

# IC Provides On-Card Regulation for Logic Circuits

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## introduction

Because of the relatively high current requirements of digital systems, there are a number of problems associated with using one centrally-located regulator. Heavy power busses must be used to distribute the regulated voltage. With low voltages and currents of many amperes, voltage drops in connectors and conductors can cause an appreciable percentage change in the voltage delivered to the load. This is aggravated further with TTL logic, as it draws transient currents many times the steady-state current when it switches.

These problems have created a considerable interest in on-card regulation, that is, to provide local regulation for the subsystems of the computer. Rough preregulation can be used, and the power distributed without excessive concern for line drops. The local regulators then smooth out the voltage variations due to line drops and absorb transients.

A monolithic regulator is now available to perform this function. It is quite simple to use in that it requires no external components. The integrated circuit has three active leads—input, output and ground—and can be supplied in standard transistor power packages. Output currents in excess of 1A can be obtained. Further, no adjustments are required to set up the output voltage, and overload protection is provided that makes it virtually impossible to destroy the regulator. The simplicity of the regulator, coupled with low-cost fabrication and improved reliability of monolithic circuits, now makes on-card regulation quite attractive.

## design concepts

A useful on-card regulator should include everything within one package—including the power-control element, or pass transistor. The author has previously advanced arguments against including the pass transistor in an integrated circuit regulator.<sup>1</sup> First, there are no standard multi-lead 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, for a logic-card regulator, these arguments can be answered effectively.

For one, if the series pass transistor is put on the chip, the integrated circuit need only have three terminals. Hence, an ordinary transistor power package can be used. 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 current—limit adjustments unnecessary.

Thermal protection limits the maximum junction temperature and 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.

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, the 5V 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

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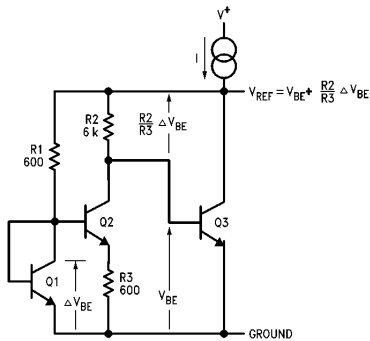
loose enough that it is relatively easy to design an internal reference that is much more stable than required, even for temperature variations as large as 150°C.

#### circuit description

The internal voltage reference for this logic-card regulator is probably the most significant departure from standard design techniques. Temperature-compensated zener diodes are normally used for the reference. However, these have breakdown voltages between 7V and 9V which puts a lower limit on the input voltage to the regulator. For low voltage operation, a different kind of reference is needed.

The reference in the LM109 does not use a zener diode. Instead, it is developed from the highly-predictable emitter-base voltage of the transistors. In its simplest form, the reference developed is equal to the energy-band-gap voltage of the semiconductor material. For silicon, this is 1.205V, so the reference need not impose minimum input voltage limitations on the regulator. An added advantage of this reference is that the output voltage is well determined in a production environment so that individual adjustment of the regulators is frequently unnecessary.

A simplified version of this reference is shown in Figure 1. In this circuit, Q<sub>1</sub> is operated at a relatively high current



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Figure 1. The low voltage reference in one of its simpler forms.

density. The current density of Q<sub>2</sub> is about ten times lower, and the emitter-base voltage differential ( $\Delta V_{BE}$ ) between the two devices appears across R<sub>3</sub>. If the transistors have high current gains, the voltage across R<sub>2</sub> will also be proportional to  $\Delta V_{BE}$ . Q<sub>3</sub> is a gain stage that will regulate the output at a voltage equal to its emitter base voltage plus the drop across R<sub>2</sub>. The emitter base voltage of Q<sub>3</sub> has a negative temperature coefficient while the  $\Delta V_{BE}$  component

across R<sub>2</sub> has a positive temperature coefficient. It will be shown that the output voltage will be temperature compensated when the sum of the two voltages is equal to the energy-band-gap voltage.

Conditions for temperature compensation can be derived starting with the equation for the emitter-base voltage of a transistor which is<sup>2</sup>

$$V_{BE} = V_{g0} \left( 1 - \frac{T}{T_0} \right) + V_{BE0} \left( \frac{T}{T_0} \right) + \frac{nkT}{q} \log_e \frac{T_0}{T} + \frac{kT}{q} \log_e \frac{I_C}{I_{C0}} \quad (1)$$

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 which depends on how the transistor is made (approximately 1.5 for double-diffused, NPN transistors),  $k$  is Boltzmann's constant,  $T$  is absolute temperature,  $I_C$  is collector current and  $V_{BE0}$  is the emitter-base voltage at  $T_0$  and  $I_{C0}$ .

The emitter-base voltage differential between two transistors operated at different current densities is given by<sup>3</sup>

$$\Delta V_{BE} = \frac{kT}{q} \log_e \frac{J_1}{J_2} \quad (2)$$

where  $J$  is current density.

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

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

$$V_{ref} = V_{g0} \left( 1 - \frac{T}{T_0} \right) + V_{BE0} \left( \frac{T}{T_0} \right) + \frac{kT}{q} \log_e \frac{J_1}{J_2} \quad (3)$$

Differentiating with respect to temperature yields

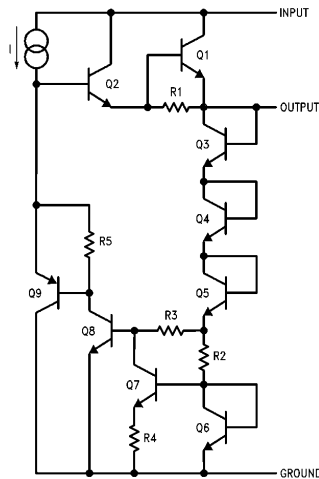
$$\frac{\partial V_{ref}}{\partial T} = -\frac{V_{g0}}{T_0} + \frac{V_{BE0}}{T_0} + \frac{k}{q} \log_e \frac{J_1}{J_2} \quad (4)$$

For zero temperature drift, this quantity should equal zero, giving

$$V_{g0} = V_{BE0} + \frac{kT_0}{q} \log_e \frac{J_1}{J_2} \quad (5)$$

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.

A simplified schematic for a 5V regulator is given in *Figure 2*. The circuitry produces an output voltage that is approximately four times the basic reference voltage. The emitter-base voltage of Q<sub>3</sub>, Q<sub>4</sub>, Q<sub>5</sub> and Q<sub>8</sub> provide the negative-temperature-coefficient component of the output voltage. The voltage dropped across R<sub>3</sub> provides the positive-temperature-coefficient component. Q<sub>6</sub> is operated at a considerably higher current density than Q<sub>7</sub>, producing a voltage drop across R<sub>4</sub> 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<sub>3</sub> will be proportional to this differential, so a temperature-compensated-output voltage can be obtained.



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**Figure 2. Schematic showing essential details of the 5V regulator.**

In this circuit, Q<sub>8</sub> is the gain stage providing regulation. Its effective gain is increased by using a vertical PNP, Q<sub>9</sub>, as a buffer driving the active collector load represented by the current source. Q<sub>9</sub> drives a modified Darlington output stage (Q<sub>1</sub> and Q<sub>2</sub>) which 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.

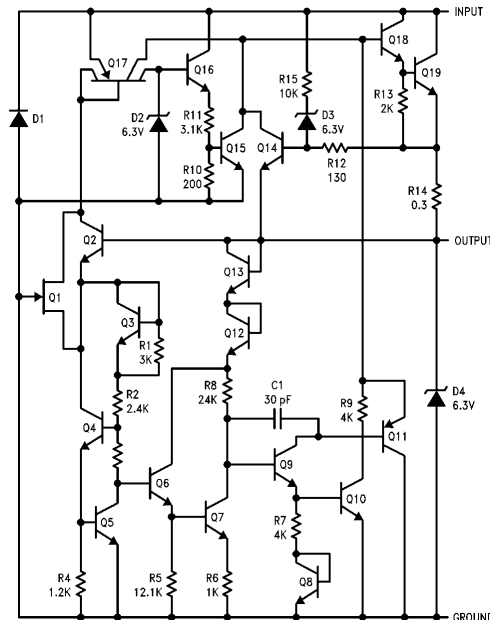
*Figure 3* shows a complete schematic of the LM109, 5V regulator. The  $\Delta V_{BE}$  component of the output voltage is developed across R<sub>8</sub> by the collector current of Q<sub>7</sub>. The emitter-base voltage differential is produced by operating Q<sub>4</sub> and Q<sub>5</sub> at high current densities while operating Q<sub>6</sub> and Q<sub>7</sub> at much lower current levels. The extra transistors improve tolerances by making the emitter-base voltage differential larger. R<sub>3</sub> serves to compensate the transconductance<sup>4</sup> of

Q<sub>5</sub>, so that the  $\Delta V_{BE}$  component is not affected by changes in the regular output voltage or the absolute value of components.

The voltage gain for the regulating loop is provided by Q<sub>10</sub>, with Q<sub>9</sub> buffering its input and Q<sub>11</sub> its output. The emitter base voltage of Q<sub>9</sub> and Q<sub>10</sub> is added to that of Q<sub>12</sub> and Q<sub>13</sub> and the drop across R<sub>8</sub> to give a temperature-compensated, 5V output. An emitter-base-junction capacitor, C<sub>1</sub>, frequency compensates the circuit so that it is stable even without a bypass capacitor on the output.

The active collector load for the error amplifier is Q<sub>17</sub>. It is a multiple-collector lateral PNP<sup>4</sup>. The output current is essentially equal to the collector current of Q<sub>2</sub>, with current being supplied to the zener diode controlling the thermal shutdown, D<sub>2</sub>, by an auxiliary collector. Q<sub>1</sub> is a collector FET<sup>4</sup> that, along with R<sub>1</sub>, insures starting of the regulator under worst-case conditions.

The output current of the regulator is limited when the voltage across R<sub>14</sub> becomes large enough to turn on Q<sub>14</sub>. This insures 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 7V, current through R<sub>15</sub> and D<sub>3</sub> reduces the limiting current,



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**Figure 3. Detailed schematic of the regulator.**

again to minimize the chance of secondary breakdown. The performance of this protection circuitry is illustrated in Figure 4.

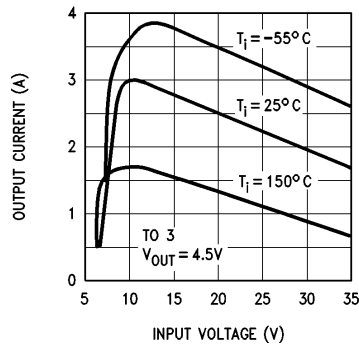


Figure 4. Current-limiting characteristics.

Even though the current is limited, excessive dissipation can cause the chip to overheat. In fact, the dominant failure mechanism of solid state regulators is excessive heating of the semiconductors, particularly the pass transistor. 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, for any reason, the temperature regulator turns on and reduces internal dissipation to prevent any further increase in chip 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,  $Q_{15}$ , is the actual temperature sensor because, with a constant voltage applied across the junction, the collector current rises rapidly with increasing temperature.

Although some form of thermal protection can be incorporated in a discrete regulator, IC's 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.

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 rise is caused by failure of the pass transistor such that the current is not limited, the aluminum conductors on the chip will fuse, disconnecting 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 1A.

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 Figure 5 shows that it remains low out to 10 kHz even without a capacitor. The ripple rejection also remains high out to 10 kHz, as shown in Figure 6. 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  $\mu\text{F}$  capacitor to prevent oscillations under all conditions.

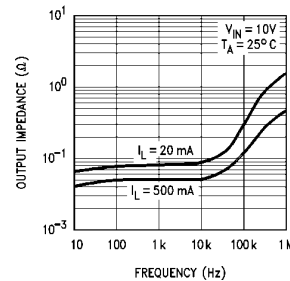


Figure 5. Plot of output impedance as a function of frequency.

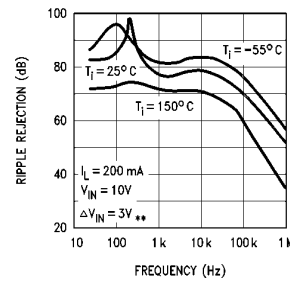
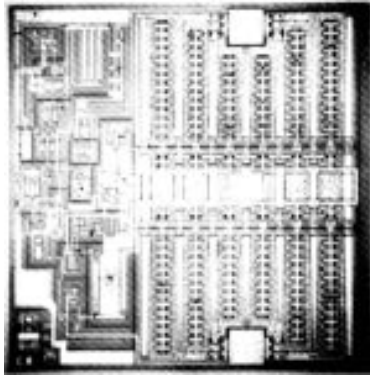


Figure 6. Ripple rejection of the regulator.

Figure 7 is a photomicrograph of the regulator chip. It can be seen that the pass transistors, which must handle more than 1A, occupy most of the chip area. The output transistor is actually broken into segments. Uniform current distribution is insured 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.



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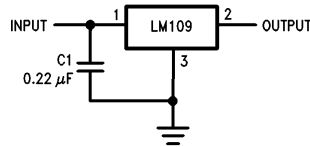
**Figure 7. Photomicrograph of the regulator shows that high current pass transistor (right) takes more area than control circuitry (left).**

**TABLE I. Typical Characteristics of the Logic-Card Regulator:  $T_A = 25^\circ\text{C}$**

Parameter	Conditions	Typ
Output Voltage		5.0V
Output Current		1.5A
Output Resistance		0.03 $\Omega$
Line Regulation	$7.0\text{V} \leq V_{IN} \leq 35\text{V}$	0.005%/V
Temperature Drift	$-55^\circ\text{C} \leq T_A \leq 125^\circ\text{C}$	0.02%/°C
Minimum Input Voltage	$I_{OUT} = 1\text{A}$	6.5V
Output Noise Voltage	$10\text{ Hz} \leq f \leq 100\text{ kHz}$	40 $\mu\text{V}$
Thermal Resistance Junction to Case	LM109H (TO-5)	15°C/W
	LM109K (TO-3)	3°C/W

#### applications

Because it was designed for virtually foolproof operation and because it has a singular purpose, the LM109 does not require a lot of application information, as do most other linear circuits. Only one precaution must be observed: it is necessary to bypass the unregulated supply with a 0.22  $\mu\text{F}$  capacitor, as shown in Figure 8, to prevent oscillations that



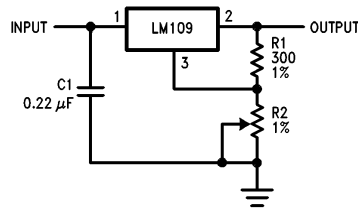
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**Figure 8. Fixed 5V regulator.**

can cause erratic operation. This, of course, is only necessary if the regulator is located on appreciable distance from the filter capacitors on the output of the dc supply.

Although the LM109 is designed as a fixed 5V regulator, it is also possible to use it as an adjustable regulator for higher

output voltages. One circuit for doing this is shown in Figure 9.

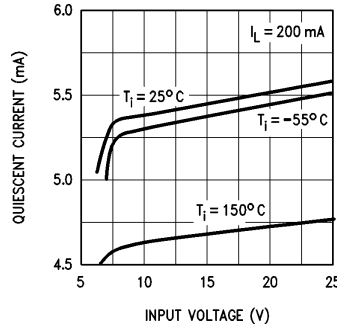


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**Figure 9. Using the LM109 as an adjustable-output regulator.**

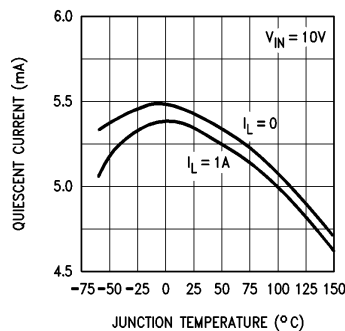
The regulated output voltage is impressed across  $R_1$ , developing a reference current. The quiescent current of the regulator, coming out of the ground terminal, is added to this. These combined currents produce a voltage drop across  $R_2$  which raises the output voltage. Hence, any voltage above 5V 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 greatly affected by variations in input voltage, load or temperature. However, it is not completely insensitive, as shown in Figures 10 and 11, 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 a couple percent.



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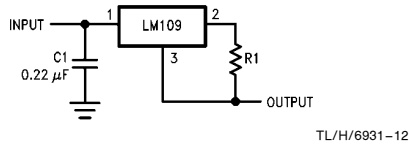
**Figure 10. Variation of quiescent current with input voltage at various temperatures.**



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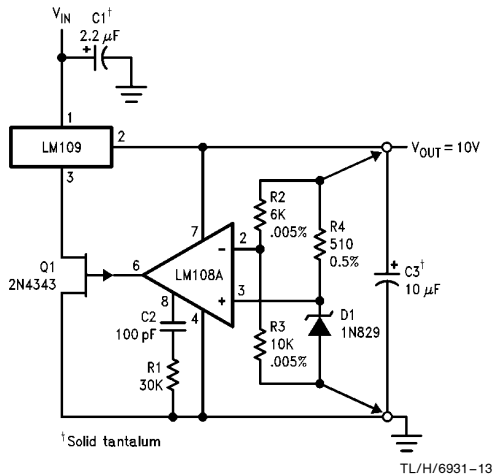
**Figure 11. Variation of quiescent current with temperature for various load currents.**

The LM109 can also be used as a current regulator as is shown in *Figure 12*. The regulated output voltage is impressed across  $R_1$ , which determines the output current. The quiescent current is added to the current through  $R_1$ , and this puts a lower limit of about 10 mA on the available output current.



**Figure 12. Current regulator.**

The increased failure resistance brought about by thermal overload protection make the LM109 attractive as the pass transistor in other regulator circuits. A precision regulator that employs the IC thusly is shown in *Figure 13*. An operational amplifier compares the output voltage with the output voltage of a reference zener. The op amp controls the LM109 by driving the ground terminal through an FET.



**Figure 13. High stability regulator.**

The load and line regulation of this circuit is better than 0.001%. Noise, drift and long term stability are determined

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by the reference zener,  $D_1$ . Noise can be reduced by inserting 100 k $\Omega$ , 1% resistors in series with both inputs of the op amp and bypassing the non-inverting input to ground. A 100 pF capacitor should also be included between the output and the inverting input to prevent frequency instability. Temperature drift can be reduced by adjusting  $R_4$ , which determines the zener current, for minimum drift. For best performance, remote sensing directly to the load terminals, as shown in the diagram, should be used.

**conclusions**

The LM109 performs a complete regulation function on a single silicon chip, requiring no external components. It makes use of some unique advantages of monolithic construction to achieve performance advantages that cannot be obtained in discrete-component circuits. Further, the low cost of the device suggests its use in applications where single-point regulation could not be justified previously.

Thermal overload protection significantly improves the reliability of an IC regulator. It even protects the regulator for unforeseen fault conditions that may occur in field operation. Although this can be accomplished easily in a monolithic regulator, it is usually not completely effective in a discrete or hybrid device.

The internal reference developed for the LM109 also advances the state of the art for regulators. Not only does it provide a low voltage, temperature-compensated reference for the first time, but also it can be expected to have better long term stability than conventional zeners. Noise is inherently much lower, and it can be manufactured to tighter tolerances.

**reference**

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