

Oct. 12, 1965 M. MINTZ ET AL 3,211,989
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TEMPERATURE COEFFICIENT IMPEDANCE TO PREVENT LEAKAGE CURRENT
Original Filed May 19, 1958 2 Sheets-Sheet 1

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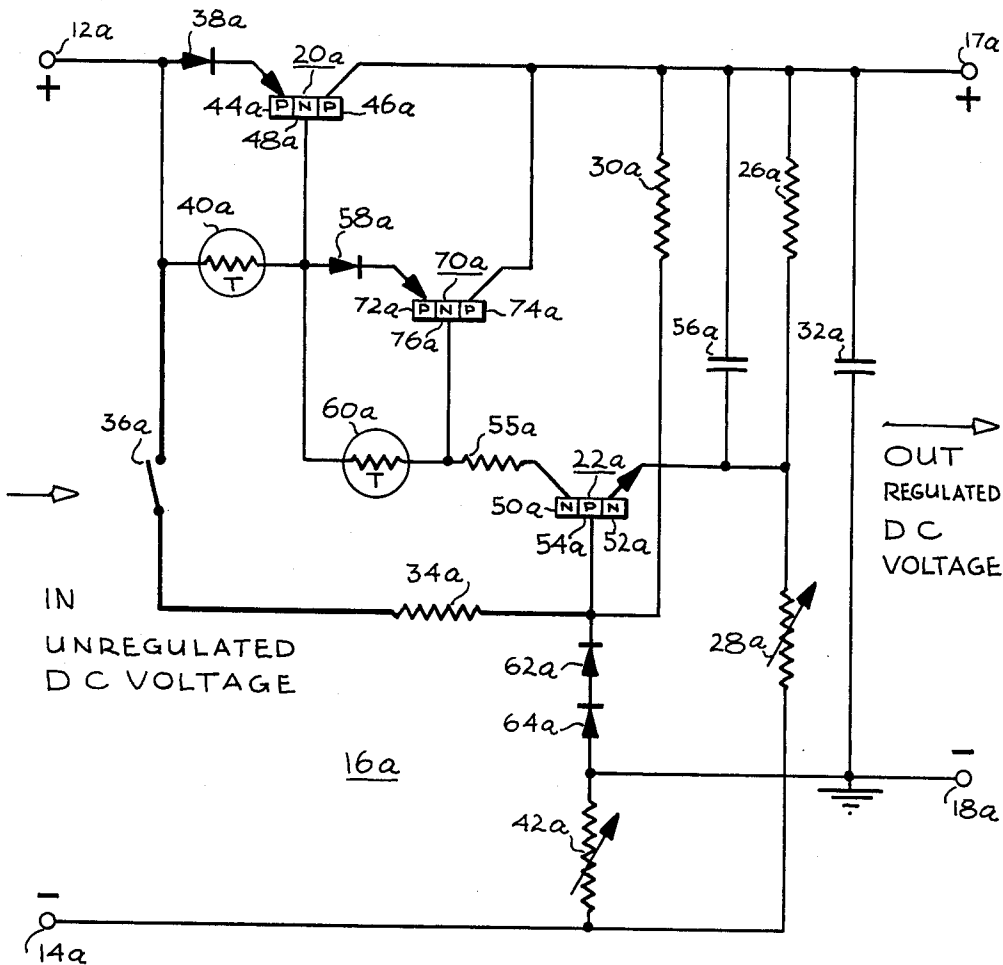


Fig. 2

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VOLTAGE REGULATOR EMPLOYING A NON-LINEAR IMPEDANCE AND NEGATIVE TEMPERATURE COEFFICIENT IMPEDANCE TO PREVENT LEAKAGE CURRENT

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Continuation of application Ser. No. 736,047, May, 19, 1958. This application Dec. 7, 1961, Ser. No. 161,327
6 Claims. (Cl. 323-22)

This invention relates to power supply circuits and, while not limited thereto, is herein described with reference to a transistorized voltage regulator circuit embodying the invention. The present application is a continuation of our copending application Serial No. 736,047, filed May 19, 1958, entitled "Power Supply" now abandoned.

While transistorized voltage regulator circuits are known that provide substantially constant direct current output voltage, such circuits have not proven entirely satisfactory due to certain inherent characteristics of transistors. For example, a load short circuit often results in the destruction of some of the transistors in the regulator circuit. The use of fuses in such regulator circuits has not proven practical due to the comparatively long lag time of fuses conventionally available—the transistors in such circuits usually burn out before the fuses are actuated. Then, too, such transistorized circuits have not operated reliably under conditions of extreme temperature changes, such as would be encountered in power supplies in airborne applications. For example, high ambient temperatures often result in excessive leakage current through the transistors (especially at low or zero signal current) leading to poor regulation and low power output, and sometimes to the destruction of the transistors. Furthermore, previous voltage regulator circuits have not been completely satisfactory in providing desirable voltage regulation over different output or load voltages.

Accordingly, one of the objects of this invention is the provision of an improved transistorized circuit capable of operation at relatively high ambient temperatures and at the same time capable of sustaining load short circuits without harm.

Another object is the provision of an improved fuseless protective arrangement for a transistorized power supply circuit.

A further object of the invention is the provision of an improved transistorized voltage regulator circuit capable of maintaining desirable operating characteristics over relatively wide temperature variations.

Still another object is the provision of an improved voltage regulator circuit capable of providing substantially uniform load voltage regulation substantially independent of the magnitude of the load voltage.

In accordance with one of the features of the invention, a transistorized circuit is provided that is self-protective against load short circuits or overloads. When subjected to such an overload, the circuit ceases operation until reset. The circuit of the invention includes two transistorized stages. The first of the stages, a load current regulator stage, is controlled by the second or bias control amplifier stage. The bias control amplifier stage, connected to control the flow of bias current to the first stage during normal operation of the circuit, is connected to be biased into conduction by the flow of load

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current through the first or load current control stage. Once in operation, the circuit will pass load current until a reduction in load voltage, caused by a load short circuit or overload, causes a reduction in conduction bias to the second stage; this bias reduction cuts off the operation of the entire circuit. According to the invention, a starting or auxiliary biasing lead is provided; this biasing lead is adapted to be either manually or automatically temporarily connected to the second or bias control stage for initiating load current flow. Thus, the transistorized circuit of the invention is constructed so that once it is biased into operation it remains in stable operation providing self-biasing until a load short circuit or overload is encountered, whereupon the output of the circuit ceases until the starting bias referred to is again applied.

According to another feature of the invention a transistorized circuit includes a reverse biasing network to compensate for transistor leakage current at high ambient temperatures. This compensation is realized by providing, at high temperatures, a path from a current source directly to the transistor base (by-passing the transistor emitter), with this path having a lower impedance than the path from the current source directly to the transistor emitter. The transistor base (with a p-n-p type transistor) is thus biased at a positive potential higher than that of the emitter (in the absence of signal current flow). As a consequence of this reverse biasing, no appreciable leakage current flows through the emitter at high ambient temperatures (leakage current flow through the emitter would be amplified and, at high temperatures, may be larger than the signal current). The reverse biasing network of the invention, as embodied in the circuit referred to, makes use of a non-linear voltage dropping element, such as a unilateral conduction device that has a substantially constant voltage drop across it regardless of current flow through it (for example, a crystal diode). This non-linear voltage dropping element is connected in series with an emitter lead of the transistor of the first or load current amplifier stage, and a negative temperature coefficient resistance device (such as a thermistor) is connected to by-pass current flow directly to the base lead of the transistor. If leakage current flows through the transistor, a voltage drop occurs across the non-linear element (the voltage drop being usually a fraction of a volt in the case of a crystal diode). Since a smaller voltage drop takes place across the negative temperature coefficient resistance device than across this non-linear voltage dropping element, the flow of leakage current causes the base to become more positive than the emitter at high temperatures by virtue of the voltage drop across the non-linear element. This reverse bias condition tends to reduce leakage current through the transistor by biasing the transistor base toward cut-off.

Yet another feature of the invention is the provision of an improved output or load voltage control for a transistorized voltage regulator circuit such as the one described above. A variable, positive feedback arrangement is connected to adjust load voltage regulation in the regulator circuit independently of the magnitude of the output voltage to be regulated. This arrangement is realized by means of a variable resistor connected in series with the reference voltage source of the voltage regulator, and between the regulator circuit input and output. Adjustment of this variable resistor varies the bias voltage (from a tap on a voltage sensing network)

to the load current control stage of the regulator without any appreciable effect on the load voltage. Thus, desirable voltage regulation may be realized over a range of different load voltages.

In the drawings, wherein like reference characters refer to like circuit elements and features:

FIGURE 1 is a circuit diagram of a two-stage transistorized voltage regulator circuit embodying the invention; and

FIG. 2 is a diagram of a three-stage transistorized voltage regulator circuit embodying the invention.

Referring now to FIG. 1, direct current is fed into input terminals 12 and 14 of a series type transistorized voltage regulator circuit 16 embodying the invention from a conventional direct current power supply source 10, and is taken from the regulator circuit by means of output terminals 17 and 18. The regulator circuit 16 illustrated by way of example includes: (a) a two-stage amplifier to provide the amplification required for voltage regulation, the amplifier being made up of two series-connected transistors 20 and 22 of opposite polarity types; (b) a breakdown or zener diode 24 for establishing a reference potential for the circuit; (c) an output voltage sensing network including two series-connected resistors 26 and 28; and (d) an output filter here illustrated as capacitors 32 and 56, the second capacitor 56 serving to increase the high frequency gain of the voltage regulating feedback loop by lowering the alternating current impedance of the loop.

In accordance with the invention, the regulator circuit 16 also includes, as will be explained in detail below: (a) a novel amplifier biasing circuit, comprising a resistor 34 and a switch 36 connected in series, for turning on the voltage regulator circuit after it has been automatically turned off as a result of being subjected to an output short circuit as well as for initiating the operation of the regulator circuit; (b) a novel reverse biasing circuit, comprising a non-linear voltage dropping device such as a crystal diode 38 and a negative temperature coefficient resistance device such as a thermistor 40, for permitting operation of the amplifier transistors 20 and 22 at high ambient temperatures without excessive leakage current; and (c) a novel positive feedback circuit including the variable resistor 42, for improved output voltage regulation.

In the two-stage amplifier of the voltage regulator circuit the first transistor 20 carries the full load current i_m , while the second transistor 22 acts as a bias control or feedback amplifier that regulates the load current flow through the first transistor. The first or load current regulator transistor 20 is therefore preferably a high power transistor, while the second or bias control transistor 22 may be a low power one. In operation of the voltage regulator circuit 16 a constant output voltage E_o , which may, for example, be 25 volts, is provided from a varying input voltage E_i , which may, for example, be nominally 30 volts. The excess input voltage $E_i - E_o$ (5 volts in the example) is taken up substantially across the collector 46 to base 48 junction of the first transistor 20. Any tendency toward increasing output voltage causes a compensating increase in voltage between the collector 46 and emitter 44 of the first transistor due to the reduction in the flow of first transistor biasing current i_b through the collector 50 of the second transistor 22.

In detail, in the regulator circuit 16 load current i_m from the positive voltage source terminal 12 flows into the first transistor 20 (a p-n-p type) through the emitter 44 thereof, and out of the transistor through the collector 46 (assuming an appropriate bias on the transistor base 48). The load current i_m then flows toward the positive output terminal 17. The negative return through the voltage regulator circuit is from the negative output terminal 18, through the positive feedback resistor 42 to be described, and to the negative input terminal 14. The biasing current i_b of the first transistor 20 flows into the

emitter 44 thereof and out through the base 48. This biasing current i_b then becomes the load current through the second transistor 22 (an n-p-n type). This current i_b flows through a current limiting resistor 55, connected between the first transistor base 48 and the second transistor collector 50, through the second transistor collector 50 and out of the emitter 52. The flow of bias current i_{z1} for the second transistor 22 is, during normal operation of the voltage regulator circuit, into the transistor 22 through the base 54 thereof and out of the transistor through the emitter 52 thereof, and finally to the negative voltage source terminal 14.

The current supply i_{z2} for the voltage reference or zener diode 24 flows from the positive side of the output circuit through a voltage dropping resistor 30 to the diode 24, then through the positive feedback resistor 42 to the negative source terminal 14. The combined biasing current i_{z1} and zener diode supply current i_{z2} is referred to in the drawing as i_z .

In operation of the regulator circuit 16 of FIG. 1, the starting switch 36 is closed (as by being manually closed or by being automatically closed by, for example, an automatic switch connected to close the circuit for a short period of time when initiation of current flow is desired). This closing of the starting switch initiates the flow of a starting or auxiliary biasing current to the second transistor 22 causing it to become conductive. When the second transistor 22 becomes conductive, biasing current i_b for the first transistor 20 is applied to the first transistor causing it to become conductive. The first and second transistors 20 and 22 are thus turned fully on until the output voltage E_o builds up to a value where the error voltage between the output sensing circuit and voltage reference circuit is essentially zero (the sensing circuit being the series resistors 26 and 28, and the reference circuit being the zener diode 24 and resistor 42). Any potential difference or error voltage between a sensing circuit pick-off point (point A) and the reference potential (the potential at the base 54 of the second transistor 22) affects the bias on this second transistor 22; the error voltage is thus amplified and phase inverted by this second transistor 22, so as to appear as a potential across the emitter 44 to collector 46 junction of the first transistor 20, cancelling the error voltage. At this point of operation, the voltage regulator circuit is stable and the output is regulated. The switch 36 is then opened and the regulation continues since both transistors 20 and 22 are conductive. Since the circuit reaches stable operation in a very short period of time, the switch may in practice be only momentarily closed in order to initiate operation. Once regulation of the output voltage is realized, the zener diode supply resistor 30 supplies substantially all of the zener diode current and the second transistor biasing current. The current for the zener diode is taken from the output side of the voltage regulator circuit 16 so that minimum current changes are imposed on the voltage reference circuit. Capacitors 32 and 56 may be connected in a conventional manner to stabilize and improve the transient performance of the regulator circuit.

In the event of an output short circuit, the reference voltage, across the zener diode 24, will drop to zero. This drop causes the base 54 of the second transistor 22 to have the same potential as that of the emitter 52 thereof. Since, as is known, the base must be more positively biased than the emitter for an n-p-n transistor to remain conductive, the second transistor 22 now ceases to conduct. When the second transistor is cut off, no first transistor 20 biasing current i_b can flow; this cuts off the operation of the first transistor 20. The foregoing sequence results in a cessation in the operation of the voltage regulator circuit. Thus the circuit is inherently self-protective against output short circuits. Since the base 54 of the second transistor must be made more positive than the emitter in order to initiate operation of the circuit, the circuit remains off even after the removal of the output

short circuit. In order to reestablish operation of the circuit, the switch 36 is again momentarily actuated, allowing the reference voltage to build up, rendering the second transistor 22 conductive, and thus starting the flow of output current from the regulator circuit.

While the transistors have been described with reference to a first transistor 20 of a p-n-p type and a second transistor 22 of an n-p-n type, it will be appreciated that the polarity types of the transistors may be reversed, with the polarity of other circuit connections similarly reversed so as to effect the circuit operation described. Also, while the switch 36 has been indicated as being a momentarily on switch, it will be appreciated that other switching arrangements may be used for starting the flow of output voltage. For example, a magnetic relay or thermal switch may be used to establish a bias on the second transistor 22 for starting the operation of the regulator circuit.

According to another feature of the invention, an improved reverse biasing circuit is provided that permits operation of transistors at high ambient temperatures without excessive leakage current. While this feature is of especial utility in the use of germanium transistors, it also proves useful with other types of transistors, such as those of the silicon variety. The reverse biasing circuit is made up of a non-linear voltage dropping element that has a substantially constant voltage drop characteristic thereacross, that is, a substantially constant voltage drop across it regardless of current flow through it, and a negative temperature coefficient device. The non-linear voltage dropping device is here exemplified by the crystal diode 38, and the negative temperature coefficient device by the thermistor 40. The thermistor 40 has a voltage drop characteristic thereacross that is substantially greater than that of the crystal diode 38 at normal temperatures, that is, at temperatures at which the transistor 20 exhibits substantially no leakage current flow. However, at temperatures substantially higher than normal, where the transistor exhibits leakage current flow, the thermistor 40 exhibits a voltage drop characteristic thereacross that is at least as small as that across the crystal diode 38. The diode 38 is connected in series with the first transistor emitter 44 for conduction in a direction toward the transistor 20, and the thermistor 40 is connected between the positive side of the source voltage and the transistor base 48. At low ambient temperatures the thermistor 40 acts substantially as an open circuit allowing transistor operation in the manner described above. In the event of high ambient temperatures, the thermistor 40 lowers the external resistance between the emitter 44 and the base 48 to a value less than the resistance across the diode 38. This lowered external resistance allows leakage current (in the absence of signal current) to flow directly to the transistor base 48, biasing the base to a value more positive than the emitter. This reverse biasing tends to cut off the transistor to the flow of leakage current. The flow of leakage current through the transistor is undesirable since this current flow would be amplified by the transistor and may, at high temperatures, be larger than the signal current flow.

According to still another feature of the invention, a variable resistor 42 is used as a positive feedback control element for adjusting the load voltage regulation substantially independently of the magnitude of the output voltage provided by the regulator circuit. The feedback control according to this feature is used to let the voltage sensing portions of the regulator circuit "see" (in the presence of an output voltage drop due to increased load current) a voltage change greater than that which actually takes place across the output terminals 17 and 18. The resultant over compensation for load circuit voltage drop is used to provide improved voltage regulation.

Normally, the voltage of the power delivered by a power supply decreases with increasing load. A voltage regulator circuit usually serves to minimize the voltage

drop (rather than compensate for the voltage drop). According to this feature of the invention, the sensitivity of the voltage regulator circuit is increased so as to maintain the output voltage substantially uniform regardless of load. Indeed, the circuit according to this feature can actually be adjusted to provide increasing voltage with increased load! The load voltage is sampled at point A, the potential at point A varying in proportion to the instantaneous value of the actual load voltage. In order to increase the sensitivity of the circuit to changes in load, point A is connected to appear to drop in potential at a faster rate than the rate at which the load voltage actually tends to decrease with increasing load. This simulation of the effect of a great drop in output voltage is used to let the voltage regulator circuit compensate to a greater degree than it would in the absence of this simulated great voltage drop. Thus the regulator is made to see a greater change than that which actually exists in the output. The actual amount of over compensation is chosen (by adjustment of the resistance of the variable resistor 42) such that, over the variations in load over which the regulator circuit is designed to operate, the output voltage remains substantially uniform at the desired level. The foregoing is realized by having the reference source, zener diode 24, in series with the feedback control resistor 42. Adjustment of the variable resistor 42 determines the potential of point B, the connection between the zener diode 24 and the variable resistor 42, for adjusting the level of the voltage applied to the zener diode 24. The variable resistor 42 is connected in series between the negative input and output terminals 14 and 18, respectively, and in series with the reference potential source, the zener diode 24. The voltage magnitude control resistor 28 is of the order of thousands of ohms resistance, while the feedback control resistor 42 is of the order of a fraction of an ohm to a few ohms in resistance. From the foregoing it is seen that the variable output voltage control resistor 28 adjusts the magnitude of the output voltage E_o , while the variable feedback control resistor 42 is used to adjust the rate of voltage compensation of the circuit to changes in load current.

FIG. 2 is a circuit diagram of a three-stage voltage regulator circuit embodying the principles described with respect to FIG. 1. The circuit portions in the diagram of FIG. 2 corresponding to circuit portions in the diagram of FIG. 1 will be referred to with the same numerals as those used in FIG. 1 with the exception that the letter "a" will be used to designate the circuit portions of FIG. 2.

The three-stage transistorized voltage regulator circuit 16a of FIG. 2 is similar both in circuit arrangement and in operation to that of FIG. 1 with the exception that an intermediate amplifier stage is connected in cascade between the first and second amplifier stages illustrated in the circuit of FIG. 1. This intermediate amplifier stage, provided by a transistor 70a of the same polarity type as that in the first regulator stage 20a, contributes to the provision of an over-all circuit having greater gain, and thus improved voltage regulation action, than that of the circuit of FIG. 1. The second transistor 70a is connected so that the biasing current of the first transistor 20a flows through the second transistor 70a under the control of this second transistor. The bias current for the second transistor 70a, in turn, flows through, and is controlled by, the last transistor 22a. Thus, each transistor controls the flow of bias current in the transistor in the stage preceding it. While a single intermediate stage is used in the circuit of FIG. 2, it will be appreciated that any number of intermediate amplifier stages may be used between the input and output amplifiers (provided by transistors 20a and 22a, respectively) for providing increased gain and resultant increased voltage regulation control. The additional intermediate amplifier stages are serially connected in the regulator circuit in a manner similar to that of the intermediate stage of the regulator circuit of FIG. 2.

As is the case with the first transistor 20a, a high temperature, reverse biasing, leakage current compensation arrangement is provided for the second transistor 70a. This compensation arrangement is made up of a crystal diode 58a and thermistor 60a connected to the base 48a of the first transistor 20a and to, respectively, the emitter 72a and base 76a of the second transistor 70a. The function and connection of these elements 58a and 60a are substantially the same as those in the preceding stage where the diode 38a and thermistor 40a provide leakage current compensation for the first transistor 20a at high ambient temperatures. As is the case in the circuit of FIG. 1, a current limiting resistor 55a is connected between the collector 50a of the final transistor 22a and the base 76a of the transistor 70a of the preceding stage for limiting the current flow and dissipation of the last transistor 22a. Also, a number of diodes may be connected in series so that the total voltage drop across the diodes provides the desired reference voltage. Thus, for example, two serially connected zener diodes 62a and 64a are used in the circuit of FIG. 2.

While the invention has been described as embodied in an improved transistorized voltage regulator circuit for a power supply, it is apparent that the principles may be applied to other transistorized circuits where circuit immunity from load short circuits and/or increased temperature and voltage operation versatility is desired.

What is claimed is:

1. In combination:

a direct current source,
load means,

a semiconductor device having a principal current path including input and output electrodes and a control current path including said input electrode and a control electrode,

means for connecting said principal current path and said load means in series across said source,

means responsive to variations in the output voltage applied to said load means and connected to said control electrode for regulating the impedance of said principal current path as a function of said output voltage,

a non-linear impedance device connected in series with said principal current path between said input electrode and said source, and

a negative temperature coefficient resistance means connected in shunt with the series combination of said control current path and said non-linear impedance device.

2. In a voltage regulation circuit:

a source of unregulated voltage direct current;
a load circuit;

a semiconductor device having a principal current path including collector and emitter electrodes and a control current path including said emitter electrode and a control electrode;

means for connecting said principal current path and said load circuit in series across said source;

means for sensing variations in the voltage applied to said load circuit;

means responsive to said sensing means for applying a control current to said control current path as a function of the voltage applied to said load circuit so that the impedance of said principal current path is varied as a function of the load circuit voltage;

a non-linear impedance voltage dropping means connected in series with said principal current path between said emitter and said source for developing a relatively constant biasing potential in response to a predetermined range of load currents flowing therethrough; and

negative temperature coefficient resistance means connected across the series combination of said control current path and said voltage dropping means for shunting a greater portion of said control current

around said semiconductor device in response to increased ambient temperatures and vice versa.

3. A control circuit suitable for use in regulating the supply of power to an output load from a source of electrical power, said circuit comprising:

first and second transistors each having a base and current input and output portions, said second transistor being coupled in such a biasing relationship to said first transistor as to conduct all bias current flow of said first transistor so that only during conduction of said second transistor is said first transistor conductive;

a leakage current compensation network including a non-linear impedance voltage dropping element having one end connected to the current input portion of said first transistor, and a negative temperature coefficient resistance device connected between the other end of said non-linear impedance voltage dropping element and the base of said first transistor; voltage-sensitive means connected at one end to the base of said second transistor to prevent current flow therethrough when the voltage drop across the output load is less than a predetermined value; and

a voltage-divider arrangement connected across the output load and to the other end of said voltage-sensitive means, a voltage tap on said voltage-divider arrangement being connected to the current output portion of said second transistor;

said second transistor remaining conductive as long as the voltage across the load is greater than said predetermined value as a function of the voltage drop across said voltage-sensitive means.

4. The circuit defined in claim 3 wherein said non-linear impedance voltage dropping element is a diode connected for normal conduction in a direction of normal current flow through said first transistor, said negative temperature coefficient resistance device is a thermistor, and said voltage-sensitive means is a zener diode.

5. The circuit defined in claim 4 wherein said circuit further includes auxiliary by-pass biasing means momentarily connectable to the base of said second transistor for initiating conduction of said second transistor to initiate current flow through said first transistor when the voltage across the output load is conditionally less than said predetermined value.

6. A control circuit suitable for use in regulating the supply of power to an output load from a source of electrical power, said circuit comprising:

first and second transistors each having a base and current input and output portions, said second transistor being coupled in such a biasing relationship to said first transistor as to conduct all bias current flow of said first transistor so that only during conduction of said second transistor is said first transistor conductive;

means coupled to the base of said second transistor for establishing a bi-level reference potential thereat, the potential being substantially at one level during normal conductive operation of the control circuit and at the other level upon overload of the output load;

an output voltage sensing network coupled to the output load for sensing an overload condition, said network additionally being coupled to the output current portion of said second transistor and to said means;

a biasing circuit for selectively rendering said second transistor conductively operative after it has been rendered inoperative in response to an overload condition; and

a reverse-biasing circuit including a non-linear impedance voltage dropping device and a negative temperature coefficient resistance device respectively coupled in series between the input current portion of said first transistor and the base thereof for permitting

operation of said first transistor without excessive leakage current.

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