

June 25, 1935.

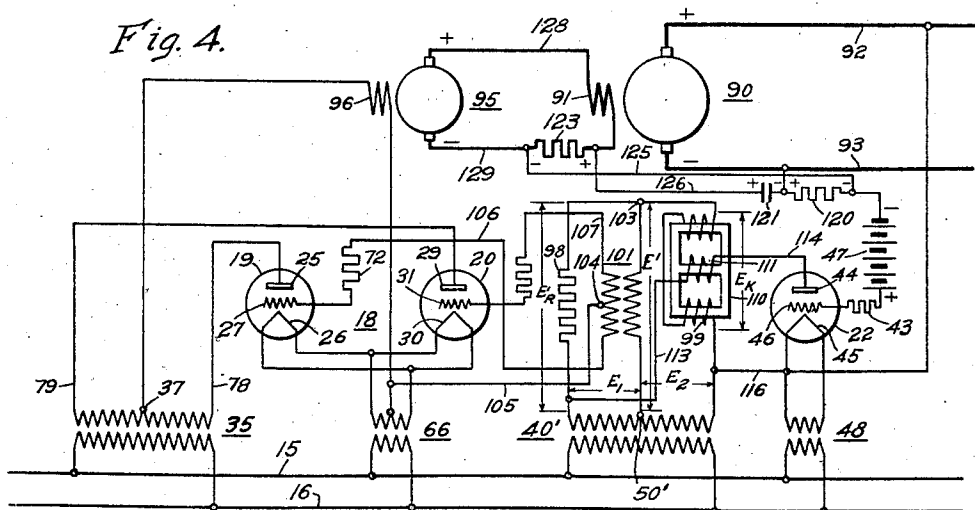
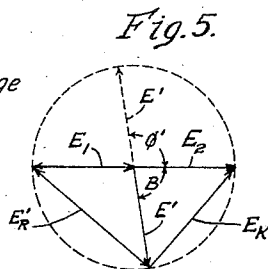
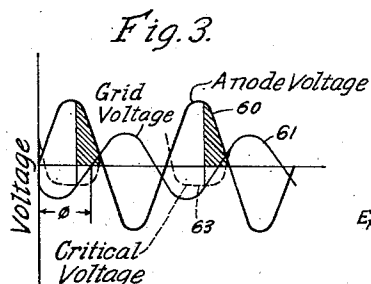
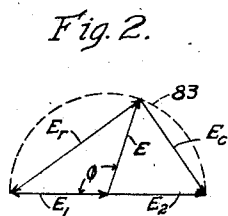
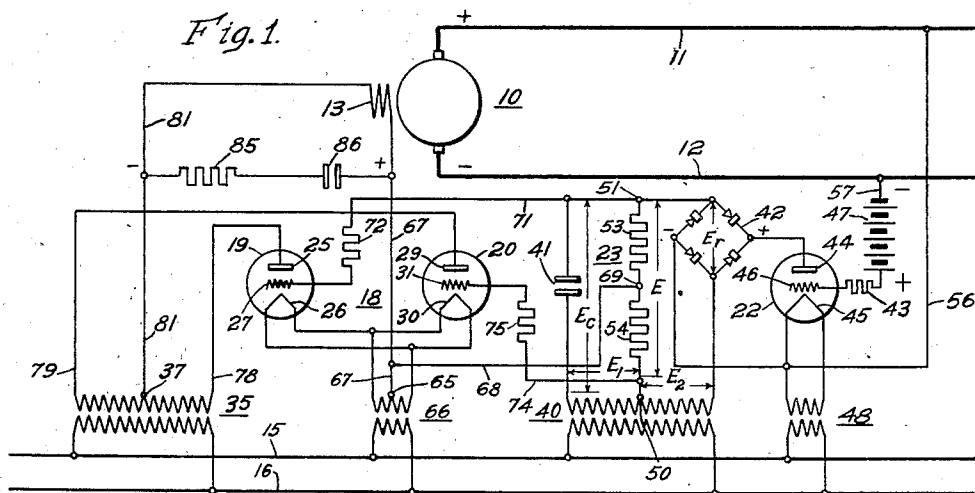
F. H. GULLIKSEN

2,005,892

ALTERNATING CURRENT REGULATOR

Filed Oct. 13, 1931

2 Sheets-Sheet 1



WITNESSES:

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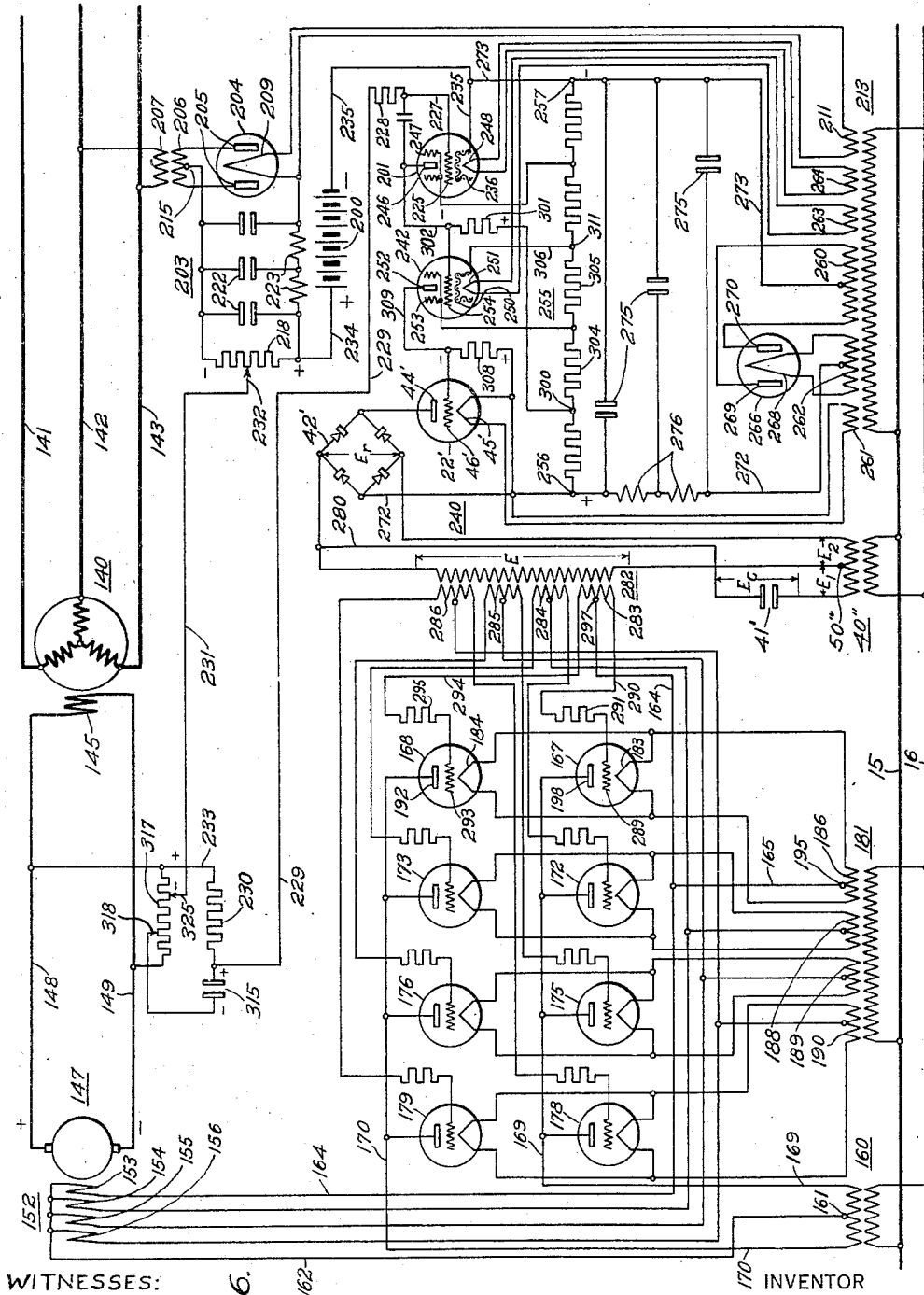
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2 Sheets-Sheet 2



WITNESSES:

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Fig. 6.

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2,005,892

ALTERNATING-CURRENT REGULATOR

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pany, a corporation of Pennsylvania

Application October 13, 1931, Serial No. 568,537

6 Claims. (Cl. 171-119)

My invention relates to regulators and has particular relation to electronic-tube regulators for dynamo-electric machines.

Electronic-tube regulators, when utilized with dynamo-electric machines, possess inherent advantages over the well known vibrating-contact and other mechanically-moving-part regulating devices. Because of the absence of mechanical inertia in the electron tubes, regulators utilizing them are much faster in responding to, and in correcting errors in, the quantity regulated, and in addition, the possibility of mechanical trouble is removed.

Regulators of the electronic-tube type, having been more recently developed than the older movable-part structures mentioned, have been subject to limitations which have considerably restricted their field of application. My invention is directed to a regulating system which overcomes such limitations through the incorporation of the novel and desirable features to be particularized hereinafter.

It is one object of my invention to provide an electronic-tube regulator for dynamo-electric machines which is capable of handling relatively large values of machine-field current.

It is another object of my invention to provide a regulator of the type described which permits energization of the machine-field windings from an alternating-current source of power.

It is a further object of my invention to provide an electronic-tube regulator which is applicable to both alternating-current and direct-current machines.

An additional object of my invention is to provide a regulator which utilizes a plurality of machine-field current-carrying tube devices so disposed that failure of one of the tubes will not impair to an appreciable degree the effectiveness of the regulator.

It is a still further object of my invention to provide a regulator of the type described, which, in addition to the features above named, possesses extremely high sensitivity and regulatory precision.

Another object of my invention is to provide a regulator of the type described having improved means of attaining an anti-hunting characteristic.

An additional object of my invention is to provide a regulator of the type described having improved load-compensating means.

In practicing my invention, I dispose in the energizing circuit of the machine field windings a plurality of grid-controlled electronic tubes in a

manner that a full-wave rectifying action is obtained, thereby permitting the utilization of an alternating-current source of power to supply the machine-field excitation. The characteristics of such tubes, which are preferably of the gas or vapor-filled variety, allow them to be controlled in a highly satisfactory and reliable manner, thereby permitting the desirable rectifying characteristics to be advantageously utilized in regulators of the type under consideration.

To effect the necessary control of these tubes, I utilize an improved form of grid-potential phase-shifting bridge circuit operable by a triode vacuum tube having a grid-control circuit disposed to be energized by a direct-current potential dependent upon the voltage or other electrical characteristic of the regulated machine. In accordance with well understood practice, a standard potential battery is utilized in this last-named circuit, and in the case of voltage regulators for direct-current generators, for example, this standard battery may be connected directly in opposition with the machine armature terminals. In the case of alternating-current generators or other machines, the same effect is obtained by interposing current-rectifying and filtering equipment intermediate the regulated machine terminals and the control-grid circuit.

The improved anti-hunting characteristics of the regulator of my invention are obtained through the use of a series-connected resistor and capacitor energized in response to changes in the voltage impressed upon the exciting-field winding or to changes in the current flowing therein, the resistor being disposed in the control-grid circuit of the vacuum tube above mentioned in a manner that the grid bias is prematurely changed in proportion to the rate of change of the machine excitation.

To effect load-compensation in the regulating system of my invention, I make provision for introducing into the control-grid circuit of the voltage-change-detecting tube a modifying potential which varies in accordance with the excitation of the regulated generator so that the value of voltage which the regulator will maintain is made to depend upon the degree of generator loading.

To further improve reliability with respect to the machine-field-current-carrying tubes, I provide the regulated machine with a plurality of parallel-arranged field-winding sections, each of which is connected for energization from an alternating-current power source through a pair of grid-controlled electronic tubes disposed to ef-

fect full-wave rectification. Because of this expedient, the failure of any one tube in the combination will have negligible effect upon the regulator performance since the remaining tubes are of sufficient capacity to compensate for the loss of the one.

To obtain the extremely high sensitivity and precision which many regulator applications require, I interpose intermediate the quantity change-detecting tube, associated with the standard-potential battery and regulated machine, and the grid-potential phase-shifting circuit for the field-current-carrying tubes, a vacuum-tube or other suitable amplifier which permits exceedingly small changes in the regulated quantity to be effective in producing the desired corrective change in machine excitation.

My invention itself will best be understood through a description of specific embodiments thereof when taken in conjunction with the accompanying drawings, in which:

Figure 1 is a diagrammatic view of apparatus and circuits arranged in accordance with one form of my invention when applied to regulate the voltage of a direct-current generator,

Fig. 2 is a diagram of vectors illustrating the action of the phase-shifting bridge circuit utilized in the system shown in Fig. 1,

Fig. 3 is a diagram of curves illustrating the manner in which the grid-controlled gas-filled electron-discharge devices utilized by the regulating system of my invention in the field-winding circuit of the regulated machine function to rectify and control the magnitude of exciting current supplied to the winding from an alternating-current source.

Fig. 4 is a diagrammatic view of apparatus and circuits arranged in accordance with a second form of my invention applied to effect voltage regulation of a direct-current generator having a separate exciter.

Fig. 5 is a diagram of vectors illustrating the manner in which the phase-shifting bridge circuit of the system shown in Fig. 4 functions, and

Fig. 6 is a diagrammatic view of apparatus and circuits arranged in accordance with one form of my invention, which utilizes a sensitivity-increasing amplifier, when applied to effect voltage regulation of an alternating-current generator having an exciter provided with a multi-circuit field winding.

Referring to the drawings, in Fig. 1, I have shown a direct-current generator 10 disposed to energize circuit conductors 11 and 12. The generator is provided with an exciting-field winding 13. Energization of the field winding from an alternating-current power source, represented by conductors 15 and 16, is effected through the utilization of rectifying means 18 comprising electronic tubes 19 and 20.

The regulating system of my invention shown in Fig. 1, of which tubes 19 and 20 form a part, is disposed to maintain constant the voltage between generator conductors 11 and 12. To effect such regulation, a voltage-change-responsive vacuum tube 22 is disposed in a control-potential-bridge circuit 23 to effect changes in the conducting characteristics of the field-current-carrying tubes by suitably modifying the control potential impressed upon the grid elements thereof.

Electronic tube devices 19 and 20 are preferably of the well known hot-cathode variety. As shown, tube 19, for example, comprises two major elements,—an anode or plate 25, and an electri-

cally-heated cathode 26, and one minor or control-grid element 27. Tube 20 will be seen to comprise similarly disposed elements 29, 30 and 31.

To supply exciting current to machine-field winding 13, a transformer 35, having a primary winding, energized from alternating-current power-source conductors 15 and 16, and a secondary winding connected with the tubes 19 and 20 and the field winding 13 in the manner shown, is utilized. Full-wave rectification of the alternating-current is obtained by disposing each of the tubes in a circuit which includes, as an energizing source, the portion of the secondary winding of transformer 35 on either side of a symmetrically-located tap connection 37.

Each of the tubes possesses the well known characteristic of passing current between the major elements in one direction only,—from anode to cathode,—so that when energized from an alternating-current source, current passage can take place only during the positive half cycle. Thus, when connected as in the system of Fig. 1, tube 19 passes current through machine-field winding 13 during one half of the alternating-current cycle, while tube 20 similarly passes current through the winding during the other half of the cycle, and the full-wave rectification desired is thereby effected.

The portion of this positive half cycle during which conduction takes place, and hence the effective current passed, may be regulated by suitably modifying the control potential impressed upon the grid element of the tube.

In the control of gas-filled tubes disposed in alternating-current circuits, two fundamental methods well known in the art are available. In the first or "magnitude" method, an alternating-current control potential having a fixed-phase relation with the potential impressed upon the major elements of the tube is varied in magnitude in accordance with the changes which it is desired to make in the major element-circuit current. The second or "phase-shift" method utilizes an alternating-current control-grid potential of substantially constant magnitude but of shiftable phase position with respect to the potential acting in the major element circuit of the tube. It is this second or phase-shift method which I prefer to utilize in the system of my invention, although it will be understood that, if desired, the magnitude method of control may also be applied.

The control-potential bridge circuit 23 is accordingly of the phase-shifting variety. As illustrated it is energized from power-source conductors 15 and 16 through a transformer 40, the secondary winding of which is connected with a capacitor 41 and a rectifier unit 42 in series-circuit relation. Rectifier 42 may be of any suitable type such as the well known metallic-oxide full-wave variety illustrated in Fig. 1, the output terminals of which are respectively connected to the anode and cathode elements 44 and 45 of detector tube 22. This particular bridge circuit is the same as that shown and described in my copending application Serial No. 621,141, filed July 7, 1932, and assigned to the same assignee as this invention.

The grid element 46 of tube 22 is disposed in a circuit which includes a standard-potential battery 47 connected in opposition with generator-circuit conductors 11 and 12 in well known manner. The cathode or filament element 45 of the tube may be supplied with heating-current

from any suitable source, as from conductors 15 and 16 through a transformer 48.

The control potentials for field-current carrying tubes 19 and 20 derived from bridge circuit 23 are caused to be dependent upon the voltage acting between mid-tap connection 50 of the winding of transformer 40 and a connection 51 which is common to capacitor 41 and rectifier 42. As illustrated in Fig. 1, this is accomplished by disposing in series-circuit relation, between these two points in the bridge circuit, two resistor elements 53 and 54 and connecting these resistors with the grid and cathode elements of the two grid-glow tubes in the manner shown. It will be understood that should it be desired a grid-transformer may be utilized instead of the resistors named to accomplish the same result.

In the system shown in Fig. 1, normal voltage of the generator is of a value slightly greater than that of standard battery 47, in order that grid element 46 of vacuum tube 22 may be maintained at a small value of negative potential. Such a negative bias will be seen to obtain for this condition, since cathode element 45 of tube 22 is joined, by means of conductor 56, with generator conductor 11, and the negative polarity points of both the generator and the battery are joined by means of conductor 57. Grid element 46 of the tube, connected with battery 47 through a grid resistor 43, is thus maintained at a potential, which, for the normal-voltage condition assumed, is negative with respect to that of cathode element 45.

The voltage of transformer 40 acting upon the rectifier 42 and the capacitor 41 in series produces in these elements potential drops having some such phase relation as is given by the vector diagram of Fig. 2. In this diagram, vectors E_1 and E_2 indicate the voltages acting in the two sections of the transformer secondary winding, vectors E_r and E_c indicate the voltage drops occurring in the rectifier and the capacitor units, respectively, and vector E designates the potential acting between points 50 and 51 of the bridge circuit or upon resistor elements 53 and 54 in series.

At the normal voltage of generator 10, the phase position of vector E , with respect to the power-source voltage, is of some intermediate value, such as indicated in Fig. 2 by the angle θ . In the diagram of curves of Fig. 3, in which curve 60 designates the voltage impressed upon the anode element of either of the field-current carrying tubes, and curve 61 the control potential impressed upon the grid element of the tube, θ designates the angular displacement between these two potential curves.

Before a grid-controlled gas-filled tube can conduct current through the major-element circuit, it is necessary that the control grid element be maintained at a potential in excess of some given critical value. Such a series of minimum or critical values of grid voltage, is represented in Fig. 3 by curve 63. This curve will be recognized as applying to a hot-cathode tube of the mercury-filled type, which tube behaves in a manner that if a negative bias be maintained on the grid in excess of a given series of values throughout the cycle, no current conduction between the major elements can take place. However, if this negative grid-bias voltage falls below the critical value indicated by curve 63, conduction from that point during the remainder of the positive-half cycle will take place. Consequently, when the displacement of the grid volt-

age is that given by angle θ , current conduction from anode to cathode of the tube will result during the shaded portion of the positive half cycle. It will be apparent that the starting point of such conduction may be changed by shifting the phase position of the control potential.

During the half cycle of alternating-current supply voltage in which the right-hand end of the secondary winding of transformer 35 is positive with respect to the left-hand end, an energizing current for the machine-field winding 13 may be permitted to flow through a circuit which extends from the right side of this winding through conductor 78, the anode and cathode elements 25 and 26 of tube 19, the mid-tap connection 65 of transformer 66, conductor 67, machine-field winding 13 and conductor 81, back to the mid-tap connection 37 of the winding of transformer 35.

Likewise, during the half of the alternating-current cycle when the left side of the transformer winding is positive with respect to the right, an energizing current for the machine-field winding may be permitted to flow through tube 20 through a circuit which extends from the left side of the secondary winding of transformer 35 through conductor 79, the anode and cathode elements 29 and 30 of tube 20, mid-tap connection 65 of transformer 66, conductor 67, machine-field winding 13 and conductor 81 back to mid-tap connection 37 of the winding.

In the system of Fig. 1, the control potentials for the tubes 19 and 20 are impressed upon the grid elements through a circuit which includes, for tube 19, cathode element 26, mid-tap connection 65 of a cathode-heating transformer 66, conductors 67 and 68, mid-point 69 of series-connected resistors 53 and 54, resistor 53, conductor 71 and grid resistor 72, back to grid element 27. In the case of tube 20, the circuit extends from the cathode element 30, transformer tap 65, conductors 67 and 68, resistor 54 of bridge circuit 23, conductor 74 and a grid resistor 75 back to grid element 31.

For the normal-voltage condition of the regulated generator 10 assumed, the phase position of the control potential impressed upon the grid elements of the field-current carrying tubes is such that the effective current which the tubes pass to the machine-field winding is of a value sufficient to maintain the voltage in the armature of the generator at this normal value.

In the event that the generator voltage is caused to decrease below the desired value, the negative bias of the grid element 46 of detector tube 22 is reduced, the tube impedance is lowered and the effective resistance of rectifier 42 is likewise decreased. This lowers the total impedance of the bridge circuit 23, increases the current through the series-connected capacitor 41 and rectifier 42, thereby increasing the voltage drop across the condenser, designated in Fig. 2 by E_c , and decreasing the voltage drop across the rectifier 42, designated by vector E_r .

Since these last-named vectors are always displaced from one another by the angle of substantially 90° shown, and since the total impressed voltage, given by the sum of vectors E_1 and E_2 , remains unchanged, the intersection of vectors E_r and E_c will be caused to move along a path which forms a semi-circle 83 drawn upon E_1 and E_2 as a diameter.

Hence, when vector E_c is lengthened and vector E_r is shortened, vector E will be rotated in a coun-

ter-clockwise direction to a new position in which the displacement angle θ is of a value smaller than that shown. Reference to the curves of Fig. 3 will show that as angle θ is decreased, the intersection of grid-voltage curve 61 with critical-voltage curve 63 will be moved to the left and current conduction by the field-current carrying tubes will start at an earlier period in the positive half cycle. Such being the case, the effective current passed through the machine-field winding will be raised, and the voltage of the regulated generator 10 will be correspondingly increased.

In a similar manner, if the voltage of generator is caused to increase above the desired value, the negative bias impressed upon grid 46 of vacuum tube 22 will be raised, the tube impedance will likewise be increased and the effective resistance of rectifier unit 42 will be raised. This action raises the impedance of the phase-shifting bridge circuit and decreases the current therein, thereby causing the voltage drop across the capacitor 41 to decrease and the voltage drop across the rectifier to increase.

Reference to Fig. 2 will indicate that such a shortening of vector E_c and a lengthening of vector E_r causes vector E to be rotated in a clockwise direction to a position in which displacement angle θ is of a higher value. Such a higher displacement angle means that control potential curve 61 will be moved to the right in Fig. 3 to be further out of phase with anode voltage curve 60, and as a result the current conduction of the field-current carrying tubes will start at a later point during each positive half cycle. Such being the case, the effective value of machine-field winding current will be lowered, and the voltage of generator 10 will be appropriately decreased.

If desired, filtering apparatus may be utilized in the field winding circuit in order to smooth out the rectified current pulsations and eliminate any resulting ripples which these pulsations might cause to be present in the voltage of the regulated generator. One well known type of filtering equipment which may be used is indicated in the form of a resistor 85 connected in series with a capacitor 86 across the field winding 13 in the manner shown. When so disposed, these elements act in a well known manner to smooth out the ripples of rectified current and thus make the energizing current of the field winding of a more nearly uniform value throughout the alternating-current cycle.

The critical voltage curve 63 of Fig. 3 applies, as has been mentioned, to an electronic tube of the mercury-filled type. Other equivalent types of tubes may also be successfully utilized in the system of my invention, as for example the equally well known gas-filled and cold-cathode devices. The critical voltage characteristics of certain gas filled tubes, for example, differ somewhat from those given by curve 63 of Fig. 3 since current conduction or break-down between cathode and anode of such tube may be prevented by making the grid element voltage lower than a series of positive values during the positive half cycle of alternating current impressed upon the tube anode. It will be apparent, however, that the effect of shifting the grid potential curve 61 would be exactly comparable in this situation as in the one explained, although the exact values of the phase displacement would, of course, be somewhat modified from those which apply to the mercury tube characteristic illustrated. It should be noted, therefore, that the system of

my invention may utilize electronic tubes of a wide variety of types.

The phase-shifting bridge of the modification of my invention shown in Fig. 1 utilizes, as has been seen, a capacitor connected in series with an adjustable effective-resistance unit. This particular arrangement possesses the advantage of providing a distortionless shift of grid potential, a feature which is found to be particularly desirable in regulating applications of the type under consideration. While this is perhaps the most satisfactory method of attaining grid-potential control, I have found that other types of phase-shifting bridge circuits may also be utilized in the system of my invention, as for example, one which comprises a fixed resistor connected in series with an adjustable inductance for energization from the alternating-current source of power. One form of this last-mentioned scheme is shown in Fig. 4.

In Fig. 4, a direct-current generator 90 having an exciting-field winding 91 supplies voltage to circuit conductors 92 and 93. An exciting generator 95 energizes field winding 91 in a well known manner by current which varies in accordance with the excitation of a field winding 96 of the exciter. Winding 96 is energized from an alternating-current power source designated, as in Fig. 1, by conductors 15 and 16 through an electronic tube rectifying hook-up which is shown as being identical with that already explained in connection with Fig. 1.

The regulating system of Fig. 4 is disposed to maintain constant the voltage between generator conductors 92 and 93 and to accomplish this, the triode vacuum tube 22, mentioned in connection with Fig. 1, is disposed to have its grid electrode 46 acted upon by a potential determined by the difference between the voltage of standard-voltage battery 47 and that of generator 90.

Intermediate tube 22 and the field-current-carrying tubes 19 and 20 is disposed the second modification of the phase-shifting bridge circuit already mentioned. This, like the first modification of phase-shifting bridge circuit, is the same as that shown and described in my copending application Serial No. 621,141, filed July 7, 1932, and assigned to the same assignee as this invention.

As illustrated, this bridge circuit comprises a resistor 98 connected in series with the windings 99 of an adjustable reactance device for energization by the secondary winding of a transformer 40', the primary winding of which is connected with power-source conductors 15 and 16. The primary winding of a grid-potential transformer 101 is connected for energization by the voltage acting between mid-tap connection 50' of transformer 40' and a connection 103 which joins resistor 98 with adjustable reactance windings 99.

Transformer 101 is utilized to couple the bridge circuit with the control elements of the field-current carrying tubes. The secondary winding of this transformer is provided with a mid-tap connection 104 which is joined by means of conductor 105 to cathode elements 26 and 30 of tubes 19 and 20, while the two ends of this winding are respectively connected to influence grid elements 27 and 31 of grid-glow tubes 19 and 20 by means of conductors 106 and 107, respectively.

The windings 99 mentioned form a part of an adjustable reactance device of well known type, they being associated with a magnetically-saturable core member 110 which is provided with an exciting winding 111. The passage of direct current through winding 111 causes the reactor

core 110 to become saturated and thus reduces the effective reactance of windings 99 carried thereon, the magnitude of such reduction being dependent upon the magnitude of this exciting current.

This exciting current for winding 111 may be supplied from any suitable source, such as from transformer 40' through a circuit which includes the major elements 44 and 45 of vacuum tube 22. Tube 22 functions in well known manner to rectify the alternating-current impressed upon this circuit and to control the magnitude of the resulting pulsating-direct current in exciting winding 111 in accordance with the control potential impressed upon grid element 46 of the tube.

In operation of the system of Fig. 4 thus far described, normal voltage of the regulated generator 90 is of a value slightly greater than that of opposition-connected standard-potential battery 47 in order that, as in the case of the system of Fig. 1, the potential impressed upon grid element 46 of vacuum tube 22 may normally be of a small negative value. For this condition, an intermediate value of exciting current is allowed to flow through winding 111 of the bridge-circuit reactor through a circuit which extends from the left side of the secondary winding of transformer 40' through conductor 113, the winding 111, conductor 114, anode and cathode elements 44 and 45 of vacuum tube 22, and conductor 116 back to the right-hand side of the secondary winding of transformer 40'.

This value of exciting current causes windings 99 of the reactor to offer some such intermediate value of reactance to the flow of alternating-current that the voltage drop across the windings, caused by the energization from transformer 40' through resistor 98, is of a value represented in the vector diagram of Fig. 5 by vector E_k .

In Fig. 5, as in Fig. 2, previously described vectors E_1 and E_2 designate the bridge circuit energizing voltages supplied by transformer 40'. For the conditions assumed, resistor 98 will have a voltage drop therein given by vector E'_R , which bears a 90° phase relation with respect to inductive circuit vector E_k . The voltage acting upon transformer 101 is designated by E' , which voltage for the particular conditions assumed, has a phase displacement with respect to the power-circuit-supply voltage of a value given by angle beta.

It will be seen that the control potential impressed upon the grid elements of field-current carrying tubes 19 and 20 is dependent for its phase position upon voltage E' , and, for the normal voltage of generator 90, this position is such that there is allowed to flow through field winding 96 of exciter 95 current sufficient to cause the exciter voltage to be of the proper value to excite generator field winding 91 to the degree required to reduce this normal voltage in regulating generator 90.

A decrease in the voltage of generator 90 will be seen to lower the value of negative bias impressed upon grid 46 of vacuum tube 22. This increases the current passed by the tube through exciting winding 111 of the bridge-circuit reactor and further saturates reactor core 110, thereby lowering the reactance of windings 99. This decreases the total impedance of the bridge circuit.

The current through resistor 98 and reactor windings 99 is accordingly increased and the voltage drop across the resistor, given by vector E'_R , is raised, while the voltage drop across the reactor windings, given by vector E_k , is lowered.

The lengthening of vector E'_R and the shortening of vector E_k causes vector E' to be rotated in a counter-clockwise direction to decrease the value of displacement angle beta.

The connections of transformer 101 with the grid elements of grid-glow tubes 19 and 20 are such that a decrease in the angle beta, which is the equivalent of an increase in angle theta in Fig. 5, effects a shift of grid-control potential, which is represented by vector E' , because of crossing of grid conductors 106 and 107, in Fig. 4 in such a direction that the exciter-field current is caused to be raised. Therefore, by this modification in the control potential, the voltage of generator 90 is thus brought back to normal.

It will be apparent that a rise in the voltage of generator 90 produces effects opposite to those given for the action resulting from a decrease in generator voltage, so that in the event of such a rise the voltage of generator 90 is thus caused to be corrected in a manner similar to that already explained.

In co-pending application, Serial No. 543,514, by J. H. Ashbaugh and myself, filed June 11, 1931, and assigned to the same assignee as this invention, there is shown and described anti-hunting means for vacuum-tube regulators applied to dynamo-electric machines having separate exciters. The means there shown comprise a series-connected resistor and condenser disposed to be energized by the voltage of the machine exciter, the resistor being connected in the grid-control circuit of the regulator tubes in a manner that changes in the exciter voltage, by causing the condenser to draw a current through the resistor result in a modification of the grid-control potential in accordance with the rate of change of the exciter voltage, this modification being of such a nature that over-shooting of the corrective action is prevented. Such anti-hunting means are especially desirable because the speed of regulator response is not slowed down thereby.

In combination with the system of Fig. 4 of this application, I have shown anti-hunting means of the general type just described, such means comprising a resistor 120 connected in the grid-control circuit of vacuum tube 22, intermediate generator conductor 92 and the positive terminal of standard potential battery 47. A capacitor 121 is connected in series with this resistor and the two are disposed for energization by a voltage drop which the passage of exciting current supplied to generator-field winding 91 sets up in a resistor 123 included in this field-winding circuit.

It will be apparent that the desired anti-hunting action may be obtained by this manner of energization, as well as by the method shown and described in the previously mentioned co-pending application in which energization is had directly from the exciter terminals.

In operation of the anti-hunting means shown in Fig. 4, when the voltage of generator 90 is being corrected in a rising direction the voltage of exciter 95 is caused to increase so that the current in generator-field winding 91 and resistor 123 will accordingly be raised. This increasing potential, impressed upon resistor 120 and condenser 121 by means of conductors 125 and 126 which when connected as shown are of negative and positive polarities, respectively, causes condenser 121 to draw a charging current, which current in flowing through resistor 120 in a direction from left to right causes the left-hand end

of this resistor to assume a positive potential with respect to the right-hand end.

It will be seen that such an added polarity in the grid-control circuit artificially lowers the grid bias of vacuum tube 22 and thus prematurely arrests and prevents over-shooting of the corrective action.

In a similar manner, when the voltage of generator 90, is being corrected in the lowering direction, the voltage of exciter 95 is caused to decrease so that the current supplied to generator-field winding 91 through resistor 123 is accordingly caused to decrease. The voltage drop across resistor 123 thus also decreases and condenser 121 is allowed to send a discharge current through the circuit which includes resistor 120. This discharge current causes the right end of resistor 120 to assume a positive polarity with respect to the left end, and the value of negative bias impressed upon grid 46 of vacuum tube 22 is thus artificially lowered. Hence, the corrective action of the regulator is prematurely arrested and prevented from over-shooting.

As has been pointed out, it is apparent that, should it be desired, resistor 120 and condenser 121 may be energized directly from the terminals of the exciter 95 by connecting conductor 126 to exciter conductor 128, and conductor 125 to exciter conductor 129.

In addition to the direct-current generator applications shown in Figs. 1 and 4, the regulating systems of my invention may likewise be applied to alternating-current machines. Such an application is depicted in Fig. 6 in which the alternating-current generator to be regulated is shown at 140. In addition to the armature windings which are respectively connected with generator-circuit conductors 141, 142 and 143, the generator comprises an exciting-field winding 145 which is energized by an exciting generator 147 connected thereto by means of conductors 148 and 149 of positive and negative polarities, respectively. Exciting current for the field windings 152 of the exciter, and energizing current for the various electronic-tube devices utilized in the regulating system, is supplied from alternating-current power source conductors 15 and 16 in a manner similar to that utilized in the systems of Figs. 1 and 4.

To further increase reliability as regards continuity of operation of the electronic tubes utilized to rectify and control the current which energizes the exciter field windings 152, a multi-section winding is provided. As shown it comprises four sections 153, 154, 155 and 156, although it will be understood that a greater or lesser number of sections may be provided if desired. With each section is associated an independent pair of electronic tubes in a position intermediate the winding section and an exciting current supply transformer 160. Thus section 153 of the exciter winding is energized by a circuit which includes tubes 167 and 168, section 154 by a circuit including tubes 172 and 173, section 155 through tubes 175 and 176, and section 156 through tubes 178 and 179.

The cathode elements of each of the pairs of tubes named are supplied with current by means of a separate section of the secondary winding of a transformer 181, the primary winding of which is energized from power source conductors 15 and 16. Thus cathode elements 183 and 184 of tubes 167 and 168, respectively, are energized from winding section 186 of transformer winding 181, while the cathode elements of tubes 172

and 173 are similarly connected to winding section 188, those of tubes 175 and 176 with winding section 189 and those of tubes 178 and 179 with winding section 190.

It will thus be seen that during the half cycle of alternating-current supply voltage when the left side of the secondary winding of transformer 160 is of positive polarity with respect to the right side, exciter-field winding section 153 may be energized through a circuit which extends from the left side of the transformer winding through conductor 170, anode and cathode elements 192 and 184 of tube 168, mid-tap connection 195 of transformer winding 186, conductors 165 and 164, exciter-field winding section 153, and conductor 162 back to the mid-tap connection 161 of the exciting-current supply transformer winding mentioned.

In a similar manner, during the other half cycle of alternating-current supply voltage, or when the right side of the secondary winding of transformer 160 is of a positive polarity with respect to the left end, exciter-field winding section 153 may be energized from a circuit which extends from the right end of the transformer winding mentioned, through conductor 169, anode and cathode elements 198 and 183 of tube 167, mid-tap connection 195 of transformer-winding section 186, conductors 165 and 164, field winding 153, and conductor 162 back to the mid-tap connection 161 of the secondary winding of transformer 160.

In a similar manner, exciter-field winding sections 154, 155 and 156 are energized through one or the other of the tubes which comprise the pairs with which these winding sections are respectively associated.

To control the magnitude of the exciter-field current in accordance with deviations from a desired value of the voltage of generator 140, the apparatus and circuits shown at the right-hand side of the diagram of Fig. 6 are utilized. As in the systems of Figs. 1 and 4, this apparatus comprises a phase-shifting bridge circuit, shown generally at 240, in combination with vacuum-tube voltage-change-detecting means. As will be seen, bridge circuit 240 is disposed to supply control potential to the grid elements of the several pairs of field-current carrying tubes just described.

In order that the alternating-current voltage of regulated generator 140 may be compared with the unidirectional voltage of a standard-potential battery 200, current-rectifying and filtering means, shown generally at 203, are utilized. As illustrated, such means comprise a full-wave rectifying device 204 of the well-known electronic-tube type having a pair of anode elements 205 which are connected with the ends of a secondary winding 206 of a transformer whose primary winding 207 is energized from generator circuit conductors 142 and 143. Rectifier 204 further comprises a hot-cathode electron-emissive element 209 which may be supplied with heating current from any suitable source, such as from the secondary winding section 211 of a transformer 213, the primary winding of which is energized from power-source conductors 15 and 16.

The secondary winding 206 of the generator-energized transformer mentioned is provided with a mid-tap connection 215 which forms the negative side of a direct-current output circuit of the rectifier, the cathode element 209 of tube 204 forming the positive side of this output cir-

cuit, which circuit is connected in well known manner to a voltage-stabilizing resistor 218.

As tube 204 passes current only in the direction from anode to cathode, it will be seen that, in the connection shown, the lower end of resistor 218 will always be maintained at a positive potential with respect to the upper end.

To smooth out the pulsations in rectifier voltage impressed upon this resistor, well known filtering apparatus comprising capacitors 222 and inductances 223 connected in the manner shown between the rectifier 204 and the resistor 218 may be utilized. With this arrangement, it will be apparent that there will be impressed upon resistor 218 a direct-current potential whose magnitude is directly dependent upon the value of alternating-current voltage between generator circuit conductors 142 and 143.

In opposition with resistor 218 is connected standard-potential battery 200 before-mentioned, in a circuit so disposed that there will be impressed upon grid element 225 of a voltage-change detecting tube 201 a control potential determined by the difference in the voltages of the two devices. This circuit will be seen to extend from grid element 225 of vacuum tube 201 through conductor 227, a grid resistor 228, conductor 229, an anti-hunting resistor 230, conductor 233, a section of a load-stabilizing resistor 317, an adjustable-tap connection 325, conductor 231, adjustable tap connection 232, a portion of resistor 218, conductor 234, standard-potential battery 200, and conductor 235, back to a cathode element 236 of vacuum tube 201.

The adjustable tap connection 232 mentioned is so positioned along the length of resistor 218 that, at the desired normal voltage of regulated generator 140, the rectified potential, acting in the portion of resistor 218 included in the control-grid circuit just traced, will be slightly greater than that of standard-potential battery 200, in order that grid element 225 of vacuum tube 201 may be given a negative bias with respect to cathode element 236.

In order that the sensitivity of the regulating system shown in Fig. 6 may be of a high order, I provide amplifying means intermediate detector tube 201 and the phase-shifting bridge circuit 240. As illustrated, such amplifying means comprise, in addition to vacuum tube 201, a second and similar vacuum tube 242, the output circuit of which is disposed to act upon a third vacuum tube 22'. Tubes 201 and 242 are of the well known pentode type, tube 201, for example, comprising, in addition to the cathode and control-grid elements 236 and 225 already named, an anode or plate element 246, a screen-grid element 247, and a cathode-heating coil 248. Similarly, tube 242 comprises a cathode or electron-emissive element 250, a cathode-heating coil 251, an anode or plate element 252, a screen-grid element 253, and a control-grid element 254.

Direct-current voltage for energizing and maintaining the respective elements of the amplifying tubes 201 and 252 at the necessary potentials may be supplied in any suitable manner. In the system illustrated, I utilize for this purpose a plurality of series-connected resistors 255 in combination with means for impressing a direct-current potential of suitable magnitude upon them in such manner that, in the particular connection shown, the left-hand terminal 256 of these resistors will be maintained at a positive polarity with respect to the right-hand terminal 257.

It will be understood that this energizing potential may be supplied from any suitable source. Thus, in the system of Fig. 6, I have shown a rectifier-filter scheme of well-known type for deriving it from alternating-current source conductors 15 and 16 through transformer 213. This transformer, which has been mentioned previously, is provided with a multi-section secondary winding comprising a main section 260 and five auxiliary or cathode-heating sections 261, 262, 263, 264 and 211.

To convert the alternating-current potential derived from winding 260 to direct current, a rectifier tube 266 is utilized in the manner shown. This rectifier is of the full-wave type and comprises an electron-emissive cathode element 268 deriving heating current from transformer winding 262, and two anode or plate elements 269 and 270 respectively connected to the ends of transformer winding 260.

The rectifier potential is derived from mid-tap connections of transformer windings 262 and 260 to which are respectively connected output circuit conductors 272 and 273 of positive and negative potentials. To smooth out the pulsations in this rectifier current, in order that a steady direct-current voltage may be obtained for energizing series-connected resistors 255, a filter circuit comprising capacitors 275 and resistors 276 connected in the manner shown is utilized.

Connections of amplifier tubes 201 and 252 shown in Fig. 6 are identical with those shown and more completely described in connection with Fig. 1 of my co-pending application serial No. 543,518, filed June 11, 1931 and assigned to the same assignee as this invention. In that application, it is pointed out that the use of screen-grid tubes in the amplifier permits of self-compensation for changes in the voltage of the tube-energizing supply source. It is also there pointed out that the method of coupling the two amplifier tubes is a modification of the resistance-coupled scheme and is so arranged that high amplification is obtainable, the connections being such that a change due to grid control in the anode-to-cathode current of tube 201 is caused to produce a change in the opposite direction in the magnitude of anode-to-cathode current of tube 242.

The phase-shifting bridge circuit shown at 240 will be seen to be similar to bridge circuit 23 of Fig. 1, it comprising a capacitor 41' series connected with a rectifier unit 42' for energization from the secondary winding of a transformer 40''. Associated with the rectifier unit is a triode vacuum tube 22' having an anode element 44' a cathode element 45' and a control grid element 46' disposed in a manner exactly similar to that shown for the similarly represented devices in the system of Fig. 1.

Intermediate a mid-tap connection 50'' of the secondary winding 40'' and the connection common to capacitor 41' and rectifier 42', indicated by conductor 280, is connected the primary winding of a transformer 282 having a secondary winding comprising sections 283, 284, 285 and 286. Each of these sections is connected to act upon the grid elements of a separate pair of field-current carrying tubes. Thus, for example, the lower end of winding section 283 is connected to grid element 289 of tube 167 by means of conductor 290 and grid resistor 291, while the upper end of the same winding is connected to grid element 293 of tube 168 by means of conductor 294 and resistor 295. A mid-tap connection 297 of

winding section 283 is joined, by means of conductors 164 and 165 and winding section 186 of transformer 181, to cathode elements 183 and 184 of tubes 167 and 168.

5 In a similar manner, winding section 284 of transformer 282 acts upon the grid elements of tubes 172 and 173, section 285 upon tubes 175 and 176, and section 286 upon tubes 178 and 179.

10 With the particular arrangement shown, it will be apparent that the phase position of the control potential acting upon the grid elements of the several field-current carrying tubes is directly dependent upon the phase position of the voltage impressed upon the primary winding of transformer 282.

15 Because of the similarity of phase-shifting bridge circuit 240 of Fig. 6 with respect to circuit 23 of Fig. 1, the vector diagram of Fig. 2, which applies to circuit 23, may also be applied to circuit 240. Thus the voltage impressed upon this circuit by transformer 40'' may be represented by the sum of vectors E_1 and E_2 , the voltage drop in capacitor 41' and rectifier 42' being shown by vectors E_c and E_r , respectively. Hence, the voltage impressed upon transformer 282 is given by vector E , while the displacement of this voltage with respect to that of the potential acting between power-source conductors 15 and 16 may be designated for some particular value of effective resistance of the rectifier unit, by angle θ .

20 In the operation of the regulating system so far described, normal voltage of generator 140 is of such a value, as has been mentioned hereinbefore, that the rectified generator potential acting in the grid-circuit portion of resistor 218 is slightly greater than that of standard-potential battery 200, in order that grid element 225 of vacuum tube 201 may be maintained at a negative potential with respect to cathode element 236 of the tube. For this condition, there is caused to flow between anode and cathode elements 246 and 236 of tube 201 a current through a circuit which extends from positive-potential point 300 in the resistor combination 255 through a coupling resistor 301, conductor 302, anode and cathode elements 246 and 236 of tube 201, and conductors 235 and 273 back to negative-potential point 257 of resistor combination 255.

25 This current causes a voltage drop in resistor 301 making the lower end positive with respect to the upper end, which upper end is connected to grid element 254 of tube 242. The magnitude of this potential drop is slightly greater than the combined drop in sections 304 and 305 of resistor group 255, and since cathode element 250 of tube 242 is joined to the right end of resistor 305 by means of conductor 306, there will for this condition, be impressed upon grid element 254 a negative potential with respect to cathode element 250. This negative grid bias for tube 242 permits a current to flow from anode to cathode of this tube through a circuit which extends from positive conductor 256 of resistor combination 255, through a coupling resistor 308, conductor 309, anode and cathode elements 252 and 250 of vacuum tube 242, and conductor 306 back to negative potential point 311 of resistor combination 255.

30 The current flow through resistor 308 produces a voltage drop in the resistor, making the lower end positive with respect to the upper end, and, since this resistor is connected intermediate grid element 46' and cathode element 45' of

vacuum tube 22', a negative grid bias is there impressed upon this last-named tube.

35 The value of this bias is such that the impedance between the anode and cathode elements of tube 22' causes the effective resistance of rectifier unit 42' to be of some intermediate value which displaces the control voltage impressed upon the grid elements of the several tubes of the field current-carrying circuit to the extent required to provide the excitation for inducing in regulated generator 140 the desired voltage. As has been mentioned, the vector diagram of Fig. 2 illustrates some such relation.

40 A rise in the voltage of regulated generator 140 increases the value of negative grid bias impressed upon tube 201 and thus decreases the anode to cathode current of this tube. This current decrease lowers the voltage drop in resistor 301 and thus acts to decrease the negative grid bias of vacuum tube 242. As a result, the anode-to-cathode current of this tube is raised and the current and voltage drop in resistor 308 is increased so that the negative bias of vacuum tube 22' is likewise appropriately increased.

45 Tube 22', accordingly, increases its impedance so that the effective resistance of rectifier 42' is increased. Such an increase acts to lengthen vector E_r and shorten vector E_c of Fig. 2, thus increasing the displacement angle θ between grid-control voltage vector E and the power source voltage whose direction is given by vectors E_1 and E_2 .

50 Such increase in displacement will be seen, from examination of Fig. 3, to decrease the effective current passed by the electronic tubes in the exciter-field winding circuit and to thus decrease the voltage of exciter 147. This decreases the excitation of and voltage induced in regulated generator 140 to the desired magnitude.

55 A decrease in the voltage of regulated generator 140 will be seen to act in a manner opposite to that just explained, to decrease the negative grid bias of vacuum tube 201 and raise the plate current of this tube. This effects an increase in the negative grid bias of vacuum tube 242 and decreases the plate current of this tube. Such decrease lowers the negative grid bias of vacuum tube 22' which lowers the tube impedance and decreases the effective resistance of rectifier unit 42'. As a result, the displacement angle between the grid-control potential and supply voltage is decreased, the effective current passed by the tubes in the exciter-field winding circuit is raised, and the voltage of generator 140 is appropriately corrected back to the desired value.

60 In order to prevent over-shooting during corrective action, I combine with the regulating system of my invention the exciter-energized series-connected resistor-capacitor anti-hunting means already referred to as being shown and described in co-pending application, Serial No. 543,514. The resistor 230, already mentioned as being included in the control-grid circuit of vacuum tube 201, is connected in series with a capacitor 315 for energization from exciter conductors 148 and 149 through a circuit which includes an adjusting resistor 317 provided with shiftable tap connection 318. The purpose of this adjustable feature is to vary the sensitivity or responsiveness of the anti-hunting means.

65 In operation of these means, changes in the voltage of exciter 147 cause condenser 315 to draw a current through resistor 230 and induce therein a voltage drop which acts to prematurely arrest the corrective action and prevent over-shooting

thereof in a manner which has been completely explained hereinbefore, in connection with the regulating system of Fig. 4, as well as in the previously mentioned co-pending application, Serial No. 543,514.

In order that the regulating system of my invention may compensate the generator voltage in accordance with the load carried by the generator, I provide means, as has been mentioned, for introducing into the control-grid circuit of the voltage-change-detecting tube, a modifying potential which varies in accordance with the excitation of the regulated machine. This load-compensating scheme, which is the same as that covered in my copending application, Serial No. 568,538, filed October 13, 1931 and assigned to the same assignee as this invention, comprises, in the system of Fig. 6, the portion of exciter-energized resistor 317 included in the control-grid circuit intermediate conductors 231 and 233, the shiftable tap connection 325 being provided to adjust the degree of compensation effective.

In operation of the compensating means, when regulated generator 140 is operating at light load the excitation required is of a relatively low value and the voltage of exciter 147 is correspondingly low so that the potential introduced into the grid circuit of vacuum tube 201 by resistor 317 is of a small value, which value may be suitably accounted for by properly setting tap connection 232 on resistor 218. As the generator load increases, greater excitation is required to maintain the voltage at the original value, and the exciter voltage is accordingly increased by regulator action. This increase raises the compensating potential introduced by resistor 317 into the grid-control circuit.

In the connection shown such a rise in compensating potential will be seen to require that the generator voltage be maintained at a higher value in order to restore the grid-control circuit to the normal stable condition, since the load-compensating portion of resistor 317 is connected in opposition with the effective-generator-voltage portion of resistor 218. Consequently, as the generator load increases, the regulator will be caused to increase the generator voltage, at a rate determined by the position of tap-connection 325 on resistor 317. It will be apparent also that the regulated voltage may similarly be caused to decrease with rising generator load by connecting resistors 317 and 218 in cumulative instead of opposition relation.

While I have shown and described certain specific embodiments of my invention, I am fully aware that many further modifications thereof are possible. My invention, therefore, is not to be restricted except insofar as is necessitated by the prior art and by the spirit of the appended claims.

I claim as my invention:

1. In a regulating system for an electrical generator having a field winding energized from an alternating-current power source through a circuit which includes current-rectifying and control means comprising a gas-filled electron-discharge device having a grid element, the combination of a phase-shifting bridge circuit made up of a transformer winding energized from said alternating-current source and disposed to act upon a capacitor connected in series with a full-wave rectifier unit the output terminals of which are connected to the anode and cathode elements of a triode vacuum tube the grid element of which is disposed to be acted upon by a potential deter-

mined by a quantity to be regulated, and means for impressing upon the grid element of said gas-filled discharge device a control potential derived from said bridge circuit between an intermediate point in the said transformer winding and the connection joining the said capacitor with the said rectifier unit.

2. Regulating apparatus for an electrical generator having an exciting-field winding comprising an electronic tube current-rectifying means disposed in a circuit for energizing said field winding from an alternating-current power source, grid-element means associated with said rectifying means for controlling the current supplied to said field winding in accordance with the phase position, with respect to the voltage of said power source, of an alternating-current control potential impressed thereon, and means for supplying and shifting the phase position of said control-potential comprising a transformer winding energized from said power source, a capacitor and a full-wave rectifier connected in series for energization from said winding, a vacuum tube having anode and cathode elements connected to the output terminals of said rectifier and a grid element disposed to be acted upon by a potential determined by a quantity to be regulated, the control potential impressed upon the said grid-element means of the rectifying means being derived from the voltage acting between an intermediate point in the said transformer winding and the connection joining the said rectifier and capacitor.

3. In a regulating system for an electrical generator having exciting means energized from an alternating-current power source through a circuit which includes current-rectifying means of the electronic tube type, and potential modifying means disposed to impress upon said rectifying means a control potential determined by the voltage of said generator, the combination of an amplifier interposed between the regulated generator and said rectifying means for the purpose of increasing the sensitivity of the system, said amplifier comprising two vacuum tubes each having an anode, a cathode, a screen-grid and a control grid element, a source of power for energizing said elements, and resistance-coupling circuits for the amplifier tubes disposed in such manner that a change in control-grid bias voltage on the first or input tube in one direction acts to change the grid bias of the second or output tube in the opposite direction.

4. In a voltage regulating system for an alternating-current generator having an excitation-control circuit energized from an alternating-current power source through current-rectifying means of the electronic tube type disposed to be acted upon by a control potential, the combination of means for causing said control potential to vary in accordance with changes in the voltage of said generator comprising a rectifier energized by the generator voltage, a standard potential direct-current source, a phase-shifting bridge circuit disposed to supply the control potential to said first-mentioned rectifying means, said bridge circuit having an adjustable element in the form of an electronic tube, and a circuit for impressing upon said tube a voltage determined by the difference between the voltage of said standard potential source and that appearing at the output terminals of said rectifier.

5. In a regulating system for a dynamo-electric machine having exciting means energized from an alternating-current power source through a

circuit which includes current-rectifying and control means in the form of a grid-controlled electron-discharge device, the combination of a phase-shifting bridge circuit energized from said power
5 source and disposed to impress an alternating-current control potential upon said device, a full wave rectifier and an electronic tube connected in said bridge circuit for the purpose of adjusting the phase position of said control potential, means
10 for impressing a control voltage upon said tube, and means for varying said voltage in accordance with a characteristic of said machine.

6. In a voltage regulating system for an elec-

trical generator having an excitation-control circuit energized from an alternating-current power source through electronic-tube current-rectifying means, the combination of means, including
5 a phase-shifting bridge circuit for impressing a control potential upon said rectifying means, a full-wave rectifier connected in said circuit and an electronic tube connected to said rectifier to adjust the phase-shift effected by the circuit,
10 means for impressing a control voltage upon said tube, and means for varying said control voltage in accordance with the voltage of said generator.

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