New Developments in IC Voltage Regulators

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Abstract—A temperature-compensated voltage reference that provides numerous advantages over zener diodes is described along with the implementation of thermal overload protection for monolithic circuits. The application of these and other advanced design techniques to IC voltage regulators is covered, and an example of a practical design is given.

Introduction

MONOLITHIC regulators have been receiving considerable attention during the last year or two. With the exception of operational amplifiers and voltage comparators, regulators lead other categories of linear devices in sales. Hence, considerable effort has gone into improving their performance and general utility.

Increasing the output-current capability, reducing the number of external components, and minimizing external trimming are obvious areas for improvement of older designs. Higher reliability under actual field conditions is less obvious, but probably more essential. Minimum input voltages less than the present 7–9 V would also increase the usefulness of these circuits.

Some techniques for realizing these objectives will be described. Further, a practical design for an on-card regulator that provides 5 V for logic circuits will be given. This circuit has three active leads, so it can be supplied in standard transistor power packages. It requires no external components and can reliably deliver output currents in excess of 1 A.

Design Concepts

A simplified schematic of a typical voltage regulator is shown in Fig. 1. An operational amplifier compares a reference voltage with a fraction of the output voltage and controls a series-pass transistor to regulate the output. Some form of overload protection is usually provided. Here, the output current is limited by Q_1 and R_1.

The low cost of IC regulators has created a considerable interest in on-card regulation, that is, to provide local regulation for each printed-circuit card in a system. Rough preregulation is used in the main power source, and the power is distributed without excessvie concern for line drops. The local regulators then smooth out the voltage variations caused by line drops and eliminate the transients on the main power bus.

A useful on-card regulator must include everything within one package, including the series-pass transistor. The author has previously advanced arguments against

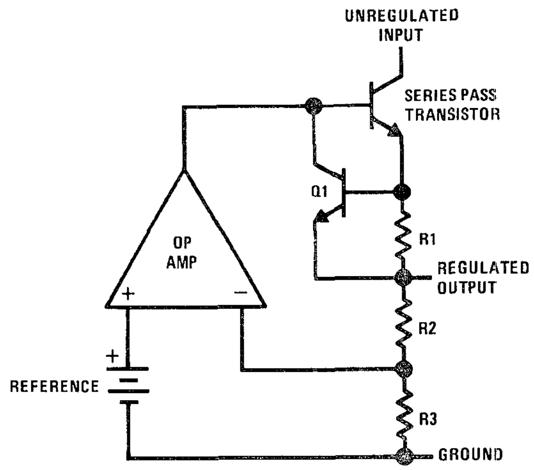

Fig. 1. Basic series regulator circuit.

including the pass transistor in an integrated-circuit regulator [1]. First, there are no standard multilead power packages. Second, integrated circuits necessarily have a lower maximum operating temperature because they contain low-level circuitry. This means that an IC regulator needs a more massive heat sink. Third, the gross variations in chip temperature due to dissipation in the pass transistors worsen load and line regulation. However, these problems can be largely overcome using the new techniques, especially for the kind of regulator required by digital systems.

It is conceptually possible to build a complete IC regulator that has only three external terminals. Hence, an ordinary transistor power package can be used, circumventing the package problem. The practicality of this approach depends on eliminating the adjustments usually required to set up the output voltage and limiting current for the particular application, as external adjustments require extra pins. A new solid-state reference, to be described later, has sufficiently tight manufacturing tolerances that output voltages do not always have to be individually trimmed. Further, thermal overload protection can protect an IC regulator for virtually any set of operating conditions, making adjustments unnecessary.

Thermal protection limits the maximum junction temperature, providing a constant-power limit that protects the regulator regardless of input voltage, type of overload, or degree of heat sinking. With an external pass transistor, there is no convenient way to sense junction temperature, so it is much more difficult to provide thermal limiting. Thermal protection is, in itself, a very good reason for putting the pass transistor on the chip.

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When a regulator is protected by current limiting alone, it is necessary to limit the output current to a value substantially lower than is dictated by dissipation under normal operating conditions to prevent excessive heating when a fault occurs. Thermal limiting provides virtually absolute protection for any overload condition. Hence, the maximum output current under normal operating conditions can be increased. This tends to make up for the fact that an IC has a lower maximum junction temperature than discrete transistors.

Additionally, a 5-V regulator works with relatively low voltage across the integrated circuit. Because of the low voltage, the internal circuitry can be operated at comparatively high currents without causing excessive dissipation. Both the low voltage and the larger internal currents permit higher junction temperatures. This can also reduce the heat sinking required, especially for commercial-temperature-range parts.

Lastly, the variations in chip temperature caused by dissipation in the pass transistor do not cause serious problems for a logic-card regulator. The tolerance in output voltage is loose enough that it is relatively easy to design an internal reference that is much more stable than required, even foı temperature variations as large as 150 °C.

Voltage Reference

Temperature-compensated zener diodes are normally used as the reference element in solid-state regulators. However, these devices have breakdown voltages greater than 6 V, which puts a lower limit on the input voltage to the regulator. Further, they require tight process control to maintain a given tolerance; and they are relatively noisy.

A new reference has been developed that does not use zener diodes. Instead, it uses the negative temperature coefficient of emitter-base voltage in conjunction with the positive temperature coefficient of emitter–base voltage differential of two transistors operating at different current densities to make a zero temperature coefficient reference. Practical references can be made at voltages as low as the extrapolated energy band-gap voltage of the semiconductor material, which is 1.205 V for silicon.[1]

A simplified version of this reference is shown in Fig. 2. In this circuit, Q_1 is operated at a relatively high current density. The current density of Q_2 is about 10 times lower and the emitter–base voltage differential ΔV_{BE} between the two devices appears across R_3. If the transistors have high current gains, the voltage across R_2 will also be proportional to ΔV_{BE}. Q_3 is a gain stage that will regulate the output at a voltage equal to its emitter-base voltage plus the drop across R_2.

Conditions for temperature compensation can be derived starting with the equation for the emitter–base voltage of a transistor, which is [3]

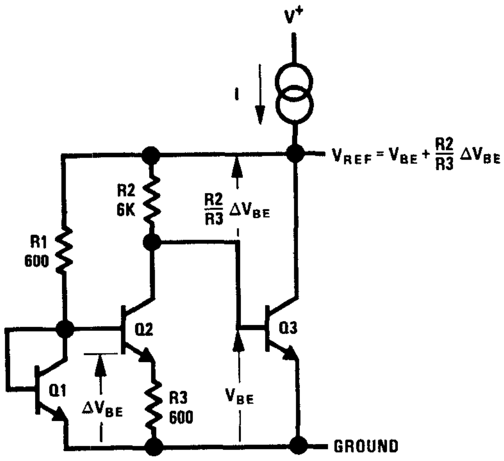

Fig. 2. The low voltage reference in one of its simpler forms.

$$V_{BE} = V_{g0}\left(1 - \frac{T}{T_0}\right) + V_{BEO}\left(\frac{T}{T_0}\right) + \frac{nkT}{q}\log_e\left(\frac{T_0}{T}\right) + \frac{kT}{q}\log_e\frac{I_C}{I_{C0}} \tag{1}$$

where V_{g0} is the extrapolated energy band-gap voltage for the semiconductor material at absolute zero, q is the charge of an electron, n is a constant that depends on how the transistor is made (approximately 1.5 for IC transistors), k is Boltzmann's constant, T is absolute temperature, I_C is collector current, and V_{BEO} is the emitter–base voltage at T_0 and I_{C0}.

Further, the emitter–base voltage differential between two transistors operated at different current densities is given by [4]

$$\Delta V_{BE} = \frac{kT}{q}\log_e\frac{J_1}{J_2} \tag{2}$$

where J is the current density.

Referring to (1), the last two terms are quite small and can be made even smaller by making I_C vary as absolute temperature. At any rate, the terms can be ignored because they are of the same order as errors caused by nontheoretical behavior of the transistors that must be determined empirically.

If the reference is composed of V_{BE} plus a voltage proportional to ΔV_{BE}, the output voltage is obtained by adding (1) in its simplified form to (2):

$$V_{ref} = V_{g0}\left(1 - \frac{T}{T_0}\right) + V_{BEO}\left(\frac{T}{T_0}\right) + \frac{kT}{q}\log_e\frac{J_1}{J_2}. \tag{3}$$

Differentiating with respect to temperature yields

$$\frac{\partial V_{ref}}{\partial T} = -\frac{V_{g0}}{T_0} + \frac{V_{BEO}}{T_0} + \frac{k}{q}\log_e\frac{J_1}{J_2}. \tag{4}$$

For zero temperature drift, this quantity should equal

[1] A similar reference based on emitter–base voltage was described in [2]; however, it did not operate at low voltages nor was it particularly suited to monolithic construction.

zero, giving

$$V_{g0} = V_{BEO} + \frac{kT_0}{q} \log_e \frac{J_1}{J_2}. \tag{5}$$

The first term on the right is the initial emitter–base voltage while the second is the component proportional to emitter-base voltage differential. Hence, if the sum of the two are equal to the energy band-gap voltage of the semiconductor, the reference will be temperature compensated.

In practice, for minimum drift, it is necessary to make the output voltage somewhat higher than was theoretically determined. This tends to compensate for various low-order terms that could not be included in the derivation. The typical performance of a circuit set for minimum temperature drift is shown in Fig. 3. It should be possible to get even lower drift as more experience is gained with the nontheoretical terms.

Some of the advantages of this reference that have not been pointed out are that the emitter–base voltage of n-p-n transistors is the most predictable and well understood parameter in an IC. And the generation of the ΔV_{BE} component depends only on matching, which is easily accomplished in a monolithic circuit. That is why the initial tolerance of the reference can be controlled easily, eliminating individual adjustments for many applications. In addition, the reference uses the same kind of parts that make up the error amplifier—transistors and resistors—and it employs them in essentially the same way. Therefore, it is no longer an outstanding source of noise, as is a zener diode; and large bypass capacitors are not needed to remove the noise. Further, long-term stability that is comparable to the error amplifier can also be expected.

Thermal Overload Protection

Older IC regulators relied on current limiting for overload protection. This required an external resistor to determine a safe limiting current that depended on the maximum input voltage, the highest operating ambient temperature, and the heat sinking available for the IC package.

Actually, the dominant failure mechanism of solid-state regulators is excessive heating of the semiconductors. Thermal protection attacks the problem directly by putting a temperature regulator on the IC chip. Normally, this regulator is biased below its activation threshold so it does not affect circuit operation. However, if the chip approaches its maximum operating temperature because of excessive internal dissipation, the temperature regulator turns on and reduces output current to prevent any further increase in chip temperature. Hence, if current limiting is included to ensure that the current-handling capability of the aluminum conductors and the secondary breakdown ratings of the pass transistor are not exceeded, it is virtually impossible to damage the circuit as long as the operating voltages are kept within ratings.

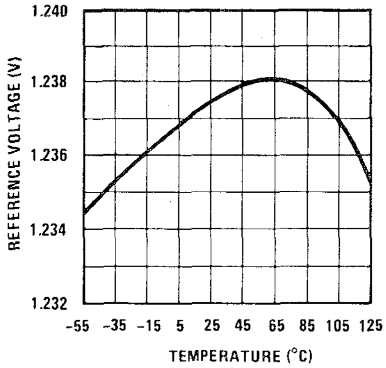

Fig. 3. Typical temperature characteristic of the low voltage reference.

Although some form of thermal protection can be incorporated in a discrete regulator, ICs have a distinct advantage: the temperature sensing device detects increases in junction temperature within milliseconds. Schemes that sense case or heat-sink temperature take several seconds, or longer. With the longer response times, the pass transistor usually blows out before thermal limiting comes into effect.

The concept of thermal overload protection for ICs is not entirely new.[2] But the early designs did not have sufficient control on the limiting temperature to be practical. However, if the emitter–base turn-on voltage of a transistor is used to sense the chip temperature, a ±10 °C tolerance on limiting temperature can be maintained in a production environment without any external trimming.

Circuit Description

As mentioned earlier, a fixed 5-V regulator to be used as an on-card regulator for digital logic circuits was selected to evaluate the aforementioned techniques. A simplified schematic of the circuit used is shown in Fig. 4. The circuitry produces an output voltage that is approximately four times the basic reference voltage, or 5 V. The emitter-base voltage of Q_3, Q_4, Q_5, and Q_8 provide the negative-temperature-coefficient component of the output voltage. The voltage dropped across R_3 is the positive-temperature-coefficient component. Q_6 is operated at a considerably higher current density than Q_7, producing a voltage drop across R_4 that is proportional to the emitter–base voltage differential of the two transistors. Assuming large current gain in the transistors, the voltage drop across R_3 will be proportional to this differential, giving a temperature-compensated output voltage.

In this circuit, Q_8 is the gain stage providing regula-

[2] To the best of the author's knowledge, thermal protection was first used on a Continental Device regulator designed by G. Porter and announced in early 1967.

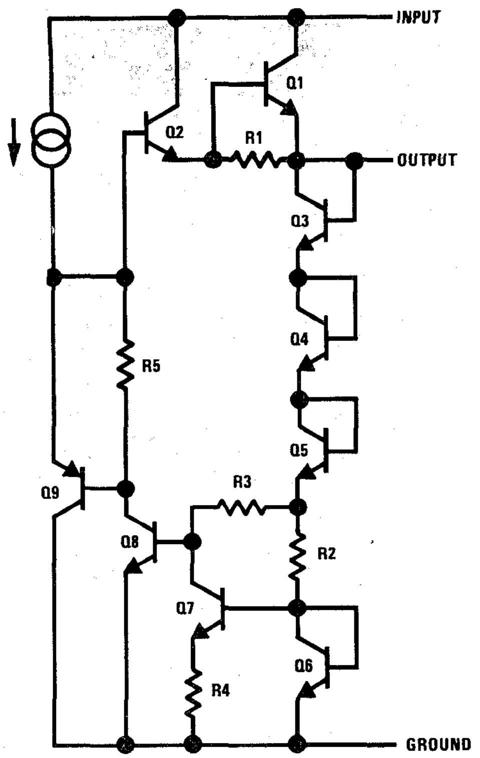

Fig. 4. Schematic showing essential details of the 5-V regulator.

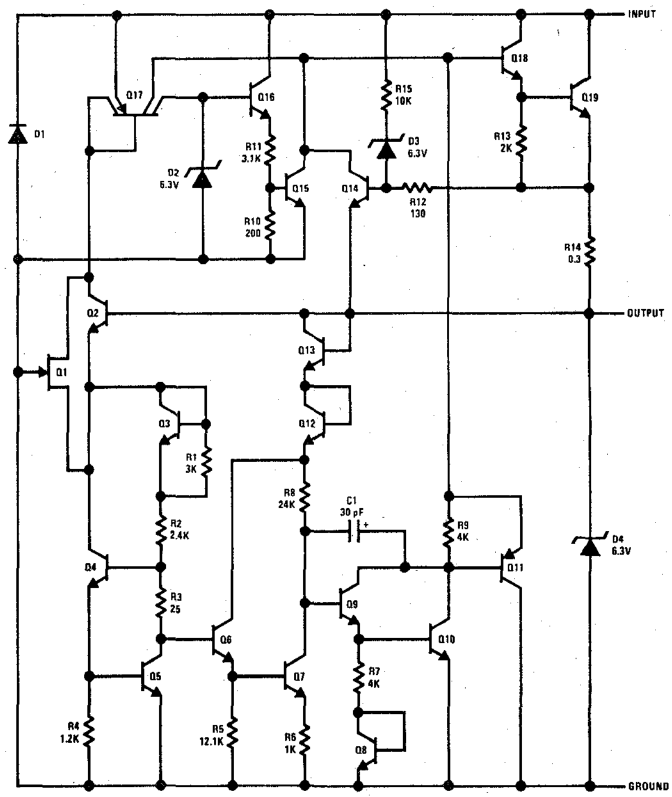

Fig. 5. Detailed schematic of the regulator.

tion. Its effective gain is increased by using a vertical p-n-p Q_9 that acts as a buffer driving the active collector load represented by the current source. Q_9 drives a modified Darlington output stage that acts as the series-pass element. With this circuit the minimum input voltage is not limited by the voltage needed to supply the reference. Instead, it is determined by the output voltage and the saturation voltage of the Darlington output stage.

Fig. 5 shows a complete schematic of the LM109 regulator. The reference is modified considerably over the simplified version to make it easier to manufacture. Q_4 and Q_6 are included both to develop a larger emitter–base voltage differential for Q_7 and to make the circuit less sensitive to production variations in current gain. Q_9 is also used to buffer the regulating transistor Q_{10}. The operating current of Q_9 is proportional to emitter–base voltage differential, as determined by R_7 and Q_8 [6]. R_3 serves to compensate for the transconductance of Q_5[6], so that the voltage delivered to Q_6 is relatively insensitive to changes in output voltage. An emitter–base junction capacitor C_1 frequency compensates the circuit so that it is stable even without a bypass capacitor on the output.

The active collector load for the output stage is Q_{17}. It is a controlled-gain p-n-p[6]. The output current is equal to the collector current of Q_2, with an auxiliary current being supplied to the zener diode controlling the thermal shutdown D_2. Q_1 is a collector FET [6] that along with R_1 ensures starting of the regulator under worst case conditions.

The output current of the regulator is limited when the voltage across R_{14} becomes large enough to turn on Q_{14}. This ensures that the output current cannot get high enough to cause the pass transistor to go into secondary breakdown or damage the aluminum conductors on the chip. Further, when the voltage across the pass transistor exceeds 7 V, current through R_{15} and D_3 reduces the limiting current, again to minimize the chance of secondary breakdown. The performance of this protection circuitry is illustrated in Fig. 6.

Even though the current is limited, excessive dissipation can cause the chip to overheat. However, if its temperature increases to about 175°C, Q_{15} will turn on and reduce the current further to maintain a constant temperature.

The thermal protection circuitry develops its reference voltage with a conventional zener diode D_2. Q_{16} is a buffer that feeds a voltage divider, delivering about 300 mV to the base of Q_{15} at 175°C. The emitter–base voltage of Q_{15} is the actual temperature sensor because with a constant voltage applied across the junction the collector current rises rapidly with increasing temperature.

Another protective feature of the regulator is the crowbar clamp on the output. If the output voltage tries to rise for some reason, D_4 will break down and limit the voltage to a safe value. If this is caused by failure of the pass transistor such that the current is not limited, the aluminum conductors on the chip will fuse, discon-

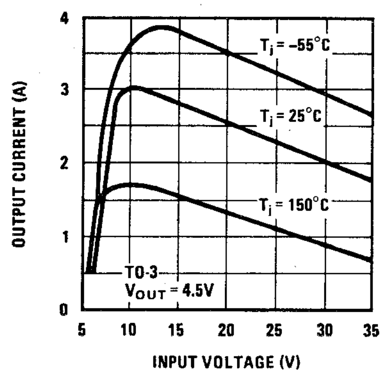

Fig. 6. Current-limiting characteristics.

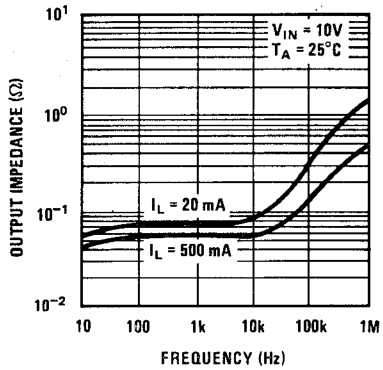

Fig. 7. Plot of output impedance as a function of frequency.

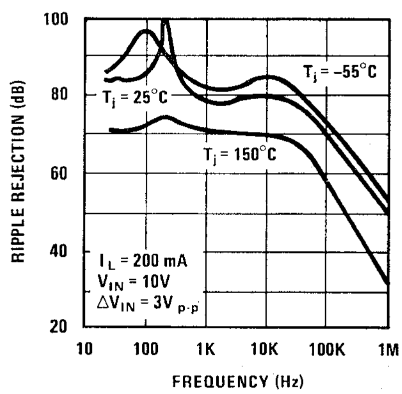

Fig. 8. Ripple rejection of the regulator.

necting the load. Although this destroys the regulator, it does protect the load from damage. The regulator is also designed so that it is not damaged in the event the unregulated input is shorted to ground when there is a large capacitor on the output. Further, if the input voltage tries to reverse, D_1 will clamp this for currents up to 1 A.

The internal frequency compensation of the regulator permits it to operate with or without a bypass capacitor on the output. However, an output capacitor does improve the transient response and reduce the high-frequency output impedance. A plot of the output impedance in Fig. 7 shows that it remains low out to 10 kHz without a capacitor. The ripple rejection also remains

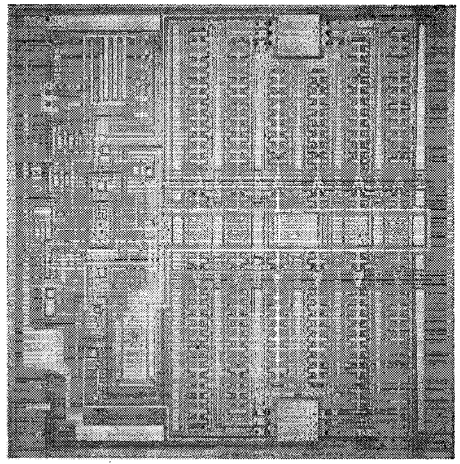

Fig. 9. Photomicrograph of the regulator shows that a high-current pass transistor takes more area than control circuitry.

TABLE I
TYPICAL CHARACTERISTICS OF THE LOGIC-CARD REGULATOR: T_A = 25 °C AND V_{IN} = 9 V

Output voltage		5.0 V
Output current		1.5 A
Output resistance		0.03 ohm
Line regulation	7.0 V $\leq V_{IN} \leq$ 35 V	0.005 percent/V
Temperature drift	−55 °C $\leq T_A \leq$ 125 °C	0.02 percent/°C
Minimum input voltage	I_{OUT} = 1 A	6.5 V
Output noise voltage	10 Hz $\leq f \leq$ 100 kHz	40 μV
Thermal resistance	LM109H (TO-5)	15 °C/W
junction to case	LM109K (TO-3)	3 °C/W

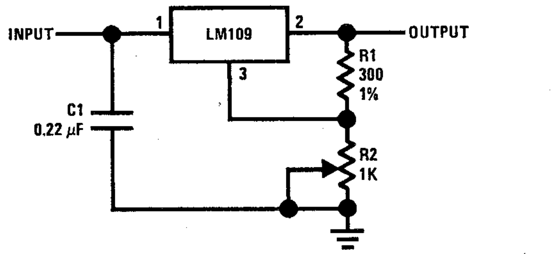

Fig. 10. Using the LM109 as an adjustable-output regulator.

high out to 10 kHz, as shown in Fig. 8. The irregularities in this curve around 100 Hz are caused by thermal feedback from the pass transistor to the reference circuitry. Although an output capacitor is not required, it is necessary to bypass the input of the regulator with at least a 0.22-μF capacitor to prevent oscillations under all conditions.

Fig. 9 is a photomicrograph of the regulator chip. It can be seen that the pass transistors, which must handle more than 1 A, occupy most of the chip area. Q_{19} is actually broken into segments. Uniform current distribution is ensured by also breaking the current limit resistor into segments and using them to equalize the currents. The overall electrical performance of this IC is summarized in Table I.

Although the LM109 is designed as a fixed 5-V regulator, it is also possible to use it as an adjustable regulator for higher output voltages. One circuit for doing

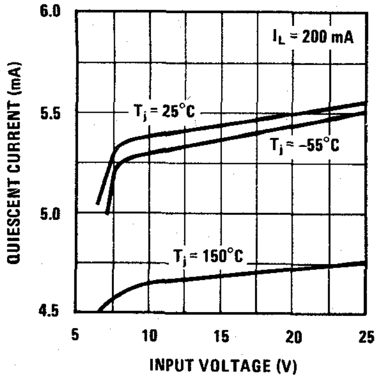

Fig. 11. Variation of quiescent current with input voltage at various temperatures.

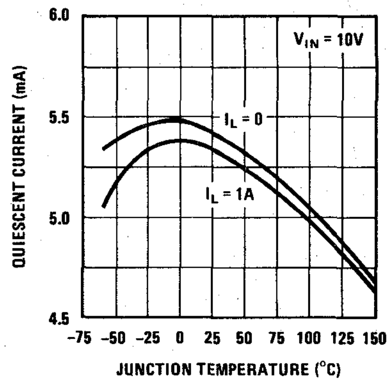

Fig. 12. Variation of quiescent current with temperature for various load currents.

this is shown in Fig. 10. The regulated output voltage is impressed across R_1, developing a reference current. The quiescent current of the regulator, coming out of the ground terminal, is added to this. These combined currents produce a voltage drop across R_2 that raises the output voltage. Hence, any voltage above 5 V can be obtained as long as the voltage across the integrated circuit is kept within ratings.

The LM109 was designed so that its quiescent current is not affected greatly by variations in input voltage, load, or temperature. However, it is not completely insensitive, as shown in Figs. 11 and 12 so the changes do affect regulation somewhat. This tendency is minimized by making the reference current through R_1 larger than the quiescent current. Even so, it is difficult to get the regulation tighter than two percent.

Conclusions

The techniques described significantly advance the state of the art in IC regulators and can be expected to make them even more attractive as a substitute for discrete designs. A 5-V regulator has already been made, and the validity of the approach established on mass-produced devices. In the future, fully adjustable regulators that operate on input voltages as low as 2 V can be expected. Furthermore, the reference shows definite possibilities for replacing zener diodes in applications requiring good long-term stability.

Thermal overload protection that directly senses and controls the junction temperature of the pass transistor should improve the reliability of regulators considerably. This is particularly obvious if the largely unpredictable electrical and environmental conditions to which a regulator may be exposed in field use are taken into account. Some degree of thermal protection can be incorporated into a discrete regulator. However, proper design is quite difficult and the protection is not completely effective because it is not possible to measure directly the junction temperature of the power transistor.

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