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VOLTAGE REGULATING ARRANGEMENT

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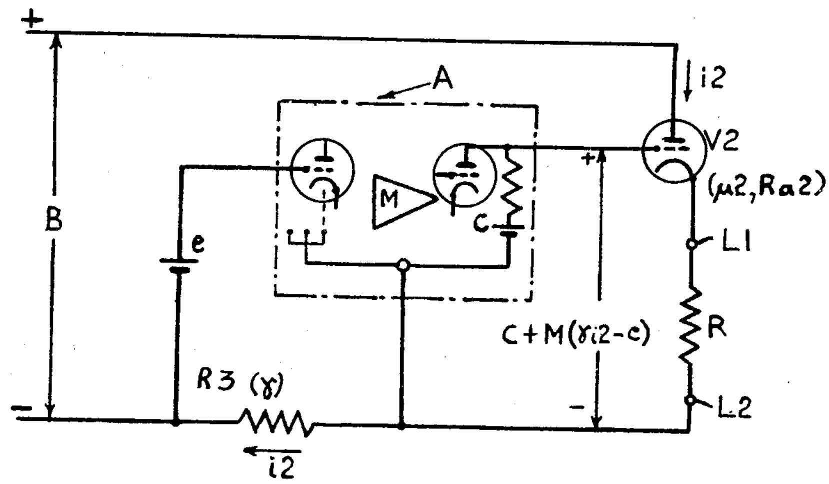

Fig.1.

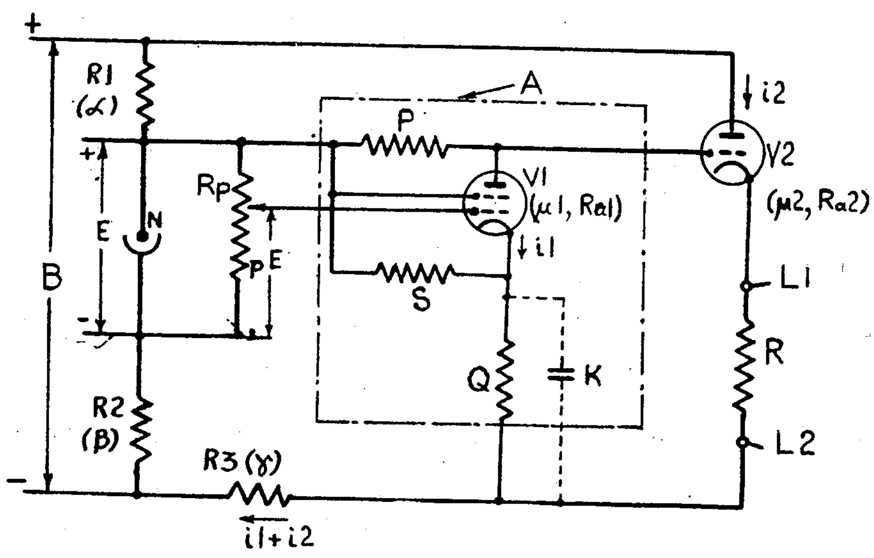

Fig.2.

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VOLTAGE REGULATING ARRANGEMENT

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The present invention relates in general to voltage regulating arrangement and, in particular, to an improved voltage regulator of the electronic type.

One of the objects of the invention is to provide an improved voltage regulating circuit, of the type having an input circuit energized from a source of direct current subject to variations in voltage and having an output circuit from which a direct current load is energized by the source, wherein the output voltage is readily controllable over a wide range by adjustment of a potentiometer.

A further object of the invention is to provide a voltage regulator of the above type having novel and improved circuit arrangements for preventing variations in the output voltage when the input voltage changes.

Another object of the invention is to provide a voltage regulator of the above type incorporating improved circuit arrangements for causing the output voltage to be dependent in a controllable manner upon the load circuit, or for causing the output voltage to be independent of the load current.

A still further object of the invention is to provide an improved voltage regulating arrangement which is adaptable to fulfill any of the preceding objects separately or in any desired combination at a time.

According to the invention a circuit arrangement is provided in which a space discharge device or thermionic valve is connected in series with the load and has a control electrode or grid on which there is impressed a voltage which is derived from the input voltage supply and the output current in such manner to increase positively with increase of load current and negatively with increase of the supply voltage and vice versa.

In a preferred form the positive terminal of the input supply is connected to the anode of a thermionic valve while the negative terminal is connected to a small resistance, the cathode of the valve and the other terminal of the resistance being connected to the output while the control grid of the valve is supplied, via a polarity reversing stage or stages, with a voltage having one component which is proportional to the input supply and having a second component which is proportional to the load current.

The invention will be better understood by referring to the accompanying drawing in which Figure 1 is a theoretical circuit diagram illustrating the general principles of the invention, while Figure 2 indicates an actual circuit by which the invention may be carried into effect.

Referring to Figure 1, B represents the input voltage supplied by a variable voltage source of which the positive terminal is connected to the anode of a thermionic valve V2 having an amplification factor $\mu 2$ and a resistance Ra2. The negative terminal of the supply battery is connected through a small resistance R3, having the value γ, whose other terminal is connected to the terminal L2. The cathode of the valve V2 is connected to the terminal L1, L1 and L2 being the output terminals to which the load represented by the resistance R is connected. The rectangle A and the apparatus schematically shown therein represents a valve circuit to which the terminal L2 is connected directly while the negative terminal of the input supply voltage is connected through a source of potential represented by the battery e having its negative terminal connected to the negative terminal of R3 and its positive terminal connected to a grid of a valve in the equipment A. The valve equipment in A is assumed to be the direct coupled type, to have the magnification factor M, to provide a polarity reversal of voltage and to have means for supplying a constant voltage C, so that the voltage across the input terminals of A (represented by the positive terminal of R3 and the positive terminal on e) result in a magnified voltage of $C+M\,(\gamma i2-e)$ which is applied to the grid of the valve V2 as shown. It will be noted that by this means a positive voltage is applied to the grid of the valve V2 which of course increases with the increase of the load circuit current $i2$, and decreases with increase of e.

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Considering therefore the circuit of V2 and making the usual substitution for a generator of $\mu 2$ times the grid cathode voltage and having a resistance Ra2 for V2 we have:

$$e_g = C + M(\gamma i2 - e) - i2R$$

Thus the equivalent voltage in the anode circuit is

$$\mu 2 e_g = \mu 2[C + M(\gamma i2 - e) - i2R]$$

and the anode or load current is

$$i2 = \frac{\mu 2[C + M(\gamma i2 - e) - i2R] + B}{Ra2 + R + \gamma}$$

or

$$i2 = \frac{\mu 2(C - M\cdot e) + B}{(\mu 2 + 1)R + Ra2 - \gamma(\mu 2\cdot M - 1)} \qquad (1)$$

From this equation it is possible to deduce the following:

(1) The effective resistance in series with the load R is

$$\frac{Ra2 - \gamma(\mu 2\cdot M - 1)}{\mu 2 + 1}$$

For positive values of γ this internal resistance has a maximum positive value of

$$\frac{Ra2}{\mu 2 + 1}$$

that is to say it is slightly less than the reciprocal of the transconductance (g_m) of V2. The internal resistance will be zero when γ equals

$$\frac{Ra2}{\mu 2\cdot M-1}$$

and will be negative for any greater values of γ up to the practical limit when the denominator of Equation 1 becomes zero in which condition the circuit is unstable.

(2) If e includes a component which is a fraction q of B and of the same sign as B as shown in Fig. 1 then the effects of B on $i2$ may be reduced and ultimately become zero when the fraction q is made equal to

$$\frac{1}{\mu 2\cdot M}$$

and since the circuit is direct coupled this holds true for permanent or random changes in B. If q be made larger than this value then the variations in the output, due to variations of B will be of opposite sense.

(3) If e has another component $p.E$, where E is a constant voltage and p is a fraction not greater than unity, then the output will include a component proportional to $p.E$. Now if the zero conditions of (1) and (2) are combined with (3) we have:

$$\gamma=\frac{Ra2}{\mu 2M-1} \qquad \text{(Condition 1)}$$

and

$$e=\frac{B}{\mu 2M}+pE \qquad \text{(Condition 2)}$$

Then

$$i2=\frac{\mu_2 C-\mu 2M\left(\frac{B}{\mu 2M}+pE\right)+B}{(\mu 2+1)R+Ra2-\frac{(\mu 2M-1)Ra2}{\mu 2M-1}}$$

or

$$i2=\frac{\mu 2(C-M\cdot p\cdot E)}{(\mu 2+1)R} \qquad (2)$$

Having provided a component E of the right polarity it is obvious that it could be used as the supply C if the second order effects of $\gamma.i2$ be neglected, when we obtain:

$$i2=\frac{\mu 2\cdot E(1-M\cdot p)}{(\mu 2+1)R} \qquad (3)$$

This latter equation shows that the objects of the invention have been attained, for by varying p from zero to 1 a linear control of the output voltage

$$\frac{\mu 2}{\mu 2+1}\cdot E$$

at any resistance load R can be obtained and the output is independent of $\mu 2$ if $\mu 2$ is very much larger than 1. It is independent of M if this be made constant by negative feedback within the equipment A. Further it is independent of B or of the load current. Furthermore E can be obtained from the supply terminals by means of the voltage drop on a neon tube or similar device having a critical potential; such neon tube or its equivalent being energised from the input supply terminals, whilst this voltage can also supply A if the current drain of A be small, which is feasible since A merely has to provide a voltage gain. It should be noted that it is possible to use the supply B for the voltage C but by reference to Equation 1 it will be seen that the fraction q to obtain zero output variations with variations of the supply voltage B will now be increased to

$$\frac{\mu 2+1}{\mu 2\cdot M} \text{ or } \frac{1}{M}$$

if $\mu 2$ be large. As this input is positive to the grid circuit of a valve in A, such a connection may hamper the full use of the circuit and particularly the range of output voltage control, so that it is not a preferred arrangement. Where, however, such a wide range of control is not needed, connection of the output resistance of A to the positive supply terminal is perfectly feasible.

Referring now to Fig. 2 it will be noted that the valve equipment A is shown in detail by way of example, although any form of direct coupled amplifier having an odd number of valves may be used, and consists of a pentode or tetrode valve V1 whose anode is directly connected to the grid of the valve V2 and via the anode resistance P to the positive terminal of a voltage E. The screen grid is also connected to the positive terminal of E and through a resistance S to the cathode of the valve V1. The cathode is connected to the output terminal L2 via a resistance Q. The constant voltage supply E is derived from across the terminals of a neon tube N which is fed from the positive terminal of the input supply voltage B via a resistance R1, having the value α, and from the negative terminal of the supply voltage by a resistance R2, having the value β. The grid potential for V1 is taken directly from the potentiometer Rp connected across the neon lamp N to give the fractional control voltage pE, whilst the resistance R2 gives the fraction qB for neutralising the effects of B on the load current $i2$.

It is preferred to use a pentode valve for V1 because the permissible range of output voltages is larger without incurring the possibility of grid current flowing whilst the magnitude of the stable gain is also much larger which permits of lower values for R3 and R2.

It has been pointed out that the stability of the output is dependent upon the gain M of the equipment A and by making Q of the nature of 10,000 ohms compared with a slope of the transconductance of the valve of say 6 milliamp/volts as much as 35 decibels of negative feedback is obtained which not only ensures adequate stability for M with differing valves and for variations in the life of a valve, but also reduces considerably the current drain $i1$ on E. The gain M is substantially the ratio P/Q and the only limit to this mutually favourable process of increased stability and reduced current consumption is brought about by extraneous voltages which may be picked up at P and reduction of high frequency response due to the anode capacity. A value of M about 10 is found to give the optimum range of output voltage from V1 and the corresponding anode resistance P of 100,000 ohms satisfies all normal conditions of extraneous disturbances and frequency response. The latter may be improved when necessary by shunting Q with a condenser k, as shown in dotted lines, so that the anode and cathode time constants are of the same order.

The purpose of the resistance S is as follows. In calculating the complete performance equation of the practical circuit corresponding to the simple Equations 1, 2 and 3, it is found that an additional term appears in the numerator brackets, of the form

$$\frac{-N}{\mu 1+1}$$

where N is the ratio of the resistances P to Q and $\mu 1$ is the grid/screen-grid amplification factor of V1. This term reduces considerably the practical range of output voltages of A, and is due to the standing anode current which would be obtained in V1 if the grid were connected to the lower end of Q. Hence it follows that by raising the cathode voltage by an amount equal to the cutoff grid voltage of V1 (which voltage is equal to the screen voltage divided by $\mu 1$) this term can be deleted. Thus S is made such that it is $\mu 1$ times Q, when the desired result is obtained, and the full output equation for $i2$ is simplified. If $\mu 1$ be large, and there is no reason why this should not be 60, it will be seen that the additional current drain on E will be negligible.

As regards the neon tube circuit connected across the busbars, R2 is of such value that it can provide the fraction

$$q=\frac{1}{\mu 2 \cdot M}$$

of the supply B, whilst R1 absorbs the remaining fraction. The potentiometer fraction $p.E$ provides the control of the output voltage on R, and since only a potential is required, the current drain of Rp can also be made very small.

With this practical arrangement, and with the above "zero" adjustments for R2 and R3, the full output equation of the circuit is as follows:

$$i2=\frac{\mu 2 \cdot E}{(\mu 2+1)R}\left(1+\frac{1}{\mu 2}-N p\right) \qquad (4)$$

Hence by making E comparable with the minimum value of B, the maximum output (when p is 0) is not far short of the input from B, and the conversion efficiency is high. The minimum output is not zero as is indicated by the Equation 4 when

$$p=\frac{\mu 2+1}{\mu 2 \cdot N}$$

but is limited due to the approach to the non-linear portion of the anode characteristic of V1. This occurs when the anode-cathode voltage becomes less than about one-fifth of the screen/cathode voltage, with increasing p values. Whilst at first sight this fact would appear to permit of an output voltage range of 5:1, in actual fact and because of the increasing voltage drop on Q, the maximum output range is limited to about 3.5:1. In practice an output range of some 3:1 has been obtained, dependent on the minimum ratio of B to E, that is the degree of change in B which it is desired to eliminate in the output.

It might be thought that the fraction $q.B$ derived from the neon circuit by means of R2, would vary with the setting of Rp, owing to the changing current drain of V1 on the neon tube. If however the complete circuit is analysed, it will be found that while the voltage on R2 does alter with p, yet the potential input to V1 does contain a constant B term, which is very slightly less than the simple ratio

$$\frac{\beta}{\alpha+\beta}$$

so that for all practical design purposes the latter ratio can be used and final adjustment given in situ. When this has been done the elimination of B from the output load holds good at all settings of p, provided $\mu 2$ remains constant.

If the source E includes an internal resistance, as it will do with common types of neon tube, then a component of B varying with p does appear in the output. However, such a component can be turned to some advantage in offsetting the inevitable changes in $\mu 2$ with p, i. e. the changes of $\mu 2$ with the output voltage setting. For a given load resistance, as the output current falls with increasing p the $\mu 2$ also falls in practical valves. But according to deduction (2) above, such a change in $\mu 2$ will need an increase in the B fraction fed to V1, for elimination of B from the output. This is precisely what is given by internal resistance of E, so that provided this resistance is not too large, some mitigation for the changes in $\mu 2$ can be obtained, as regards the maintenance of zero output changes due to B.

Another point of some importance to the design of V1 is the possibility that this valve might be operated with too large a negative grid-cathode voltage, when p is 0 and the load current is a maximum. However it can be shown that provided R2 and R3 are adjusted so as to eliminate respectively the variations of B in the output load and the internal resistance presented to the output load, and B is always greater than E, then the grid input voltage of V1 developed between the grid and the return cathode lead from Q, is never less than zero. Hence the anode current of V1 cannot be less than that value obtained if the grid were connected to the return cathode lead from Q, so that not only is the valve V1 never cutoff by the input but the linearity of the circuit of V1 is maintained (i. e. the gain M is constant because the minimum slope is still reasonable). This state of affairs assumes that the maximum output from V2 is limited due to the flow of grid current therein at about −1 volt between the grid and cathode.

In the practical application of the invention, it will be necessary to establish the conditions of maximum output watts and efficiency, and a better understanding of the scope of the invention will be obtained thereby. When set up as described, the output voltage $i2.R$, for a given p value, will be constant and independent of R, until grid current begins to flow in V2. But as V2 still functions essentially as a cathode follower, we have

$$i2\ (\text{maximum})=\frac{B-\mu 2}{R+Ra2}$$

assuming that grid current commences to flow at −1 grid/cathode volts. If the constant output voltage $i2.R$ be denoted by Vo, then

$$i2\ (\text{maximum})=\frac{B-\mu 2-Vo}{Ra2}$$

and the maximum watts output, Wm, is given by,

$$Wm=\frac{(B-\mu 2)\,Vo-Vo^2}{Ra2}$$

Putting Vo equal to $s(B-\mu 2)$ where s is less than unity, we have:

$$Wm=\frac{(B-\mu 2)^2 \cdot s(1-s)}{Ra2} \qquad (5)$$

Also, and neglecting the small current drain on B by the circuit prior to V2, the power efficiency is given by,

$$\text{Efficiency}=\frac{Vo}{B}=s\cdot\frac{(B-\mu 2)}{B} \qquad (6)$$

For a given output valve, in which $\mu 2$ will generally be small compared to B, we can say, therefore, that the watts output is proportional to $s(1-s)$ and the efficiency is proportional to s. Hence the optimum watts output is obtained when s is 0.5 and the output varies symmetrically about this value of s, but the efficiency is linearly proportional to s. The invention is therefore capable of delivering a substantially constant output wattage over a wide range of controllable output voltages, at the expense of the efficiency over the lower range. For instance, if s be permitted to vary between 0.75 and 0.25 (by varying p as described before), the variation of permissible watts output is 0.25:0.1875, or 1.33:1, but the loss in V2 varies as 0.0625:0.56 so that V2 would have to be designed to dissipate about twice the substantially constant output watts over this range of voltage. Such a range of 3:1 is also consistent with the practical working range of V1 mentioned before.

The invention is not limited in scope by the attainment of a small or substantially zero internal resistance. For instance by increasing R3 from the zero internal resistance value of

$$\frac{Ra2}{\mu 2 \cdot M-1}$$

upwards, the internal resistance can be made negative. The circuit will then be perfectly stable in this condition for changes in R provided the denominator of Equation 1 remains positive. The circuit will also still possess the remaining features of controllable output voltage free from supply changes. Again, an output can be taken from between the anode of V2 and the positive supply terminal, and the characteristics of such an output will be those of a constant current generator; again the output voltage can be controlled as well as being free from supply changes, for such a load resistance merely adds to Ra2, and these features are independent of Ra2 by inspection of Equation 1. Alternatively a constant current output independent of, and in addition to, the constant voltage output, controllable in the same manner, and free to the same degree of supply voltage changes, can be obtained by changing V2 to a pentode or tetrode valve with its screen connected to the positive busbar and the constant current load taken from between the anode and the positive busbar. The only limit to this output is determined when its voltage becomes such that the anode/cathode voltage of V2 is equal to or less than about one-fifth of the screen/cathode voltage. Assuming that $\mu 2.Ra2$, now refer to the parameters of the pentode or tetrode considering the screen and anode as connected together, it follows that the minimum screen/cathode voltage for $i2$ maximum with reduction in R, is $\mu 2+i2.Ra2$, which in turn becomes $B-Vo$. Hence the maximum constant current output from the anode, consistent with maximum constant voltage output from the cathode, is about 0.8 $(B-Vo)$, which if Vo maximum be limited to 0.75B, as postulated, is still 0.2B in the worst case. The current value will be the closer to $i2$ as the screen current is smaller (i. e. dependent on the choice of valve). Hence even under the previously postulated conditions designed to provide a maximum of constant voltage output from the cathode, a reasonable constant current output can also be obtained. Again since the anode current is a constant fraction of the cathode current, and the triode parameters of the pentode or tetrode output valve are not altered by the anode output within the above limits of operation, it follows that the constant current anode output is equally controllable and free from supply variations.

The above modification, i. e. replacing V2 by a pentode or tetrode valve and inserting a suitable resistance in the anode to positive busbar, is also useful in reducing the anode dissipation of the valve. By these means it becomes feasible to use a valve with a low anode dissipation, since a large part of the total valve dissipation is now expended within the external anode resistance, so that the increase of valve dissipation with low output voltage settings on R no longer presents a major difficulty in the selection of a suitable output valve. In addition, of course, the dissipation in this anode resistance can be used, so that the conversion efficiency of the circuit is greatly increased.

The stability of the adjustments for producing zero supply variations in the output and zero internal resistance, are directly bound up with the stability of the output valve parameters $\mu 2$ and Ra2, and if it is desired to avoid readjustment with life or differing samples then some degree of feedback can be incorporated. For instance the slope of the valve V2 can be stabilised at a reduced value by the insertion of an additional series-cathode resistance, whilst Ra2 can be stabilised at a higher value by the insertion of series anode resistance, or, in the case of a pentode or tetrode V2 by a common screen and anode resistance to the positive supply busbar. These two methods simultaneously stabilise $\mu 2$.

It will be appreciated that the invention is based on the application of otherwise well known principles used in the control and design of feedback amplifiers, to the case of a direct current amplifier providing a direct current output, instead of the more usual alternating current output. Any thermionic amplifier must be supplied from a direct current source, and functions to convert input potential variations into similar output current variations in the output load, and this applies equally well to a direct coupled direct current amplifier. It follows therefore, that if the direct current potential input consists of (a) a controllable, constant direct current potential, (b) a suitably poled fraction of the supply voltage, and (c) a suitably poled potential proportional to the output load current, then the output of the amplifier will consist of direct current power of controllable voltage, and, by adjustment of (b) and (c), free from any form of supply variation or change with load current. Any one or combination of these features may of course be used, since they depend only on the addition of the respective component input potentials.

In any amplifier, the power output is derived from the output stage, and increase of load current will normally produce a fall in output voltage due to the internal resistance of the output stage. If this fall is to be counteracted, then the grid voltage of the output valve must increase positively with load current. From the nature of a direct coupled output valve stage it can be seen that such a grid voltage change cannot be produced using direct couplings, unless a reversal of polarity be introduced between the change of load current and the desired change of grid voltage. Furthermore changes in supply voltage produce changes of output of similar sense, and to counteract these by grid voltage change, also needs a reversal of polarity. Hence the amplifier of the invention must include such a polarity change between the input potentials and the output current or voltage. A single additional valve prior to the output stage will accomplish this effect, with economy, although of course any number of odd valved stages will suffice if in particular circumstances the required gain is not obtainable with one valve.

Reverting to the output stage, if this is to be direct coupled and requires control voltages on the grid, then it is obvious that the grid will have a voltage intermediate between the supply busbars if additional supply voltages are precluded. If the output were taken from between the anode and the positive supply busbar, as is conventional, this would mean that the cathode would also have to be raised to a voltage intermediate between the busbars in order to operate the valve over the normal negative grid/cathode voltage range. As additional batteries are precluded for this purpose, it follows that a cathode resistance will be required, which will absorb a considerable fraction of the available direct current output and increase the internal resistance of the stage. Hence the most practicable arrangement for the output valve, consists in taking the output from between the cathode and the negative supply busbar, when the necessary cathode resistance is comprised by the load itself; the anode being taken of course to the positive supply busbar.

The invention may be used for providing outputs having any or all of the above described features in the manners described or modified by well-known circuit variations, from battery supplies of poor stability and/or internal resistance, or from power rectifier units operated from alternating supplies. In the latter case use of the invention may be made to dispense with the commonly used choke/capacity output filter, provided the minimum value of the voltage on the storage condenser is taken for design purposes, for by adjusting the resistance R2 in the manner described both the ripple voltage on the storage condenser and any other permanent or random change in this voltage may be substantially eliminated from the output.

I claim:

1. An electronic voltage regulator comprising a supply circuit having positive and negative terminals; a load circuit having positive and negative terminals; a space discharge device having a cathode, an anode, and a grid; said anode and cathode being connected to the positive terminals of the supply circuit and the load circuit, respectively; a first resistor connected between the negative terminals of said circuits; a second resistor connected in a circuit across the negative and positive supply terminals; a direct current amplifier tube having a control grid and an anode; said anode connected to said first grid so as to impress a control potential thereon, said control potential having two oppositely poled components; said control grid connected to said resistors so as to cause one of the oppositely poled components to vary in proportion to the load current through the first resistor and the other poled component to vary in proportion to the supply circuit voltage across the second resistor to thereby render the load circuit voltage constant independent of the load current and the supply circuit voltage; a glow discharge tube in series with the second resistor across the positive and negative supply circuit terminals; a voltage divider connected directly across the said glow discharge tube, said control grid connected to said voltage divider in such a manner as to permit variation of the load circuit voltage to any desired value.

2. An electronic voltage regulator as claimed in claim 1 wherein said direct current amplifier tube also includes a cathode, said cathode being connected through a fourth resistance to the negative terminal of the load circuit, said fourth resistor providing a negative feedback to stabilize the gain of said amplifier.

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