April 11, 1967 M. I. ROSENBERG ET AL 3,314,000

ELECTRICAL SYSTEM

Filed Aug. 30, 1963 4 Sheets-Sheet 1

FIG. 1.

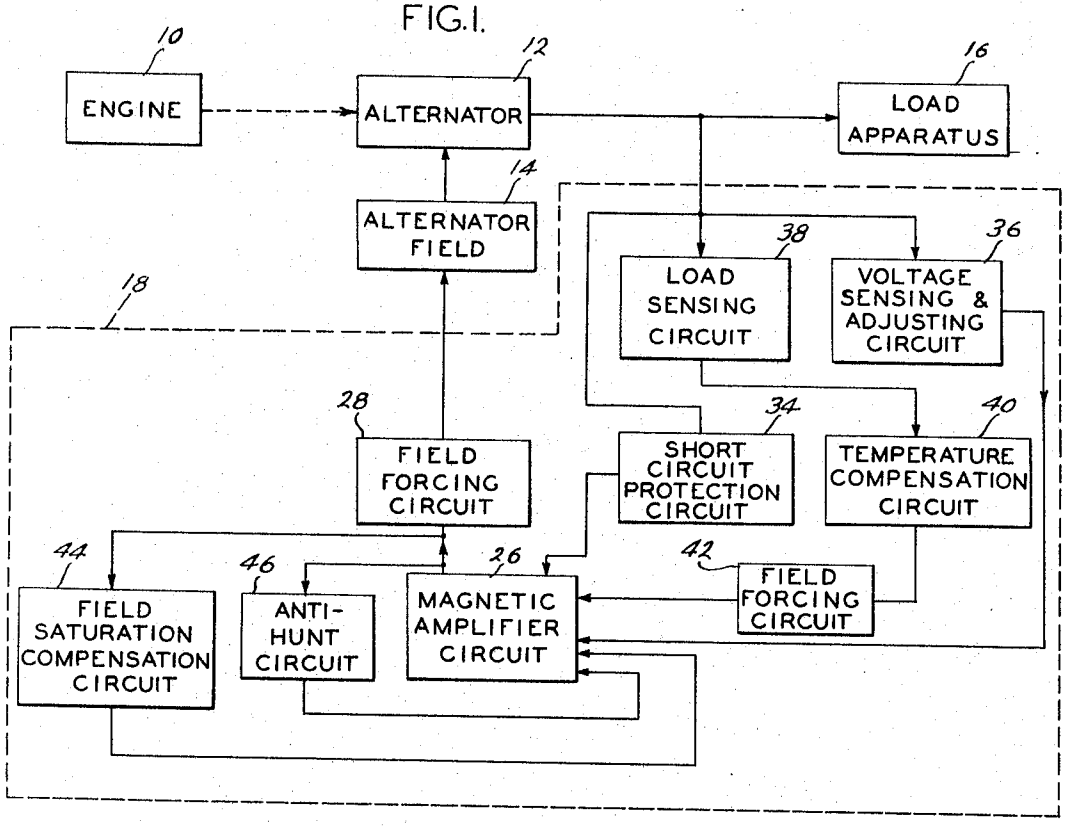
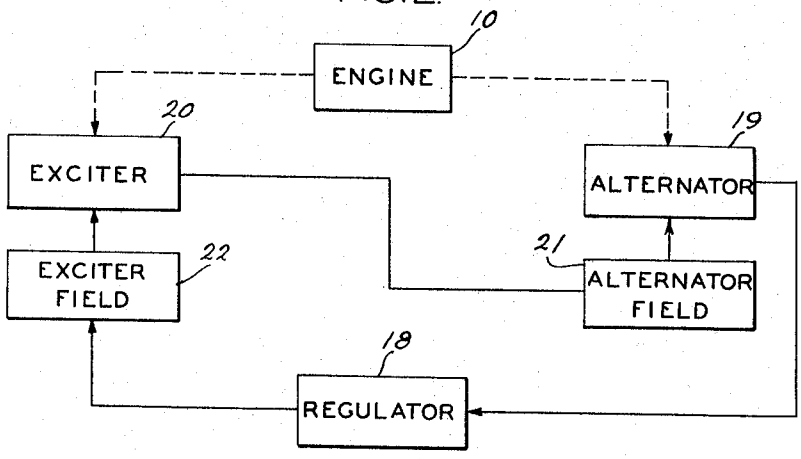


FIG. 2.



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ELECTRICAL SYSTEM

Filed Aug. 30, 1963 4 Sheets-Sheet 2

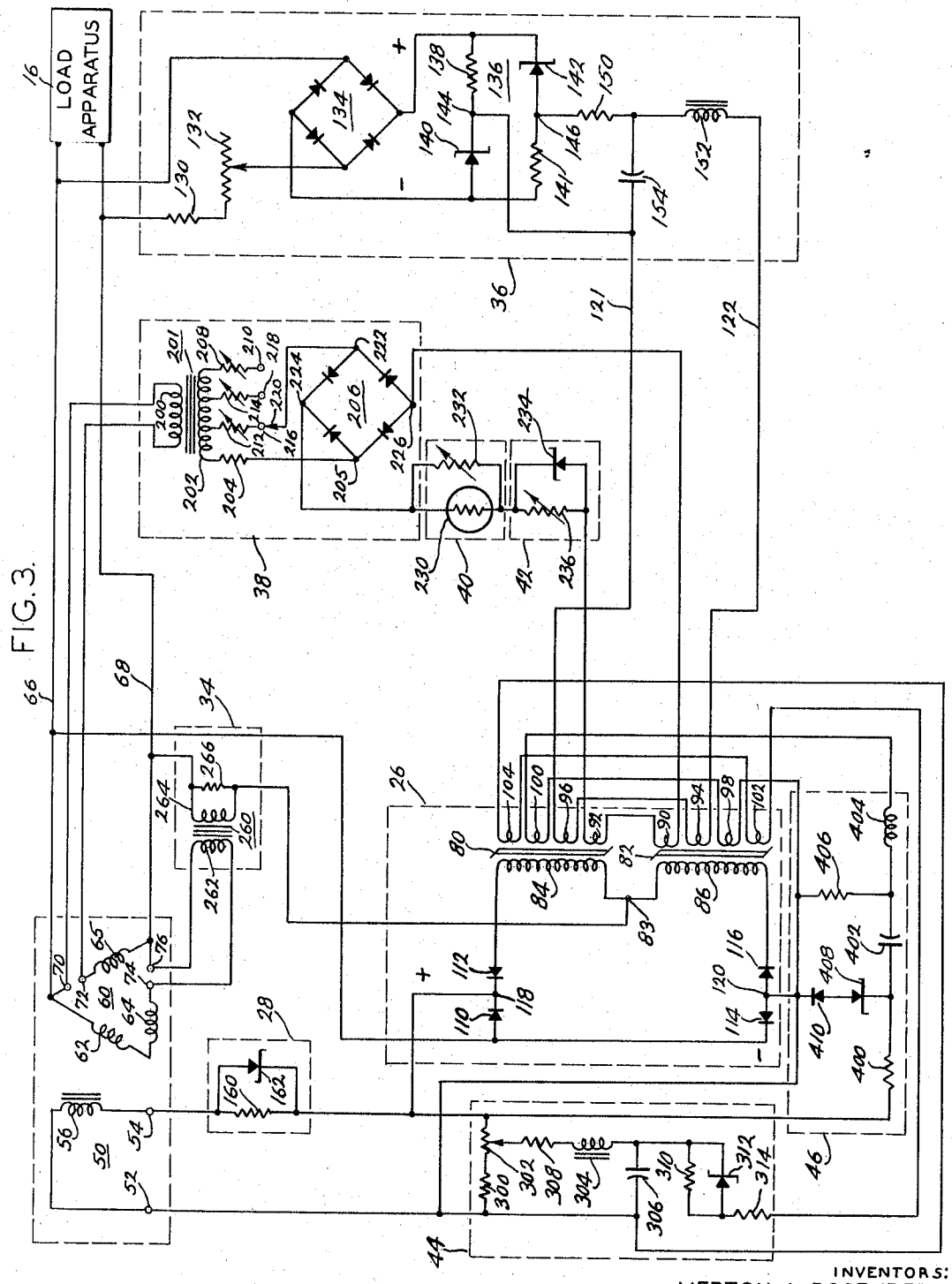


FIG. 3.

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ELECTRICAL SYSTEM

Filed Aug. 30, 1963 4 Sheets-Sheet 3

FIG. 4

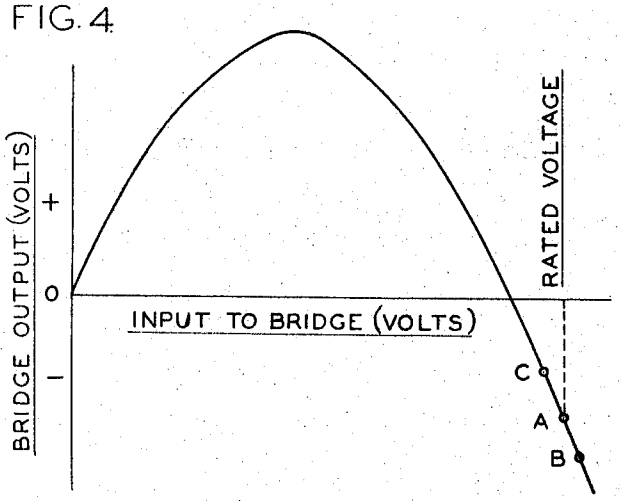


FIG. 5.

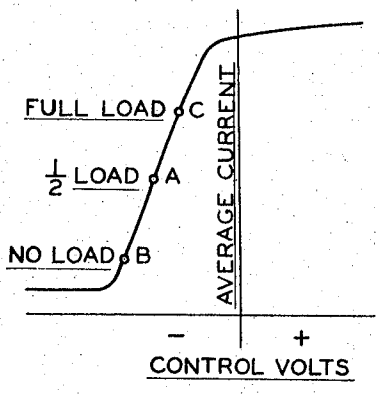


FIG. 6.

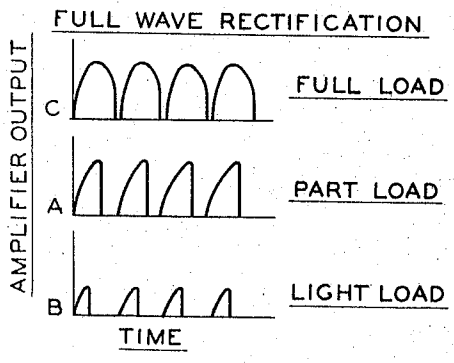


FIG. 7

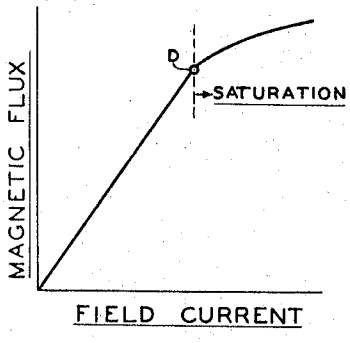


FIG. 9.

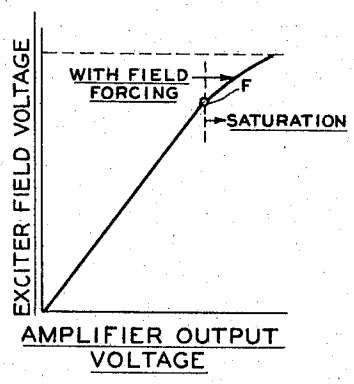
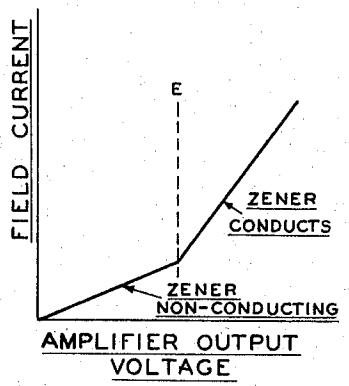


FIG. 8.



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ELECTRICAL SYSTEM

Filed Aug. 30, 1963 4 Sheets-Sheet 4

FIG. 10A.

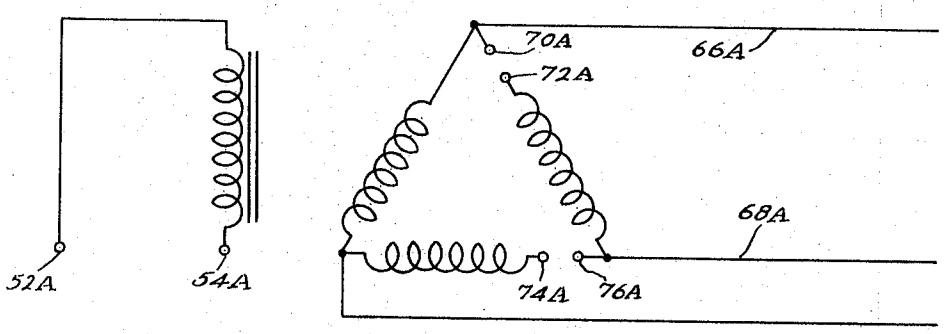


FIG. 10B.

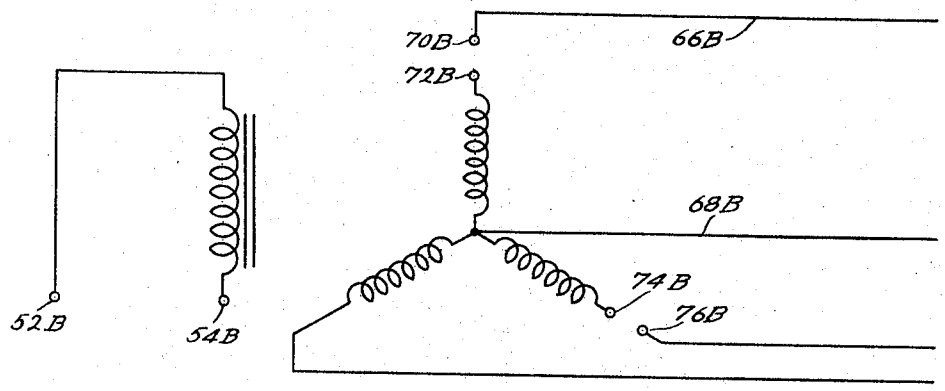
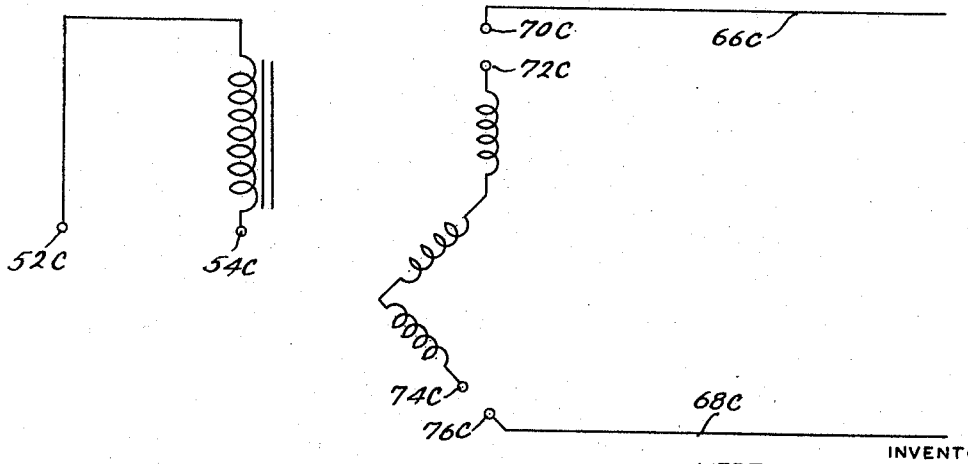


FIG. 10C.



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3,314,000

ELECTRICAL SYSTEM

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Filed Aug. 30, 1963, Ser. No. 305,596
4 Claims. (Cl. 322—25)

This invention relates to systems for controlling the output of a source of electrical power having a control element, by applying to said control element a control signal derived from the output of said source. More particularly it relates to voltage regulators for stabilizing or otherwise controlling automatically the output voltage of a generator of electrical voltage, where the term "generator" is used broadly to include an alternator, for example.

Systems are known in the prior art which are intended to stabilize the output voltage of an electrical generator at a predetermined rated voltage despite tendencies for it to change in response to such factors as changes in load drawn from the generator, changes in speed of the power source driving the generator, changes in ambient temperature, and others. This has been accomplished in the past to a substantial degree by sensing output voltage and/or current of the generator to derive control signals and feeding back the control signals to control the current through the field element of the generator in degenerative phase, thereby to oppose deviations from the desired output voltage. In such systems it is desirable that deviation of the generator output voltage from the desired rated voltage be held to as small a value as possible, and that if a substantial deviation does occur the desired output voltage be regained as soon as possible. It is also desirable in certain applications that the stabilization be effective over a wide range despite tendencies for the field element to become saturated for high currents through it, and that the generator system be adapted to start up quickly without need for an external current supply. In addition in some instances it is desirable that, when the generator output is short-circuited, the generator be made to deliver a high current output for a period sufficient to operate a high-level circuit breaker, so that the generator can be used safely even with load apparatus using a circuit breaker which operates only at such relatively high levels.

It is therefore an object of the invention to provide a new and improved voltage regulating system of the class in which signals derived from the output of the system are fed back to a control element of a voltage-generating source.

Another object is to provide such a system which maintains the output voltage of said generator very close to a predetermined rated voltage level.

A further object is to provide such a system which is capable of providing rapid generator voltage build-up on starting without requiring an additional current source.

Another object is to provide such a system which is effective to provide stabilization of said output voltage over a wide range of variation in factors tending to change said output voltage, despite the fact that the control element used to control automatically said output voltage exhibits a saturation effect at relatively low values of the control signal applied thereto.

It is also an object to provide such a system in which compensation is provided to stabilize the output voltage of the source against changes in temperature.

A further object is to provide such a system in which, upon substantial short-circuiting of said source, a large pulse of current is produced and maintained for a time sufficient to actuate a high-level circuit breaker.

Another object is to provide a new and improved

anti-hunt circuit suitable for use in feedback-type regulators for electrical generators.

It is also an object to provide apparatus accomplishing all or a number of the foregoing objects simultaneously in a particularly simple and effective manner.

In accordance with the invention the above objects may be achieved simultaneously by a system embodying a number of specially-cooperating novel features, each of which features, however, may be used to advantage without the others to accomplish one or more of the above objects. In particular, in accordance with the invention in one aspect there is employed a voltage-sensing circuit for producing a control voltage varying in dependence on the magnitude of the output voltage of the source to be regulated, which control voltage is fed back in effect to a control element of the source, such as the field element of a generator, to control the output voltage. The voltage sensing circuit is such that the control voltage is of one polarity for the relatively small output voltages produced when the source is first started up and is fed back to the control element in regenerative phase to assist in rapid build-up of the source output voltage; however, when the output voltage has built-up to a predetermined extent the control voltage changes to the opposite polarity and increases in said opposite polarity for further increases in output voltage. Accordingly the feedback control is then in degenerative phase so as to oppose further increases in output voltage and to stabilize it at a predetermined level during normal operation. This voltage-sensing circuit is constructed and adjusted so that during normal operation the control voltage produced thereby is of said opposite polarity

Preferably a load-current sensing circuit is also used which senses the magnitude of the load current drawn from the source and produces a control voltage for effectively increasing the gain of the feedback circuit for higher load currents, thereby providing closed stabilization or regulation at high loads without introducing system instability for smaller loads. Preferably also, the control voltages from the voltage-sensing and load-current sensing circuits are fed back by way of an amplifier, and a negative temperature coefficient element is disposed between the load-current sensing circuit and the amplifier to compensate for fall-off of source output voltage with increased temperature.

According to another feature, the "hunting" which tends to occur in the source output voltage, as well as in the control voltage supplied from the amplifier to the control element, due to the feedback-control action of the regulating system, is minimized while retaining the ability of the system to provide rapid correction and to recover quickly following sudden extreme load changes, such as sudden change from full load to no load, by means of a novel "anti-hunt" circuit. This "anti-hunt" circuit employs capacitive means sufficiently large to feed back hunting variations from the output of the amplifier to its input, while blocking direct voltages, and voltage-breakdown means such as a Zener diode connected in circuit with the capacitive means to limit the voltage level to which the capacitive means can charge in response to decreases in load, thereby preventing the slow recovery times which would otherwise be produced by full charging and subsequent discharging of the capacitive means.

According to another feature a wide range of control for the regulating system is provided despite a relatively low saturation level of the control element of the source above which the control capability of the control element is greatly decreased; this is accomplished by means of one or more circuits having non-linear voltage-current characteristics disposed in the regulating system so that when the control voltage applied to the control element increases from below to above the level for which substantial satu-

ration of the control element begins, the non-linear circuit provides a more rapid increase in said control voltage to counteract the saturation effect.

A further feature involves a novel short-circuit protection circuit arrangement for providing and maintaining for a substantial interval a large output current from the source when the output terminals of the source are short-circuited, even though the regulator system includes an element such as a magnetic amplifier supplied with operating voltage from the output terminals of the source and which therefore tends to reduce the source output when the above-mentioned short-circuiting occurs. The preferred form of the latter circuit is used with a source which provides an additional current in different phase from that normally used to operate the magnetic amplifier, and uses the latter additional current to increase greatly the output of the magnetic amplifier when a short-circuit occurs, in a manner described in detail hereinafter. In this manner the source is enabled to provide adequately-high current for a sufficient time to operate a high-level circuit breaker upon the occurrence of a short-circuit in the load apparatus.

These and other objects and features of the invention will be more readily appreciated from a consideration of the following detailed description of a particular embodiment thereof, taking together with the accompanying drawings in which:

FIGURE 1 is a block diagram illustrating the functional interrelationships of various elements of a preferred embodiment of the invention;

FIGURE 2 is a block diagram illustrating an alternative overall arrangement of a system employing the invention;

FIGURE 3 is a schematic circuit diagram representing in detail a preferred embodiment of the invention;

FIGURES 4 through 9 are graphical representations illustrating certain characteristics of particular elements of a preferred embodiment of the invention; and

FIGURES 10A, 10B, and 10C are schematic diagrams illustrating the regulator connections for various phase arrangements of the alternators.

Referring first to FIGURE 1, the block diagram therein indicates the broad functional elements and their interrelationships in accordance with the invention as applied to a voltage source comprising a simple form of electrical generator without separate exciter. As shown, an engine **10** provides mechanical drive for alternator **12**, which has the usual alternator field **14** and which supplies output power to any suitable load apparatus **16**, which may include a circuit breaker. The regulator **18** is supplied with output power from the alternator and applies a controlled current to the alternator field **14** to maintain constant the voltage supplied to the load apparatus **16**. Accordingly the alternator field serves as a control element for the generator. It will be understood that other types of generators having other types of control elements may be utilized, for example as shown in FIGURE 2 where the engine **10** drives the alternator **19** and exciter **20** of an exciter-type generator, the exciter controlling the alternator field **21** and the regulator **18** being connected between the output of the alternator and the exciter field **22**.

As shown in FIGURE 1, regulator **18** includes a magnetic amplifier circuit **26** the output of which is passed through field-forcing circuit **28** to the alternator field **14** to control the strength of magnetic field in the generator and hence the generator output. The magnetic amplifier circuit **26** is supplied with gating signals from the output of alternator **12** by way of a connection which includes short-circuit protection circuit **34**, the function of which is to produce sufficient output from the amplifier circuit to force the alternator field **14** so that the alternator **12** sustains a short circuit current for a sufficiently long time to trip a relatively high current circuit breaker in the load apparatus **16** upon the occurrence of a short circuit or extremely heavy load produced by the load apparatus.

Magnetic amplifier circuit **26** is provided with four input control signals which act automatically to control the magnitude of the output of the amplifier circuit to the alternator field **14**. One of these controls is derived from the output of the alternator **12** by way of voltage sensing and adjusting circuit **36**, and acts in a direction to counter increases or decreases in the output voltage of the alternator during normal operation, while providing regenerative feedback during initial voltage build-up when the alternator is first started.

Another control signal is derived by the load sensing circuit **38**, which senses the alternator output current and supplies a control signal to the magnetic amplifier by way of temperature compensation circuit **40** and field forcing circuit **42**. The direction of control is in a direction to increase the alternator field current, and hence the alternator output voltage, as the alternator load current increases. The temperature compensation circuit **40** responds to ambient temperature changes which tend to change the alternator output voltage, to cause the magnetic amplifier to produce compensating changes in the current through the alternator field **14**. The function of the field-forcing circuits **28** and **42** is to compensate for saturation of the magnetic element of the alternator field **14** in response to high field currents, by producing a greater rate of increase of alternator field current in response to control voltage for such high field currents than for alternator field currents below the saturation level.

Although not essential, preferably another control for magnetic amplifier circuit **26** is derived from the output of the magnetic amplifier by way of field saturation compensation circuit **44**. This circuit arrangement serves also to compensate for the non-linear characteristics of the alternator field produced by magnetic saturation therein, and may include a control for "trimming" the amount of feedback provided by the regulator.

The remaining control for magnetic amplifier circuit **26** is derived from its own output by way of the anti-hunt circuit **46**, the phase of the feedback in this case being negative. The function of the anti-hunt circuit **46** is to minimize those variations in the output voltage of alternator **12** which the regulator itself tends to introduce, while at the same time permitting the regulator to respond with adequate speed in compensating for load voltage or load current variations and in recovering from the effects of such variations.

With this general organization of the system in mind, the detailed circuitry of a specific embodiment of the invention suitable for one application thereof will now be described in detail.

Referring now to FIGURE 3, the invention as shown is applied to a single-phase delta-connected A.C. alternator of a type involving no exciter, and employing an alternator field **50** having a pair of current input terminals **52** and **54**, connected in series with a field winding **56** disposed in conventional manner about a suitable magnetic material, and a multi-phase winding arrangement **60** coupled thereto and including three windings **62**, **64** and **65** arranged to supply output power to load apparatus **16** by way of leads **66** and **68**. Terminals **70** and **72** are provided between the adjacent ends of windings **62** and **65**, while terminals **74** and **76** are provided between the adjacent ends of windings **64** and **65**, the current paths between the members of each pair of terminals being provided by connections within the regulator **18** as described hereinafter.

The magnetic amplifier circuit **26** for regulator **18** in this case comprises a Ramey-type magnetic amplifier of the full-wave type, using two magnetic cores **80** and **82** of "square-loop" material such as 50% nickel and 50% iron, and two respective gate-windings **84** and **86**. Each of the cores **80** and **82** has associated with it four control windings constituting pairs (**90**, **92**), (**94**, **96**), (**98**, **100**) and (**102**, **104**), the members of each pair being connected respectively in series with each other and prefer-

ably being counter-wound so that undesirable effects of electromotive force of self-induction are minimized.

The gating signals for the magnetic amplifier are supplied from across the output leads **66** and **68** of the generator, in one case from lead **68** by way of short-circuit protection circuit **34**, to the interconnection **83** of the gating windings **84** and **86**, and in the other case from the generator output lead **66** in parallel to both opposite ends of the gating windings by way of the diode pair **110**, **112** and the diode pair **114**, **116** respectively. Diodes **110** and **112** are disposed with their cathode elements directly interconnected, while diodes **114** and **116** have their anode elements directly interconnected. The arrangement is such as to produce between the interconnection **118** of diodes **110** and **112**, and the interconnection **120** of diodes **114** and **116**, a unidirectional pulsating output voltage from the amplifier having an average value which depends upon the control current flowing through the control windings **90**, **92**, **94**, **96**, **98**, **100**, **102** and **104**, according to known principles of magnetic amplifier operation.

The voltage generated between interconnections **118** and **120** is supplied by way of field-forcing circuit **28** to the input terminals **54** and **52** respectively, of the alternator field **50**. Increases in the voltage between interconnections **118** and **120** therefore produce increases in the field current and greater output from the generator across output leads **66** and **68**. Accordingly, the voltage produced by the generator depends upon, and is controlled by, the current through the above-mentioned control windings of the magnetic amplifier **26**.

The voltage-sensing and adjusting circuit **36** has its input terminals connected between output leads **66** and **68** of the generator and has its output leads **121** and **122** connected in series with control windings **94** and **96** of amplifier **26**. It is the function of circuit **36**, broadly, to respond to increases in magnitude of the voltages between output leads **66** and **68** of the generator to increase the current control windings **94** and **96** in the positive-feedback sense while the generator output voltage is initially building up, and therefore to produce an increased output voltage at interconnections **118** and **120** and an enhanced field current for assisting in this building up; and, after stable operating conditions have been produced, to respond to any changes in generator output voltage to change the current through control windings **94** and **96** in the negative-feedback sense, thereby to oppose the last-mentioned changes in generator output voltage.

To this end the output voltage at leads **66** and **68** is supplied by way of fixed current-limiting resistor **130** and variable series resistor **132** to opposite points on a conventional bridge rectifier circuit **134**, the other diametrically-opposed terminals of which bridge rectifier circuit are interconnected by the resistor and Zener-diode bridge circuit **136**. The latter circuit consists of a first series combination of a resistor **138** and Zener diode **140**, and, in parallel with it, a second series combination of another resistor **141** and a second Zener diode **142**. The order of the resistors and Zener diodes in the two branches of the circuit is opposite, and both diodes are poled so that their cathodes are connected to the more positive end of circuit **136**. Output from circuit **136** is taken between the two center taps **144** and **146** in the two parallel branches thereof.

In operation, when the voltage between generator output terminals **66** and **68** is very low, as when the generator is started with only a small remanent flux existing in the alternator field, the voltage across the Zener diodes **140** and **142** is relatively low and they are therefore in their low-current, reverse-biased condition, presenting a high resistance to current flow. The impedance of the Zener diodes is therefore at these times large compared with that of resistors **138** and **141**, so that the voltage at center tap **144** is more positive than that at center tap **146**, producing a current through control windings **94** and **96** in the polarity to increase the current in the field winding **56** and rapidly increase the output voltage of the generator in regenerative fashion.

Referring to FIGURE 4, which is a plot showing as ordinates the average voltage of interconnection **144** relative to that of interconnection **146**, and showing as abscissae the average voltage applied across Zener diode bridge circuit **136** by rectifier bridge **134**, the operation for low generator output voltages is represented by the initial portion of the curve as it increases toward a maximum value of average output voltage. However, with increased input voltage to circuit **136** the Zener diodes begin to become conductive during the more positive portions of the input half-waves, with the result that a negative component of output voltage is thereby introduced to oppose the positive component. The average output voltage at interconnection **144** with respect to interconnection **146** therefore increases less rapidly with input voltage, and then begins to fall. For still larger generator output voltages the average output voltage of bridge **136** becomes zero and then becomes negative with respect to the voltage at interconnection **146**. When the voltage at tap **144** has a reference negative value such as A in FIGURE 4, corresponding to the occurrence of the rated output voltage of the generator, the feedback for the system is degenerative, rather than regenerative, in that if an increase in generator output voltage due, for example, to decrease in load should occur, the average voltage at interconnection **144** will increase in a negative sense toward a point such as B in FIGURE 4, which produces an increase in the negative current through the control windings **94** and **96** so as to decrease the current through field winding **56** and oppose the above-mentioned generator output voltage increase. Similarly, a decrease in generator output voltage, due for example to an increase in load, will produce a shift toward point C of FIGURE 4 and a corresponding increase in field current so as to produce an opposing increase in generator output voltage.

FIG. 5 illustrates the relationship between the average control voltage across control coils such as **94** and **96** of magnetic amplifier **26**, and the average current produced at the output of the magnetic amplifier. The operating points A, B, and C of FIGURE 5 correspond to the similarly labelled points of FIGURE 4. Thus, as shown in FIGURE 5, the negative control voltage from bridge circuit **136** operates the magnetic amplifier near the center of its operating range at point A when normal output voltage for the generator has once been established, although the magnetic amplifier output is shifted toward the lower-current point B when the generator output voltage tends to increase and toward the higher-current point C when it tends to decrease.

The instantaneous magnetic amplifier outputs producing the average conditions shown in FIGURE 5 are represented in FIGURE 6, in which the parts A, B and C thereof are graphs having time as a common abscissae and having as ordinates the instantaneous voltage produced at the output terminals **118** and **120** of the magnetic amplifier **26** for different values of control voltage applied thereto. Graph **6A** corresponds to the normal operation of the generator at the rated-voltage points indicated by the corresponding points A in FIGURES 4 and 5. Graph **6B** represents this output voltage when, due to decreased load or for other reasons, the output voltage of the generator tends to increase. Graph **6C** shows the magnetic amplifier output voltage when the generator voltage tends to fall, corresponding to points C in FIGURES 4 and 5.

The normal operating output voltage, or rated voltage, of the generator is adjusted to point A on the negative portion of the characteristic of FIGURE 4 by varying the position of the tap on variable resistor **132**. The resistor **150** and the inductor **152** in series with control windings **94** and **96**, and capacitor **154** in shunt therewith, provide filtering of the voltage applied to the latter windings from

voltage bridge circuit **136**, while at the same time providing a time constant sufficiently short to enable adequate control in response to rapid changes in generator output voltage. In addition, the latter filter circuit helps to prevent application to voltage bridge cricuit **136** of any unbalanced signals induced in the control windings **94** and **96** by the gating signals in the magnetic amplifier **26**.

As mentioned previously, there is preferably connected in series with field winding **56** a field-forcing circuit **28**, comprising the parallel combination of resistor **160** and Zener diode **162**, the Zener diode **162** being connected in the polarity such that its cathode is connected directly to the positive output terminal **118** of magnetic amplifier **26** and hence is reverse biased. The value of resistor **160** is selected so that, when current less than that required to produce saturation of the magnetic material of the alternator field **50** is passing, the voltage across resistor **160** is insufficient to produce substantial reverse current through Zener diode **162**. However, when the current to the field coil increases to the level at which substantial saturation of the magnetic material of the field begins to occur, the voltage across resistor **160** becomes sufficiently large to produce reverse breakdown of the Zener diode **162**, so that the current through the field coil increases more rapidly than previously with increases in the output voltage of the magnetic amplifier **26**. The result is that the magnetic field produced by coil **56** is forced to increase substantially despite saturation of the magnetic material, and the range of control of the field current of the generator output voltage is thereby substantially extended.

More particularly, FIGURE 7 shows the general nature of the relationship between the current through field coil **56** plotted as abscissae and the magnetic flux produced by the alternator field plotted as ordinates, illustrating that for an initial range of low field currents the magnetic flux increases relatively rapidly and substantially linearly with field current, until at a point D saturation begins to occur, as indicated by the substantially less rapid increase of magnetic flux with field current. Accordingly, past the saturation point D the magnetic amplifier **36** would be required to provide much larger increases in current in order to produce a given increase in magnetic flux for controlling the generator output.

FIGURE 8 shows the effect of the Zener diode characteristic which compensates for this saturation effect. In FIGURE 8, absicissae represent the output voltage of magnetic amplifier **26** while ordinates represent the corresponding field current. As shown, in a relatively low range of amplifier output voltages below the point E the field current increases substantially linearly and at a relatively low rate, but after point E is reached the field current increases at a substantially higher rate because of conduction through Zener diode **162**. The field current at point E at which the Zener begins to conduct at a higher rate is made substantially the same as the field current corresponding to point D in FIGURE 7 at which saturation of the alternator field becomes substantial, by approprate selection of the value of resistor **160** and the breakdown voltage of the Zener diode **162**. The result is the relationship, illustrated by the graph of FIGURE 9, between magnetic amplifier output voltage plotted as abscissae and alternator output voltage produced in response thereto plotted as ordinates, wherein point F corresponds to the above-mentioned point D of FIGURE 7. In FIGURE 9 it is shown that the exciter field voltage increases at a relatively rapid rate in response to increases in output voltage of amplifier **26** even substantially beyond the knee of the saturation curve of the alternator field, establishing an additional range of control due to the phenomenon described hereinbefore and designated herein as field forcing.

Summarizing then the operation of the portion of the system thus far described in detail, when the generator is first started up the small amount of remanent magnetism of the magnetic core of the alternator field provides some generator output voltage which is rectified and provided in regenerative phase by way of magnetic amplifier **26** and field forcing circuit **28** to the alternator field to increase the current and magnetization therein, which in turn increases the generator output voltage, resulting in a rapid regenerative build-up of generator output voltage, until the Zener diodes **140** and **142** cause the feedback control voltage to drop to zero and then to reverse in polarity so as to establish a negative feedback control for normal full voltage operation. Acocrdingly, no external current source, such as a battery, is required to build up magnetization of the alternator field when the generator is started up.

Additional control for magnetic amplifier **26** is provided by the load sensing circuit **38**. The input to this circuit comprises the transformer primary winding **200** of transformer **201** connected in series between terminals **70** and **72** of alternator armature **60**, thereby to sense the magnitude of the load current drawn from the generator by load apparatus **16**. The secondary winding **202** of transformer **201** is connected at one end to a resistor **204** and thence to one input terminal **205** of bridge rectifier **206**. Secondary **202** is also provided with a variable resistor **208** connected between its other end and a terminal **210**, and with two additional variable resistors **212** and **214** connected between respectively different intermediate taps on a secondary **202** and terminals **216** and **218** respectively. A variable connection **220** is provided which may be connected at will to any of the terminals **210**, **216**, and **218**, and in the case shown is connected to terminal **216**. The other terminals are connected to tap **220** when the regulator is connected to alternators having other types of winding arrangements, as described hereinafter.

Variable tap **220** is connected to a terminal **222** of bridge **206** diametrically opposite terminal **205** thereof, so as to apply across the input to bridge **206** a voltage varying substantially in proportion to the load current of the generator output. Bridge **206** is of conventional bridge-rectifier form and may utilize, for example, silicon diodes for each of the four diode elements thereof, which may be connected similarly to the diodes in bridge circuit **134**.

The output terminals **224** and **226** of the bridge circuit **206** are connected to the series combination of control windings **90** and **92** of magnetic amplifier **26**, terminal **224** being connected thereto by way of temperature compensation circuit **40** and field-forcing circuit **42**. The polarities of the direct voltages produced, and of the control windings **90** and **92**, are such that an increase in load on the generator, which normally tends to decrease the voltage supplied to the load apparatus **16**, produces an increase in the current through control windings **90** and **92** so as to increase the output voltage of the magnetic amplifier by regenerative feedback and increase the current through field coil **56**. In effect the circuit operates to increase the gain of the regulator at higher load currents for which higher gain does not produce instability as it would at lower load currents, thereby improving the closeness of regulation at high load currents. Furthermore, the use of such a load-sensing feedback circuit in addition to the voltage sensing control circuit described previously provides for quicker control of the output voltage.

The temperature compensation circuit **40** is located, as shown in FIGURE 3, in series with the lead supplying current from the load sensing circuit to the control windings **90** and **92**, and comprises a thermistor **230** having a negative temperature coefficient of resistance, shunted by a variable resistor **232**. This circuit is designed to compensate for the decrease in output voltage of the generator which tends to occur when the ambient temperature increases. In operation, when the ambient temperature increases, tending to produce a decrease in generator output voltage, the resistance of thermistor **230** also de-

creases, increasing the control current to control windings 90 and 92 so as to oppose the decrease in generator output voltage. By suitable adjustment of the value of variable resistor 232 a high degree of temperature compensation over a relatively wide range can readily be obtained.

The field-forcing circuit 42, also located in series between the load sensing circuit and control windings 90 and 92, comprises Zener diode 234 and variable resistor 236 in parallel therewith. The latter circuit functions similarly to field-forcing circuit 28 in that when the current passing through resistor 236 to control windings 90 and 92 increases beyond a predetermined point for which saturation of alternator field 50 begins, the voltage then produced across variable resistor is sufficient to cause substantial reverse conduction in Zener diode 234, thereby increasing more rapidly the current supplied to control coils 90 and 92 of the magnetic amplifier 26 when needed to compensate for alternator field saturation and also for induction motor starting as described previously herein. Variable resistor 236 will normally be adjusted to provide inception of Zener diode conduction at the desired current level, and can be varied in connection with variable resistor 232 to achieve temperature compensation over the desired temperature range.

Accordingly, the feedback circuit last described combines a load-sensing control, temperature compensation control, and an additional field-forcing function within a common feedback circuit loop using a common pair of control windings of the magnetic amplifier.

An additonal feature of the invention is the short-circuit protection circuit 34, which in this example comprises an iron-core transformer 260 having its primary 262 connected in series between terminals 74 and 76 of the alternator arrangment 60, and having its secondary 264 connected in parallel with a resistor 266, the latter parallel combination being in series between output lead 68 of the generator and the interconnection of the two gating coils 84 and 86 of magnetic amplifier 26. The transformer preferably provides a 180° phase shift from primary to secondary, and in the present example the phase of current in winding 64 is 120° out of phase with that in winding 65, so that the voltage induced in the secondary 264 by the primary 262 during normal operation is only 60° out of phase with that produced in the secondary by alternator winding 65. In addition, the transformer winding arrangement is preferably such that normally the magnitude of voltage induced in the transformer secondary by the primary is small compared with that due to winding 65. Accordingly, during normal operation the current in primary 262 has only a relatively minor effect on the gating signal to the magnetic amplifier. However, when a short-circuit occurs in the load apparatus 16 the voltage across output conductors 66 and 68 of the alternator approaches zero, while the high current produced through alternator winding 64 by the short-circuiting induces a high voltage in secondary 264 which is applied to the gating windings of the magnetic amplifier and thence to the field element of the alternator to increase greatly the output current of the generator, typically to four or five times the normal full load current for several seconds. Accordingly enough electrical current is delivered to the load apparatus to operate even a high-current circuit breaker therein, which otherwise might not be operated.

In the particular form of the invention shown, a field compensation circuit 44 is connected between the output terminals of the magnetic amplifier 26 and control windings 102 and 104 thereof. Input to the field compensation circuit is applied across the resistor 300 and the resistance of potentiometer 302 connected in series. The voltage developed between the adjustable tap of potentiometer 302 and the opposite end of resistor 300 is applied to a filter circuit comprising series inductor 304 and shunt capacitor 306 by way of an isolating and current-limiting resistor 308 so that the voltage developed across capacitor 306 is a smoothed D.C.-voltage varying substantially in proportion to the average output voltage of magnetic amplifier 26. The latter smoothed voltage is fed back to the control windings 102 and 104 by way of the field-forcing circuit comprising the parallel combination of resistor 310 and Zener diode 312, and by way of the series current-limiting resistor 314. The feedback to the input control windings is in regenerative phase. Accordingly, when the input to any of the control windings of the magnetic amplifier increases to the point where the current to the alternator field 50 is in the range for which field saturation begins to occur, the voltage fed back by the field compensation circuit further augments the output of the magnetic amplifier to produce a more than linear increase in field current, thereby compensating further for the less-than-linear increase in magnetic flux due to the core saturation in the alternator field. Potentiometer 302 provides for adjustment of the amount of positive feedback occurring, and the series limiting resistors reduce the loading effect of the circuit on the output of the magnetic amplifier and limit the current fed back to the control windings 102 and 104, the values of the circuit elements being such as to prevent runaway or instability in the magnetic amplifier.

A further feature of the invention comprises the anti-hunt circuit 46 also connected between the output terminals of the magnetic amplifier 26 and the input thereof, in this case to control windings 98 and 100. In normal operation, the generator output voltage tends to oscillate from above to below its desired value due to the feedback control action of the regulator. Such undesired oscillation or "hunting" is opposed by the "antihunt" circuit 46, which also improves voltage stability at no load. The input to this circuit is applied from the output connections 118 and 120 of the magnetic amplifier, and is supplied to control windings 98 and 100 in series by way of series resistor 400, capacitor 402 and inductor 404. Resistor 406 and the series combination of Zener diode 408 and ordinary diode 410 are connected respectively between connection 120 and opposite sides of capacitor 402 as shown.

In operation of the anti-hunt circuit, the capacitor 402 permits feedback in degenerative phase, by way of resistor 400 and inductor 404, of variations of the magnetic amplifier output due to hunting, while blocking direct voltages. In order to provide appropriate feedback under normal operating conditions the capacitor will normally be relatively large. However this introduces the difficulty that if a heavy load is applied and then removed abruptly, the capacitor will charge up rapidly to a high value but will require appreciable time to discharge thereafter, and hence will not respond as quickly as is desired. Zener diode 408 remedies this condition by breaking down when the voltage on capacitor 402 tends to rise above a predetermined value, thus providing a low-resistance shunt path for current by way of diode 410 which arrests further charging of the capacitor. Accordingly the capacitor discharges to a given voltage more rapidly than otherwise to provide the desired rapid recovery. Diode 410 is poled to permit easy current flow when Zener diode 408 breaks down, and to block flow in the opposite direction to prevent short-circuiting of opposite polarity signals by the Zener diode.

FIGURES 10A, 10B and 10C indicate the manner in which the regulator may be connected to generators of the three-phase delta, three-phase Y and single-phase open V types, respectively. The terminals and leads indicated by number and letter combinations in each case are to be connected to the regulator in the same manner as the correspondingly-numbered terminals and leads in FIGURE 3. When a generator of the single-phase open V type is used, connection 220 of FIGURE 3 is moved to contact terminal 218, and when the generator is of the

three-phase delta or three-phase Y type this connection is moved to terminal **210**.

Accordingly there is provided a regulator which, while requiring no moving parts, provides very close regulation of generator output voltage, for example to within a few hundredths of a percent, despite substantial changes in speed of the engine driving the generator, in the load current drawn from the generator, in ambient temperature, in characteristics of the generator, and in characteristics of circuit elements of the regulator, even though various of these changes may occur rapidly. At the same time actuation of protective fusing is assured on short-circuiting of the generator, and rapid build-up of generator voltage on starting-up is provided without need for an external current source. The regulator is stable and reliable in operation, making it practical for it to be hermetically sealed, and operates effectively even with a generator which is less than ideal in that its field saturates at relatively low field current. It will be understood that while use of all of the various features of the invention in combination provides the best results in most applications, less than all may be used to advantage in applications in which one or more of the features provided are not considered necessary.

While the invention has been described with particular reference to specific embodiments thereof, it may be embodied in a variety of forms differing from those specifically described herein without departing from the spirit and scope of the invention as defined by the appended claims.

We claim:

1. In a voltage regulator system of the class adapted to provide stabilization of an electrical generator having a current-controlled magnetic field element by feeding back a portion of the output voltage of said generator in degenerative phase to control the current through said field element, said generator being responsive to increases in current in said field element to increase said output voltage at a relatively rapid rate for values of said current in a first relatively low range and to increase said output voltage at a substantially lower rate for values of said current in a second, higher range for which substantial saturation of said field element occurs:

means for deriving from said output voltage a control voltage varying in accordance with variation in the magnitude of said output voltage;

means for feeding back said control voltage to said field element to vary the current in said field element in the sense to oppose changes in said output voltage; and

means for providing a more rapid increase in said control voltage with changes in said output voltage for values of said control voltage producing values of said field current in said second range than for values of said control voltage producing values of said field current in said first range;

said last-named means comprising the parallel combination of a zener diode and a resistive element disposed in said means for feeding back said control voltage, said zener diode being poled to break down in its reverse-conduction direction when the voltage across said resistive element exceeds a predetermined voltage, said resistive element being responsive to current therethrough to produce a voltage across itself which is below said predetermined voltage for values of said field current in said first range and above said predetermined voltage for values of said field current in said second range.

2. In a voltage-stabilized electrical generator system:

an electrical generator having output terminals and output windings for producing output voltages at said output terminals for application to load apparatus susceptible to short-circuiting, and having a field element responsive to increases in current therein to increase said output voltage;

a voltage regulator having input terminals supplied with said output voltage and having output terminals connected to control said current in said field element normally to oppose departures of said output voltage from a predetermined value thereof;

said regulator comprising a magnetic amplifier having gating windings which are normally supplied with operating voltage from said output terminals of said generator and which are connected to said field element to provide said control of current therein;

means responsive to increases in current drawn from said generator by said load apparatus upon short-circuiting therein to generate and supply to said gating windings a voltage sufficient to increase sharply said current in said field element, threby to maintain a high current from said generator for a time sufficient to operate a high-current circuit-breaking device connected thereto;

said last-named means comprising a transformer having a primary winding and a secondary winding, said gating windings being connected to said output terminals of said generator by way of said secondary winding, said generator comprising a plurality of mult-phase output windings, one of which output windings is connected across said output terminals of said generator and another of which output windings is connected in series with said primary winding of said transformer; and

field-forcing means connected between said output terminals of said regulator and said field element, said field-forcing means comprising the parallel combination of a voltage-breakdown device and a current-conductive element, said voltage-breakdown device being normally non-conductive for relatively smaller output voltages at said regulator output terminals but strongly conductive for relatively larger output voltages at said regulator output terminals.

3. Apparatus in accordance with claim **1**, in which said means for deriving from said output voltage a control voltage includes a magnetic amplifier responsive to said output voltage to produce said control voltage and having output terminals and input control terminals, said means for providing a more rapid increase in said control voltage being connected between said output terminals of said magnetic amplifier and said field element.

4. Apparatus in accordance with claim **3**, comprising additional feedback means for feeding back a portion of the output signal at said output terminals of said magnetic amplifier to said input control terminals in regenerative phase, said additional feedback means including a parallel combination of an additional zener diode and an additional resistive element in shunt with said zener diode, said last-named parallel combination being disposed in series between said output terminals of said magnetic amplifier and said input control terminals thereof.

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