Feb. 24, 1953 J. E. WILLIAMS 2,629,854

ELECTRONIC VOLTAGE REGULATOR

Filed Jan. 29, 1952 2 SHEETS—SHEET 1

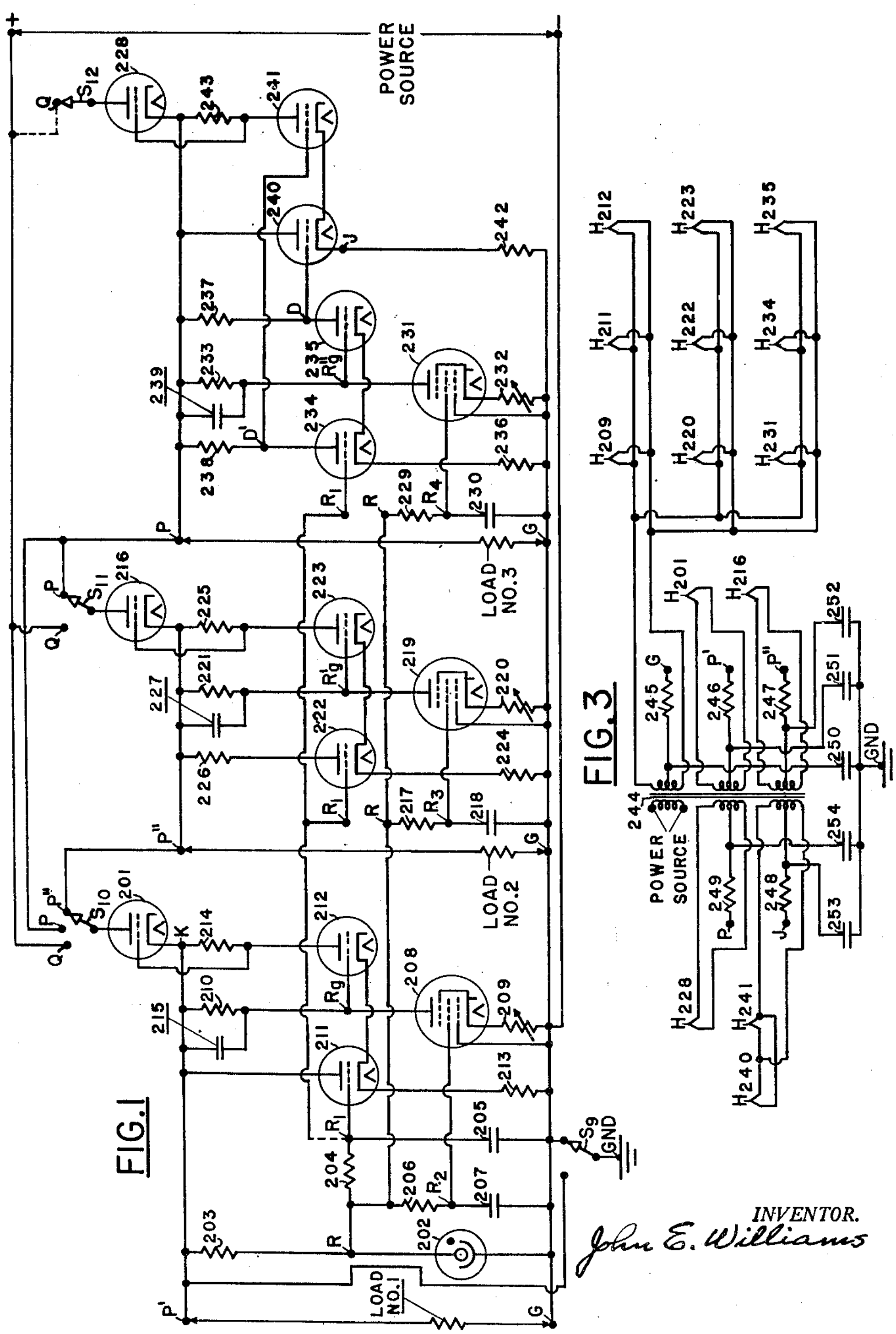

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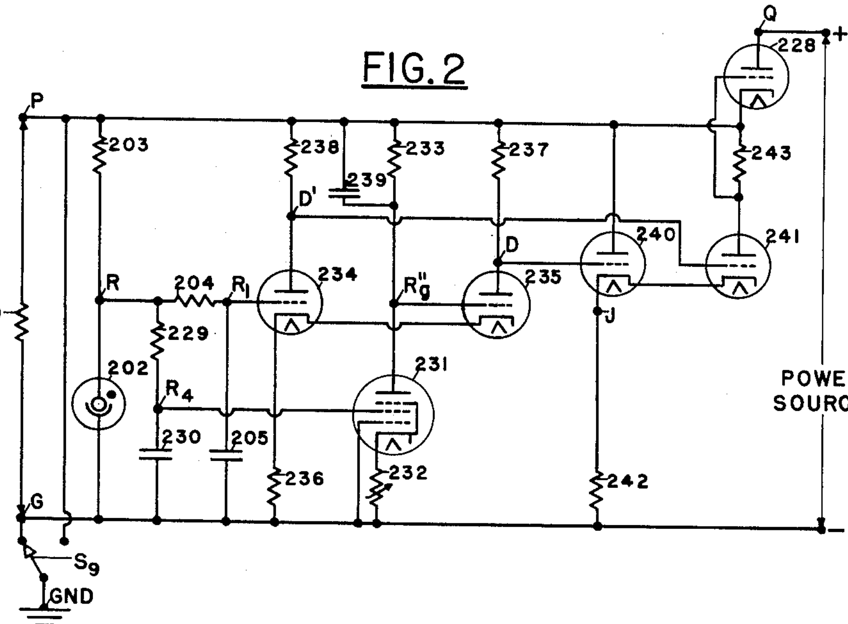
FIG. 2



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ELECTRONIC VOLTAGE REGULATOR

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26 Claims. (Cl. 323—22)

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The present invention relates to an electronic voltage regulator, and more particularly to an electronic voltage regulator utilizing a constant voltage drop across the plate load resistance of a pentode to effect substantially exact transference of residual error voltages as excitation actuating corrective action.

In the known art electronic voltage regulators depend on the variable plate resistance of a current regulating tube interposed between the positive energizing terminal of a power source and the positive output terminal of the regulator, the control-grid voltage of the current regulating tube being suitably actuated by variable plate current of an auxiliary control tube in response to excitation derived by sampling the regulated voltage delivered to the voltage regulator load.

Three general methods have been proposed to provide effective excitation of the control-grid of a control tube, all three methods requiring that the cathode potential of the control tube be held substantially positive in relation to the potential of the voltage regulator negative output terminal. The first method then shunts a resistance network across the positive and negative output terminals and obtains control-grid excitation of the control tube by potentiometer means, only a portion of the error voltage being available to impose corrective action within the voltage regulating array. The second method connects the anode of a gaseous discharge tube to the regulator positive output terminal and completes energization of said gaseous discharge tube by connecting the cathode thereof through a voltage dropping resistor to the regulator negative output terminal, the control-grid of the control tube being excited by connection to the cathode of the gaseous discharge tube. While the second method transfers the full value of error voltage as excitation to the control-grid of the control tube, this second method suffers by also including random voltages originating in the gaseous discharge tube which are then amplified, thus limiting the availability of corrective action. The third method utilizes a complex network including a gaseous discharge tube, a filtering section and an auxiliary triode section to establish a stable voltage above ground potential at the cathode of a first control triode section, the auxiliary triode section and the control triode section being contained in a twin triode tube having a cathode common to both triode sections. The third method then utilizes potentiometer means shunted across the positive and negative output terminals of the array to obtain control-grid excitation of the first control tube. While the third method substantially overcomes the adverse effects of random voltages originating in the gaseous discharge tube, here again only a portion of the error voltage is made available for initiating corrective action.

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The major object of the present invention is to provide an electronic voltage regulator in which the disadvantages above referred to are substantially avoided.

Another object of the present invention is to provide two regulated voltages derived from a common power source and, in a direct-coupled sweep generator and associated direct current amplifier, essential; firstly, to generation of a linear sweep voltage and, secondly, to conversion of the generated sweep voltage to full-wave relations symmetrical with respect to a conversion midpoint potential, the conversion midpoint potential being required to maintain a substantially constant value.

A further object of the present invention is to provide a ballast regulator capable of maintaining a constant potential at a particular electrical point in an interlocking amplifier as amplifier energizing current through that particular electrical point varies in cancellation of amplifier phase-shift.

According to the present invention and in addition to the gaseous discharge tube, filter section and auxiliary triode cited above, there is provided an exciter and transfer pentode so arranged as to effect substantially exact transference of residual voltage-regulated error voltages to the control-grid of a comparator tube, thereby actuating optimum corrective action within the voltage regulating array.

Before proceeding to a detailed description of the present invention let it first particularly be noted that with the control-grid, screen-grid and suppressor-grid potentials of a pentode held constant each with respect to cathode potential, the plate current, or anode current, of a pentode is substantially independent of plate voltage. Accordingly, the voltage drop across a plate load resistor related to a pentode so operating is substantially constant, and changes in potential occurring at the positive terminal of plate supply voltage are transferred to the pentode plate with substantial exactness and without introducing loss of transit time. Electronic tubes capable of so operating particularly include types 6SJ7, 12SJ7, 6SH7 and 12SH7.

Other and further objects of this invention will be understood from the specification herein-after following by reference to the accompanying drawings in which:

Fig. 1 is a schematic circuit diagram of a voltage regulator having a basic regulating array incorporating an exciter pentode, optionally capable of operation with either the positive or negative voltage regulator output terminal connected to ground potential, and further capable of energization; firstly, by an independent power source, secondly, in parallel as one of a plurality of voltage regulating arrays and, thirdly, as the low potential section of a plurality of voltage regulating arrays energized in series-connected cascade.

Fig. 2 is a schematic circuit diagram of a voltage regulator, combining in one unit the basic means of Fig. 1 establishing reference voltages and the means limiting the plate heat dissipation of component tubes at high values of regulated voltage.

Fig. 3 is a schematic circuit diagram showing means for heating the cathodes of the component electronic tubes of Figs. 1 and 2.

In order that this invention may clearly be understood and readily placed in effect it will now more fully be described with reference to preferred illustrative embodiments thereof as shown in the several figures wherein like circuit characters refer to like parts or circuit points of like relationship.

Referring now to Fig. 1, a direct current power source is first indicated with its positive energizing terminal connected to circuit point Q and its negative energizing terminal connected to circuit point G, circuit point G being the voltage regulator negative output terminal and having a potential particular thereto, the potential particular to circuit point G being taken herein as the voltage regulator primary reference potential. Circuit characters **201** and S_{10} respectively indicate a current regulating triode and a three position selector switch, the triode plate being energized by connection to the moveable arm of selector switch S_{10} and the cathode of the current regulating triode being connected at circuit point K to circuit point P′, circuit point P′ being the voltage regulator first-load positive output terminal and having potential particular thereto, the potential particular to circuit point P′ being the voltage regulator secondary reference potential, the difference in potential between the secondary and primary reference potentials being the voltage regulator first-load output voltage and including a residual difference in potential constituting a residual error voltage. Circuit characters P, P″, and Q respectively indicate three optional energizing terminals of selector switch S_{10}. Circuit character **203** indicates a voltage dropping resistor connected at one end to circuit point P′ and at the other end to circuit point R. Circuit character **202** indicates a cold-cathode gaseous-discharge tube with its cathode connected to circuit point G and its anode energized by connection to circuit point R, thereby establishing a voltage regulator preliminary reference voltage between circuit points R and G, circuit point R being the voltage regulator preliminary reference point and having a preliminary reference potential particular thereto.

Circuit characters **204** and **205** respectively indicate a filter resistor and a filter capacitor series-connected at circuit point R_1, the opposite end of filter resistor **204** being energized by connection to circuit point R and the opposite terminal of filter capacitor **205** being connected to regulator

negative output terminal G, circuit point R_1 being the voltage regulator first stabilized reference point and having a first stabilized reference potential particular thereto, the difference in potential between the voltage regulator first stabilized and primary reference potentials being the voltage regulator first stabilized reference voltage. Circuit characters **206** and **207** respectively indicate a filter resistor and a filter capacitor series-connected at circuit point R_2, the opposite end of filter resistor **206** being energized by connection to circuit point R and the opposite terminal of filter capacitor **207** being connected to regulator negative terminal G, circuit point R_2 being the voltage regulator first screen-grid voltage supply terminal and having a second stabilized potential particular thereto, the potential difference between circuit points R_2 and G being the voltage regulator first screen-grid supply voltage. Circuit character **208** indicates an exciter pentode, the suppressor-grid thereof being connected to the cathode thereof, the control-grid thereof being connected to regulator negative output terminal G, and the screen-grid thereof being connected to circuit point R_2. Circuit character **209** indicates a manually-variable self-biasing resistor with one end thereof connected to regulator negative output terminal G and with the opposite end thereof connected to the cathode of exciter pentode **208**. Circuit character **210** indicates a transfer or comparator resistor with one end thereof energized by connection to circuit point P′ and with the opposite end thereof connected at circuit point R_g to the plate of exciter pentode **208**, resistor **210** being the plate load resistor of exciter pentode **208**, also being the voltage regulator comparator resistor, and circuit point R_g being the voltage regulator comparator point and having voltage regulator comparator potential particular thereto. For each manual adjustment of self-biasing resistor **209**, the suppressor-grid screen-grid and control-grid voltages of exciter pentode **208** are held constant, the plate current of exciter pentode **208** is held constant, the voltage drop across exciter pentode plate load resistor **210** is held constant, and residual error voltages occurring at regulator positive output terminal P′ are transferred with substantial exactness and without loss of transit time to voltage regulator comparator point R_g. Circuit character **215** indicates a filter capacitor shunt-connected across plate load resistor **210** to deny amplification of microphonic and Shott-effect voltages originating in exciter pentode **208**.

More particularly, exciter pentode **208** energized and controlled as described above constitutes pentode means transferring voltage regulator residual error voltages with substantial exactness from voltage regulator positive output terminal P′ to voltage regulator comparator point R_g. Circuit character **211** indicates a reference triode with the plate thereof energized by connection to voltage regulator positive output terminal P′, with the cathode thereof connected through voltage-dropping cathode reference resistor **213** to voltage regulator negative output terminal G, and with the control-grid thereof connected to voltage regulator first stabilized reference point R_1 establishing at the cathode of reference triode **211** a substantially constant first cathode reference potential and establishing across reference resistor **213** a substantially constant first cathode reference voltage.

Circuit character **212** indicates a comparator triode with the plate thereof energized by connection through voltage dropping resistor 214 to the regulator positive output terminal P', with the cathode thereof connected to the cathode of reference triode 211, and with the control-grid thereof connected to voltage regulator comparator point R_g. A difference of potential exists between voltage regulator first cathode reference potential and voltage regulator comparator potential, and constitutes voltage regulator comparator voltage which, for each manual adjustment of exciter pentode self-biasing resistor 209, includes a voltage regulator average comparator voltage and the instantaneous voltage regulator first-load residual error voltage. The plate current of comparator triode 212, being responsive to voltage regulator comparator voltage, establishes across plate load resistor 214 a voltage regulator average control voltage and also establishes thereacross an amplified and inverted voltage regulator error-control voltage responsive to voltage regulator residual error voltage. The control-grid of current regulating triode 201 being connected to the plate of triode 212, the plate current of current regulating triode 201 is responsive to voltage regulator average control voltage and to voltage regulator error control voltage. The cathode of triode 201 being electrically common with the positive output terminal, the regulated plate current of triode 201 divides at circuit point P', into a voltage regulator exciter current and a voltage regulator load current delivered to the indicated voltage regulator load, the voltage regulator output voltage being maintained substantially constant by the controlled conductance of current regulating triode 201, any changes in voltage regulator exciter current being negligible in comparison with permissible changes in voltage regulator load current.

More particularly comparator triode 212 connected, energized and excited as described above, constitutes amplifier means responsive to voltage regulator comparator voltage as defined and effectively controlling the conductance of current regulating triode 201. Also more particularly exciter pentode 208, connected, energized and excited as described above, additionally constitutes pentode means including a manually-variable self-biasing resistor controlling desired adjustment of voltage regulator output voltage. Circuit characters S_9 and GND respectively indicate a two-point selector switch and ground potential, the moveable arm of selector switch S_9 being connected to ground potential and the two selective terminals of switch S_9 being respectively connected one each to voltage regulator output terminals G and P', selectively providing operation of the voltage regulator above or below ground potential.

With further reference to Fig. 1, I have found that suitable results may be obtained by employing the following tubes and circuit constants: power source voltage—400 to 600 volts; load No. 1 voltage 250 volts, adjustable; tube 202—type OB2; tubes 211 and 212—each one half of type 6SC7 or 12SC7; tube 208—type 6SJ7 or 12SJ7; tube 201—type 6L6 triode-connected, or a plurality of triode-connected 6L6 tubes connected in parallel; resistor 204—2 megohms, 1 watt, composition; adjustable resistor 209—1000 ohms, preferably Wirt type GCA potentiometer; resistor 203—20,000 ohms, 1 watt, preferably Shallcross type BX193E; resistor 206—50,000 ohms, 1 watt, preferably Shallcross type BX193E; resistor 210—75,000 ohms, 1 watt, preferably Shallcross type BX193E; resistor 213—50,000 ohms, 1 watt, preferably Shallcross type BX193E; resistor 214—500,000 ohms, 1 watt, preferably Shallcross type BX193E; capacitors 205 and 207 each 4 microfarads, paper, oil-filled, preferably Aerovox type 609 MSB; capacitor 215—0.1 microfarad, paper, oil-filled tubular, preferably Aerovox type 1039 M.

Continuing with reference to Fig. 1, I have observed, and it will be clear to those versed in the art: that the filter means including circuit elements 204 and 205 converts the preliminary reference voltage established between preliminary reference point R and primary reference point G into a first stable reference voltage between first stabilized reference point R_1 and primary reference point G; that a first cathode reference potential common to the cathodes of tubes 211 and 212 is substantially established above primary reference potential by the plate current of reference triode 211 flowing through first cathode reference resistor 213, as for instance 50,000 (ohms) times .00207+.00004 (amps.)=105.5 (volts), 0.00207 ampere being the plate current of reference triode 211, and 0.00004 ampere being the plate current of comparator triode 212, corresponding to an average control voltage of 20 volts developed across resistor 214; that the limiting values of regulated voltage across load No. 1 are established, in the case of the lower limit, by plate voltage sufficient to the maintenance of required plate current through reference triode 211 under class A conditions, and in the case of the upper limit, by the allowable plate heat dissipation of tube 211, the two limits approximating a selective range of regulated voltage between 225 and 600 volts; that the lower limit of regulated voltage may be dropped approximately to 175 volts by employment of a type 6J5 or 12J5 tube as reference triode 211 in combination with a type 6SF5 or 12SF5 as tube 212; that the filter means including circuit elements 206 and 207 additionally converts the preliminary reference voltage established between preliminary reference point R and primary reference point G into a first screen-grid supply voltage between circuit points R_2 and G, stabilized for each manual adjustment of self-biasing resistor 209; that the cathode potential of comparator triode 212 being established by first cathode reference voltage above primary reference potential, and the control-grid potential of comparator triode 212 being established below secondary reference potential by the voltage drop across comparator resistor 210, also secondary reference potential at circuit point P' being voltage-regulated with respect to primary reference potential at circuit point G, comparator voltage, or more particularly comparator triode control-grid voltage, is responsive to intentional change in exciter pentode plate current; that intentional change of exciter pentode plate current may conveniently and preferably be effected by variation of the value of self-biasing resistor 209 or may alternatively and less satisfactorily be effected by potentiometer means returning the exciter pentode control-grid to the moveable arm of a potentiometer comprising self-bias resistor 209; that intentional change in comparator voltage employing potentiometer means involving comparator resistor 210 is theoretically possible but practically undesirable; that pentode means including a manually-variable self-biasing resistor provides convenient and effective control of voltage regulator output voltage as desired; that residual changes of potential occurring at the regulator positive output terminal and taken with reference to primary reference potential at the regulator negative output terminal constitute residual error voltages; that pentode means including a comparator resistor (voltage-dropping plate load resistor) conveniently, effectively, and with substantial exactness, effects transfer of residual error voltages from the potential level of the regulator positive output terminal to the potential level of the voltage regulator comparator point, thereby and with substantial exactness, including voltage regulator residual error voltages as a component of comparator triode control-grid voltage; that the voltage regulating array of Fig. 1 may effectively be employed to provide a regulated voltage above or below ground potential; and that the corrective advantage of the voltage regulating array, utilizing the tubes and circuit constants indicated, approximates 480 times and is adequate in effecting energization of a linear sweep generator.

Continuing with reference to Fig. 1, an additional or second-load voltage regulating array is energized by connecting terminals Q, P, P'', G, R and R_1 respectively to identically designate terminals of the first-load array, as shown, the primary, preliminary and first stabilized reference potentials of the first-load voltage regulating array now being shared with the second-load voltage regulating array, i. e., G, R and R_1 and the preliminary and first stabilized reference voltages of the first-load now being common to the circuits of the first-load and second-load arrays. Circuit characters P'' and G respectively indicate positive and negative output terminals and an independent voltage-regulated second load is shown connected therebetween. Circuit characters **216** and S_{11} respectively indicate a current regulating triode and a two position selector switch, the plate of current regulating triode **216** being energized by connection to the moveable arm of selector switch S_{11} and the cathode of current regulating triode **216** being connected to regulator positive output terminal P''. Circuit characters Q and P respectively indicate two optional positive energizing terminals of S_{11}. Circuit characters **217** and **218** correspond directly to **206** and **207** of the first-load array with R_3 corresponding to R_2 and having thereon a potential relative to G, the potential difference being referred to as the second screen-grid supply voltage. The voltage transferring means corresponds directly to that of the first-load array and comprises elements **221**, **227**, **219** and **220** similar to previously-described elements **210**, **215**, **208** and **209**, the circuit point R_g' corresponding to R_g. By this means the residual error voltage between G and P'' is transferred with substantial exactness to R_g'.

Circuit characters **222**, **224**, **223**, **225** and **216** likewise correspond in function and arrangement to similar elements **211**, **213**, **212**, **214** and **201**. There is thus provided an independent output across terminals P''—G, employing only **203** and **202** with filter means **204** and **205** of the first-load array, or a cascade of regulation with second-load terminal P'' connected to P'' of S_{10} and S_{10} contacting P'', S_{11} providing energization for the cascade. An additional resistance element **226** is shown between P'' and the plate of the reference triode **222**, use of which as a voltage-dropping protective resistor is optional for limiting the plate dissipation if required, the preferred value thereof being zero ohms.

As thus described, it is seen that for each manual adjustment of the exciter pentode self-biasing resistor **220**, a second comparator voltage, when first-load and second-load arrays are in cascade, is established at R_g', which includes a second average comparator voltage and a second instantaneous residual error voltage. The plate current of triode **223** being responsive thereto establishes a second average control voltage and a second error control voltage responsive to the instantaneous residual error voltage, both being impressed across resistor **225**, as across **214** of the first-load array.

The plate current of comparator triode **223**, being responsive to voltage regulator second comparator voltage, establishes across plate load resistor **225** a second voltage regulator average control voltage, and also establishes across plate load resistor **225** an amplified and inverted second voltage regulator error control voltage responsive to second voltage regulator instantaneous residual error voltage. The control-grid of current regulating triode **216** being connected to the plate of comparator and control triode **223**, the plate current of current regulating triode **216** is directly responsive to both second voltage regulator average control voltage and to second voltage regulator error control voltage, and the controlled conductance of triode **216** functions ot maintain a substantially constant second voltage regulator output voltage as desired. More particularly, comparator triode **223**, connected, energized and excited as described above, constitutes amplifier means responsive to voltage regulator second comparator voltage effectively controlling the conductance of current regulating triode **216**. Also more particularly, exciter pentode **219**, connected, energized and excited as described above, additionally constitutes pentode means including a manually variable self-biasing resistor controlling desired adjustment of second voltage regulator output voltage.

With further reference to the second-load array, I have found that suitable results may be obtained by employing the following tubes and circuit constants; power source voltage—750 volts D. C.; load No. 2 voltage—500 volts; voltage regulator negative output terminal G connected to ground potential; selector switch S_{11} activated on positive energizing terminal Q; selector switch S_{10} activated on positive energizing terminal P'', a portion of second voltage regulator load current being utilized to energize a first voltage regulator in series-connected cascade; tubes **222** and **223**—each, one half of type 6SC7 or 12SC7; tube **216**—type 6L6 triode-connected or a plurality of triode-connected 6L6 type tubes connected in parallel; resistor **217**—50,000 ohms, 1 watt, preferably Shallcross type BX193E; resistor **226**—zero ohms; resistor **224**—50,000 ohms, 1 watt, preferably Shallcross type BX193E; resistor **225**—500,000 ohms, 1 watt, preferably Shallcross type BX193E; resistor **221**—200,000 ohms, 1 watt, preferably Shallcross type BX193E; variable resistor **220**—1,000 ohms, preferably Wirt potentiometer type GCA; capacitor **218**—4 microfarads, paper, oil-filled, preferably Aerovox type 609 MSB; capacitor **227**—0.1 microfarad, paper, oil-filled tubular, preferably Aerovox type 1089M.

Continuing with reference to Fig. 1, I have observed, and it will be clear to those versed in the art: that the second-load voltage regulating array is of the same character as the first-load voltage regulating array, shares utilization of the preliminary and first stabilized reference voltages of the first-load array, provides independent filter means establishing a second screen-grid supply voltage, and, while capable of operation in parallel-connected energization, is primarily intended to function as an intermediate unit of a plurality of related voltage regulating arrays, energized in series-connected cascade, by a single power source; that the intermediate voltage regulating array of Fig. 1 utilizing the tubes and circuit constants indicated above provides a corrective advantage approximating 480; that the first-load and second-load voltage regulating arrays of Fig. 1, when energized in series-connected cascade, combine to further reduce the residual error voltage of the first-load array of Fig. 1, as for instance, now providing cumulative corrective advantage theoretically approximating 225,600, and when so energized are adequate for energization of a cathode ray tube direct-connected linear sweep generator and related conversion of the single-sided generated sweep voltage to full-wave relations, customary diode-locking provisions no longer being required.

A further additional voltage regulating array is energized by connecting terminals Q, P, G, R and R_1 thereof respectively to other identically indicated terminals of Fig. 1, as shown, the primary, preliminary, and first stabilized reference potentials now being shared with the third-load voltage regulating array, and the preliminary and first stabilized reference voltages now being common to the circuits of all arrays. Circuit characters P and G respectively indicate positive and negative output terminals and an independent voltage regulated load, i. e., load No. 3, is shown connected therebetween. Circuit characters 228 and S_{12} respectively indicate a current regulating triode and an energizing switch, circuit character Q indicating a selective positive energizing terminal of switch S_{12}, the plate of current regulating triode 228 being energized by connection to the moveable arm of switch S_{12}, and the cathode of triode 228 being connected to third voltage regulator positive output terminal P. Circuit characters 229 and 230 correspond to 206 and 207 of Fig. 1 being a filter resistor and a filter capacitor series-connected between R and G at circuit point R_4 which is voltage regulator third screen-grid voltage supply terminal having a fourth stabilized potential particular thereto, the potential difference between circuit points R_4 and G being third screen-grid supply voltage. Circuit character 231, like 208, indicates an exciter pentode with the suppressor-grid connected to the cathode thereof, control-grid connected to G, and with the screen-grid thereof energized by connection to voltage regulator third screen-grid voltage supply terminal R_4. Circuit character 232 indicates a manually-variable self-biasing resistor connected as 209 of Fig. 1. Circuit character 233 corresponds to 210 of Fig. 1 and is a voltage-dropping comparator resistor, connected to P and to the plate of exciter pentode 231, circuit point R_g'' corresponding to R_g being voltage regulator third comparator point and having a voltage regulator third comparator potential particular thereto. For each manual adjustment of self-biasing resistor 232, the control-grid, screen-grid, and suppressor-grid voltages of exciter pentode 231 are held constant, residual error voltages occurring at the potential level of regulator positive output terminal P being transferred with substantial exactness to the potential level of regulator third comparator point R_g''. Circuit character 239 indicates a filter capacitor shunt-connected across regulator third comparator resistor 233 to deny amplification of microphonic and Shott-effect voltages originating in excitor pentode 231. Circuit characters 234 and 235 respectively indicate the third regulator first reference triode and the third regulator comparator triode, the cathodes of triodes 234 and 235 being connected to a common electrical point, said common electrical point being connected through third regulator first cathode reference resistor 236 to third regulator negative output terminal G. Circuit characters 237 and 238 indicate voltage-dropping, protective, preferably equal, plate load resistors, each being connected at one end thereof to P, resistor 237 being connected at the opposite end thereof to the plate of comparator triode 235, resistor 238 being connected at the opposite end thereof to the plate of reference triode 234, the cathodes of reference and comparator triodes 234 and 235 now having a first cathode reference potential both common and particular thereto, the control-grid of reference triode 234 being excited by connection to first stabilized voltage reference terminal R_1, and the control-grid of comparator triode 235 being excited by connection to third regulator comparator point R_g''. A difference of potential exists between third regulator first cathode reference potential and third regulator comparator potential, constituting third regulator comparator voltage and including third regulator average comparator voltage and third regulator instantaneous residual error voltage. Reference triode 234, being responsive to voltage regulator first stabilized reference voltage, and comparator triode 235, being responsive both to voltage regulator third comparator potential and to third regulator comparator voltage, act to establish, between the plates of triodes 234 and 235, a voltage regulator intermediate voltage, which is differentially variable and amplified as excited by changes in third regulator comparator voltage. Circuit characters 240 and 241 respectively indicate the third regulator second reference triode and the third regulator control triode, the plate of triode 240 being energized by connection to output terminal P, the plate of triode 241 being energized by connection through third regulator control resistor 243 to output terminal P, the cathodes of triodes 240 and 241 being connected together at common electrical point J and further connected through third regulator second cathode reference resistor 242 to regulator negative output terminal G, circuit point J being a third regulator second cathode reference point having a third regulator second cathode reference potential particular thereto, the control-grid of reference triode 240 being excited by connection at circuit point D to the plate of comparator triode 235, the control-grid of control-triode 241 being excited by connection at circuit point D′ to the plate of triode 234, and the control-grid of current regulating triode 228 being connected to the plate of control triode 241.

Triodes 234, 235, 240 and 241, energized and controlled as described above constitute amplifier means including a control resistor, responsive to third regulator residual error voltage and effectively controlling the conductance of current regulating triode 228 to maintain a substantially constant third regulator output voltage. Triodes 234, 235, 240 and 241 also constitute amplifier means including a control resistor, responsive to third regulator average comparator voltage and effectively controlling the conductance of third regulator output triode 228 to establish third regulator average output voltage.

With further reference to the third-load array, I have found suitable results may be obtained by employing the following tubes and circuit constant; power source voltage—1000 volts D. C.; load No. 3 voltage—750 volts; voltage regulator negative output terminal G connected to ground potential; selector switch S_{12} activated on positive energizing terminal Q; selector switch S_{11} activated on positive energizing terminal P; selector switch S_{10} activated on positive energizing terminal P'', a portion of third regulator load current being utilized to energize the intermediate voltage regulator, and a portion of intermediate voltage regulator load current being utilized to energize the first voltage regulator; tube **231**—type 6SJ7 or 12SJ7; tubes **234** and **235**—each one half of type 6SC7 or 12SC7; tubes **240** and **241**—each one half of type 6SC7 or 12SC7; tube **228**—type 6L6, triode-connected, or a plurality of triode-connected type 6L6 tubes connected in parallel; variable resistor **232**—1000 ohms, preferably Wirt type GCA potentiometer; resistors **229** and **236**—each 50,000 ohms, 1 watt, preferably Shallcross type BX193E; resistor **233**—325,000 ohms, 2 watts, preferably Shallcross type BX196E; resistors **237** and **238**—each 325,000 ohms, 1 watt, preferably Shallcross type BX193E; resistor **243**—500,000 ohms, 1 watt, preferably Shallcross type BX193E; capacitor **230**—4 microfarads, paper, oil-filled, preferably Aerovox type 609 MSB; capacitor 239—0.1 microfarad, paper, oil-filled tubular, preferably Aerovox type 1089M.

Continuing with reference to Fig. 1, I have observed and it will be clear to those versed in the art; that the third-load voltage regulating array is of the same character as the first-load voltage regulating array extended to include means limiting the plate heat dissipation of component tubes when operating at higher values of regulated output voltage, shares utilization of the preliminary and first stabilized reference voltages, provides independent filter means establishing a third screen-grid supply voltage, and, while capable of operation in parallel-connected energization, is primarily intended to function as a higher voltage regulating unit of a plurality of related voltage regulating arrays energized in series-connected cascade by a common power source; that the third-load voltage regulating array, utilizing the tubes and circuit constants indicated above, provides within itself, a corrective advantage theoretically exceeding 25,000; that the corrective advantage of the high potential, intermediate potential, and low potential voltage regulating arrays, energized in series-connected cascade, is cumulative, approximating, in the case of the low potential array of Fig. 1, the product of the respective corrective advantages of the high potential, intermediate potential and low potential voltage regulating arrays, and approximating, in the case of the intermediate potential array, the product of the corrective advantages of the high potential and intermediate potential voltage regulating arrays; that, by successive inclusion of additional pairs of tubes in the plurality of pairs of tubes comprising the amplifier means of the high potential array, voltage regulation can be effected at still higher values of regulated voltage without exceeding the safe plate heat dissipation ratings of component tubes; that the combined voltage regulating arrays of Fig. 1, energized in series-connected cascade, are adequate for energization of a cathode ray tube direct-connected linear sweep generator, conversion of the generated sweep voltage from half-wave to full-wave relations, and amplification of the converted sweep voltage in an interlocking D. C. and A. C. amplifier.

Referring now to Fig. 2, the preliminary voltage reference means and filter means of Fig. 1 are combined with the third-load voltage regulating array thereof to provide an independent voltage regulating array capable of operation at higher values of voltage regulator output voltage. A direct current power source is first indicated with its positive energizing terminal connected to circuit point Q and with its negative energizing terminal connected to circuit point G, the voltage regulator negative output terminal. Circuit character P indicates the voltage regulator positive output terminal. A voltage regulator output load is shown connected between output terminals P and G.

Circuit character **243** indicates the voltage regulator control resistor. R and R_1 respectively indicate voltage regulator preliminary and first stabilized reference points, again respectively having voltage regulator preliminary reference potential and voltage regulator first stabilized reference potential particular thereto. Circuit character R_4 now indicates the voltage regulator second stabilized reference point and also indicates the voltage regulator screen-grid voltage supply positive terminal. D and D' respectively indicate the plate terminals of triodes **235** and **234**. Circuit character J indicates the cathode terminal of triode **240**. Circuit characters S_9 and GND respectively indicate a two position selector switch and ground potential.

With further reference to Fig. 2, I have found that suitable results may be obtained by employing the tubes and circuit constants indicated in the case of Fig. 1 for identically indicated tubes and circuit elements, with the exception that voltage dropping resistor **203** requires a value of 100,000 ohms, 5 watts, when incorporated in the array of Fig. 2.

Referring now to Fig. 3, conventional means heating the cathodes of the component electronic tubes of the voltage regulating arrays of Fig. 1, and subsequently of Fig. 2, is shown energized by an A. C. power source. Circuit character **244** indicates a heater transformer with multiple secondary center-tapped windings. Circuit characters **245**, **246**, **247**, **248**, and **249** respectively indicate isolating filter resistors. Circuit characters G, J, P, P', and P'' respectively indicate heater-means reference terminals, operatively connected to identically indicated terminals of the voltage regulating arrays of Figs. 1 and 2. Circuit characters H_{228}, H_{216}, H_{201}, H_{240}, H_{241}, H_{208}, H_{211}, H_{212}, H_{219}, H_{222}, H_{223}, H_{231}, H_{234}, and H_{235}, respectively indicate the heater elements of component electronic tubes corresponding to the above identifying subscripts.

With further reference to Fig. 3 the cathode heating means indicated, being conventional, is believed to require no further detailed description. I have, however, observed that voltage regulator operation may be improved by incorporating an A. C. voltage regulating device, as for instance, a Solar voltage regulator, in the heater power supply circuit. I have also observed voltage regulator operation may further be improved by employing voltage regulated direct current to energize the cathode heating elements, heater direct current being derived from the voltage regulating array itself, or independently from an auxiliary voltage regulator. Direct current energization of cathode heater elements has not, however, been necessary at interlocking amplifier voltage gains not exceeding 50,000.

It is to be noted that the performance of each of the arrays described is markedly improved by anti-shock mounting. It will be further understood that filter capacitors may be employed in parallel with the indicated loads as may be desired for various applications and, while the invention has been described with reference to the figures shown, various modifications, deletions and additions thereto may be made without departing from the spirit of the invention within the scope of the appended claims.

What I claim is:

1. In a voltage regulator fed from positive and negative terminals of a power supply supplying current to a load, linearly variable impedance means connected in series with said load between said terminals, voltage control means in shunt with the load establishing a steady preliminary potential above said negative terminal potential, pentode means including a resistor and pentode tube series-connected in shunt with the load, said tube having a cathode, grid and screen grid at fixed relative potentials and an anode connected through said resistor to said impedance means thereby fixing anode current of the pentode and impressing residual error voltages passed by the impedance means thereacross, voltage amplifying means energized in shunt with the load and comprising a plurality of tubes, one pair thereof having cathodes at common potential and plates supplied by individual connection to the impedance means, said pair of tubes having grids respectively at said preliminary potential and the potential of said pentode anode, and means responsive to the resulting amplified error voltage controlling the impedance of said impedance means to nullify said residual error in proportion to corrective amplification advantage of the regulator.

2. In the regulator of claim 1, said amplifying means comprising a plurality of tubes each pair having cathodes at common potential and anodes resistively connected individually to said impedance means, the respective grids of tubes of succeeding pairs being connected to the anodes of the preceeding pair in reverse order.

3. In the regulator of claim 1, said pentode and amplifier tube cathodes being connected to said negative terminal by resistors, said pentode cathode resistor being variable to effect control of the potential of the pentode anode and to control the voltage across the load.

4. In the regulator of claim 1, filter means comprising a resistor and condenser series-connected between said grid of a first said amplifier tube and the negative terminal for stabilizing said preliminary potential against transient voltages in said voltage control means, and further filter means comprising a resistor and condenser connected in series and shunting said voltage control means, arranged to provide a filtered and stabilized potential at said screen grid of the pentode below said preliminary potential.

5. In a regulator according to claim 1 a second said pentode means, a second said voltage amplifying means and a second said variable impedance means connected as in claim 1 and supplied from a second said power supply, the first said tube of said second amplifying means being connected to the corresponding grid of the regulator of claim 1, and said power supply of the regulator of claim 1 comprising the corresponding load in series with the second variable impedance, whereby a cascade of voltage regulation from a single source is provided.

6. In a voltage regulator having a current controlling impedance series connected to a direct current source at the positive of two terminals thereof and having electronic means for varying said impedance in compensation for variations of voltage from said source, means in series with said source and impedance establishing a substantially fixed preliminary voltage from one said terminal, pentode means including a resistor and pentode tube series-connected between said impedance and said one terminal, said tube having a cathode and grid at fixed potentials and a screen grid at a potential controlled by said preliminary voltage whereby residual error voltages passed by said impedance are transferred virtually without loss through said resistor to its junction with said tube, amplifying means comprising a plurality of triodes connected respectively between said impedance and said one terminal, a pair of said triodes having cathodes at a common potential and grids thereof at said preliminary and said transferred voltages respectively, and means applying the amplified error voltage directly in control of said impedance.

7. In a regulator according to claim 6 a second said direct current source and series-connected current controlling impedance, said one terminal thereof being connected to the first said one terminal, a second said pentode means series-connected between said second impedance and said one terminal and having the screen grid thereof controlled by said preliminary voltage, a second said amplifying means connected as in claim 6 between said second impedance and one terminal, a second pair of triodes thereof being connected as in claim 6 with grids thereof at said preliminary voltage and said transferred voltage of the second pentode means, respectively, said current source of claim 6 being at terminals connected respectively to said second impedance and said one terminal.

8. In a precision electronic voltage supply circuit having a power supply connected at one terminal to the circuit negative output terminal taken at a primary reference potential and at the other terminal to the anode of a current and voltage regulating tube from the cathode of which is connected the circuit positive output terminal taken at a secondary reference potential, means establishing a preliminary reference potential including a resistance and gas tube series-connected respectively from said positive to said negative terminal, pentode means transferring residual output error voltage to a lower potential comparator point, said pentode means having an anode and a resistive error voltage connection thereto, a cathode biasing connection to said negative output terminal and having constant current therein independently of said error voltage, the pentode having a screen-grid thereof supplied from a potential source resistively derived from said preliminary reference potential, and electronic voltage amplifying means having a control grid at the potential of said comparator point and a corresponding cathode at fixed potential relative to said first reference potential, the amplified voltage therefrom being applied in inverted control of said current regulating tube, whereby substantially the entire said error voltage is applied after amplication to control said regulating tube.

9. In a circuit according to claim 8 said amplifier means having said cathode potential fixed by cathode follower means controlled at a grid thereof by said preliminary reference potential, a cathode follower resistance being connected to said first reference potential terminal and said follower means being supplied from said output terminal, said follower resistance being in circuit from said corresponding cathode to the negative output terminal.

10. In a circuit according to claim 8 said amplifier means comprising three amplifying stages, said control grid and cathode thereof comprising the first stage, all said stages being parallel-energized from said positive output terminal, the second and third stages having a common cathode resistive connection to said negative output terminal, the second stage being grid-controlled from the output of the first stage, the third stage being grid-controlled by potential derived from said preliminary reference potential.

11. In an electronic voltage regulator having a current regulating tube connected to the positive terminal of a power supply, the cathode connected to a positive voltage output terminal, and the negative supply terminal being connected to the negative output terminal, means comprising a gas tube and resistance in series, the latter connected to the positive output terminal and the former to the negative output terminal for establishing a preliminary stabilized reference potential, pentode means for referring variations of output potential exactly to a final reference point comprising a resistor connected at one end to said output terminal whereof the other end comprises said final reference point and is connected to a pentode tube therein having a grid thereof connected substantially to the negative output terminal, the cathode thereof being connected by self-biasing means to the negative output terminal and having a screen-grid controlled by said stabilized potential, a reference triode having plate potential controlled by the regulator output, grid potential controlled by said preliminary reference potential and a cathode connected to the negative output terminal through a reference impedance, a control triode having a grid connected at said final reference point and a plate connected to said positive output terminal through voltage dropping means including a resistance to the lower potential end of which is connected the grid of the current regulating tube.

12. In an electronic voltage regulator operating from a power supply the negative terminal of which connects to a negative voltage output terminal and the positive terminal of which connects to the anode of a current regulating tube, a positive output terminal being connected to a cathode of said tube, means establishing a preliminary reference potential including a resistance and gaseous tube series connected respectively from said positive to negative output terminals, reference triode means including a triode having a plate connected to said positive output terminal, a grid connected at said reference potential and a cathode connected to the negative output terminal through a reference resistance said means establishing on last said resistance a substantially fixed potential, means referring residual error voltages at the output terminals with substantial exactness to a control point including a pentode connected at its plate to said point and thence by resistive means to the cathode of said regulator tube, said pentode being connected for constant current conduction regardless of plate voltage, the grid thereof being at fixed potential relative to regulator negative output potential and the cathode at adjustably fixed potential thereabove, the screen-grid potential being fixed relative to said preliminary reference potential, and amplifying means controlled by the difference between said substantially fixed potential and said potential at said point, said difference potential being inverted upon amplification and referred to the grid of the regulating tube for control of voltage output.

13. In a regulator according to claim 12 said amplifying means comprising a triode having a cathode negative voltage connection through said reference resistance, whereby said reference triode means stabilizes the voltage at the cathode of last said triode at a regulated constant value.

14. In a regulator according to claim 12 said amplifying means comprising a plurality of amplifying tubes connected and arranged for cumulative amplification of said residual error voltages and referral thereof inversely to the grid of the regulating tube.

15. In a voltage stabilizer having a power supply connected at one terminal thereof to the negative output voltage terminal at a primary potential and at the other terminal thereof to the anode of a current regulating tube, the cathode of which connects to the positive voltage output terminal, resistance means connected in series with gas discharge tube means from said positive to said negative output terminals for establishing at the positive side of said gas tube means a preliminary reference potential stabilized in response to output voltages, filter means further stabilizing said reference potential, cathode follower means controlled by the filtered reference potential and connected across said output voltage terminals providing a substantially constant potential above said primary potential, pentode means transferring residual output error voltage to a lower potential including a by-passed resistor in a voltage supply path thereto from the positive output terminal, a cathode biasing connection to the negative output terminal and a screen-grid controlling potential derived from said preliminary reference potential whereby said error voltage is transferred substantially without change to said lower potential, amplifying means controlled by voltage between said further stabilized potential and said lower potential, and means whereby the resulting amplified voltage is inverted and referred to a control element of said current regulating tube in control of the output voltage.

16. In a voltage stabilizer according to claim 15 said amplifying means comprising a plurality of amplifying triodes the first of which is grid controlled from said lower potential and the last of which is grid controlled from a potential proportionally exceeding said reference potential.

17. An electronic voltage regulator supplied at positive and negative input terminals with variable direct current power, comprising a first current regulating tube having a grid, an anode connected to said positive terminal and a cathode connected to a positive output terminal of the regulator, voltage stabilizing means including a resistor and gaseous regulator tube connected respectively to said positive output terminal and said negative terminal and mutually joined at an intermediate preliminary reference potential, filter means stabilizing said reference potential, pentode voltage-transfer means including a pentode tube having a grid at the potential of said negative terminal, a cathode connected to said negative terminal through resistive self-

biasing means, an anode connected through resistive means to said output terminal and a screen-grid connected to receive energization responsive to said reference potential, whereby residual error voltages between said negative and said output terminals are transferred substantially without loss of time or magnitude to said pentode anode, voltage amplifying means including at least one pair of tubes each having a cathode, grid and anode and each energized by anode connection to said output terminal and by common cathode connection to said negative terminal, a potential dropping resistor being interposed between the negative terminal and said common cathode connection, the last tube of each said pair having a load resistor between its anode and said output terminal, the first tube of a first pair being grid-controlled at said stabilized reference potential and the second tube of the pair being grid-controlled at said transferred voltage below said output potential, and means applying resulting amplified voltage inversely to said grid of the current regulating tube in control of an output voltage between said positive output and negative terminals.

18. The voltage regulator of claim 17 wherein said amplifying means includes a plurality of pairs of tubes arranged for cumulative amplification of the voltage between said stabilized reference potential and said pentode anode potential, each pair having individual thereto a common voltage-dropping resistive connection to the negative terminal a final said pair having a first tube grid-connected to the anode of the last tube of a prior said pair, a second tube grid-connected to the anode of the first tube of said prior pair, and wherein the grid of the current controlling tube is controlled from the anode potential of the second tube of said final pair.

19. The voltage regulator of claim 17 having a second positive output terminal, a second said current regulating tube, a second said voltage amplifying means and a second said pentode voltage transferring means each constructed similar to and arranged in circuit relative to said second output terminal as like elements of claim 16 relative to first said output terminal, said variable direct current supply being now connected to the anode of the second current regulating tube and to said negative terminal, said second positive output terminal now being said positive input terminal of the regulator of claim 16, said screen-grid supply and said stabilized reference potential of the regulator of claim 16 being common with corresponding second said pentode means and amplifying means, respectively, whereby a cascade of voltage regulation is achieved from a single supply with output selectively above, below and partly above and partly below ground potential.

20. The voltage regulator of claim 17, wherein the positive terminal of the voltage supply is the positive output of a second similar regulator the current regulating tube of which is fed from the positive terminal of a varying direct current supply, the negative terminals thereof being joined, the means establishing said preliminary stabilized reference potential of the first said regulator being common to both, said output terminals being selectively groundable at will.

21. The voltage regulator of claim 20 wherein the voltage supply is derived from the positive output terminal of a third similar regulator the current regulating tube of which is fed from the positive terminal of a varying direct current supply, the negative terminals of the component

regulators being joined, the means establishing said preliminary stabilized reference potential being common to the first, second and third said regulators, said output terminals being selectively groundable at will.

22. In an electronic voltage regulator having a power supply and a current controlling tube connected at an anode thereof to the higher voltage terminal of said supply and a cathode thereof connected to the regulator positive output terminal, and having the negative output terminal connected to the lower voltage terminal of said supply, a voltage dropping resistor and gaseous regulator diode series-connected between said output terminals the common junction thereof being at the lower voltage end of said resistor and having thereat a reference potential, filter means in shunt with said diode stabilizing said reference potential, a reference triode having a grid thereof responsive to said reference potential, an anode thereof being connected to said positive output terminal and a cathode thereof connected through an impedance to said negative output terminal, an exciting pentode connected at an anode thereof to the positive output terminal through a resistor, having a cathode and grid connected to the negative output terminal through self-biasing means, a screen-grid of the pentode being connected responsively to said reference potential, whereby potential at said pentode anode is responsive to output potential regardless of current therethrough, a second triode having a grid thereof controlled by said pentode anode potential and a cathode thereof connected through said impedance to said negative output terminal, said second triode having an anode supplied from the positive output terminal through a load resistor, the grid of said current controlling tube being controlled by potential at the lower potential end of said load resistor, whereby substantially the full error voltage at said output terminals is applied between the grids of said triodes for amplified control of grid voltage at said current regulating tube.

23. In the regulator of claim 22 a resistor and capacitor connected in series, respectively, from said common junction to said negative output terminal and establishing therebetween a current source connected to said screen grid at lower potential than and responsive to said reference potential.

24. In the regulator of claim 22 said self-biasing means comprising a manually adjusted resistance element whereby the average current through said second triode is adjusted to vary the regulator output voltage.

25. A regulator according to claim 22 wherein said components except said current controlling tube are operated below ground potential, said triode and pentode tubes functioning to maintain voltage stability when said positive output terminal is substantially at ground potential.

26. In a regulator according to claim 22, a second positive output terminal, a negative output terminal connected to first said negative output terminal, a second pair of triodes and associated resistances connected and arranged substantially as in claim 1 with anodes supplied from said second positive output terminal, a second pentode arranged as in claim 1 having an anode supplied through a resistor from said second positive output terminal and a screen-grid thereof connected responsively to said reference potential, a component control-grid and cathode being arranged

in self-biasing connection to said negative output terminal, the grids of said pair of triodes being connected respectively to the first said reference triode grid and the anode of said second pentode, said load resistor of the second pair being connected to said second positive output terminal, a second said current controlling tube being energized from a power source with a cathode at second output terminal potential and a grid at anode potential of the second triode of the second pair, and said second positive output terminal being said higher voltage terminal of said supply of the array of claim 1, whereby a cascade

of voltage regulation is achieved, any said output terminal of which may be at ground potential.

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