particularly to apparatus for regulating the voltage across a load to which current is supplied from an alternating-current supply source.

An object of the invention is to provide, in a current supply apparatus, means for gradually increasing the load current during a starting period and for gradually decreasing the load current during a shut-down period.

Another object is to provide apparatus for minimizing voltage changes across a load during operating periods, for gradually increasing the load voltage during a starting period and for gradually decreasing the load voltage during a shut-down period.

In supplying current to a load, it is desirable in many cases, not only to maintain the load voltage or current substantially constant during an operating period, but also to increase the load voltage at a substantially uniform rate during a starting period in which the energization of the load is initiated and to decrease the load voltage at a substantially uniform rate during a shut-down period in which the load is being de-energized. For example, where the load to be energized comprises filamentary cathodes or cathode heaters of thermionic devices, the useful life of the devices may be extended if the current supplied to the cathodes or cathode heaters is increased gradually from zero to the operating current value and decreased gradually from the operating current value to zero.

To provide for such a wide range of output voltage variation, it might at first appear necessary to greatly increase the size of the components of the voltage regulating apparatus. However, since the wide control range is required only during the relatively short periods during which the supply of current to the load is being started or stopped, it has been found that the regulating apparatus could be designed, in accordance with the invention, to provide for the wide range of output voltage variation with only a relatively small increase in the size of the components of the regulating apparatus and with only slight increase of cost. The components of the regulated current supply apparatus are subjected to currents in excess of the continuous running rated values during the starting and shut-down periods but, since these periods are of short duration, the normal thermal capacity of the components will permit these momentary overloads without detrimental effects.

In accordance with a specific embodiment of the invention, herein shown and described for the purpose of illustration, the regulated current supply apparatus disclosed in my application Serial No. 373,559, filed August 11, 1953, is modified to effect the uniform increase of load voltage during a starting period and the uniform decrease of load voltage during a shut-down period without affecting the basic operating characteristics of the regulator and with only a slight increase in size of the low power control portion of the regulating apparatus.

There is provided an autotransformer comprising a core forming a flux path partly of magnetic material and

partly of a gap or gaps devoid of magnetic material and a winding on the core. There is also provided a saturable reactor having a three-legged core of magnetic material, an impedance or power winding on each of the outer legs of the core and a biasing winding and a control winding on the middle leg of the core. Pulsating unidirectional current is supplied from an alternating-current supply source through each of the impedance windings, current being supplied through a current path comprising one of the impedance windings, a rectifying element and a portion of the autotransformer winding during half cycle periods of one polarity of the supply source and through a current path comprising the other impedance winding, a second rectifying element and said portion of the autotransformer winding during half-cycle periods of opposite polarity. During normal operating periods, current from the supply source is supplied to a load through a circuit comprising a booster portion of the autotransformer winding, the voltage across said portion being in aiding relationship with respect to the source voltage in said circuit so that the load voltage is larger than the voltage of the supply source.

A source of unidirectional standard reference voltage is provided by a circuit comprising a first rectifier and a constant voltage device, this circuit being energized through a first transformer the primary of which is connected in series with the supply source and the boosting portion of the autotransformer winding. A second rectifier is provided for furnishing a unidirectional comparison voltage which varies in accordance with load voltage changes, this rectifier being energized through a second transformer having a primary connected across the load. During normal operating periods, the load and the primary of the second transformer across the load are each connected in series with the current supply source and the booster portion of the autotransformer, as is also the primary of the first transformer. However, during the starting and shut-down periods, the load and the primary of the second transformer are connected across the entire autotransformer winding which includes not only the booster portion referred to above, but an additional portion for further boosting the voltage across the entire autotransformer winding. A voltage equal to the difference of a voltage derived from the circuit associated with the first rectifier and a voltage derived from the second rectifier is used to control the output of a magnetic amplifier from which current is supplied through a resistor to the control winding of the self-saturating saturable reactor.

A third rectifier is provided for supplying current through the resistor, just mentioned, to a bias winding of the saturable reactor. Energizing current is supplied to the third rectifier through a third transformer to the primary of which current from the supply source is supplied through a bucking portion of the autotransformer winding. The currents supplied to the biasing and control windings, respectively, of the saturable reactor set up opposed magnetomotive forces in the reactor core.

During the starting and shut-down periods, the voltage derived from the circuit associated with the first rectifier is varied at a substantially uniform rate by a motor-driven potentiometer. Initially the voltage supplied from the circuit of the first rectifier is such that the impedance of the impedance windings of the saturable reactor is very high with the result that the voltage across the autotransformer has a very low value which may be substantially zero. An increase of voltage supplied from the circuit of the first rectifier causes the current supplied to the control winding of the saturable reactor to increase, thereby increasing the voltage across the autotransformer winding and the load which

is connected across the autotransformer winding. The voltage impressed upon the third rectifier is therefore decreased to cause the current supplied to the bias winding to decrease. The current supplied to the bias winding is further decreased due to the voltage drop produced across the resistor by the increased current supplied through it to the control winding. The decreased energization of the bias winding further increases the voltage across the autotransformer winding and across the load.

When the potentiometer brush has completed its travel, the voltage across the autotransformer winding is substantially equal to the normal operating load voltage and at that time the load is disconnected from across the autotransformer winding and connected in series with the booster portion of the autotransformer and the current supply source. The load voltage is then maintained substantially constant since an increase of load voltage, for example, causes a reduction of the current supplied through the autotransformer winding and the saturable reactor to decrease the voltage across the booster portion of the autotransformer winding.

When it is desired to de-energize the load, the load is reconnected across the autotransformer winding and the brush of the potentiometer is driven at a substantially uniform rate to decrease the voltage supplied from the circuit associated with the first rectifier. The current supplied to the control winding is thus decreased and the impedance of the impedance windings of the saturable reactor is increased to cause a reduction of the current supplied to the autotransformer winding from the alternating-current supply source, thereby reducing the voltage across the autotransformer winding and the load. The current supplied from the third rectifier is increased, as a result, to cause a further reduction of the voltage across the autotransformer winding. When the brush of the potentiometer has completed its travel, the voltage across the autotransformer will be reduced substantially to zero and the load is disconnected from the current supply circuit.

The invention will now be described in greater detail with reference to the accompanying drawing in which Figs. 1 and 2, when placed side by side with Fig. 1 at the left, are a diagrammatic view of a current supply apparatus embodying the invention.

Referring to the drawing, there is provided an autotransformer **10** comprising a core **11** of magnetic material forming a flux path having therein a series gap or gaps **12** devoid of magnetic material and a winding **13** on the core. Current is supplied from an alternating-current supply source **15** through autotransformer **10** to a load **16** which may be the cathodes or cathode heaters of a large number of thermionic devices for example. The winding **13** is provided with taps **51**, **52**, **53**, **54** and **55** as shown. There is provided a transfer switch **3** comprising relays **3***a* and **3***b* the armatures of which are mechanically interlocked, as shown, so that when one of the relays is energized to move its armatures to the operated or circuit closing position, the armatures of the other relay are locked in the released or circuit opening position. Assuming for the present that relay **3***b* is operated, then a portion of autotransformer winding **13** between the taps **51** and **52** is connected in series with the alternating-current supply source **15** and the load **16**.

There is provided a saturable reactor **20** comprising a three-legged core **21** of magnetic material, impedance or power windings **22** and **23** of substantially equal turns on the outer legs, respectively, of the core, and, on the middle leg of the core, a biasing winding **24** and a control winding **25**. Windings **22** and **23** may each have 184 turns, winding **24** may have 1500 turns and winding **25** may have 1500 turns, for example. During half-cycle periods of one polarity of supply source **15**, current is supplied from the supply source **15** to a current path comprising winding **22**, an asymmetrically conducting varistor **26** in its forward or low resistance direction and the portion of autotransformer **13** between taps **52** and **54**, all in series. During half-cycle periods of opposite polarity, current is supplied from the source **15** to a current path comprising the portion **52**—**54** of autotransformer winding **13**, an asymmetrically conducting varistor **27** in its forward direction, and the winding **23**, all in series. Alternating current is thus supplied through the winding portion **52**—**54** and pulsating unidirectional current is supplied to each of windings **22** and **23**. There is provided a bridge rectifier **56** to which current is supplied from the supply source **15** through a circuit comprising a transformer **57** and autotransformer **10**. The secondary winding of transformer **57** is connected to the input terminals of rectifier **56**. The primary winding of transformer **57** is connected in series with the current supply source **15** and a portion **52**—**53** of autotransformer **10**. The currents supplied to windings **22** and **23**, respectively, cause to be set up in a magnetic circuit including the outer legs of the core **21** magnetomotive forces having opposite directions, as indicated by the arrows on the drawing. The currents supplied to windings **24** and **25**, respectively, on the middle leg, as will be described, set up magnetomotive forces which are opposed, as indicated by the arrows. In operation the resultant of the magnetomotive forces due to windings **24** and **25** may be zero or may either aid or oppose the magnetomotive forces due to windings **22** and **23** depending upon whether the magnetomotive force due to winding **25** is larger or smaller than the magnetomotive force due to winding **24**. A resistor **28** of 50 ohms, for example, is connected in series with each of windings **24** and **25** and a commutating condenser **29** of 20 microfarads, for example, is connected across winding **25** and resistor **28** in series. A resistor **17** of 20 ohms for example, is provided in a path connecting a common terminal of winding **22** and varistor **26** to a common terminal of winding **23** and varistor **27**. Current is supplied to biasing winding **24** from rectifier **56** through a circuit comprising in series, a resistor **58** of 88 ohms, for example, resistor **28** and winding **24**. Current from rectifier **56**, is also supplied to a current path comprising a resistor **40** of 250 ohms, for example, and a condenser **41** of 250 microfarads, for example, in series, to charge the condenser **41**.

The relative turns between the various taps of autotransformer winding **13** are preferably such that during normal operating periods the nominal voltage between taps **51** and **52** is 60 volts, the voltage between taps **52** and **53** is 75 volts, the voltage between taps **53** and **54** is 75 volts and the voltage between taps **54** and **55** is 50 volts, the voltage of source **15** being nominally 208 volts, and the load voltage being 236 volts. The length of the series gap may be adjusted, before the autotransformer **10** is installed in the regulating circuit, by connecting across the winding portion **51**, **52** an alternating voltage equal to or somewhat greater than the difference between the maximum and minimum voltages of the supply source **15** and adjusting the gap length until the current through winding portion **51**—**52** is equal to or slightly greater than the maximum root-mean-square load current.

There is provided a magnetic amplifier **30** for controlling the supply of rectified current from supply source **15** to the control winding **25**. The amplifier comprises a saturable reactor having a three-legged core **31** of magnetic material with impedance or power windings **32** and **33** on the outer legs, respectively, of the core and a control winding **34** on the middle leg. Windings **32** and **33** may each have 568 turns and winding **34** may have 2500 turns, for example. There is provided a transformer **37** having a primary connected to the supply source **15** and a secondary winding having a mid-

terminal. During half-cycle periods of one polarity of the supply source, current is supplied from the upper portion of the secondary winding of transformer 37 to a circuit comprising reactor winding 32, an asymmetrically conducting varistor 35 in its forward direction, resistor 28 and winding 25, all in series. During half-cycle periods of opposite polarity, current is supplied from the lower portion of the secondary of transformer 37 to a circuit comprising reactor winding 33, an asymmetrically conducting varistor 36 in its forward direction, resistor 28 and winding 25, all in series.

There is provided a comparison voltage bridge rectifier 60 for setting up across its output terminals a unidirectional voltage proportional to the alternating voltage across the load 16. The rectifier is energized through a transformer 61 having its primary winding connected across the load. A potentiometer 62 is connected across a portion of the secondary transformer winding 61 and the input terminals of the rectifier are connected through the potentiometer to the secondary winding of transformer 61, as shown. A resistor 63 of 5000 ohms, for example, is connected across the output of rectifier 60. There is provided a reference voltage supply bridge rectifier 70 to which current is supplied through a transformer 71. The primary winding of transformer 71 is connected through the portion 51—52 of the winding of autotransformer 10 to the alternating-current supply source 15.

The control circuit employs relays 4, 5 and 6, the functions of which will later be described. With relay 4 released, and relay 6 operated, there are four current paths in parallel connecting the points designated *a* and *b*, respectively. One of the paths comprises in series the output of rectifier 70, a smoothing choke coil 72 and a resistor 73 of 600 ohms, for example. A second of the paths comprises in series a resistor 74 of 300 ohms, for example, and a cold cathode, gas-filled, constant voltage device 75. A third path comprises in series a resistor 76 of 10,000 ohms, for example, and an asymmetrically conducting varistor 77. The fourth path comprises a potentiometer 78 having end terminals *n* and *o* and a terminal *p* connected to its brush. When the relay 5 is de-energized, potentiometer terminal *n* is connected through a connector 79 to point *a* and potentiometer terminal *o* is connected to point *b*, the connector 79 being provided within the tube 75 to open the third and fourth current paths when the tube 75 is removed from its socket. Energization of relay 5 reverses the potentiometer 78 in the current path so that terminal *n* is connected to point *b* and terminal *o* is connected to point *a*. The control winding 34 of the magnetic amplifier 30 is connected in a current path which may be traced from a point *c* which is the common terminal of varistor 77 and resistor 76 through the control winding 34, resistor 40 and rectifier 60 to the point *d* which is the common terminal of the constant voltage tube 75 and resistor 74.

During normal operation of the regulating circuit, relays 3*b* and 6 are operated and relay 4 is released. When the load voltage has a certain predetermined value, the average output voltage of rectifier 60 which is proportional to the load voltage is equal to the voltage across the constant voltage tube 75. For this condition, no average current flows through the control winding 34. When the load voltage decreases with respect to the predetermined value, the average output voltage of rectifier 60 will be less than the voltage across the constant voltage tube 75 and current will flow from the positive terminal of rectifier 70 through choke coil 72, resistor 73, contacts of relays 6 and 4, respectively, varistor 77 in its forward direction, control winding 34, resistor 40, resistor 63, which is across rectifier 60, and resistor 74 to the negative terminal of rectifier 70. There will thus be set up in the core 31 a magnetomotive force which aids the magnetomotive forces set up in the core due to the rectified currents flowing through windings 32 and 33, respectively. The impedances of windings 32 and 33 will thus decrease to cause the currents in these windings to increase, thereby further decreasing the impedances of these windings and further increasing the currents flowing through these windings.

The control winding 25 on the middle leg of core 21 is connected in series with windings 32 and 33 so that increased current also flows through winding 25. If it is assumed, for the purpose of explanation, that the magnetomotive forces due to the currents supplied to windings 24 and 23 are equal when the load voltage is at the predetermined value, then the increased current supplied to winding 25 will cause the magnetomotive force due to this winding to increase by a relatively large amount. The increased current supplied to winding 25 flows through resistor 28, thus increasing the voltage drop across this resistor and reducing the current supplied from rectifier 56 to biasing winding 24. The magnetomotive force due to windings 25 and 24 aid and oppose, respectively, the magnetomotive force set up due to winding 22 in one of the outer legs and the magnetomotive force set up due to winding 23 in the other outer leg of the core 21. Thus the increased magnetomotive force due to winding 25 and the decreased magnetomotive force due to winding 24 each have the effect of reducing the impedance of windings 22 and 23. Increased current is thus supplied from the source 15 through the winding portion 52—54 of the autotransformer and through windings 22 and 23 of the saturable reactor 20. Because of the increased current supplied to the autotransformer winding, the voltage across winding portion 52—53 is increased and therefore the voltage across the primary of transformer 57 is reduced. As a result the output voltage of rectifier 56 is reduced and the current supplied to biasing winding 24 is further reduced. Therefore, the impedance of windings 22 and 23 is further reduced to cause a further increase of current supplied to portion 52—54 of the autotransformer winding. The load voltage is increased in response to the voltage increase across the winding portion 51—52 which results from the supply of increased current through winding portion 52—54 of the autotransformer. The assumed decrease of load voltage is thus minimized.

If the load voltage increases to a value such that the average output voltage of rectifier 60 is larger than the voltage across the constant voltage tube 75, current will flow through the control winding 34 in a direction such that the magnetomotive force due to this winding opposes the magnetomotive forces due to windings 32 and 33. The current flows from the positive terminal of rectifier 60 through resistor 40, control winding 34, resistor 76 and resistor 74 to the negative terminal of rectifier 60. The magnetomotive force due to winding 34 is smaller than each of the magnetomotive forces due to windings 32 and 33. Therefore, the impedances of windings 32 and 33 are increased and the current flow through these windings is reduced. The resultant of the magnetomotive forces due to windings 24 and 25, therefore, has a direction opposed to the magnetomotive force of each of windings 22 and 23, thus causing the impedances of windings 22 and 23 to increase. The alternating current flowing through winding portion 52—54 of the autotransformer winding, is thus reduced and the magnitude and phase of the voltage across the portion 51—52 of the autotransformer winding changes so as to minimize the assumed rise of load voltage.

It is seen that when the average output voltage of rectifier 60 is larger than the opposing voltage across constant voltage tube 75, the current flowing through winding 34 is limited by the resistor 76. This current limitation is such that the magnetomotive force set up by the current in winding 34 is less than the opposing magnetomotive force due to each of windings 32 and 33 even if the load

voltage should rise to an abnormally high value. If this current limitation feature were not provided and, as a result, the magnetomotive force due to winding 34 should become greater than the opposing magnetomotive forces due to each of windings 32 and 33, the impedances of windings 32 and 33 would decrease, the current through winding 25 would increase and the impedances of windings 22 and 23 would decrease. In that case the rise of load voltage would produce an increase of current through the winding portion 52—54 of the autotransformer winding and thus cause a further increase of load voltage.

The regulating circuit is designed so that during normal operation the load voltage is as large as or, preferably, somewhat larger than the maximum voltage of the alternating-current supply source 15. The load voltage may be adjusted by means of the potentiometer 62. An adjustment of potentiometer 62 which increases the output voltage of rectifier 60 produces a decrease of load voltage and vice versa.

As previously stated, it is desired to increase the load voltage during a starting or warm-up period from zero to the normal load voltage at a substantially uniform rate over a certain time interval, say two minutes. During a shut-down period it is desired to decrease the load voltage at a substantially uniform rate from the normal operating voltage to zero, during a similar interval. The apparatus for producing the variation of load voltage over this wide range during the starting and stopping periods will now be described. The relays 3*a* and 3*b* of the switch 3 are deenergized when the apparatus is shut down and the load is thus disconnected from the current supply circuit.

The energization of the load is initiated by closing a start key 1. A circuit is thus completed from one terminal of the supply source 15 through contact 2*a* of a stop key 2, released, start key 1, operated, and start relay 3*a* to the other terminal of the supply source 15. Relay 3*a* is thus operated and relay 3*b* is locked out. A holding circuit for relay 3*a* is thus completed through the normally closed contact 80*a* of a limit switch 80. Operation of relay 3*a* completes a circuit for connecting the load and the primary of transformer 61 across the entire winding 13 of autotransformer 10, that is to the end terminals 51 and 55. Operation of relay 3*a* also completes an energizing circuit for relay 4 from rectifier 70, causing the relay to operate. Operation of relay 4 connects terminal *p* going to the brush of potentiometer 78 to the anode of varistor 77. Operation of relay 4 also completes a circuit for supplying current from the supply source 15 to a driving motor 81 which drives the brush arm 88 of potentiometer 78 and to an electromagnet 82 for operating a pawl 83.

The electromagnet 82, when energized, moves the pawl 83 into engagement with the gear 84 which is coupled to the planetary gear system 85. The sun gear 86 of this planetary system is driven by the motor 81 through a suitable speed reduction gear train within the housing 87. When the pawl 83 engages the gear 84, the gear 89 of the planetary system is held stationary with the result that the arm 109 is driven by the motor through the satellite gears 90 of the planetary system, shaft 91 and gears 92. While the motor is driving the arm 109, it also winds up a spiral spring 93 the inner end of which is secured to the shaft 91 and the outer end of which is secured to a fixed support 94. The potentiometer brush arm 88 is secured to one end of a shaft 95 to the other end of which is secured a dog 96 having an internally threaded portion for supporting a set screw 97. When the motor 81 and the electromagnet 82 are energized, the arm 109 is moved out of engagement with a stop 98 and drives the potentiometer shaft 95 through the set screw 97 and the dog 96, the arm 109 being linked to the dog 96 through the set screw 97. The potentiometer brush carried by the arm 88 is thus moved at a uniform rate along the winding of the potentiometer 78 from terminal *o* to terminal *n* during an interval of about two minutes. When the potentiometer brush has completed its travel, a camming surface formed by a projection of dog 96 will engage the limit switch 80 to open its contact 80*a* and close its contact 80*b*. Any further travel of the dog 96 will bring the projection of dog 96 into engagement with the fixed post 99, thereby stalling the driving motor and preventing any further motion of the potentiometer brush, thus safeguarding the potentiometer from damage through possible overdrive.

At the commencement of the starting period, when the brush of potentiometer 78 is at terminal *o*, the point *c* may be slightly positive with respect to point *b* due to the rectification by varistor 77 of alternating voltage which may be induced in winding 34. There will be a voltage drop across the 300-ohm resistor 74 between points *b* and *d* in opposition to the voltage drop between points *c* and *b* in the circuit including winding 34 connected to points *c* and *d*. There may also be present in the circuit, including winding 34, a small output voltage of rectifier 60 due to alternating current supplied to the transformer 61 the primary of which is connected across the winding of autotransformer 10. The voltage across winding 34 will then be the output voltage of rectifier 60 plus the voltage across resistor 74 minus the voltage across resistor 76. The direction of the current flow will be from the positive terminal of rectifier 60 through resistor 40, winding 34, resistor 76 and resistor 74 to the negative terminal of rectifier 60. This direction of current flow through winding 34 sets up a magnetomotive force in the core 31 of the magnetic amplifier 30 which opposes the magnetomotive forces due to windings 32 and 33. As a result, the impedance of windings 32 and 33 of the magnetic amplifier will be high, the current supplied to control winding 25 of the saturable reactor 20 will be low, the impedance of windings 22 and 23 of the saturable reactor will be high and only a very small current will flow through the winding portion 52—54 of the autotransformer winding. Thus, the voltage across the autotransformer winding and therefore the voltage across the load and across the primary of transformer 61 will be a low value near zero.

When the motor 81 drives the brush of potentiometer 78 from terminal *o* toward terminal *n* at a substantially uniform rate, the voltage between point *b* and the potentiometer brush increases at a uniform rate. Current will flow from the positive terminal of rectifier 70 through choke coil 72, resistor 73, from terminal *n* of the potentiometer to the potentiometer brush through varistor 77 and resistor 76 to the negative terminal of rectifier 70. The voltage drop across the resistor 76 is thus increased to cause the current flowing through the winding 34 to decrease. The voltage across the autotransformer 10 and the load 16 and the output voltage of rectifier 60 are thus increased at a substantially uniform rate.

The increased voltage across the autotransformer 10 will produce two effects. First, the voltage supplied to the bias rectifier 56 will decrease to cause the current supplied to the bias winding 24 to decrease. A reduction of current supplied to the bias winding 24 will reduce the current required to be supplied to the control winding 25 in order to raise the voltage across the autotransformer 10 and the load 16 to the normal operating value.

The second effect of increasing the voltage across the autotransformer is that of increasing the output voltage of the comparison voltage rectifier 60 which is proportional to the load voltage. The current in the circuit comprising the control winding 34 is of the order of a few milliamperes and, therefore, the output voltage of rectifier 60 will very closely follow the voltage appearing between the cathode of the constant voltage

tube 75, point *d*, and the brush of the potentiometer 78. Thus, the resultant voltage in the control circuit including the control winding **34** will be nearly zero at all times and, at any position of the brush of potentiometer **78**, the regulating circuit will function to minimize load voltage changes due to both voltage changes of the supply source **15** and to load current changes. When the brush of potentiometer **78** reaches terminal *n*, point *c* will be effectively at the potential of point *a* since the voltage across the varistor **77** when conducting is quite small. The voltage across the load will then be at the normal operating value determined by the setting of the potentiometer **62**.

When the output voltage of rectifier **60** has increased sufficiently in response to the movement of the brush of potentiometer **78**, the current supplied from the rectifier to relay **6** reaches a sufficient amplitude to cause relay **6** to operate. When the brush of potentiometer 78 has completed its travel to terminal *n*, the limit switch 80 is actuated by the dog **96** to open contact **80***a* and to close contact **80***b*. Opening of contact **80***a* opens the holding circuit for relay **3***a*. Closing contact **80***b* completes a circuit for energizing relay **3***b* by current from source **15** through a contact of relay **6** which has operated. Release of relay **3***a* and operation of relay **3***b* will disconnect the load and the primary of transformer 61 from across the entire winding of autotransformer 10 and will connect the load and the primary of transformer 61 each in series with the portion **51—52** of the autotransformer winding and the supply source 15. The release of relay **3***a* will open the energizing circuit for relay 4 and the release of relay 4 will disconnect the anode of varistor **77** from the brush of potentiometer 78 and connect it to point *a*. Release of relay 4 will also open the energizing circuit for the motor 81 and the electromagnet 82. The release of the pawl 83 by the de-energization of electromagnet 82 will permit the unwinding of the spiral spring 93 which was wound up while the motor was driving the brush of potentiometer 78 from terminal *o* to terminal *n*. The unwinding of spring 93 will thus return the potentiometer brush from terminal *n* to terminal *o*.

Operation of relay **3***b* completes a circuit for energizing relay **5** by current from rectifier **70**. Operation of relay 5 reverses the terminal connections of potentiometer 78 in the circuit, connecting the terminal *n* to point *b* and terminal *o* to point *a*. A holding circuit for relay 5 is completed through a contact of relay **6** to insure that relay 5 will remain operated even though relay **3***b* is subsequently released. The circuit and apparatus are now in the normal operating condition for supplying alternating current to the load and to maintain the load voltage substantially constant at the normal operating voltage.

When it is desired to de-energize the load **16**, the stop key 2 is operated to open contact **2***a* and close contact **2***b*. Opening contact **2***a* interrupts the holding circuit for relay **3***b* and closing contact **2***b* completes an energizing circuit for relay **3***a* through a contact of relay **6**. As a result, the load **16** and the primary of transformer 61 will each be disconnected from the series circuit comprising the source **15** and the booster portion **51—52** of the autotransformer winding and will be connected across the entire autotransformer winding from terminal 51 to terminal 55. Operation of relay **3***a* completes an energizing circuit for relay 4 to cause the anode of varistor 77 to be connected to the terminal *p* of the potentiometer 78. The operation of relay 4 will also complete a circuit for energizing the motor 81 and the electromagnet 82. The motor will therefore drive the brush of potentiometer 78 from terminal *o* to terminal *n*. However, since terminal *o* is now connected to point *a* and terminal *n* is now connected to point *b*, the potential of point *c* with respect to point *d* is initially a maximum, and this potential difference gradually decreases as the potentiometer brush is moved at a uniform rate from terminal *o* to terminal *n*. This decrease of potential difference between points *c* and *d* causes the current flowing through winding **34** of the magnetic amplifier **30** to increase with the result that the voltage across the winding of autotransformer **10** and the load **16** and the output voltage of rectifier **60** are decreased at a substantially uniform rate. When the output voltage of rectifier **60** has decreased sufficiently, relay 6 will be released.

The operation of the limit switch **80**, when the brush of potentiometer **78** has completed its travel from terminal *o* to terminal *n*, opens the holding circuit for relay **3***a* thereby releasing relay **3***a*. The energizing circuit for relay **3***b* is not completed by the closure of switch contact **80***b* because relay **6** is de-energized at this time. Release of relay **3***a* opens the energizing circuit for relay **4**. With relays **4** and **6** released, the holding circuit for relay **5** is opened and relay **5** releases. The release of relay **4** opens the energizing circuit for the motor **81** and the electromagnet **82** thereby permitting the spring **93** to return the brush of potentiometer **78** to terminal *o*. The circuit is thus restored to its initial condition with the load disconnected from the current supply circuit.

To avoid having relay **6** momentarily release during the interval in which one of relays **3***a* and **3***b* is being released and the other of the relays **3***a* and **3***b* is being operated, it is desirable that relay **6** should be slow to release. For this purpose a suitable condenser **100** may be connected across the winding of relay **6**, for example.

If, due to some emergency it should become necessary to de-energize the load **16** promptly, this may be done by opening switch **101** through which current from the supply source **15** is normally supplied to the current supply circuit. Regardless of the state of the activation of the current supply circuit at the time the switch **101** is opened, all the relays will be released and the brush of potentiometer **78** will be brought to terminal *o*. Subsequently, the switch **101** may be closed and the energization of the load started as previously described.

The 20-ohm resistor **17** connecting the common terminal of reactor winding **22** and the rectifying element **26** and the common terminal of winding **23** and the rectifying element **27**, has been found to be effective in minimizing the initial surge of current at the start of the period in which the saturating action begins to build up. This surge is particularly noticeable, without the resistor **17**, where the cold resistance of the filaments of the load **16** is a small fraction of the resistance of the filaments when hot. The resistor **17** could be replaced by an electrolytic condenser of low reactance and in some cases this may be a preferable arrangement.

The resultant voltage in the circuit for supplying current to the control winding 34 of the magnetic amplifier 30 comprises the output voltage of rectifier **60** and the voltage measured between points *c* and *d*. There may also be present in the circuit a transient voltage substantially proportional to the rate of change of output voltage of rectifier **56**. This transient voltage is introduced into the circuit comprising the control winding 34 due to the charge or discharge current of condenser 41 flowing through resistor 40. For example, if during normal operation the load voltage should increase to cause an increase of output voltage of rectifier **60**, the current supplied to winding 34 changes to reduce the current supplied through portion **52—54** of the autotransformer winding. The output voltage of rectifier **56** therefore increases to cause the condenser 41 to be charged through resistor 40. This charging current produces across resistor 40 a transient voltage drop in opposition to the increasing output voltage of rectifier **60**. The rate of change of current flowing through winding 34 is thus reduced. In this way, the control circuit is effectively

stabilized not only for the normal operating condition, but also during the periods in which the supply of current to the load is being started or stopped.

What is claimed is:

1. Apparatus for supplying alternating current from an alternating-current supply source to a load comprising an autotransformer having a core and a winding thereon, said winding comprising a first, a second and a third winding portion, a saturable reactor having an impedance winding and a winding means, means for supplying current from said supply source to a current path comprising said impedance winding and said second winding portion in series, means for connecting said load across said autotransformer winding, means for increasing at a substantially uniform rate over a substantial time interval the voltage across said load from zero or a very low value to a predetermined voltage, said last-mentioned means comprising means for energizing said winding means to gradually reduce the impedance of said impedance winding, and means for disconnecting said load from across said autotransformer winding and connecting said load in series with said first winding portion and said current supply source when the load voltage has increased to said predetermined voltage.

2. In combination, an autotransformer having a core and a winding thereon, said winding comprising a first, a second and a third winding portion, a saturable reactor having an impedance winding, means for supplying current from an alternating-current supply source through said second winding portion and said impedance winding in series, means for connecting a load across said autotransformer winding, means for decreasing the impedance of said impedance winding to increase the voltage across said autotransformer winding and said load, and means effective when the load voltage has increased to a desired value for disconnecting said load from across said autotransformer winding and for connecting said load in series with said first winding portion and said current supply source.

3. Apparatus for supplying current from an alternating-current supply source to a load comprising an autotransformer having a core and a winding thereon, said winding comprising a first and a second winding portion, means for connecting said load across said autotransformer winding, means for supplying current from said supply source to said second winding portion comprising means for gradually increasing said current to increase the voltage across said autotransformer winding to a predetermined desired voltage and means effective when the voltage across said autotransformer winding has increased to said predetermined voltage for disconnecting said load from across said autotransformer winding and connecting said load in series with said first winding portion and said supply source.

4. In combination, a saturable reactor comprising a core and a first, a second and a third winding on said core, the impedance of said first winding being controlled in part at least by the resultant magnetomotive force set up in said core due to currents supplied to said second and third windings, respectively, a first and a second source of unidirectional voltage, a resistor, a first circuit comprising said first voltage source, said resistor and said second winding all in series, a second circuit comprising said second voltage source, said resistor and said third winding all in series, the magnetomotive force set up in said core in response to the current in said first circuit flowing through said second winding being in opposition to the magnetomotive force set up in said core in response to the current in said second circuit flowing through third winding, the voltage set up across said resistor in response to current flowing in said first circuit being in opposition to the voltage of said second source in said second circuit.

5. The combination with an autotransformer having a winding, of a saturable reactor comprising an impedance winding, a biasing winding and a control winding all wound on a core of magnetic material, means for supplying current from an alternating-current supply source to a circuit comprising a portion at least of said autotransformer winding and said impedance winding in series, a rectifier for supplying unidirectional current to said biasing winding to set up a first unidirectional magnetomotive force in said core, a circuit for supplying current from said supply source to said rectifier through a portion of said autotransformer winding the voltage across which is in opposition to the voltage of said supply source in said circuit and means for supplying to said control winding a unidirectional current which may vary to set up in said core a second unidirectional magnetomotive force which is opposed to said first unidirectional magnetomotive force, an increase of said second magnetomotive force producing an increase of voltage across said autotransformer winding to cause a reduction of said first magnetomotive force and vice versa.

6. The combination with an autotransformer having a winding, of a saturable reactor comprising an impedance winding, a biasing winding and a control winding all wound on a core of magnetic material forming a magnetic circuit, means for supplying alternating current from an alternating-current supply source to a portion at least of said autotransformer winding to set up an alternating voltage across said autotransformer winding, said last-mentioned means comprising said impedance winding and a first rectifier for rectifying the current supplied to said impedance winding to cause a first unidirectional magnetomotive force to be set up in said magnetic circuit, a second rectifier, means for supplying current from said supply source through a circuit comprising a portion of said autotransformer winding to said second rectifier to set up a unidirectional voltage which decreases in response to a decrease of impedance of said impedance winding and vice versa, the voltage across said portion of said autotransformer winding being in opposition to the voltage of said supply source in said circuit, means for supplying current from said second rectifier to said biasing winding to set up a second unidirectional magnetomotive force in said magnetic circuit and means for supplying unidirectional current which may vary to said control winding to set up a third unidirectional magnetomotive force in said magnetic circuit to control the impedance of said impedance winding and thereby the voltage across said autotransformer winding, said second and third magnetomotive forces being in opposition with respect to each other and said first and third magnetomotive forces being in aiding relationship with respect to each other.

7. In combination, an autotransformer comprising a winding, means for supplying current from an alternating-current supply source to a portion of said winding to set up an alternating voltage across said winding, a first source of variable unidirectional voltage, a second source of unidirectional voltage the voltage of which increases in response to an increase of voltage across said autotransformer winding and vice versa, a third source of unidirectional voltage the voltage of which decreases in response to an increase of voltage across said autotransformer winding and vice versa, and means responsive to the voltages of said first, second and third sources of unidirectional voltage for controlling the supply of current from said alternating-current supply source to said portion of said autotransformer winding to control the voltage across said winding, an increase of a voltage equal to the difference of the voltages of said first and second unidirectional voltage sources increasing the voltage across said autotransformer winding and vice versa and the decrease of voltage of said third unidirectional source resulting from said increased voltage across said autotransformer winding further increasing the voltage across said autotransformer winding and vice versa.

8. A combination in accordance with claim 7 in which there are provided switching means for connecting a load across said autotransformer winding or for connecting said load in series with said alternating-current supply source and a second portion of said autotransformer winding alternatively, means for increasing the voltage of said first source of unidirectional voltage at a substantially uniform rate to a predetermined maximum voltage, means responsive to a start signal for operating said switching means to connect said load across said autotransformer winding, means responsive to said operation of said switching means for starting said means for increasing the voltage of said first source of unidirectional voltage and means responsive when said maximum voltage is reached for operating said switching means to disconnect said load from across said second autotransformer winding and to connect said load in series with said alternating-current supply source and said second portion of said autotransformer winding.

9. A combination in accordance with claim 7 in which are provided switching means for connecting a load across said autotransformer winding or for connecting said load in series circuit with said alternating-current supply source and a second portion of said autotransformer winding alternatively, means for decreasing the voltage of said first source from a maximum to a minimum value at a substantially uniform rate, means responsive to a stop signal for operating said switching means to disconnect said load from said series circuit comprising said alternating-current supply source and said second portion of said autotransformer winding and for connecting said load across said autotransformer winding and means responsive to said operation of said switching means for starting said means for decreasing the voltage of said first source.

10. In combination, an autotransformer having a winding, a saturable reactor having an impedance winding, a control winding and a bias winding all on a core

of magnetic material, a circuit comprising a first portion of said autotransformer winding and said impedance winding in series connected to an alternating-current supply source, means for rectifying the current supplied to said impedance winding to cause to be set up in said core a first unidirectional magnetomotive force, means comprising a first rectifier for setting up a first unidirectional voltage, means for energizing said first rectifier comprising a first transformer having a primary winding connected in series circuit with said alternating-current supply source and a second portion of said autotransformer winding the voltage across which portion aids the supply voltage in said circuit, a second rectifier for setting up a second unidirectional voltage, means for energizing said second rectifier comprising a second transformer having a primary winding connected across said autotransformer winding, a control circuit comprising said control winding and a resistor in series therewith, means responsive to a voltage equal to the difference of said first and second unidirectional voltages for controlling the energization of said control circuit to set up a second unidirectional magnetomotive force in said core, a third rectifier for setting up a third unidirectional voltage, means for energizing said third rectifier comprising a third transformer having a primary winding connected in series circuit with said alternating-current supply source and a third portion of said autotransformer winding the voltage across which portion opposes the supply voltage in said circuit, a biasing circuit comprising said biasing winding and said resistor in series and means for impressing said third unidirectional voltage upon said biasing circuit to set up in said core a third magnetomotive force in opposition to said first and second magnetomotive forces, the unidirectional currents supplied to said control circuit and to said biasing circuit respectively, flowing in the same direction through said resistor.

No references cited.