

May 16, 1933.

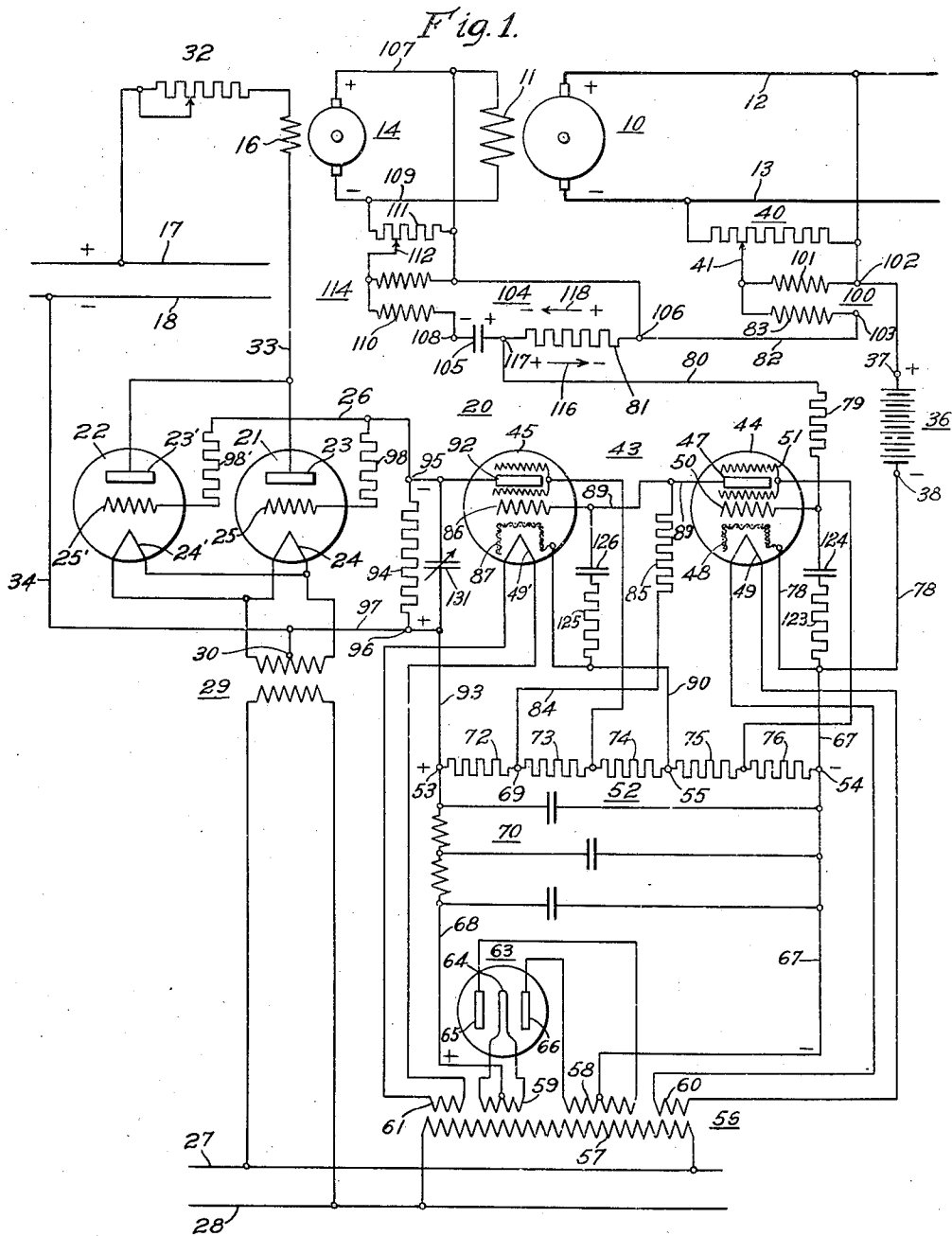
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1,909,054

VACUUM TUBE VOLTAGE REGULATOR

Filed June 11, 1931

3 Sheets-Sheet 1



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Fig. 2.

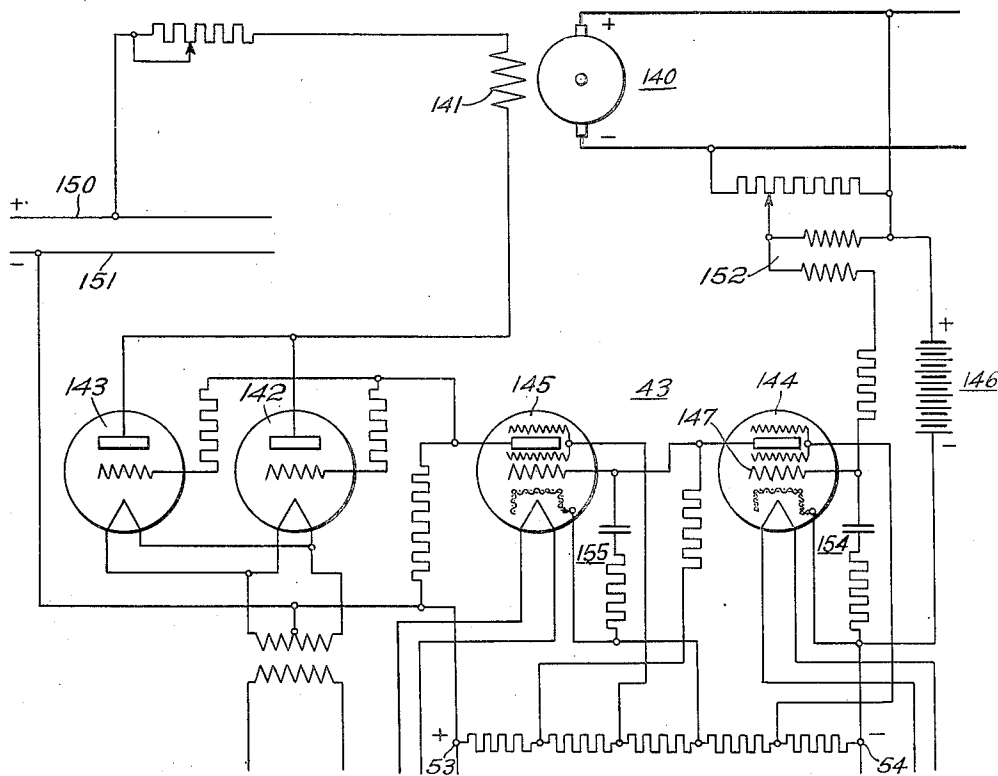


Fig. 3.

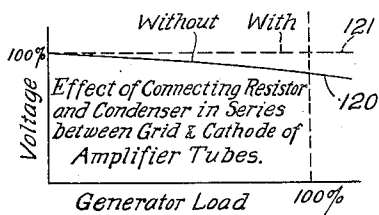


Fig. 4.

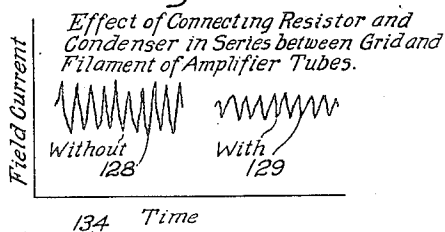
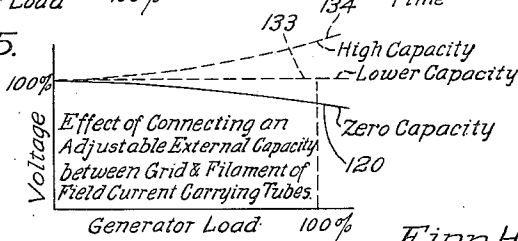


Fig. 5.



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3 Sheets-Sheet 3

Fig. 6.

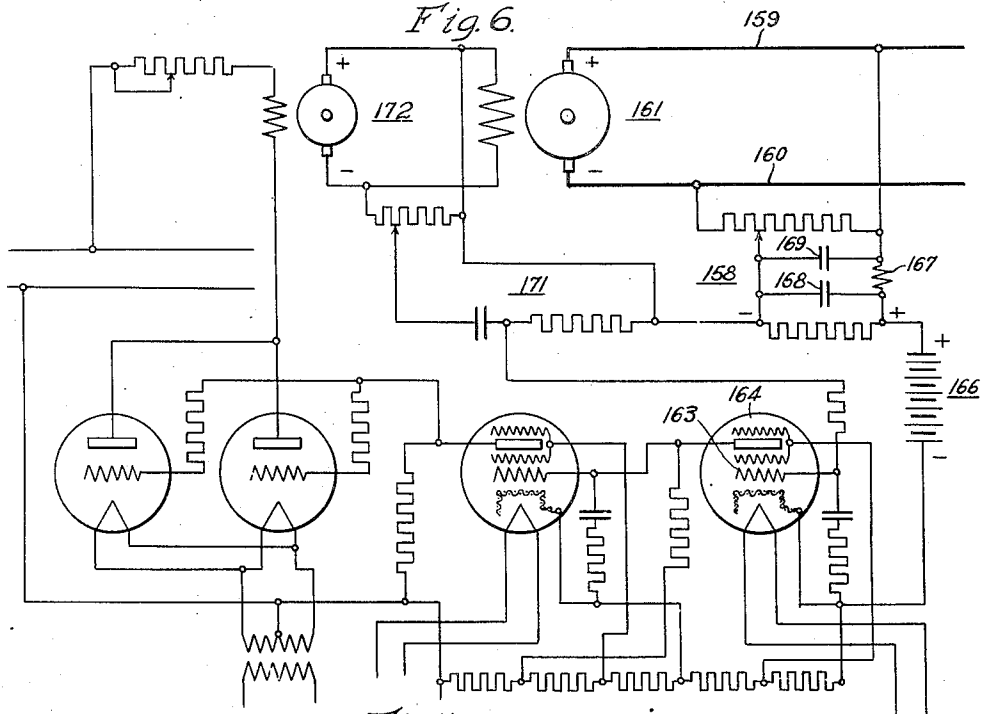
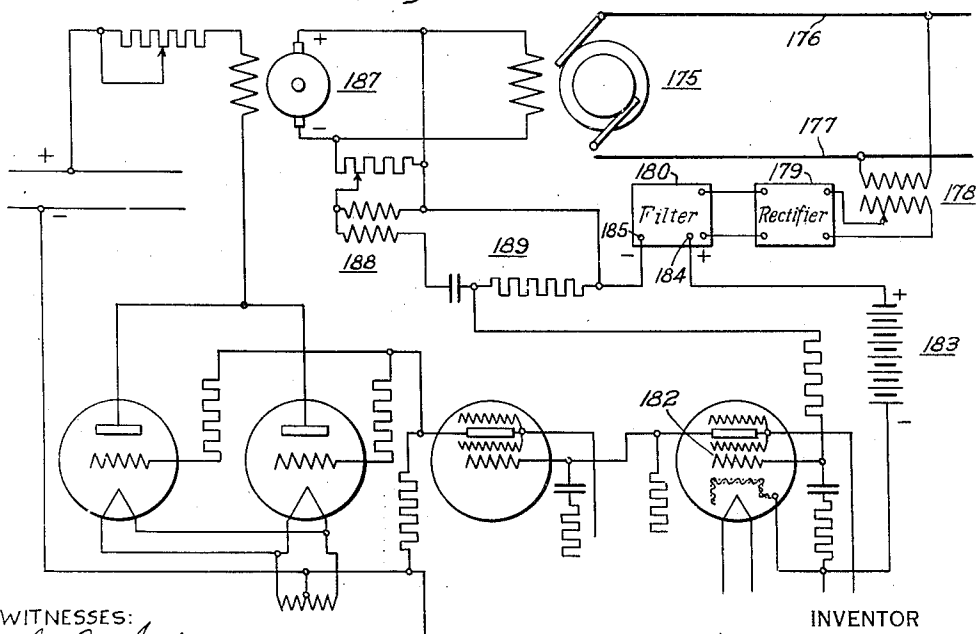


Fig. 7.



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VACUUM-TUBE VOLTAGE REGULATOR

Application filed June 11, 1931. Serial No. 543,518.

My invention relates to regulators for dynamo-electric machines and has particular relation to means for effecting improvements in the operating characteristics and general performance of vacuum-tube voltage regulators for electrical generators.

In the application of vacuum-tube regulators to electrical machines, the extremely high sensitivity of the change-responsive means, which the vacuum tubes afford, makes it essential that seemingly minor characteristics or conditions which, in the case of other types of regulators are inconsequential, be considered and compensated for.

In the case of a direct-current generator, one such condition is the presence of small and relatively rapid fluctuations in the terminal voltage of the generator, which fluctuations, spoken of as commutator ripples, are principally produced by action of the machine commutator and brushes, or, in addition, may result from dissymmetry in the machine windings. The amplitude of these ripples is found to vary with different machines, and, in generators of commercial design, it commonly has a value of from one to five per cent of the rated terminal voltage. Furthermore, for a given generator, the ripple amplitude is found to change with the operating conditions of the machine, being dependent upon the constancy of speed, the generator load, the mechanical condition of the commutator and brushes and other factors.

Tests reveal that, when vacuum-tube voltage regulators are applied to direct-current generators, these ripples act to change the value of regulated voltage in accordance with their amplitude, so that, unless some means be provided for neutralizing them, the action of the regulator is detrimentally affected thereby.

It is known that regulators applied to dynamo-electric machines having separate exciters have a pronounced tendency to overshoot in their corrective actions, due to the time delay which the inductive characteristics of the field winding circuit introduces to the corrective change. In copending application Serial No. 543,514 by J. H. Ash-

baugh and myself, filed June 11, 1931 and assigned to Westinghouse Electric and Manufacturing Company, there is described and claimed anti-hunting means for vacuum-tube regulators which utilize a series-connected resistor and condenser energized by the voltage of the machine exciter, the resistor being included in the grid-control circuit of the regulator tubes for the purpose of modifying the control potential in accordance with the direction and rate of change of the exciter voltage.

In the vacuum-tube regulating system of this invention, I propose to utilize anti-hunting means of this type. It will, therefore, be apparent that the presence of commutator ripples in the exciter voltage likewise introduces a problem, in connection with vacuum-tube regulating systems, similar to the one discussed for direct-current generators to which vacuum-tube voltage regulators are applied.

The inherent characteristics of the vacuum-tube circuits utilized in regulating systems, of the type under consideration, are such as to cause the regulator to have, in the absence of special compensating means, an inherent drooping or decreasing regulated-voltage with generator-load characteristic. In many cases, this type of characteristic is undesirable, so that, in this respect a further problem for solution is introduced.

In the majority of regulator applications, the magnitude of the field-current to be controlled is found to be greater than the capacity of a single vacuum tube of the type which the teachings of the art, in its present state, indicate to be most suitable. Consequently, it is frequently necessary to utilize a plurality of tubes connected in parallel to obtain the required current-capacity. However, the connection of the grid-control elements of the tubes directly to a common conductor, which is the method practiced in the past, has been found to reduce the total capacity of the combination to a value considerably below that given by the product of the number of tubes and the current capacity of each, so that complete utilization of the capacity of

the equipment in question has, in the past, been impossible.

Likewise, in supplying the vacuum tubes of a regulating system with the necessary energizing and operating voltages, it is frequently desirable to utilize, as a power source, the standard alternating-current lighting-supply circuit. As is known, the voltage of such commercial circuit is not ordinarily maintained at an exact value but may vary an appreciable percentage above or below an average normal value. Vacuum-tube regulators known heretofore, when so supplied, have been subject to a variation in their operating characteristics with the changes in the supply voltage, and their performance has thereby been detrimentally affected.

It is accordingly, an object of my invention to provide, in vacuum-tube voltage regulators for direct-current generators, means for eliminating the effects, on the regulator performance, of commutator ripples in the voltage of the machine regulated.

It is another object of my invention to provide, in vacuum-tube regulators for electrical generators having separate exciters, anti-hunting means which function to modify the regulating-control potential in accordance with the rate of change of the exciter voltage, with which the effects of commutator ripples in the exciter voltage may be neutralized.

It is a further object of my invention to provide, in vacuum-tube voltage regulators for electrical generators, means whereby the regulator may be given a flat- or a rising-with-load characteristic.

It is another object of my invention to provide a method of paralleling vacuum tubes which permits of full realization of the total current capacities of all of the several tubes in the combination.

It is a still further object of my invention to provide a vacuum-tube voltage regulator of high sensitivity in which the vacuum tubes are so disposed as to automatically compensate, in their operating characteristics, for changes in the voltage of the power-supply source utilized therewith.

More specifically stated, the object of my invention is to provide a vacuum-tube voltage regulator having high sensitivity, which may be applied to electrical generators of either the alternating-current or the direct-current type, with or without separate exciters, in which the effects of direct-current voltage commutator ripples are neutralized, anti-hunting means are provided, compensation for changes in the vacuum-tube power-supply source voltage is had, full utilization of parallel-connected tube capacity is obtainable, and a flat or a rising-with-load characteristic may be effected.

In practicing my invention, I attain the desired high sensitivity by interposing between the quantity-adjusting vacuum tubes

and the source of quantity-controlling forces a suitable amplifier to strengthen the inherently weak change-initiating impulses and render them more effective.

Likewise, I contemplate, for the purpose of eliminating the effects of commutator ripples, the provision of a neutralizing transformer, or of filter equipment, interposed between the direct-current machine involved and the vacuum-tube grid or control circuit of the regulator, on which the machine voltage is disposed to act.

In applications of the regulating system of my invention to machines having separate exciters, I prevent overshooting of the corrective action through the utilization of a resistor, interposed in the vacuum-tube grid-control circuit, connected in series with a condenser for energization by the voltage of the exciter, and I eliminate the detrimental effect of the commutator ripples in the exciter voltage through the utilization of a suitable neutralizing transformer.

To obtain a flat or a rising-with-load characteristic for the vacuum-tube regulator of my invention, I contemplate the provision of special coupling circuits for the vacuum tubes, which function to so modify the inherent drooping characteristic as to give the type of regulator characteristic which may be desired.

To permit of a full realization of the total current capacity of all of a plurality of parallel-connected vacuum tubes, I modify the usual parallel connection of the grid-control elements by disposing, between the required common grid-paralleling conductor and the grid-element of each tube, a resistor of suitable dimensions, which, I have discovered, will effect the result desired.

Likewise, compensation for changes in the vacuum-tube power-supply source is attained through the use, in the sensitivity-increasing amplifier of the regulator of my invention, of vacuum tubes of the screen-grid type, interconnected and energized in such manner that changes in their respective anode-to-cathode currents take place in opposite directions.

The complete regulating system of my invention, and the novel features embodied therein, will best be understood from a description of specific embodiments thereof, taken in conjunction with the accompanying drawings, in which:

Figure 1 is a diagrammatic representation of the apparatus utilized by the voltage regulator of my invention, when applied to a direct-current generator having a separate exciter, in which commutator-ripple-eliminating transformers are combined both with the main generator and with exciter-energized anti-hunting means;

Fig. 2 illustrates diagrammatically the regulator of my invention applied to a direct-

current generator having no separate exciter;

Figs. 3, 4, and 5 are diagrams of curves illustrating the characteristic-shifting effects obtainable through the provision of special coupling means in the vacuum-tube circuits of the regulating systems of Figs. 1 and 2;

Fig. 6 is a diagrammatic representation of the regulator of my invention applied to a direct-current generator having a separate exciter in which a filter type of commutator-ripple eliminator and exciter-energized anti-hunting means are incorporated; and

Fig. 7 illustrates diagrammatically the apparatus used in the voltage regulator of my invention when applied to an alternating-current generator.

Referring to the drawings, and particularly to Fig. 1 thereof, a direct-current generator 10, having a field winding 11, is there shown disposed to supply voltage to circuit conductors 12 and 13. Generator 10 may be driven by any suitable source of power (not shown). A separate exciter 14, which may be directly connected to the generator, or otherwise suitably driven, is disposed to supply exciting current to generator-field winding 11. A field winding 16 of the exciter is energized from some suitable source of direct-current voltage, represented by conductors 17 and 18, which are of positive and negative polarity, respectively.

The voltage of generator 10 is controlled, in a well known manner, by suitably adjusting the magnitude of the current in exciter-field winding 16, and to provide this adjustment, in response to changes in the generator voltage from a desired value, the vacuum-tube voltage regulator, shown generally at 20, is utilized.

In the circuit of exciter-field winding 16 are disposed one or more vacuum tubes 21 and 22, each having an anode or plate element 23 and 23', a cathode or filament element 24 and 24' and a control-grid electrode 25 and 25'. As illustrated, vacuum tubes 21 and 22 are of the well known triode type, the filaments 24 of which may be supplied with heating current from any suitable source, such as from an alternating-current circuit, represented by conductors 27 and 28, through a suitable transformer 29.

As will be observed, the energizing circuit for exciter-field winding 16 extends from positive conductor 17 of the supply source, through an adjusting rheostat 32, winding 16, conductor 33, plate elements 23 and 23' of the vacuum tubes 21 and 22, filament elements 24 and 24' thereof, a mid-tap connection 30 in the secondary winding of transformer 29 and conductor 34, to negative conductor 18 of the power-supply source.

It will be understood that adjustment in the magnitude of the current passed by tubes 21 and 22 is effected by suitably varying the

potential impressed upon the control grid-elements 25 and 25'. Likewise, it will be evident that the number of vacuum tubes disposed in the field-winding circuit, in the manner shown for tubes 21 and 22, will be determined by the magnitude of the required field current and the capacity of each tube thus employed.

In order, as has been mentioned, that the total current-carrying capacity of two or more parallel-connected tubes may be realized I have found it necessary to modify the grid-control circuit connections from the usual form, in which the individual tube grids are directly joined to a common control-circuit conductor, since tests have shown that the combined capacity of a combination, when so connected, may be considerably less than the sum of the individual tube capacities. This deficiency appears to result from local oscillations, set up in the paralleling circuits, which cause circulating currents between anode to cathode circuits of adjacently connected tubes, and thereby reduces the output of the combination.

By interposing, between each grid element and the common control conductor, a suitably dimensioned resistor, I have found that each tube may be made to deliver, to the external circuit, its full current rating, and full realization of the sum of the several capacities is thereby made possible.

In the system of Fig. 1, such resistors, shown at 98 and 98', connect grid elements 25 and 25', respectively, of tubes 21 and 22, to the grid-control conductor 26. Additional vacuum tubes may be connected in a manner similar to that shown and described for tubes 21 and 22, as will be evident, should they be required.

To provide, for the regulating system, a control potential determined by the difference in the voltage of generator 10 from a given desired value, I utilize a standard-voltage source, represented by battery 36, connected in opposition, to generator-circuit conductors 12 and 13, in the manner shown, to act upon the control circuit of the vacuum tubes. It will be observed that positive terminal 37 of the battery is joined to positive generator conductor 12, and that negative battery terminal 38 and negative generator conductor 13 are connected, in the circuit shown, to impress upon the vacuum-tube system a voltage determined by the potential difference therebetween.

An adjustment in the normal or desired value of the regulated voltage may be effected through the use of a ratio-adjusting potentiometer 40, having a shiftable tap connection 41, combined with the generator and regulator-control circuits, in well known manner.

To increase the sensitivity of the regulating system, I provide the amplifier hook-up

shown generally at 43, which, as illustrated, comprises the two vacuum tubes 44 and 45, interconnected in the manner shown. It will be recognized that tubes 44 and 45 are each of the well known screen-grid alternating-current-heated-cathode variety. Tube 44, for example, comprises an anode or plate element 47, a cathode or electron-emissive element 48, a cathode-heating coil 49, a control-grid electrode 50, and a screen-grid element 51.

Direct-current voltage for suitably energizing and maintaining the respective elements in the amplifying tubes 44 and 45 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 52 in combination with means for impressing a direct-current potential of suitable magnitude upon them, and, in such manner that, in the connection shown, terminal 53 of resistors 52 is maintained at a positive polarity with respect to terminal 54.

It will be apparent that the energizing potential may be supplied from any suitable source and, in the system of Fig. 1, I have shown a rectifier-filter scheme for deriving it from alternating-current-source conductors 27 and 28. It will be evident, however, that, if desired, a battery or auxiliary direct-current generator may be utilized.

The rectifier-filter scheme mentioned, which will be recognized as comprising well known elements, employs a transformer 56, having a primary winding 57 energized from the alternating-current-source conductors named, and a multi-section secondary winding which includes a main section 58 and three auxiliary sections 59, 60 and 61. To convert the alternating-current potential derived from winding 58 into direct current, a rectifier tube 63, or its equivalent, is utilized in the manner shown. Rectifier 63, which is of the full-wave type, comprises an electron-emissive cathode element 64, supplied with heating current from transformer winding 59, and two anode or plate elements 65 and 66, connected respectively, to the ends of transformer winding 58.

It will be observed that transformer windings 58 and 59 are provided with mid-tap connections to which are respectively connected conductors 67 and 68. These conductors will be seen to constitute the direct-current output circuit of the rectifier, which is disposed to energize series-connected resistors 52 through the connections shown.

In operation of rectifier tube 63, current is permitted to pass between the anode and the cathode elements thereof in one direction only, namely, from either anode 65 or anode 66 to cathode 64. Such being the case, during the half of the alternating-current cycle when anode element 65 is positive with re-

spect to the cathode, a current will flow from it to the cathode 64, and, during the other half of the cycle, a similar current will flow from anode 66 to cathode 64. Consequently, it will be seen that conductor 68 will be maintained at a positive potential with respect to conductor 67.

This potential is, however, of a pulsating nature, and, to smooth out these pulsations and obtain a steady direct-current voltage, the filter circuit, shown generally at 70, is utilized. This circuit comprises the condenser and reactor elements disposed in the manner shown, which, acting in a well known manner, convert the pulsating voltage supplied by the rectifier into the desired steady direct-current potential, which is impressed between points 53 and 54 of the resistor combination 52.

Secondary windings 60 and 61, of transformer 56, are utilized to supply heating current to cathode-heater coils 49 and 49' of amplifier tubes 44 and 45, respectively, connections being made thereto in the manner shown. While it would be possible to utilize a common source of heating potential for both tubes, the use of a separate transformer winding for each heating coil is found advantageous from the standpoint of eliminating capacity effect and insulation strain between the cathode and heater elements of the two separate tubes.

The use of screen-grid-type tubes in the amplifier 43 permits of self-compensation for changes in the voltage of the supply source derived from alternating-current-circuit conductors 27 and 28, which, in practice, as has been pointed out, may vary within appreciable limits. I have found that, by properly proportioning the respective screen-grid-voltage biases of the two vacuum tubes 44 and 45, changes in the voltage of supply conductors 27 and 28 result in no appreciable change in anode-to-cathode current of tubes 21 and 22. This self-compensating feature results from the action of the screen-grid elements, in combination with "staggering" of control grid 86 with respect to cathode 87 of tube 45, acted upon by the voltage drop across supply resistors 73 and 74, whereby a change, due to grid control, in the anode-to-cathode current of tube 44 is caused to produce a change in the opposite direction in the magnitude of anode-to-cathode current of tube 45. The application of this feature, in the system described, will be seen to perform a valuable function in the regulating scheme.

The resistance values of the series-connected resistors 72, 73, 74, 75 and 76 are so chosen that the respective voltage drops across them are of the proper values for maintaining the necessary and desired potential differences between the several elements of vacuum tubes 44 and 45 with which they are connected. It will be observed that the system of coupling

between the two amplifier tubes is a modification of the well known resistance-coupled scheme and is so arranged that maximum amplification is attainable, since it will be recognized that the sensitivity of the regulating scheme is directly dependent thereon.

In operation of the regulating system of Fig. 1, normal voltage of generator 10 bears a fixed ratio to the voltage of standard battery 36, the value of this ratio being determined by the setting of adjustable-resistor contact 41. For this normal or desired voltage value, the potential difference between tap connection 41 and terminal 38 of battery 36 will be of a definite negative value, for example -2 volts, and thus the potential impressed between control grid 50 and cathode 48, of vacuum tube 44, will likewise be of a similar negative value. It will be observed that cathode 48 is joined to battery terminal 38 by conductor 78, and that grid element 50 is joined to resistor tap 41 through grid resistor 79, conductor 80, resistor 81, conductor 82 and a transformer winding 83.

In vacuum-tube regulating systems of this general type known in the past, elements 81 and 83 just named, and whose functioning will subsequently be explained, have not been included, so that, in effect, adjusting tap 41 has been joined directly to grid resistor 79. Assuming for the moment that such connection obtains in the system of Fig. 1, its operation, for voltage deviations above and below the desired value, is as follows:

A rise in the voltage of generator 10, above the desired value, causes resistor terminal 41 to assume an increased negative potential with respect to battery terminal 38. Control grid 50 of vacuum tube 44, accordingly, has impressed upon it this new value of negative potential by action of the grid-control circuit. This increased negative potential acts to decrease the flow of electrons from cathode 48 to anode 47, in tube 44, and the current flow between these two elements is decreased. It will be observed that anode 47 is, at all times, maintained at a positive potential with respect to cathode 48 by the voltage drop across resistors 73 to 76, inclusive, through a circuit which extends from positive resistor terminal 69, through conductor 84, a coupling resistor 85, conductor 89, anode 47 and cathode 48 of tube 44, conductor 78 and conductor 67 back, to negative resistor terminal 54.

The decrease in this current through tube 44, which is supplied thereto through resistor 85, proportionately decreases the voltage drop through this resistor, so that a corresponding change in potential between grid element 86 and cathode element 87 of vacuum tube 45 is effected. It will be seen that grid 86 of vacuum tube 45 is joined to anode or plate 47 of vacuum tube 44 by conductor 89, and that cathode 87 of tube 45 is maintained

at an intermediate value of potential from the series-connected resistor combination mentioned, connection being made thereto, at terminal 55, by conductor 90.

For normal voltage of the generator regulated, current through coupling resistor 85 is of such value that the potential drop through this resistor is slightly in excess of the combined drop through resistor sections 73 and 74, to give grid 86 of tube 45 a definite negative bias with respect to cathode 87, of -2 volts for example, and, for such a condition, it will be seen that the potential impressed upon grid 86 of vacuum tube 45 will be of that value. Consequently, the decrease in current and voltage drop through resistor 85, caused by the rise in generator voltage mentioned, will be seen to cause a potential to be impressed upon grid 86 which is less negative with respect to that of cathode 87 than for normal voltage of the generator.

This decreased negative potential acts to increase the electron flow from cathode 87 of vacuum tube 45 to anode or plate element 92, so that the current flow between these two elements is correspondingly increased. It will be observed that anode 92 of tube 45 is maintained at a positive potential, with respect to cathode 87, of a value determined by the combined voltage drop across series-connected resistors 72, 73 and 74, anode 92 being joined to positive terminal 53 of the combination mentioned through a conductor 93 and a coupling resistor 94.

The increase in current through resistor 94 raises the voltage drop between its terminals, so that terminal 95 assumes a greater negative potential with respect to terminal 96 than for the normal voltage condition of regulated generator 10. Such being the case, grid elements 25 and 25' of exciter-field-current-carrying tubes 21 and 22 have impressed thereon an increased value of negative potential with respect to the cathode or filament element 24 of this tube. It is seen that filaments 24 and 24' of these tubes are joined to terminal 96 of resistor 94 through a conductor 97 and that grids 25 and 25' are each joined to conductor 26 and terminal 95 of this resistor through suitable resistors 98 and 98', the function of which has already been explained.

This increase in negative grid potential for vacuum tubes 21 and 22 decreases the electron flow between the plate and filament elements thereof, and hence lowers the current passed by the tubes, which current, as has been explained, energizes field winding 16 of exciter 14. This reduction in exciting current lowers the voltage of exciter 14 and correspondingly decrease the excitation of generator 10, with the result that its voltage is lowered.

Similarly, a decrease in voltage of generator 10 acts to decrease below normal the value

of negative potential impressed upon grid 50 of vacuum tube 44 with respect to cathode 48 of this tube, it being apparent that, for such condition of below-normal generator voltage, resistor-tap connection 41 will assume a lower value of negative potential with respect to terminal 38 of battery 36. The current flow from plate 47 to cathode 48 of this tube is accordingly increased, and the voltage drop through resistor 85 is correspondingly raised.

Grid 86 of vacuum tube 45 thus has impressed upon it a potential which is of an increased negative value with respect to that of cathode 87 of this tube, and the current flow from plate 92 to cathode 87 is accordingly diminished, so that the voltage drop across resistor 94 is likewise decreased. Such being the case, terminal 95 of this resistor assumes a lower negative potential with respect to terminal 96, than for the normal voltage condition of regulated generator 10.

This potential, directly affecting the grid elements of vacuum tubes 21 and 22, allows a greater flow of electrons between the filament and the plate elements thereof and permits the tubes to pass a higher value of current through field winding 16 of exciter 14. The voltage of the exciter is accordingly raised, the excitation of generator 10 is increased, and the voltage of the generator is correspondingly raised.

As has been pointed out, the terminal voltage of a direct-current generator contains ripples caused by the action of the commutator, and by lack of uniformity in the armature winding coils, which ripples are of substantial magnitude and vary with the operating conditions of the generator. In a regulating system such as is shown in Fig. 1, the ripples affect the regulator performance in a very undesirable manner in that a change in their magnitude is found to effect a change in the average terminal voltage which the regulator maintains for the generator being controlled.

To eliminate the effect of commutator ripples, I provide, in the regulating system of my invention, means for neutralizing them, so that they will not be permitted to reach the sensitive grid-control circuit of the vacuum tubes. To accomplish this result, I provide, in the system of Fig. 1, a transformer shown generally at 100, the secondary winding 83 of which has already been mentioned as being included in the potential control circuit of grid 50 of vacuum tube 44. Primary winding 101 of this transformer is disposed, in the manner shown, to be energized by the generator voltage.

By providing windings 83 and 101 with an equal number of turns and properly interconnecting them in the manner shown, changes in voltage impressed upon the primary winding by inducing similar changes

of voltage in the secondary winding, may be made to completely neutralize themselves, so that, in the system of Fig. 1, the voltage which appears between points 102 and 103 of the connection there shown will be entirely devoid of the ripples which may be present in the voltage between generator conductors 12 and 13.

It will be apparent that a ripple-eliminating transformer connected in the manner shown and described allows the average voltage of the regulated generator to act upon the regulating system, and hence in no way detrimentally affects the action of the regulator. Aside from the function of neutralizing the voltage ripples in the grid-control circuit, which is a most advantageous effect in vacuum-tube regulators, it has no other action or effect. Thus, in the system of Fig. 1, the introduction of transformer winding 83 in the control circuit of vacuum-tube grid 50 modifies the action of the regulator, which has been explained in detail, only to the extent that the undesirable commutator and other voltage ripples of generator 10 are prevented from affecting the regulating system.

It will be recognized that any regulating system for an electrical generator having a separate exciter which acts to control the excitation of the exciter in response to changes in a characteristic of the generator regulated inherently has a tendency to hunt or overshoot in its corrective action because of the inductive characteristics of the field-winding circuits involved, which introduce a time lag between a change in the exciter-field current and a final change in the generator characteristic.

To overcome this tendency, I provide, in the regulating system of my invention, anti-hunting means represented generally at 104 in Fig. 1. Such means comprise a resistor 81, which has already been mentioned as being connected in the control-grid circuit of the regulating system, and a series-connected condenser 105. This combination is disposed for energization by the voltage of exciter 14, terminal 106 of the resistor being connected to exciter conductor 107 which is of positive polarity and terminal 108 of the condenser 105 being connected to exciter conductor 109 which is of negative polarity, through a circuit which includes transformer winding 110, a portion of resistor 111, and an adjustable resistor tap 112.

In combination with adjustable tap 112, resistor 111 will be seen to serve a voltage-dividing function which is utilized to adjust the sensitivity or effectiveness of the anti-hunting means 104. Winding 110 mentioned is the secondary of a voltage-ripple-eliminating transformer 114, the function and method of connection of which will be seen to be similar to that of transformer 100 used in connection with generator 10, it being under-

stood that the transformer 114 acts to prevent commutator and other ripples in the exciter voltage from reaching and effecting the anti-hunting means 104, the resistor of which is disposed directly in the grid-control circuit of amplifier tube 44.

The anti-hunting combination 104 is basically the same as already mentioned, as that disclosed and claimed in copending application, Serial No. 543,514 by J. H. Ashbaugh and myself as joint inventors, filed June 11, 1931 and assigned to the same assignee as this invention.

In operation of the anti-hunting means 104, condenser 105 is charged to a value corresponding to the given exciter voltage acting upon it. Thus, for the normal voltage conditions of generator 10, which correspond to a given value of exciter voltage, condenser 105 has stored, in an electrostatic field associated with it, a given quantity of energy, and, for such a stable condition, it draws no charging current from the exciter, and does not supply any discharge current thereto. For the connections shown in Fig. 1, the left-hand member of the condenser is at all times of negative polarity with respect to the right-hand member, this relation being determined by the particular connections with the exciter.

A rise in exciter voltage causes condenser 105 to draw a charging current, which current, passing through resistor 81, in a direction, from right to left in the diagram, which is indicated by arrow 118 sets up in this resistor a voltage drop, making terminal 106 thereof positive with respect to terminal 117. Similarly, a fall in the voltage of exciter 14 allows condenser 105 to send a discharge current through resistor 81, in the opposite direction as indicated by arrow 116 setting up in the resistor a voltage drop which causes terminal 117 to be positive with respect to terminal 106.

It will be apparent that the magnitude of the condenser-charging or discharging current, as the case may be, will be dependent upon the rate of change of the exciter voltage, since it is evident that a high rate of change will result in a higher condenser current than a slow or more gradual rate of change. This condenser current persists for the period necessary for the condenser to change its electrostatic field to a new value which corresponds to the changed exciter potential.

Anti-hunting resistor 81, when disposed in the grid-control circuit of the vacuum-tube regulator, in the manner indicated in the diagram of Fig. 1, acts to modify the grid-control potential to prevent overshooting of the corrective actions, the magnitude of such modification being, as already pointed out, a direct function of the rate of change of the exciter voltage.

Thus, in the operation of the complete

regulating system illustrated in Fig. 1, a rise in the voltage of generator 10 above the desired value, causes, through the regulating action already explained, the voltage of exciter 14 to decrease. This decrease in voltage allows condenser 105 to send a discharge current through resistor 81 indicated by arrow 116 which resistor thus superimposes upon the grid-control circuit a voltage having the polarity represented by the signs at the ends of arrow 116, which, it will be seen, is such as to reduce the negative control potential impressed upon grid 50 of vacuum tube 44, it having been pointed out that a rise in the generator voltage sets up in this control circuit, between points 103 and 38, a potential tending to make grid 50 more negative with respect to cathode 48 than for normal generator voltage. As the voltage of generator 10 is brought back toward the desired value, the change in the exciter potential thus acts to slow down the corrective action in a manner to effectively prevent overshooting.

Similarly, a decrease in the voltage of generator 10 below the desired value causes, through the regulator action explained, the voltage of exciter 14 to increase. This increase causes condenser 105 to draw a charging current which is indicated by arrow 118, setting up in resistor 81 a voltage drop of the polarity indicated by the signs at the ends of this arrow. It will be seen that this polarity is such that the negative control voltage impressed upon grid 50 of vacuum tube 44 is increased by its action, it having been shown that, for this below-normal voltage condition, there is impressed upon the vacuum-tube control grid a lower negative potential with respect to that of cathode 48 than for normal generator voltage. Thus, it will be evident that anti-hunting means 104 slows down the corrective action as the generator voltage rises to approach the desired value, and overshooting in this direction is likewise prevented.

Experiments show that, in a resistance-coupled amplifier system of high amplification, oscillations will arise. Tests indicate that such oscillations tend to recalibrate the regulator to give the drooping characteristic shown in Fig. 3 by curve 120. Thus, for a given adjustment of the regulating equipment, the regulator will maintain the generator voltage at a slightly higher value when the generator is operating at no load than it will when the generator is operating at the higher-load values which approach the limit of its capacity.

In many applications, it is desirable that a voltage regulator shall act to maintain the potential regulated at a constant value throughout the entire load range of the machine. By combining, with the fundamental portion of the regulating system of my in-

vention already described, a series-connected resistor and a condenser between the grid and cathode elements of each of the amplifier tubes 44 and 45, I have discovered that
 5 such flat regulator characteristic is obtainable due to the suppression of the oscillations in the amplifier. Thus, in the diagram of curves of Fig. 3, the regulator characteristic, the inherent shape of which is shown
 10 at 120, may be shifted, by such means, in position to that of the flat curve illustrated at 121, and the utility of the regulating system may thereby be further broadened. The resistors and condensers mentioned are illustrated in the system of Fig. 1, by well known
 15 symbols at 123, 124, 125 and 126, respectively.

Tests indicate, as before mentioned, that the modifying effect of these elements is attained through a suppression of oscillations,
 20 which are of a plurality of different or various frequencies, and which appear to be set up in the circuits of the amplifying tubes 44 and 45. The curves of Fig. 4, which are reproductions of oscillograms of the exciter-field current, or the current through field
 25 winding 16 in the system of Fig. 1, for a given generator load condition, substantiate this explanation. Thus, section 128, of Fig. 4, taken for the regulating system of my invention without the stabilizing elements
 30 123, 124, 125 and 126 mentioned, indicates that the exciter-field current fluctuates at a high frequency above and below the mean or average value of this current. Section
 35 129 of Fig. 4, which represents the same average value of field current when the regulating system is provided with the stabilizing elements mentioned, shows that one of the effects has been to reduce the magnitude of
 40 these fluctuations, which indicates that the oscillations, in the amplifying system, already mentioned, have been considerably damped out. The result is the shifting of the regulator characteristic from the drooping type, shown by curve 120 of Fig. 3, to
 45 the flat type shown by curve 121 already mentioned.

An additional advantage to be gained through the suppression of oscillations in
 50 the amplifier circuits is the increase in tube life which the reduction of peak-voltage values and insulation stresses affords.

In certain applications, it is desirable that a voltage regulator shall possess a rising-
 55 with-load characteristic. I have discovered that the basic system of my invention, as shown, is capable of producing this result also by the addition of a very simple yet effective addition in the form of an external capacity connected between the grid and
 60 filament elements of the field-current-carrying tubes. Thus, in the diagram of Fig. 1, such modification may be made in the form of a variable condenser 131, connected to
 65 bridge coupling resistor 94. When using

condenser 131, it is found preferable to omit the previously mentioned stabilizing elements 123, 124, 125 and 126.

The modification of the regulator characteristic thereby afforded is illustrated in Fig.
 70 5 in which curve 120 represents, as in Fig. 3, the inherent characteristic of the regulator. The insertion of the proper value of capacity in parallel with coupling resistor 94 shifts the characteristic of the regulator to the flat
 75 value, indicated in Fig. 5 by curve 133, and further increase in the value of this capacity shifts the characteristic to the rising-voltage-
 80 with generator-load type illustrated by curve 134 of the same figure. It will be apparent that intermediate values of characteristic are readily obtainable through a suitable adjustment of variable condenser 131.

It will be evident that the regulating system of my invention, which comprises the
 85 amplifying apparatus designated in Fig. 1 at 43, the excitation-control vacuum tubes influenced thereby and the several auxiliaries mentioned, is not limited in its application to the combination of a direct-current generator
 90 having a separate exciter, but may in addition, be applied to other regulating situations. Thus, in Fig. 2, I have illustrated my invention as applied to the voltage regulation
 95 of a direct-current generator 140, with which no separate exciter is used. It will be observed that, in the energizing circuit of the generator field winding 141, the excitation-control vacuum tubes 142 and 143 are included
 100 and that the amplifying tubes 144 and 145 are disposed in a manner similar to that illustrated at 43 in the system of Fig. 1. The supply source for energizing the heating filaments of these tubes, and for impressing
 105 a suitable direct-current voltage between points 53 and 54 of the resistor group already described, is not shown, since it may be a duplicate of that illustrated in the system of Fig. 1, or its equivalent.

It will be apparent that, in operation, a
 110 rise in the voltage of generator 140 above a desired value, determined by standard voltage source 146, causes to be impressed upon control grid 147 of tube 144 a negative
 115 potential which functions to increase, in the manner already explained, the exciting current in field winding 141, which current is supplied from any suitable source, such as is indicated by direct-current-source
 120 conductors 150 and 151. The voltage of the generator is, accordingly, lowered by this action.

Likewise, it will be evident that a decrease below the desired value of the generator voltage impresses upon control grid 147 of vacuum tube 144 a positive potential which acts
 125 to increase the excitation of the generator and thereby raise its voltage.

It will be noted that, in the system of Fig. 2, no anti-hunting means have been provided, since it will be recognized that there is
 130

inherently little tendency for the regulator to overshoot in its corrective actions, since it acts directly in the generator field winding circuit, instead of to control the excitation of a separate exciter, as in the system of Fig. 1. To eliminate the effect of commutator ripples, transformer 152 may be disposed in the grid-control circuit, in the manner already explained.

It will be noted that, in the system of Fig. 2, I have represented regulator-characteristic modifying means in the form of the series-connected resistor and condenser between the grid and cathode elements of each of the vacuum tubes 144 and 145, these means being designated in Fig. 2 at 154 and 155, respectively. The action of these means is the same as that already described in connection with the system of Fig. 1, to give to the regulator a flat characteristic. It will be understood, however, that, should it be desired, a rising characteristic may likewise be obtained through the use of a variable condenser in the position shown at 131 in the system of Fig. 1, in this, as well as in the subsequently illustrated embodiments of my regulator.

As an alternative method of eliminating the effects of commutator ripples in vacuum-tube voltage-regulating systems applied to direct-current generators, I contemplate the provision of filter equipment interposed between the generator-circuit conductors and the vacuum-tube control-grid circuit. Thus, in the system of Fig. 6, I have illustrated this embodiment, the filter equipment being shown generally at 158, as interposed between circuit conductors 159 and 160 of the generator 161, the voltage of which is to be regulated, and the control circuit of grid element 163 of amplifier tube 164. As in the previously described embodiment, this grid-control circuit includes a standard-voltage battery 166, or other equivalent source, connected in opposition to the regulated generator.

Filter 158 may be of any suitable type well known in the art and, as illustrated, comprises an inductance 167 and two interconnected capacitors 168 and 169 which are so disposed and proportioned electrically as to damp out ripples which commutator action may introduce into the generator voltage impressed upon conductors 159 and 160.

It will be noted that the system of Fig. 6 is similar to that of Fig. 1 already explained, with the exception of the ripple-eliminating means 158 associated with the generator conductors, and the energizing circuit for the anti-hunting means 171 associated with a separate exciter 172. In this circuit, no ripple-eliminating device has been included, although it will be understood that such may be utilized should it be found desirable.

It will be understood that, due to the time

required for filter condensers 168 and 169 to change their average values of charge in accordance with deviations of the generator voltage from the desired value, the system of Fig. 6 will have a somewhat greater tendency to hunt than were this particular type of ripple-eliminating means not utilized. However, by so proportioning the elements of the anti-hunting means 171 that their effectiveness is correspondingly increased, this tendency may be properly dealt with in a manner to permit satisfactory operation of the system.

Nor is the vacuum-tube voltage-regulating system of my invention limited in its application to direct-current generators alone, but it may likewise be utilized with alternating-current generators in the manner indicated in Fig. 7. In Fig. 7, the alternating-current generator 175 supplies voltage to conductors 176 and 177 which serve to energize a transformer 178, the secondary winding of which is connected to a suitable rectifier 179, from which the rectified voltage is passed through a suitable filter 180 before being introduced into the control circuit of vacuum-tube grid 182, which circuit includes the standard-voltage source 183 and the other elements named in the systems hereinbefore described.

It will be apparent that the direct-current voltage derived from the filter-output terminals 184 and 185, which are of positive and negative polarities, respectively, will be directly proportional to the voltage of alternating-current generator 175, and that this voltage, acting in opposition with that of standard battery 183 serves, in the manner already explained, to influence the vacuum-tube regulator in response to changes from a desired value to bring about, through field-current changes for the direct-current exciter 187, the necessary corrective changes in the generator voltage.

It will be noted that a ripple-eliminating transformer 188 has been shown in connection with the anti-hunting means 189 energized by the exciter voltage, although it will be understood that this transformer may not be required in all applications. It should be noted further that some form of anti-hunting means will ordinarily be essential in the system of Fig. 7 to compensate for the time lag introduced by the condensers in the filter 180 which, without such means, would cause serious overshooting of the regulatory actions.

Although 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 limited 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 vacuum-tube voltage-regulating

system for a direct-current generator comprising a control-grid circuit for the vacuum tubes and means for impressing thereon a potential determined by the difference in the generator voltage from a desired value, means for preventing ripples in the generator voltage from influencing said circuit comprising a transformer having a secondary winding disposed in said circuit and a primary winding disposed for energization by the voltage of the generator.

2. In a vacuum-tube voltage-regulating system for a direct-current generator comprising a control-grid circuit for the vacuum-tubes and means for impressing thereon a potential determined by the difference in the generator voltage from a desired value, means for preventing ripples in the generator voltage from influencing the vacuum tubes comprising filter apparatus disposed between said generator and the said vacuum-tube grid circuit.

3. In a vacuum-tube voltage regulator for a direct-current generator, an excitation circuit for said generator, vacuum-tube control means comprising anode and cathode elements disposed to act upon said circuit and a grid-control electrode associated therewith, a circuit for impressing upon said grid electrode a potential proportional to the deviation of the generator voltage from a predetermined value, in combination, a transformer having a primary winding disposed to be energized by the voltage of said generator and a secondary winding disposed in the said grid-electrode circuit in such manner that ripples in the voltage of said generator are so neutralized that the average value only of this voltage is effective in influencing said grid electrode.

4. In a vacuum-tube voltage regulator for a direct-current generator, in combination, an excitation circuit for said generator, thermionic-tube means for the control of said circuit comprising anode and cathode elements disposed therein and a grid-control electrode associated therewith, a standard voltage source, a circuit for impressing upon said grid electrode a potential proportional to the variation of the generator voltage from that of the standard source, a transformer having a primary winding energized by said generator voltage and a secondary winding disposed in said grid circuit in such manner that rapidly recurring variations in the voltage of said generator are so neutralized that only the average value of said voltage is effective in influencing said grid electrode.

5. In a voltage-regulating system for an electrical generator having a field winding and an exciter disposed to supply current to said winding, vacuum-tube means disposed to control the voltage of said exciter, a control-grid circuit for the vacuum tubes and

means for impressing thereon a control potential determined by the magnitude of the generator voltage, anti-hunting means actuated by changes in the exciter voltage for introducing into said grid-control circuit a modifying potential to prevent overshooting of the corrective action, and means for preventing ripples in the exciter voltage from influencing said grid circuit comprising a transformer having a secondary winding disposed in the circuit of said anti-hunting means and a primary winding disposed for energization by the exciter voltage.

6. In combination with a vacuum-tube voltage regulator for a direct-current generator comprising thermionic means having anode and cathode elements and a grid-control electrode disposed to control the excitation of said generator, a standard-voltage source, a circuit for impressing upon the said grid electrode a potential determined by the difference in the generator voltage from that of the standard source, and filter apparatus disposed between said generator and said grid circuit to smooth out ripples in the voltage of said generator so that only the average value of this voltage acts upon said circuit.

7. In a voltage-regulating system for an alternating-current generator, a field winding for said generator, an exciter for energizing said winding, thermionic means having anode and cathode elements and a grid-control electrode disposed to control the voltage of said exciter, a rectifier and filter circuit energized by the generator voltage, a standard-voltage source, a circuit for impressing upon said grid electrode a direct-current potential determined by the difference in the output voltage of said filter circuit and that of the standard source, anti-hunting means actuated by changes in the exciter voltage for introducing into said grid-electrode circuit a modifying potential to prevent overshooting of the corrective action, and means for preventing ripples in the exciter voltage from influencing said circuit comprising a transformer having a secondary winding disposed in the circuit of said anti-hunting means and a primary winding disposed for energization by the exciter voltage.

8. In a voltage-regulating system for a direct-current generator, a field winding for said generator, an exciter for energizing said winding, thermionic means, having anode and cathode elements and a grid-control electrode disposed to control the voltage of said exciter, a standard-voltage source, a circuit for impressing upon said grid electrode a potential determined by the difference in the generator voltage and that of the standard source, a transformer having a primary winding disposed to be energized by the voltage of said generator and a secondary wind-

ing disposed in the said grid-electrode circuit in such manner that ripples in the generator voltage are neutralized, anti-hunting means actuated by changes in the exciter voltage for so modifying the grid-control potential as to prevent overshooting of the corrective action, and a transformer having a primary winding disposed to be energized by the voltage of said exciter, and a secondary winding disposed in the circuit of said anti-hunting means to eliminate therein the effect of ripples in the exciter voltage.

9. In a voltage-regulating system for an electrical generator, a field winding for said generator, an exciter for energizing said winding, thermionic means having anode and cathode elements and a grid-control electrode disposed to control the voltage of said exciter, a circuit for impressing upon said grid electrode a potential determined by the difference in the generator voltage from a desired value, anti-hunting means comprising a resistor and a condenser connected in series for energization by the voltage of said exciter, said resistor being included in the grid-electrode circuit to modify the grid control potential in accordance with the rate and direction of change of the said exciter voltage, and a transformer having a primary winding energized by the voltage of said exciter and a secondary winding disposed in the circuit of the said resistor and condenser to eliminate therein the effect of ripples in the exciter voltage.

10. In a voltage-regulating system for a direct-current generator, a field winding for said generator, an exciter for energizing said winding, thermionic means having anode and cathode elements and a grid-control electrode disposed to control the voltage of said exciter, a standard-voltage source, a circuit for impressing upon said grid electrode a potential determined by the difference in the generator voltage and that of the standard source, filter apparatus disposed between said generator and said grid circuit to smooth out ripples in the voltage of said generator so that only the average value of this voltage acts upon said circuit, and anti-hunting means comprising a resistor and a condenser connected in series for energization by the voltage of said exciter, said resistor being included in the grid-electrode circuit to modify the grid-control potential in accordance with the rate and direction of change of the said exciter voltage.

11. In a voltage regulator comprising, in combination with an electrical generator having a field winding and an energizing circuit therefor, one or more vacuum tubes, each having an anode, a cathode, and a control-grid electrode disposed to control said circuit, an amplifier comprising a plurality of resistance-coupled vacuum tubes each having an anode, a cathode, a screen-grid,

and a control-grid element, means for connecting the output side of said amplifier to the grids of the vacuum tubes disposed to control said field-winding circuit, means for impressing upon the input side of said amplifier a direct-current potential determined by the difference in the generator voltage from a predetermined value, and means for changing the characteristic of said regulator from the inherent drooping type to a flat or constant-regulated-voltage-with-load type comprising a resistor and a condenser connected in series between the grid and cathode elements of each of the vacuum tubes in the said amplifier.

12. In a voltage regulator comprising, in combination with an electrical generator having a field winding and an energizing circuit therefor, thermionic-tube means disposed to control said circuit, a controlling circuit for said tube means, an amplifier comprising a plurality of resistance-coupled vacuum tubes, each having an anode, a cathode, and a control-grid element, means for connecting the output side of said amplifier to influence the controlling circuit for the said thermionic-tube means, means for impressing upon the input side of said amplifier a direct-current potential determined by the difference in the generator voltage from a predetermined desired value, and means for changing the characteristic of said regulator from the inherent drooping type to a flat or constant-regulated-voltage-with-load type comprising a resistor and a condenser connected in series between the grid and cathode elements of each of the vacuum tubes in said amplifier.

13. In a voltage regulator comprising, in combination with an electrical generator having a field winding and an energizing circuit therefor, one or more vacuum tubes each having a grid element and plate and filament elements disposed to control said circuit, an amplifier comprising a plurality of resistance-coupled vacuum tubes, each having an anode, a cathode, a screen-grid and a control-grid element, means for connecting the output side of said amplifier to the grids of the vacuum tubes disposed to control said field-winding circuit, means for impressing upon the input side of said amplifier a direct-current potential determined by the difference in the generator voltage from a predetermined desired value, and means for changing the characteristic of said regulator from the inherent drooping type to a constant- or rising-regulated-voltage-with-load type comprising an adjustable electro-static capacity device connected between the grid and filament elements of the vacuum tubes disposed to control the said generator-field-winding-energizing circuit, an increase in the capacity of said device tending to shift

the regulator characteristic in the rising direction.

14. A vacuum-tube voltage regulator comprising, in combination with an electrical generator having a field winding and an energizing circuit therefor, one or more vacuum tubes, each having an anode, a cathode, and a control-grid element disposed to control said circuit, a resistance-coupled amplifier comprising a plurality of vacuum tubes each having an anode, a cathode, a screen-grid and a control-grid electrode, a source of power for maintaining potential differences between, and for energizing the circuits of, the elements of said amplifier tubes, means for connecting the output side of said amplifier to act upon the grids of the vacuum tubes disposed to control said field-winding circuit, and means for impressing upon the input side of said amplifier a direct-current potential determined by the difference in the generator voltage from a predetermined value, the potential biases on the screen-grid elements of the respective amplifier tubes being of such values that changes in the voltage of said power source do not vary the amplifying characteristics of the regulator.

15. A voltage regulator comprising, in combination with an electrical generator having a field winding and an energizing circuit therefor, one or more vacuum tubes, each having an anode, a cathode and a control-grid element disposed to control said circuit, an amplifier comprising a plurality of vacuum tubes, each having an anode, a cathode, a screen-grid and control-grid electrode, and interconnecting circuits of the resistance-coupled type therefor, a source of power for maintaining direct-current potential between the elements of said amplifier tubes, the potential biases on the screen-grid elements being of such respective values that changes in the voltage of said power source do not affect the amplifying characteristics of said amplifier, means for connecting the output side of said amplifier with the grids of the vacuum tubes associated with said field-winding circuit, and means for impressing upon the input side of said amplifier a direct-current potential determined by the difference in the generator voltage from a predetermined value.

16. In a voltage regulator comprising, in combination with an electrical generator having a field winding and an energizing circuit therefor, thermionic-tube means disposed to control said circuit, a controlling circuit for said means, an amplifier having an output circuit disposed to influence said controlling circuit, said amplifier comprising two vacuum tubes, each having an anode, a cathode, a cathode-heating, a screen-grid and a control-grid element, a source of power for maintaining potential differences between, and for energizing the circuits of the ele-

ments of said amplifier tubes, resistance-coupling circuits for said tubes disposed in such manner that a change in control-grid bias voltage on the first or input tube in the positive direction acts to change the grid bias of the second or output tube in the negative direction, and vice versa, means for impressing upon the grid of said first amplifier tube a direct-current potential determined by the difference in the generator voltage from a predetermined desired value, the vacuum tubes of the regulator being so disposed, in the manner recited, that changes in the voltage magnitude of said tube power-supply source produce no change in the amplifying characteristics of the regulator.

17. In a regulating system for a dynamo-electric machine having an excitation circuit, a plurality of vacuum tubes, each having an anode, a cathode and a control-grid electrode disposed in parallel for controlling said excitation circuit, a grid circuit for impressing upon the grid electrodes of the vacuum tubes a potential determined by a characteristic of said dynamo-electric machine, and means for suppressing oscillations and circulating or other currents in the tube circuits which act to reduce the current capacity of the combination comprising a resistor disposed between the grid electrode of each tube and a conductor of said grid circuit.

18. In a regulating system for a dynamo-electric machine comprising a plurality of parallel-connected vacuum tubes, each having an anode, a cathode and a control-grid electrode, disposed to control an excitation circuit of said machine, means for supplying to the grids of said tubes a control potential determined by a characteristic of said machine comprising a circuit and a resistor disposed between the grid electrode of each tube and a conductor of said circuit for the purpose of suppressing local tube currents which act to reduce the total current capacity of the said combination of parallel-connected tubes.

In testimony whereof, I have hereunto subscribed my name this 4th day of June 1931.

FINN H. GULLIKSEN.