Stacked voltage references improve supply's regulation

by Wes Freeman and George Erdi
Precision Monolithics Inc., Santa Clara, Calif.

By combining low-cost precision voltage references, inexpensive yet accurate power supplies that work over a wide range of voltages may be built. When suitably stacked, these voltage references even improve the regulating performance of the supply.

Consider the circuit in Fig. 1, which can be built for approximately $10. It uses two 10-volt references so combined that the supply will work over a range of 0 to 20 V, with switch S_1 selecting the 0-to-10- and 10-to-20-V ranges.

An operational amplifier isolates potentiometer R_1, which sets the output voltage to within 300 microvolts of the desired value. The op amp's short-circuit current, approximately 22 milliamperes, limits the maximum base current available to the power transistor. As a result, the maximum available output current is nearly 1 ampere.

The supply's line regulation is within 0.005% of scale reading per volt in the 10-to-20-V range. In the 0-to-10-V range, line regulation is significantly improved to within 0.0001%/V and is mainly limited by the op amp's supply rejection ratio because the output of the second reference regulates the line voltage of the first.

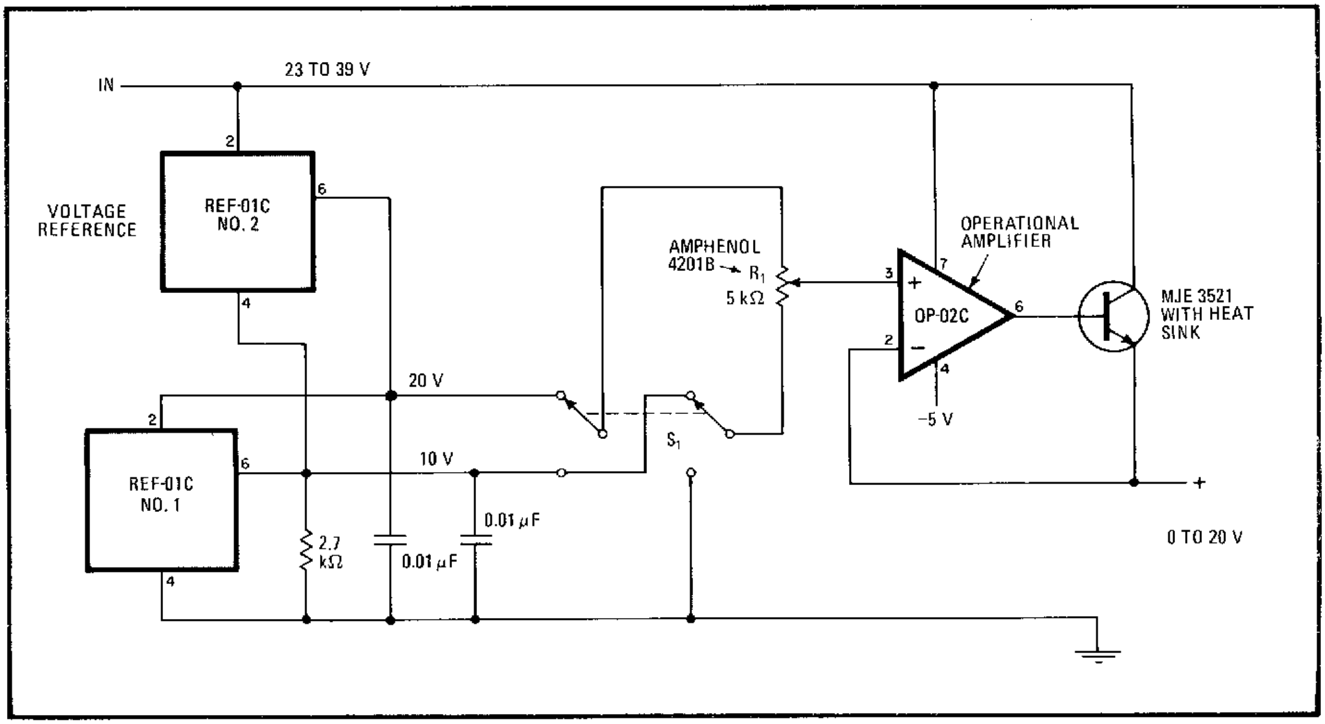
Load regulation is determined by the change in the op amp's open-loop gain versus load current. In this circuit, measured values were ±0.001%/A in the 0-to-800-mA range. Output voltage drift due to temperature is ±0.002% of scale reading per °C.

At an increase in component count and hence also in cost, the performance of the supply may be improved appreciably, as seen in Fig. 2. The addition of a third reference regulates both the 0-to-10- and 10-to-20-V ranges. A Darlington power-output transistor permits a 4-A load current.

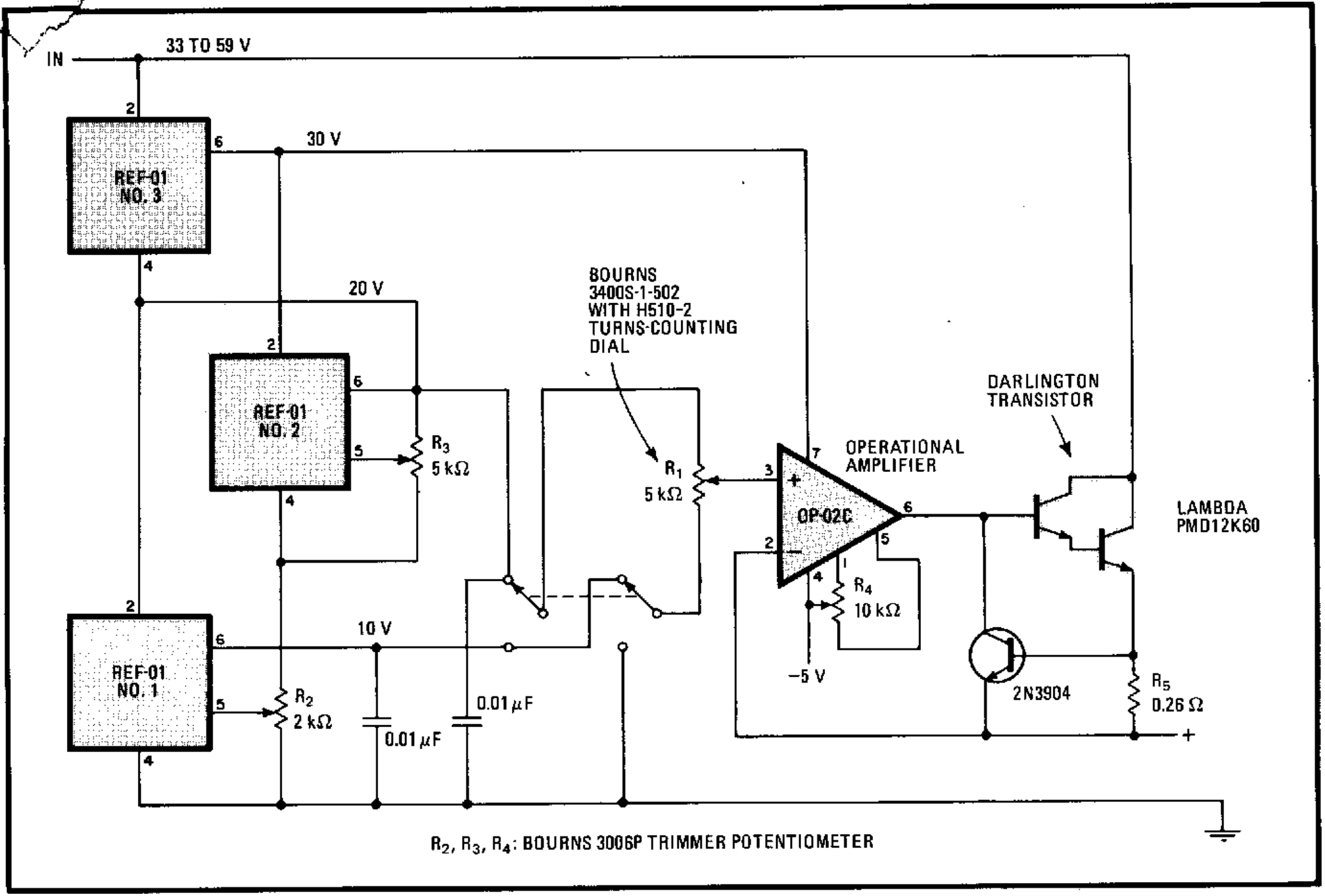
As a result, the total change in output voltage is less than ±0.001% for a change in load current of 0 to 2 A and a change in line voltage ranging from 33 to 59 V. Potentiometers R_2 and R_3 adjust the output voltage for the 10-V and 20-V ranges, respectively, while R_4 nulls the op amp's offset voltage.

The substitution of a highly linear precision potentiometer and turn-counting dial for R_1 permits a dial accuracy of ±2 mV from 0 to 20 V, with a resolution of 200 µV. Moreover, if a better grade of reference (REF-01) is employed, the temperature coefficient is ±0.001% of scale reading per °C. ☐

Designer's casebook is a regular feature in *Electronics*. We invite readers to submit original and unpublished circuit ideas and solutions to design problems. Explain briefly but thoroughly the circuit's operating principle and purpose. We'll pay $75 for each item published.



1. Piggyback. Two series-connected voltage references may be united to yield an extended supply output range with significantly improved line regulation at the lower range. The circuit's output can be set to within 300 µV of the desired value. Maximum output current is 1 A.



R$_2$, R$_3$, R$_4$: BOURNS 3006P TRIMMER POTENTIOMETER

2. Extension. When another reference is added, both ranges become extremely well regulated. Load-handling capability and supply precision are improved. Substituting a linear precision pot and turns-counting dial for R$_1$ permits setting output to within ±2mV over 0 to 20 V.

Regulating voltage with just one quad IC and one supply

by R. A. Koehler
York University, Toronto, Canada

Full-range, high-performance power supplies are often bulky and expensive because they require two independent voltage sources—one main and one reference—with associated rectifiers, filter capacitors, and reference regulator circuitry.

But only one unregulated source of about 26 volts dc and one ground-sensing quad operational amplifier are necessary in a regulated power supply that provides 1 ampere at 0 to 20 V with foldback current-limiting and overload indication. It achieves line and load regulation within ±0.02% over the full range of load conditions, even when the input voltage varies between 24 and 28 V dc. When the regulator is quiescent, its current requirement amounts to less than 10 milliamperes.

Amplifier A_1 is a self-biased, constant-current amplifier that provides a stable reference voltage [*Electronics*, March 13, 1972, p. 74]. Its output, V_1, depends on the breakdown voltage V_z of the zener diode, D_1:

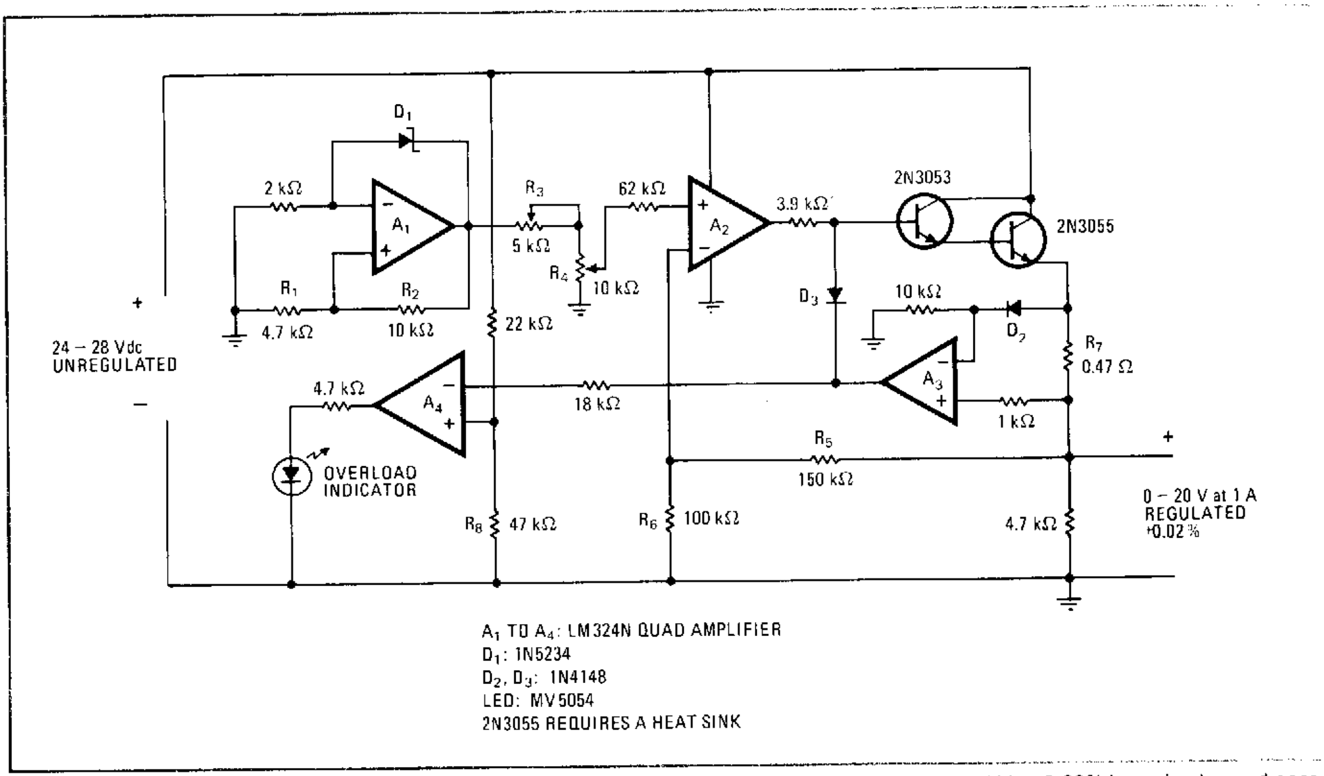
$$V_1 = V_z[1 + (R_1/R_2)]$$

It is approximately 9.1 V for the values shown in the diagram. The potentiometers R_3 and R_4 bring V_1 down to a desired value V_2, which is amplified by A_2 and the Darlington output stage to the output level:

$$V_{out} = V_2(R_5 + R_6)/R_6$$

With R_4 at its maximum-voltage position, variable resistor R_3 sets the voltage at exactly 20 V; thereafter, R_4 varies the output voltage over its full range. The output stage gain is 2.5 for the values shown.

Amplifier A_3 monitors the regulator's output current under varying loads. It compares the voltage across R_7 (a very small resistance) with the drop across diode D_2. Whenever the former is greater than the latter, the output of A_3 drops, biasing diode D_3 forward; thus it reduces the output voltage by removing the drive to the Darlington stage. If the load continues to increase, the output of A_3 becomes low enough to indicate, through amplifier A_4, and a light-emitting diode, an overload condition. The circuit's overload threshold may be changed, if desired, by changing the value of resistor R_8.



Op amp regulator. An unregulated 26-volt source becomes a 1-ampere 0-to-20-V supply regulated to within ±0.02% by a simple quad operational amplifier. Input can vary between 24 V and 28 V, and quiescent current is less than 10 mA. A light-emitting diode gives an overload indication, the level of which depends on the value of resistor R_8. Single power Darlington can replace the two transistors.

The output transistors may be replaced by a single power Darlington, such as 2N6050, to reduce the package count from three to two. ☐

Temperature limiting boosts regulator output current

by Mahendra J. Shah
University of Wisconsin, Space Science & Engineering Center, Madison, Wis.

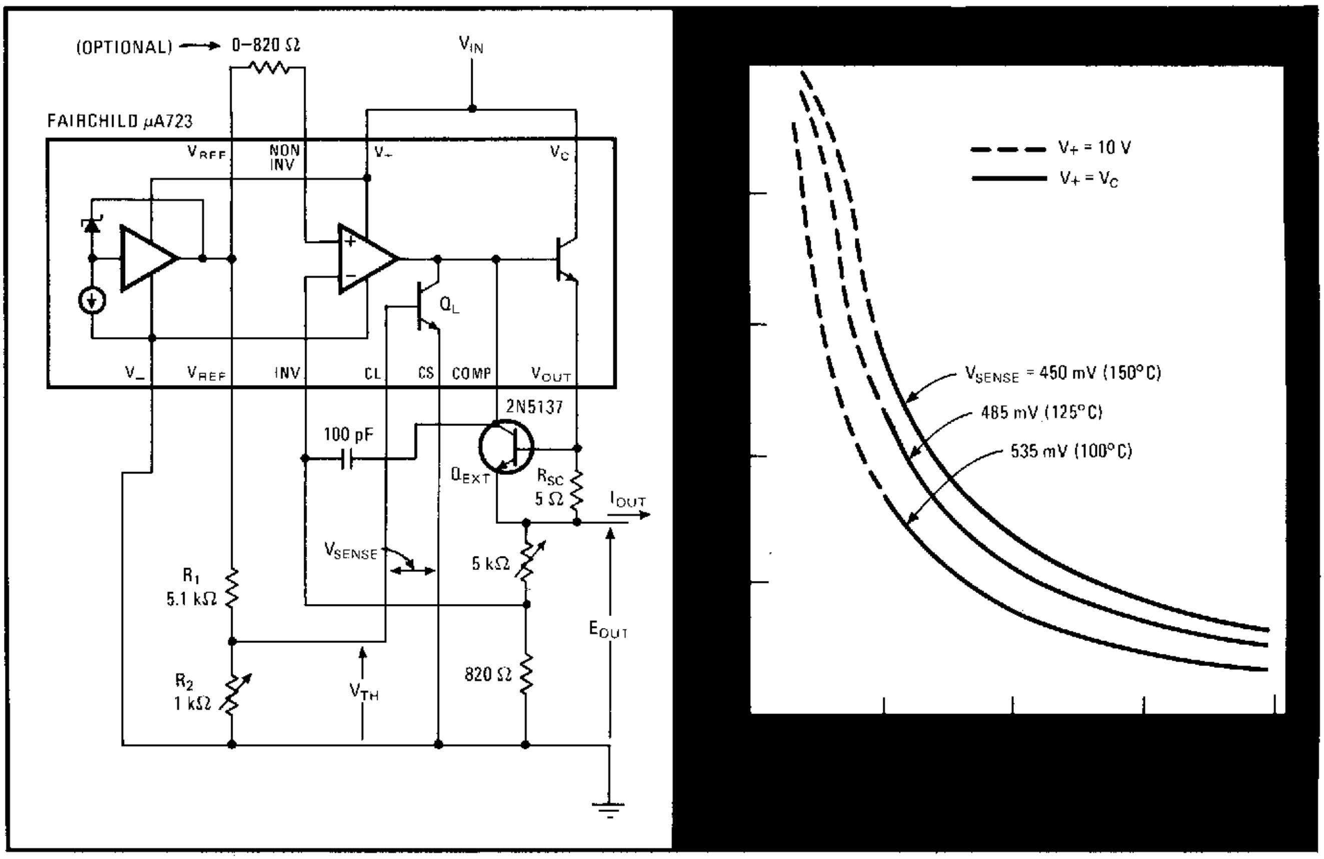
The efficiency of a precision monolithic voltage regulator can be significantly improved by limiting the junction temperature of the regulator's internal current-limiting transistor.

Conventional current limiting severely restricts the regulator's peak and average output current capability. As an example, consider the 723-type regulator, which can supply an output voltage of 7 to 37 volts. This device has a maximum storage (junction) temperature of 150°, a maximum imput/output voltage differential of 40 V, and a maximum load current of 150 milliamperes.

When the regulator's metal-can package is used without a heat sink, its internal power dissipation should be limited to 800 milliwatts at an ambient temperature of 25°C. If the input voltage to the regulator is 40 V, conventional current limiting places the worst-case current limit at 20 mA, or 800 mW/40 V. (The worst-case condition is an output short circuit to ground.) And a foldback-current-limiting approach requires a limit knee setting of 24.2 mA, or 800 mW/(40 − 7) V.

Both of these approaches significantly limit the regulator's output current capability when the regulator must supply a load continously at both intermediate and high output voltage levels, or when it must supply peak currents at any output voltage level. In contrast, temperature limiting protects the regulator from burnout, while allowing it to provide the maximum possible output current (both continuous and pulsed), regardless of output voltage level, ambient temperature, and the amount of heat sinking.

Conveniently, the regulator's own current-limiting transistor, Q_L, can be used to implement this temperature limiting. The transistor's base-emitter junction, which has a temperature sensitivity of −1.8 millivolts/°C, can act as a temperature sensor for the regulator. And the collector terminal of transistor Q_L can be connected to limit the regulator's output current.



Better short-circuit protection. Current-limiting transistor Q_L of monolithic voltage regulator acts as an on-chip thermostat, controlling its own base-emitter junction temperature and, therefore, limiting regulator output current. The threshold bias voltage (V_{th}) of Q_L's base-emitter junction is set to limit this junction's temperature to a value determined by Q_L's sense voltage (V_{sense}).

A stable voltage source is needed to bias Q_L's base-emitter junction at the threshold voltage (V_{th}) that corresponds to Q_L's sense voltage (V_{sense}) for a given junction temperature. V_{sense} is the voltage required across Q_L's base-emitter junction to implement output current limiting. Values for sense voltage, limit current, and junction temperature can be obtained from the datasheet plot of the regulator's current-limiting characteristics as a function of junction temperature.

The threshold bias voltage is easily obtained from the regulator's internal voltage reference source and the voltage divider formed by resistors R_1 and R_2. Some other regulators, like Motorola's MC1460, MC1560, MC1461, MC1561, MC1463, MC1563, MC1469, and MC1569, have a provision for junction-temperature limiting, but they require an external regulated voltage source.

When the actual junction temperature of transistor Q_L is lower than the junction-temperature limit, Q_L's base-emitter voltage is higher than the threshold bias voltage, so that Q_L is off. But when Q_L's actual junction temperature rises to the junction-temperature limit, Q_L's base-emitter voltage drops slightly below the threshold bias voltage, and Q_L turns on, limiting its maximum junction temperature by first limiting the regulator's output current.

The external current-limiting transistor, Q_{XT} and its associated resistor, R_{SC}, are needed to limit regulator output current below the 150-mA secondary breakdown limit of the regulator's internal output transistors. (The optional resistor can be included to minimize output voltage drift.) The graph shows the regulator's output current capability over the full range of input/output differential voltage for three sense-voltage settings. □

Designer's casebook

Economical series regulator supplies up to 10 amperes

by J.E. Buchanan and C.W. Nelson
Westinghouse Electric Corp., Systems Development Division, Baltimore, Md.

A highly efficient series regulator made of standard IC components is an ideal high-current digital-logic supply. It provides an output voltage of 5 to 6 volts at a current of up to 10 amperes, without needing separate bias sources or special transformers.

As shown in the figure, a standard transformer is used at the input of the circuit. The transformer's output voltage is rectified and filtered in a conventional manner for the high-current-supply path to the output of the circuit.

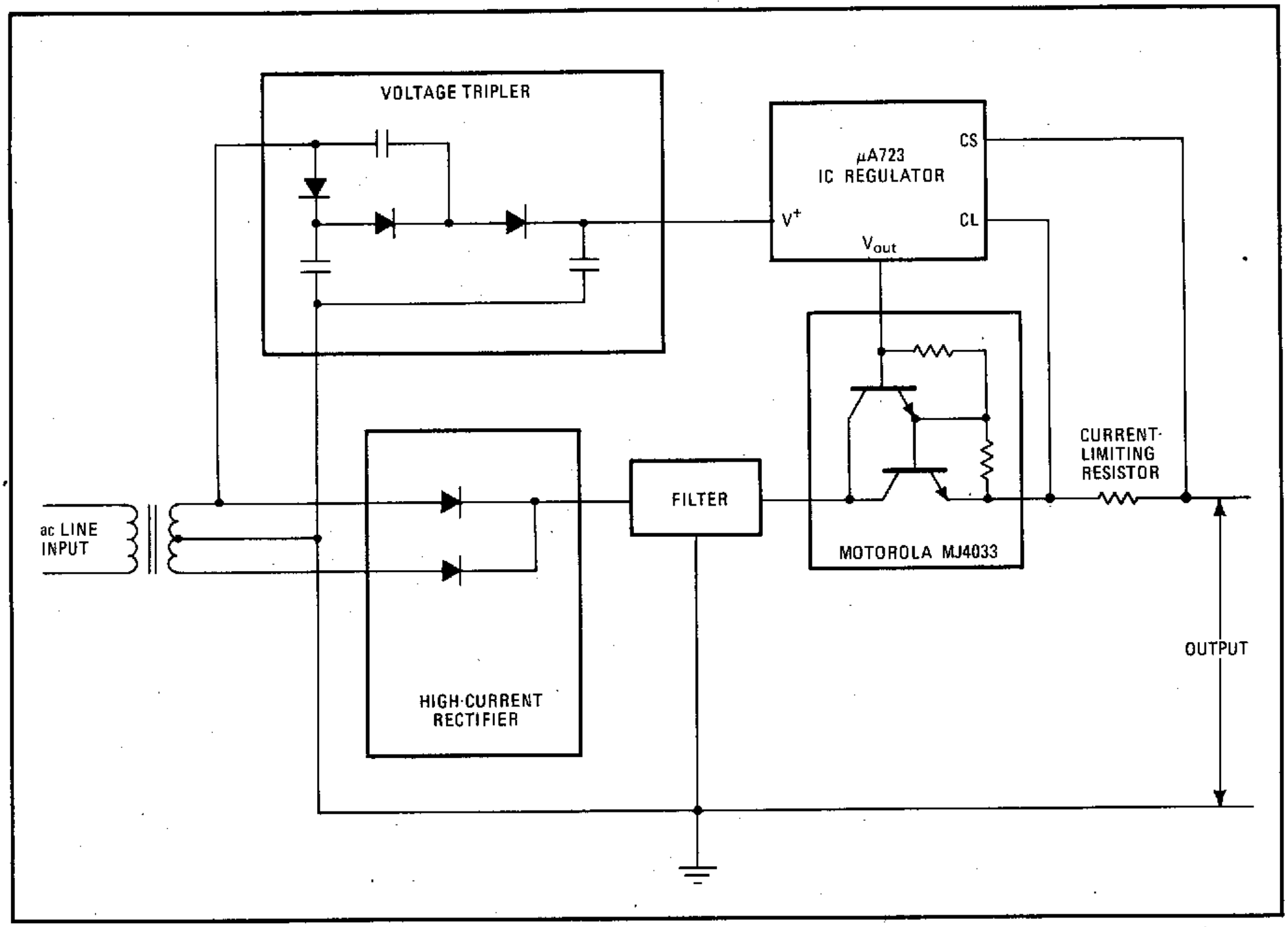
This transformer voltage also goes to a voltage tripler, which raises it so that it becomes large enough to drive the IC regulator without help from any outside bias supply. Most three-terminal IC regulators require 10 V or more to bias their internal references properly, preserving their stability with changing input, load, or temperature conditions.

The IC regulator, in turn, drives a high-current power Darlington transistor pair, which is biased by the high-current rectifier. The Darlington pair acts as the circuit's series-pass element and increases the low-milliampere current output from the IC regulator to several amperes.

The circuit's efficiency is very good because the voltage of the high-current supply path can be kept low, permitting the Darlington pair to be driven near saturation with a minimum high-current source voltage. A single transistor can be used instead of the Darlington pair if a lower output current is desired. ☐

Designer's casebook is a regular feature in Electronics. We invite readers to submit original and unpublished circuit ideas and solutions to design problems. Explain briefly but thoroughly the circuit's operating principle and purpose. We'll pay $50 for each item published.

High-current logic supply. This series regulator develops 5 volts at 10 amperes for powering digital-logic circuits. High efficiency is achieved by using a voltage tripler, which operates directly from the input-line transformer, to bias the IC regulator's internal reference. This eliminates the need for a special bias supply or a special transformer. The Darlington transistor pair serves as the series-pass element.



Foldback limiter protects high-current regulators

by A. D. V. N. Kularatna
Ratmalana, Sri Lanka

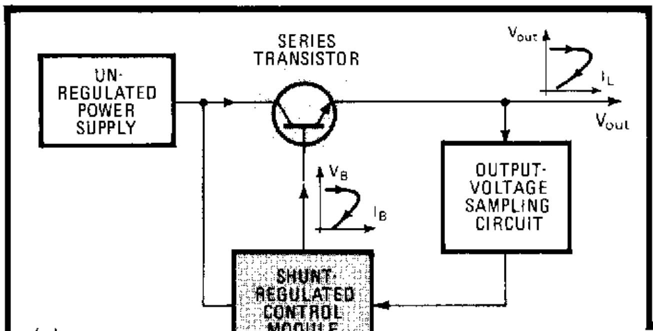
This circuit provides foldback protection for a series-regulated source that has to deliver high current. Because it requires no current-monitoring resistor, the circuit achieves wide dynamic response at good efficiency. It draws only 2% of maximum load current and its cost is reasonable.

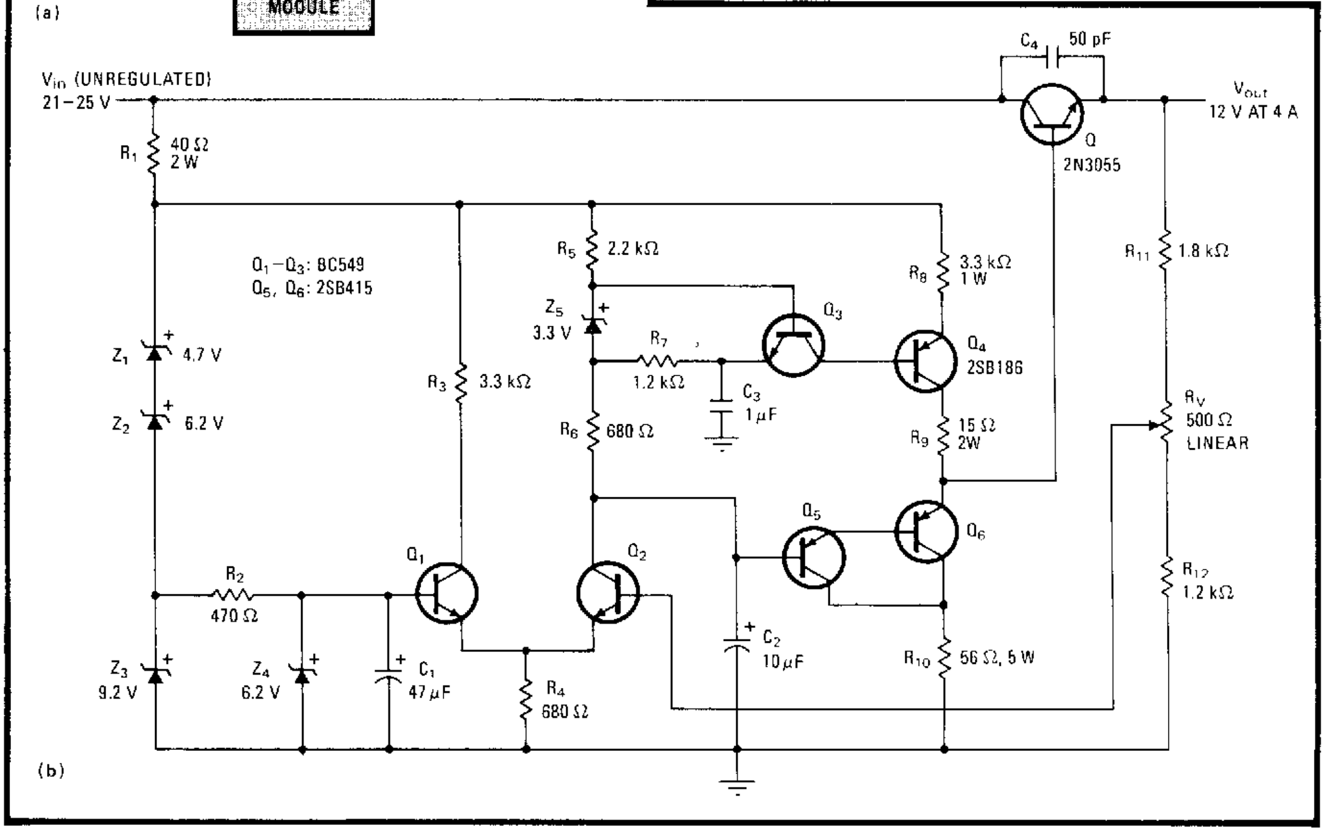
Here, a low-current shunt-regulated module (a) provides the overload protection. This module is configured into the conventional regulator system to work as a switch, in which role it quickly turns off a series-pass transistor when the load current exceeds some predetermined value.

The circuit details are explained with the aid of the diagram (b) for a representative regulator designed to deliver 12 volts at 4 amperes. Transistors Q_1 and Q_2 form a differential amplifier, which compares a 6.2-V reference to a potential derived from the 12-V output through potentiometer R_V. Shunt elements Q_5–Q_6 act to maintain the potential at the base of Q constant for any load condition by taking up the difference between the set and the actual base drive.

It is necessary that the current source Q_3-Q_4 be set to I_L/h_{fe} for proper tracking, where I_L is the maximum load current and h_{fe} is the current gain of Q. The value of the constant current, I, is $h_{feQ4}(V_{Z5} - V_{beQ3})/R_7$, so that the current is most easily set by adjusting resistor R_7.

The module requires a current of 70 to 80 milliamperes under maximum load conditions. The short-circuit output current is less than 200 mA, because the drop in





High handling. Low-current shunt regulator (a) provides foldback limiting for high-current power sources at good efficiency and reasonable cost. Circuit (b) for 12-V regulator uses differential pair Q_1–Q_2 for detecting differences in reference and output voltage, Q_3–Q_6 for maintaining output potential by suitably controlling base drive to series pass transistor Q. Z_1–Z_3 minimize output ripple.

Foldback limiter has minimal parts count

by Michael G. Lyngsie
MG-EL Consultants, Copenhagen, Denmark

Providing virtually the same function as the foldback limiter proposed by Kularatna,[1] but using a minimum of parts, this circuit delivers a well-regulated 24 volts at a maximum of 4 amperes. The circuit is extremely rugged and will meet all but the most demanding industrial requirements.

In operation, transistor Q_1 operates as a differential amplifier to detect changes in output voltage and at the same time to keep track of the reference voltage, V_Z, which is constant as long as $I_E R_6 < V_o - 6.8$. The power-Darlington stage Q_2–Q_3 that follows serves as the series-pass transistor and its associated driver.

If there is a short circuit at the output or the load requires excessive current, I_E will also increase because Q_2 and Q_3 must be driven harder. This action causes Q_1 to draw off a corresponding current that is normally delivered to the zener. Thus the zener voltage must fall, and foldback limiting is initiated. The quiescent current that will flow during foldback ($V_o \approx 0$) is solely dependent on R_1, which re-initializes the supply upon removal of the overload condition. R_1 can be made as large as desired, with the only limitation being that I_{R1} must be greater than the sum of the leakage current (I_{leak}) through capacitor C_5, and I_{DC}.

Placing the series-pass transistor, Q_3, in the negative rail offers two distinct advantages. First, the device can be operated in the common-emitter configuration, enabling Q_3 to provide voltage gain and current gain. This enhances the dynamic range of the circuit. Secondly, most industrial equipment utilizes a negative ground, and so the power transistor can be directly mounted anywhere on the chassis for efficient cooling and the problem of electrical isolation can be eliminated. Furthermore, regulation is extremely fast because the only capacitors in the circuit are associated with the input filter (C_1) and output bypass networks. Foldback action is not very fast, though, because of the large value of C_2. This capacitor can be made an order of magnitude smaller without sacrificing stability.

The output voltage will be held constant to 100 millivolts with this arrangement. Other voltages can be selected by altering the voltage-divider chain R_3–R_4–R_5. The maximum output current is approximately:

$$I_{max} = (V_o - 6.8) h_{fe\,Q2} h_{fe\,Q3} / R_6$$

neglecting I_B and the current flowing in R_2.

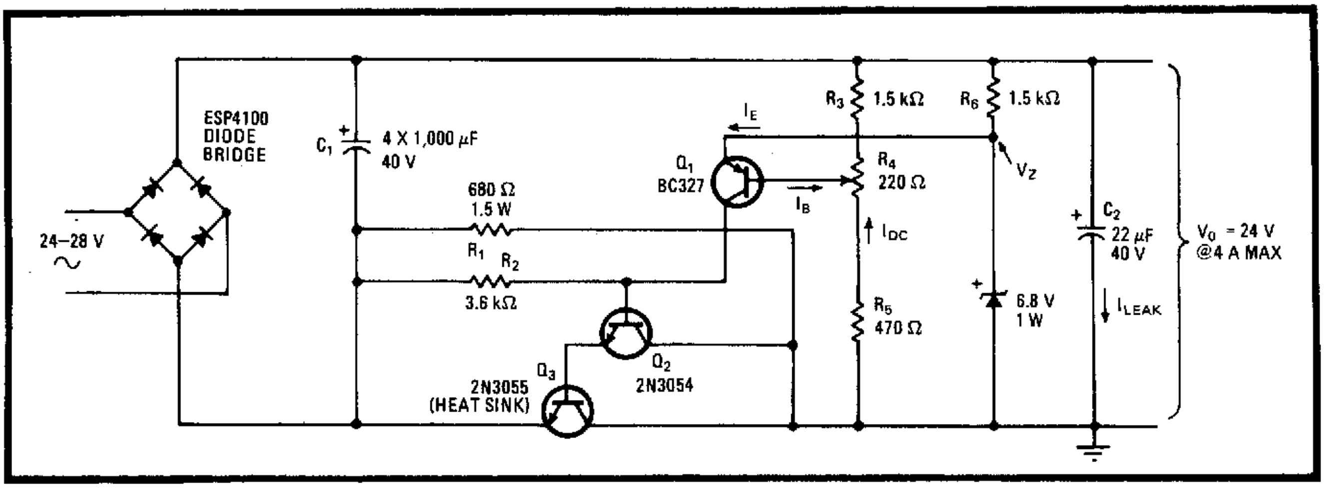
The circuit develops a slight positive temperature offset of 0.4 V after warmup, due to the positive temperature coefficient of the zener diode. If this offset proves to be annoying or unwanted, a forward-biased 1N4001 can be placed in series with the zener to eliminate the problem.

It is recommended that four 1,000-μF capacitors be used for C_1, instead of a single 4,000-μF device because of the high ripple currents (and heat generation) that will be encountered. Output ripple is only 20 mV peak to peak at 3.5 A. If desired, the ripple may be more than halved by the addition of another 1,000-μF capacitor at the input. ☐

References

1. A. D. V. N. Kularatna, "Foldback limiter protects high-current regulators," *Electronics*, Jan. 31, 1980, p. 98.

Designer's casebook is a regular feature in *Electronics*. We invite readers to submit original and unpublished circuit ideas and solutions to design problems. Explain briefly but thoroughly the circuit's operating principle and purpose. We'll pay $50 for each item published.



Rudimentary. Simple but rugged and reliable foldback limiter delivers 24 V ± 100 mV at a maximum of 4 amperes. Output ripple is only 20 mV at 3.5 A and may be reduced further simply by placing additional capacitors at input. Placing series pass element, Q_3, in ground lead gives circuit good dynamic range and simplifies solution of classic mounting-vs-isolation problem in dealing with cooling of the power transistor.

High-current voltage regulator works with negative supplies

by Robert A. Pease
National Semiconductor Corp., Santa Clara, Calif.

Monolithic voltage regulators combine the voltage-stabilizing and power-protection circuitry of discrete component designs into a single package. As a result, current-limiting, voltage-limiting, and even thermal limiting features are built into the regulating function and therefore require no further consideration by the designer. Unfortunately, most high-power monolithic voltage regulators are intended for positive-supply voltages.

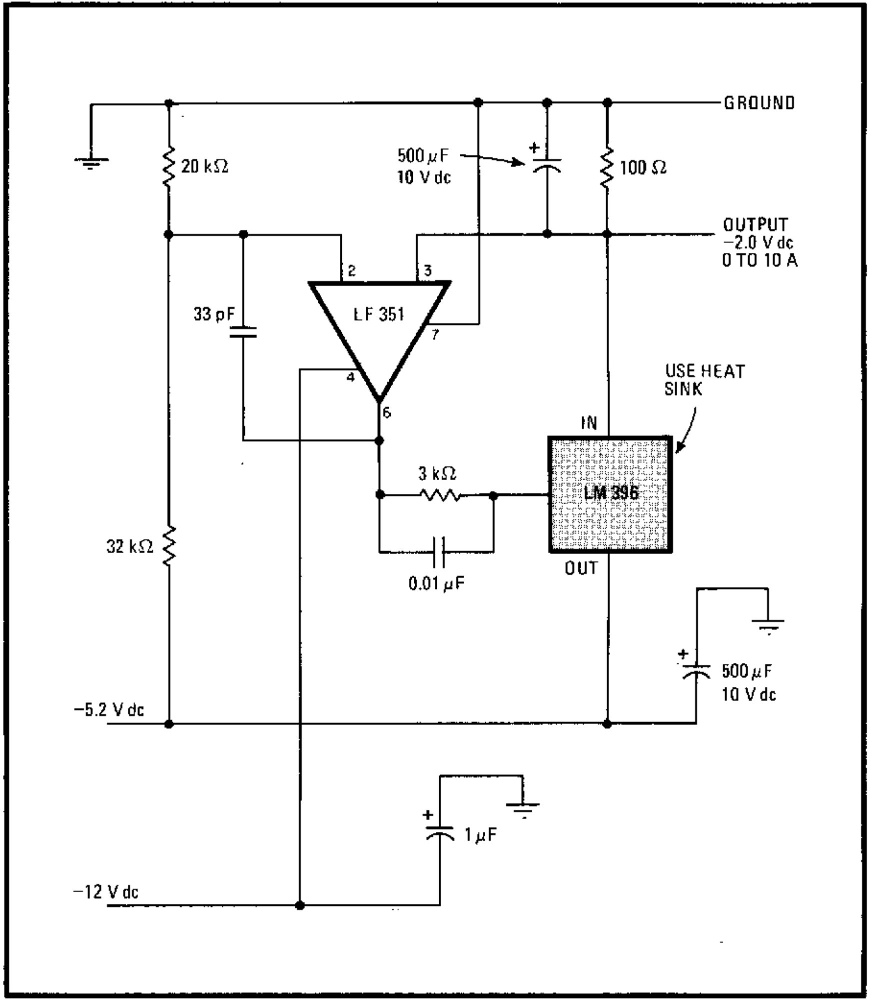
Currently, the only negative-voltage monolithic regulators that are available are those with 1.5 or 3 amperes of rated output current. The LM337 adjustable and LM345 fixed −5-volt regulators are two such devices. New high-current monolithic regulators, such as the LM338, rated at 5 A, and the LM396, rated at 10 A, are normally characterized as positive regulators. Yet they can also be used in applications calling for negative regulators, such as in an emitter-coupled-logic computer where several amperes at −2 V are often required.

The figure shows an LM396 that is controlled by an LF351 operational amplifier that holds the LM396's adjust pin at 1.25 V below the −5.2-V bus.

The accuracy of the output voltage depends on the −5.2-V supply, which is used as a reference. Short-circuit limiting to 15 A and thermal-limit protection to 170°C are provided by the LM396. Although the −12 V dc need not be closely regulated, it must be present or else the −2-V supply will fall toward −3 or −4 V, which is excessively negative.

Similarly, a positive regulator such as an LM338 or one or more LM396s have been used to regulate 5, 10, 20 A, or more of −5.2 V dc when a 9-V dc power and a −15-V dc bias supply are used. ☐

Designer's casebook is a regular feature in *Electronics*. We invite readers to submit original and unpublished circuit ideas and solutions to design problems. Explain briefly but thoroughly the circuit's operating principle and purpose. We'll pay $75 for each item published.



Both ways. An LM396 monolithic positive-voltage regulator can be used, as shown here, to regulate a 10-ampere negative supply. Feedback to the regulator chip is furnished by an LF351 operational amplifier. The LM396 regulator provides full short-circuit protection to 15 A, as well as temperature protection to 170°C.

Protected regulator has lowest dropout voltage

by Thomas Valone, *A-T-O Inc., Scott Aviation Division, Lancaster, N. Y.*
and Kelvin Shih, *General Motors Proving Ground, Milford, Mich.*

Providing an output of 5 volts at 10 milliamperes for an input of only 5.012 V, this regulator is ideal for use in many micropower applications, such as regulating the output of lithium batteries that drive low-power detection and recording instruments in the field. The circuit is useful in high-current situations also, as it can deliver up to 1 ampere at 5 V for an input of only 6.0 V. Short-circuit protection in this instance is provided by a single V-groove MOS field-effect transistor.

Contributing to the low-dropout characteristic of the circuit is the 2N6726 output transistor, which has a large junction area that allows a lower emitter-to-collector drop than most other devices, including Darlington arrangements. Thus the input-to-output voltage differential, 12 millivolts, is 6% that of one of the best low-dropout regulators reported to date.[1]

The input-to-output differential is only 350 mV at a load current of 500 mA. The 2N6726 is physically a small transistor but can dissipate 1 watt safely without a heat sink.

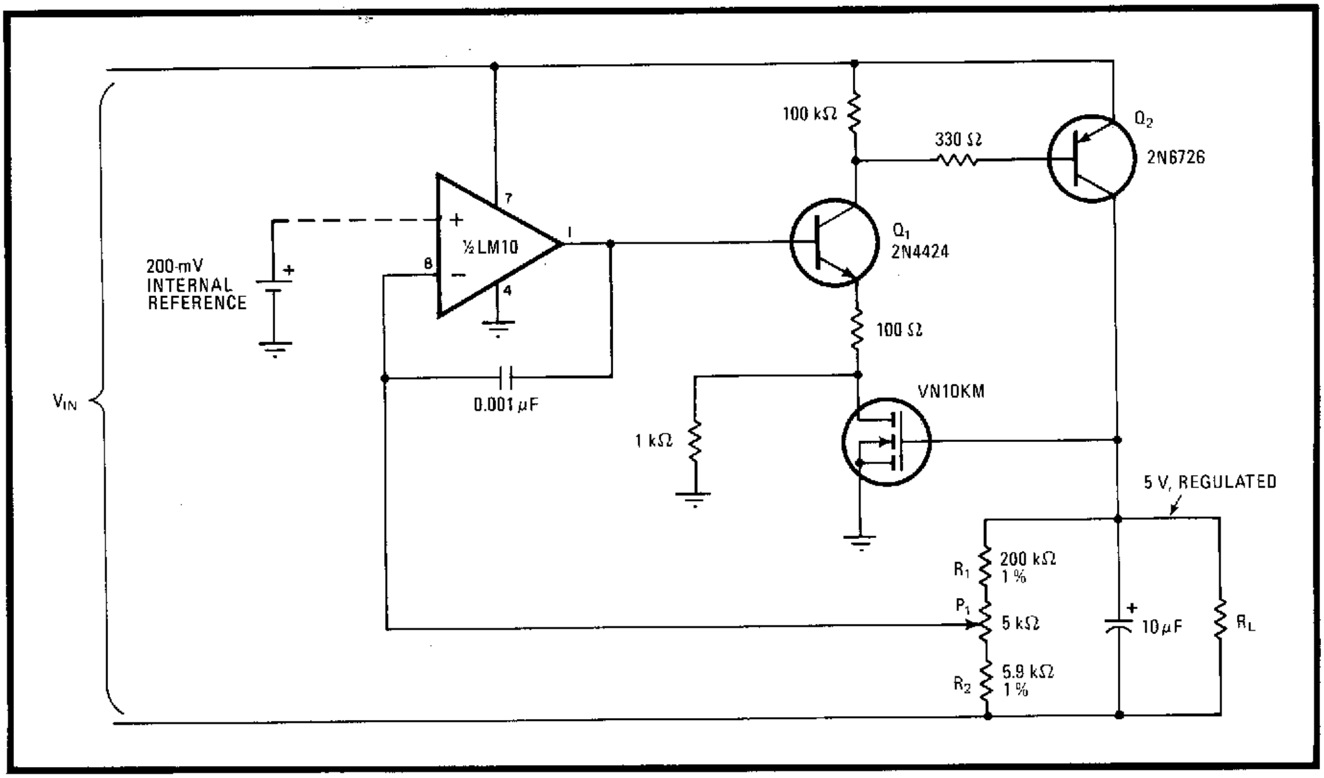
Short-circuit protection is provided by a Siliconix VN10KM, which presents a resistance of less than 10 ohms to the emitter circuit of the 2N4424 drive transistor under normal conditions. However, when the output is shorted to ground or excessive current is demanded, the drain-to-source resistance of the FET rises, safely shutting down the pass transistor. This characteristic can be used to advantage in adjustable current limiters, where the trip point is set by the input voltage. This method, incidentally, is more effective than any transistor foldback technique.

In operation, the LM10CH reference amplifier compares the voltage set by potentiometer P_1 to its internal 200-mV reference and through Q_1 acts to minimize voltage differences at the amplifier's input. With suitable selection of the component values in divider network R_1–R_2, the circuit will regulate over any voltage from 1 to 40 V. The operational-amplifier half of the LM10CH is available for other uses.

The load regulation is to within 0.3% for the range 0 to 100 mA and to within 1% for the range 100 mA to 1 A. The regulator's idle current is 320 μA. ☐

References

1. Kelvin Shih, "Micropower regulator has low dropout voltage," *Electronics*, April 12, 1979, p. 130.



Dropout limit. This low-power regulator, using output transistor operating in common-emitter configuration and having large junction area, can deliver 10 mA at 5 V for an input voltage only 12 mV higher and up to 1 A at 5 V for a 6-V input. Input-to-output voltage differential is only 650 mV at load currents of 750 mA. The V-MOS field-effect transistor provides short-circuit protection in such instances.

Reducing the dropout voltage of programmable regulators

by Carlo Venditti
The Charles Stark Draper Laboratory Inc., Cambridge, Mass.

A programmable regulator's dropout voltage—the minimum allowable potential between its input (V_{in}) and output (V_{out})—can be improved by adding an external output stage and negative feedback. The resulting regulated output voltage (E_{out}) not only approaches V_{in} more closely, but the the current-drive capability is also better, thanks to the outboard power-transistor stage.

The design technique used to achieve this improved performance is described here for Fairchild's popular μA78MG regulator, which has a nominal dropout voltage of 3.0 volts. As shown in the figure, a change in V_{in} causes V_{out} to increase temporarily. The corresponding increase at E_{out} that is applied to the control input of the μA78 forces V_{out} lower, toward the value it had initially. If the resistor network R_1 to R_3 is optimized, E_{out} can be brought to within 1.5 V of V_{in}.

Consider the case where the output voltage E_{out} is to be kept at 12.5 V ±50 mV for a V_{in} ranging from 14 to 15.5 V. When V_{in} is at 14, V_{out} cannot be above 11, owing to the dropout voltage of the regulator. Thus with an output voltage of 12.5, the voltage at the base of Q_1 is 13.1 (0.6 V higher).

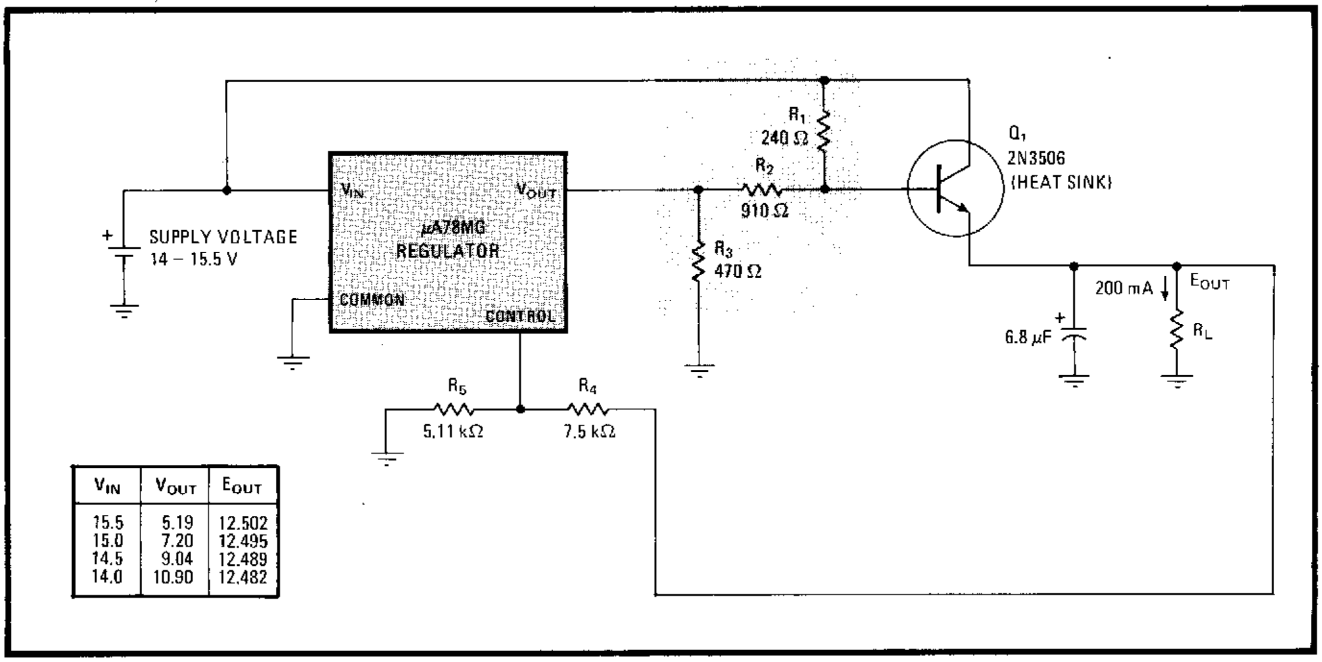
Now R_1 can be selected to pass a given value of transistor base current, I_b, of say, 1.2 milliamperes, and a current through R_2 of perhaps twice this value (2.4 mA), plus a small amount to account for variations in I_b. Thus $R_1 = (14-13.1)\text{V}/3.75\ \text{mA} = 240\ \Omega$, and $R_2 = (13.1-11)\text{V}/2.4\ \text{mA} = 910\ \Omega$.

The next condition to be addressed is the case where V_{in} assumes a value of 15.5 V, so that R_3 may be determined. Because V_{out} ultimately decreases with an increase in V_{in}, V_{out} should be made to move to its minimum value so that the maximum dynamic range of the circuit is realized. From the data sheet of the μA78, $V_{out(min)} = 5.0$ V. Note that changes in V_{out} are scaled by the R_2/R_1 ratio, and these resistors ensure that a change of $910/240 = 3.8$ V occurs for every 1-V increase in V_{in}.

Thus the current through R_2 at this time will be $(13.1-5.0)/910 = 8.8$ mA, and assuming the minimum (quiescent) current of the regulator is 2 mA, the current through R_3 is $(8.8+2.0) = 10.8$ mA. Therefore $R_3 = 5/10.8 = 470\ \Omega$. The table summarizes the actual dynamic performance of the regulator. Note the apparent dropout voltage of the regulator has been reduced to $14.0-12.482 \approx 1.5$ V when V_{in} is at its minimum.

The junction temperature of the on-chip power transistor is $T_j = \theta_{JA}P_T+T_A$, where θ_{JA} is the junction to ambient thermal resistance (80 Ω, see data sheets) and T_A is the ambient temperature. Thus, assuming $T_A = 25°\text{C}$, $T_j = 35°\text{C}$, well below the 125°C thermal shutdown temperature of the μA78.

A check on the chip's temperature will confirm that the regulator's thermal shutdown point has not been reached. The temperature reaches a maximum when $V_{in} = 14.0$. At this voltage, the regulator's output current is 20.8 mA, and the output power is $20.8\,(14-11) = 62.5$ mW. The quiescent current is 4 mA (see data sheets), and the quiescent power drain becomes $4(14\ \text{V}) = 56$ mW. As a consequence of these figures, the total output becomes $P_T = 118$ mW. □



V_{IN}	V_{OUT}	E_{OUT}
15.5	5.19	12.502
15.0	7.20	12.495
14.5	9.04	12.489
14.0	10.90	12.482

Closer. Outboard power transistor stage, and resistor pad R_1–R_3 set E_{out} to within a few volts of V_{in}, so that $(E_{out}-V_{in})$ is below μA78's dropout value. Q_1 also provides increased current capacity. Table summarizes dynamic range attained for example using technique discussed in text.

Engineer's notebook is a regular feature in *Electronics*. We invite readers to submit original design shortcuts, calculation aids, measurement and test techniques, and other ideas for saving engineering time or cost. We'll pay $50 for each item published.