Provisional Patent Application of Robert L. Baer

TITLE: HIGH VOLTAGE SHUNT REGULATOR CIRCUIT

BACKGROUND OF THE INVENTION

Federally Sponsored Research None

Field of the Invention

This invention relates generally to the field of shunt voltage regulator circuits. More specifically, it relates to a shunt voltage regulator circuit suitable for high voltage, low current applications, over a wide temperature range, and especially at elevated temperatures.

Prior Art - Shunt Voltage Regulators

Shunt voltage regulators are components or circuits that are usually connected in parallel with a particular electronic device, or across the input or output terminals of a circuit, to limit the voltage that can be applied across the device or between the terminals. The shunt regulator performs this function by conducting very little current until a preset voltage is reached, at which point the regulator becomes a very low resistance device that conducts a higher current. Many types of shunt voltage regulators are in widespread use today.

U.S. Pat. No. 5,023,543--Tse, U.S. Pat. No. 5,029,295--Bennett et al., U.S. Pat. No. 5,519,313--Wong et al., and U.S. Pat. No. 5,621,307--Beggs, all disclose a version of a temperature compensated voltage regulator. These and similar patents refer to basic low voltage regulator methods to which we will not presume to add, modify or improve.

Prior Art - Zener Diodes

A well known type of shunt voltage regulator is the zener diode. A zener diode exhibits a very high resistance, and thus allows the passage of very small currents, until a predefined reverse threshold voltage, called the "zener" voltage, is applied across it. When the zener voltage is reached and exceeded, current conduction across the zener diode junction interface increases rapidly. Zener diodes are commonly commercially available with zener voltages of about 2 volts to about 200 volts. A problem with zener diodes is that those with zener voltages above about 6 volts exhibit large positive temperature coefficients, and an increase in noise and negative resistance characteristics at low currents; these traits worsen as higher voltage zener diode devices are selected. Lower voltage zener diodes exhibit a negative temperature coefficient, but above about 6 volts true zener breakdown does not occur, with avalanche mode breakdown taking over and imparting a positive temperature coefficient. Thus, high voltage zener diodes are not generally suitable in very low current applications, especially at elevated temperatures.

A number of temperature coefficient correcting schemes involving multiple diodes are possible; included are combinations of higher and lower voltage zener diodes or combinations of lower voltage zener diodes and conventional silicon diodes. While these schemes may compensate the temperature coefficient, all are less than ideal due to space considerations, likely noise problems at very low currents, and the fact that any such temperature coefficient correction can be optimized for only a narrow current range.

A variation is the use of a thermistor as a temperature compensating element for a string of zener diodes. While this scheme can result in a more compact assembly due to the use of just a few high voltage zener diodes, the temperature coefficient optimization can only be made over a very narrow current range, and there remains the likelihood of noise problems at very low currents.

Prior Art - Leaky Diode

One manufacturer (Comprobe) of oil well logging sondes utilized conventional silicon diodes as high voltage regulator devices. The diodes had to be selected for appropriate reverse leakage characteristics, a time consuming process resulting in a low yield of usable devices. The leaky diode high voltage regulator was unreliable and extremely temperature unstable, and its use was long ago discontinued.

Prior Art - Corona Mode Gas Tube Devices

The prior art also includes a gas discharge diode tube operating in the corona mode of discharge. This device operates as a high voltage equivalent of a zener diode, and it functions well with low shunt regulation currents and at high temperatures (characterized to 150° C and usable to 200° C). However, these devices are fragile, expensive, and they require a radioactive component (a beta emitter). They are no longer manufactured, at least in part due to misplaced concerns about their radioactivity. One would have to literally eat such a device in order to sustain any real chance of damage from the radiation, but even then the more likely injury would be from the broken glass of the tube envelope.

Prior Art - U.S. Pat. No. 5,949,122--Scaccianoce

U.S. Pat. No. 5,949,122--Scaccianoce discloses an integrated circuit that provides thermal compensation for a series string of zener diodes, in which several bipolar transistors are connected as V_{BE} multipliers. While this circuit provides temperature-stable high voltage regulation, it may not work well at very low collector currents. This is because the bipolar transistors are connected in a common emitter configuration, in which the collector current (I_C) in each transistor is equal to the base current (I_B) multiplied by the common emitter gain (H_{FE}) of the transistor. The value of H_{FE} for a typical bipolar transistor is in the range of about 10 to about 200. Since the collector current in the Scaccianoce device is the shunt regulation current, the base current would be between 0.5% and 10% of the shunt regulation current. Thus, at low shunt regulation currents (i.e., up to about 500 microamps), the base current would be at or near the value of the collector cutoff current (the collector-to-base leakage current, or I_{CBO}) for typical bipolar transistors. There are bipolar transistors with values of I_{CBO} low enough to allow the Scaccianoce device to work at low shunt regulation currents, but the value of I_{CBO} exhibits a large positive temperature coefficient, especially at temperatures above about 100° C. Thus, as a practical matter, a device constructed in accordance with the Scaccianoce disclosure to operate at low shunt regulation currents would be limited to operation at temperatures of 125° C or less.

Prior Art - U.S. Pat. No. 6,222,350--Mosley

U.S. Pat. No. 6,222,350--Mosley discloses a high voltage shunt regulator circuit comprising high voltage zener diodes connected in series with a thermal compensation device. This Mosley apparatus includes the mistake of using a string of noisy avalanche mode zener diodes at currents that virtually guarantee negative resistance and the specter of oscillation or other noise. Furthermore, the design requires costly adjustment of each and every thermal compensation device used in the unit. Note that operation above 150° C is questionable, since very few components are specified above 125° C, and none above 175° C.

SUMMARY OF THE INVENTION

Summary of the Invention - Objects and Advantages of the Invention

One object and advantage of the present invention is to provide an improved stable high voltage regulation method and apparatus that can operate with low shunt regulation currents over a wide temperature range, and especially at elevated temperatures.

Another object and advantage is the avoidance of the use of avalanche mode zener diodes in the present invention.

Further objects and advantages of the present invention are to provide a device that meets said operational criteria in a space-efficient and shock-resistant package.

Still further objects and advantages will become apparent from a consideration of the ensuing description and drawing.

Summary of the Invention

Broadly, the present invention is a high voltage shunt regulator circuit comprising a voltage-controlled resistive device to regulate voltage, a low voltage device having a predetermined reverse conduction threshold voltage in series with said voltage controlled resistive device, and a thermal compensation device comprising a voltage sensing resistive divider in combination with said thermal compensation device. The voltage-controlled resistive device is preferably a MOSFET, with its source connected to ground via an appropriate stable voltage reference. The voltage divider is formed by a first resistor connected from the voltage to be regulated and the gate of the MOSFET and continues to the thermal compensation device, and then to a second resistor connected to ground. The thermal compensation device is selected and its operating bias is also selected so as to substantially track the temperature coefficient of the MOSFET. This allows efficient operation at temperatures at least as high as 125° C, and usable operation above 150° C is observed. Stable and low noise operation is exhibited with low shunt regulation currents of about 25 microamps up to about 5 amps. However, the present invention is preferably realized by optimization in the 25 microamp to about 500 microamp range.

The zero temperature coefficient point of current regulation can be adjusted over a wide range, thereby allowing the use in a wide variety of applications.

The present invention is preferably realized with discrete components, thereby minimizing costs. Because only a few components are needed, even for the regulation of high voltages in relatively high temperature environments, efficient use of space is achieved. Furthermore, the use of solid-state components provides a high degree of resistance to mechanical shocks and vibrations.

DESCRIPTION OF THE DRAWING

Brief Description of the Drawing

FIG. 1 is a circuit diagram of a 900 volt regulator constructed in accordance with a preferred embodiment of the present invention.

Drawing Reference Numerals and Letters

1	Voltage Amplifier	9	Terminal
2	Temperature Compensating Device	10	Terminal
3	Terminal	D	Drain
4	Terminal	G	Gate
5	Terminal	S	Source
6	Voltage Reference Diode	R1	Resistor
7	MOSFET	R2	Resistor
8	MOSFET		

DETAILED DESCRIPTION OF THE INVENTION

The present invention, in its preferred embodiment, exploits an advantageous characteristic of MOSFET devices that allows matching of thermal characteristics. Different part types can be used so that cost and space is minimized, by using different currents in the two devices. This can be done for any given current flowing through the regulating element, and can be adjusted so that a usable range of currents through the regulating element will exhibit a low temperature coefficient. This temperature compensation allows the regulating MOSFET to act as a cascode voltage amplifier, thereby producing regulation of a voltage substantially greater than the voltage reference in the source of the MOSFET.

A MOSFET voltage amplifier 1, suitable for use in the present invention to achieve the above-mentioned goal, is shown in FIG. 1. The voltage amplifier 1 comprises a MOSFET 7 having a drain D, a source S, and a gate G. The drain D is connected to a first terminal 5, and the source S is connected to a voltage reference diode 6 at terminal 10. The voltage reference is also connected to final terminal 3. The MOSFET 7 shown in FIG. 1 is an n-channel MOSFET; it will be understood that a p-channel MOSFET can be used instead, with circuit modifications that will readily suggest themselves to those skilled in the pertinent art.

The voltage divider comprises a first resistor R1 connected between the drain D at terminal 5 and the gate G of the MOSFET 7 at terminal 4. A temperature compensating device 2, is the second MOSFET 8 wherein the gate G and the drain D are connected to the gate G of MOSFET 7 at terminal 4, and a second resistor R2 is connected between the source S at terminal 9 and terminal 3. Variations across this composite voltage divider drive the gate G of MOSFET 7, changing its conductivity in a manner that keeps terminal 9 at the same voltage as terminal 10. This tracking is maintained as long as the gate to source voltage of the two MOSFETs track over temperature and current. The regulator circuit is designed to provide a regulated voltage that can be adjusted from a low voltage approximately 4 volts greater than the voltage reference 6 to a high voltage near the breakdown voltage of MOSFET 7, with shunt regulation currents as low as about 25 microamps.

Although a specific example of a preferred embodiment of the invention has been described in detail above, the principles of the present invention will be readily employed in voltage regulator circuits having a wide range in the values of their operational parameters (e.g., total regulated voltage, shunt regulation current, ambient operating temperature). Thus, voltage regulator circuits in accordance with the present invention will be easily designed, with reference to the instant disclosure, by those skilled in the pertinent art to accommodate a wide variety of needs and applications.

While a specific preferred embodiment has been described herein, it will be appreciated that a number of variations and modifications may suggest themselves to those skilled in the pertinent art. For example, while the preferred embodiment described herein uses N-channel MOSFETs, P-channel MOSFETs may also be used, with circuit modifications that would be readily apparent to those skilled in the pertinent art. These and other variations and modifications should be considered within the spirit and scope of the present invention, as defined in the claims that follow.

CLAIMS

I claim:

1. A voltage regulator circuit for operation through a temperature range from as low as about -80° C to about 150° C or above, with a shunt regulation current of no more than about 500 microamps comprising:
   a voltage-controlled resistive device to regulate voltage; and
   a low voltage device having a predetermined reverse conduction threshold voltage in series with the voltage controlled resistive device; and
   a thermal compensation device comprising a voltage sensing resistive divider in combination with said thermal compensation device, to control the voltage-controlled resistive device.
2. The voltage regulator circuit of claim 1, wherein the voltage-controlled resistive device is a MOSFET.
3. The voltage regulator circuit of claim 1, wherein the thermal compensation device is a MOSFET having the drain and the gate connected together.
4. The voltage regulator circuit of claim 1, wherein the low voltage device is a zener diode or other voltage reference.
5. The voltage regulator circuit of claim 2, wherein the low voltage device is a zener diode or other voltage reference.
6. The voltage regulator circuit of claim 3, wherein the low voltage device is a zener diode or other voltage reference.
7. The voltage regulator circuit of claim 1, wherein the low voltage device includes a plurality of zener diodes or other voltage references connected in series.
8. The voltage regulator circuit of claim 2, wherein the low voltage device includes a plurality of zener diodes or other voltage references connected in series.

9. The voltage regulator circuit of claim 3, wherein the low voltage device includes a plurality of zener diodes or other voltage references connected in series.

10. The voltage regulator circuit of claim 1, wherein the circuit operates with a shunt regulation current of between about 25 microamps and about 500 microamps.

11. The voltage regulator circuit of claim 2, wherein the circuit operates with a shunt regulation current of between about 25 microamps and about 500 microamps.

12. The voltage regulator circuit of claim 3, wherein the circuit operates with a shunt regulation current of between about 25 microamps and about 500 microamps.

13. A voltage regulator circuit for operation through a temperature range from as low as about -80° C to about 150° C or above, with an optimized shunt regulation current set between about 25 microamps and about 5 amps:

a voltage-controlled resistive device to regulate voltage; and

a low voltage device having a predetermined reverse conduction threshold voltage in series with the voltage controlled resistive device; and

a thermal compensation device comprising a voltage sensing resistive divider in combination with said thermal compensation device, to control the voltage-controlled resistive device.

14. The voltage regulator circuit of claim 13, wherein the voltage-controlled resistive device is a MOSFET.

15. The voltage regulator circuit of claim 13, wherein the thermal compensation device is a MOSFET having the drain and the gate connected together.

16. The voltage regulator circuit of claim 13, wherein the low voltage device is a zener diode or other voltage reference.

17. The voltage regulator circuit of claim 14, wherein the low voltage device is a zener diode or other voltage reference.

18. The voltage regulator circuit of claim 15, wherein the low voltage device is a zener diode or other voltage reference.

19. The voltage regulator circuit of claim 13, wherein the low voltage device includes a plurality of zener diodes or other voltage references connected in series.

20. The voltage regulator circuit of claim 14, wherein the low voltage device includes a plurality of zener diodes or other voltage references connected in series.

21. The voltage regulator circuit of claim 15, wherein the low voltage device includes a plurality of zener diodes or other voltage references connected in series.

ABSTRACT

A high voltage shunt regulator circuit includes a high voltage device with a predetermined low voltage reverse-conduction threshold connected in series, in counterbalance with a thermal compensation device connected in series with voltage sensing resistors. The high voltage device is a single voltage-controlled resistive device, preferably a MOSFET. The voltage divider is formed by a first resistor connected from the voltage to be regulated and the gate of the MOSFET and continues to the thermal compensation device, and then to a second resistor connected to ground. The MOSFET source connects to ground via an appropriate stable voltage reference. The operating bias of the thermal compensation device is adjusted to substantially track the temperature coefficient of the MOSFET. This can be done for any given current flowing through the regulating element, and can be adjusted so that a usable range of currents through the regulating element will exhibit a low temperature coefficient.

FIG. 1