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New Current-Sense Amplifiers Aid Measurement and Control

This application note details the use of high-side current sense amplifier integrated circuits (ICs). Several circuits are described to provide battery fuel-gauging, constant-current battery charging and a protection circuit to prevent damage in response to excessive loads, short circuits and wrong polarity connections to the battery.

The conventional current-measurement circuit-a discrete difference amplifier fed by the signal voltage across a current-sense resistor-is giving way to smaller, less expensive integrated circuits. The monolithic MAX471, for example, integrates the amplifier with a 35mΩ sense resistor and is capable of sensing continuous currents as high as 3A.

A similar device, the MAX472, allows measurement of virtually any current by connecting current-sense and gain-setting resistors external to the package.

Both amplifiers sense the *high-side*load current and produce a current-source output that may be referenced to ground. That capability lets you generate a ground-referenced output voltage, proportional to load current, by connecting a single resistor between the output and ground. The MAX471 has a fixed internal gain that delivers 500µA per ampere of sensed current, and the MAX472 lets you choose the current-sense and gain-setting resistors for an output range of 0mA to 1.5mA. The MAX472 offers more flexibility, but requires a bit more design work.

High-side sense resistors (between power source and load) are preferable to a low-side resistor between the load and power-source return. Low-side sense resistors produce voltage drops that can disrupt the system's ground connection and complicate the charging and power-management circuitry.

Internal workings

The MAX471 and MAX472 contain two cross-connected difference amplifiers (**Figure 1**), each driving an npn transistor. Current through the sense resistor develops a voltage that turns one amplifier off and the other on. The active amplifier's npn transistor then produces a current that flows from the more positive side of the sense resistor, through the gain-setting resistor (RG1 or RG2), and through the transistor to the OUT terminal.

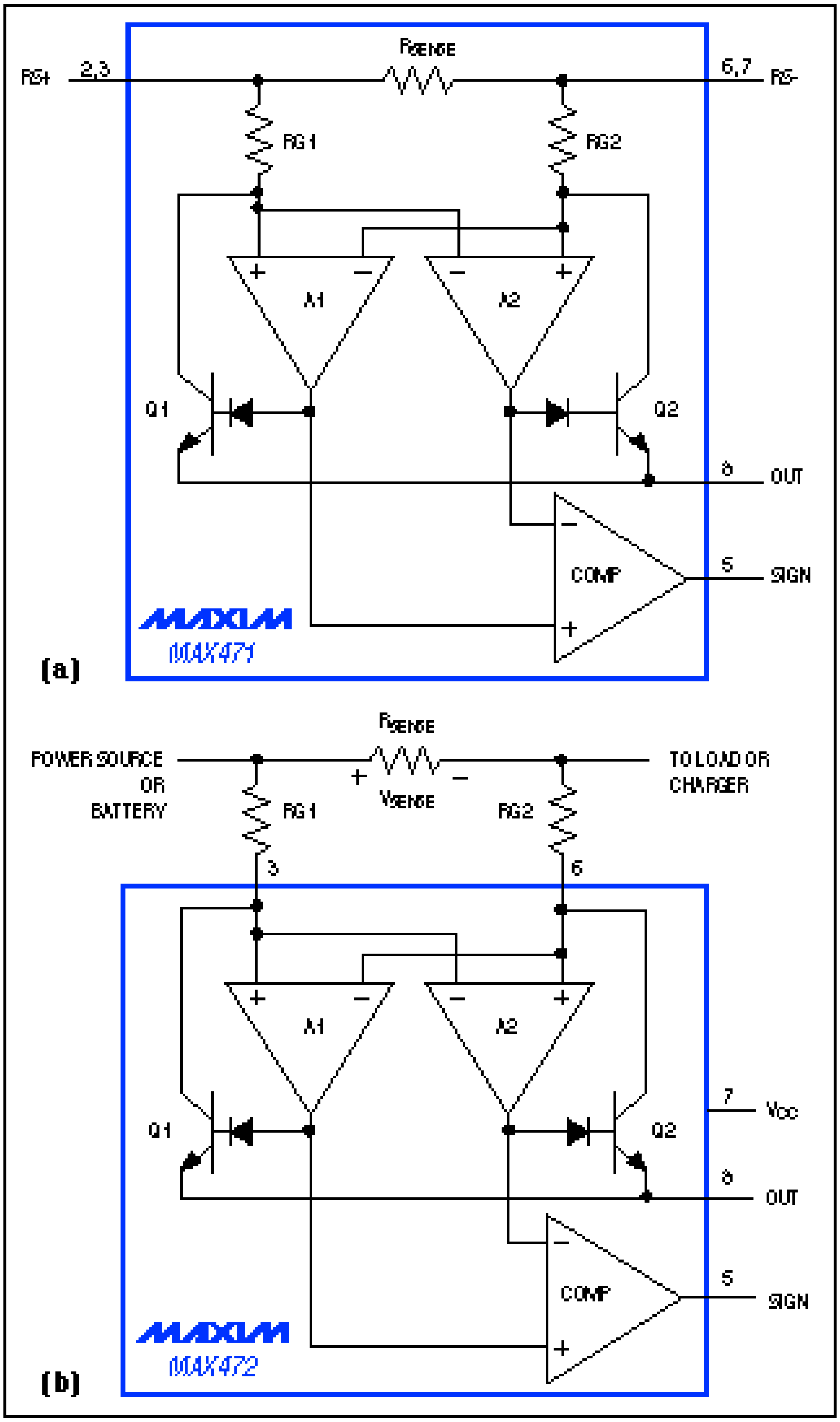

*Figure 1. Internal current-sense and gain-setting resistors enable the MAX471 (**a**) to measure currents up to 3A. For higher current levels, add external sense and gain resistors to the otherwise similar MAX472 (**b**).*

An opposite-polarity current through RSENSE turns this diff-amp off and the other on, producing an output current that always flows in the same direction. Direction of the sensed current is indicated by the SIGN output. This open-drain output simplifies the interface to logic circuitry operating at supply voltages within the IC's 3V to 36V supply range.

Gain-setting resistors RG1 and RG2 (internal to the MAX471 and external to the MAX472) determine the ratio between the sensed current and the OUT current. These resistors should be matched to assure similar accuracy in both directions. Assuming RG1 = RG2 = RG, you can calculate the desired ratio simply by dividing the gain-resistor value into the sense-resistor value:

$I_{OUT} / I_{SENSE} = R_{SENSE} / RG$.

The MAX471 ratio is internally set at 0.5mA/A, which produces an output of 1.5mA when the sensed current is 3A. The MAX472 lets you select sense and gain resistors to measure virtually any level of current, provided the maximum at OUT does not exceed 1.5mA.

The role of ADCs in current measurement

The ICs described above were designed primarily for measuring current flow from batteries. If the flow is fairly steady, you can measure the corresponding output voltage (developed across ROUT in **Figure 2**) with an A/D converter. Each digital sample then represents a "snapshot" of the current flowing through RSENSE. To detect the direction of current flow, you can either sample the SIGN output or connect SIGN to an I/O line on the controller.

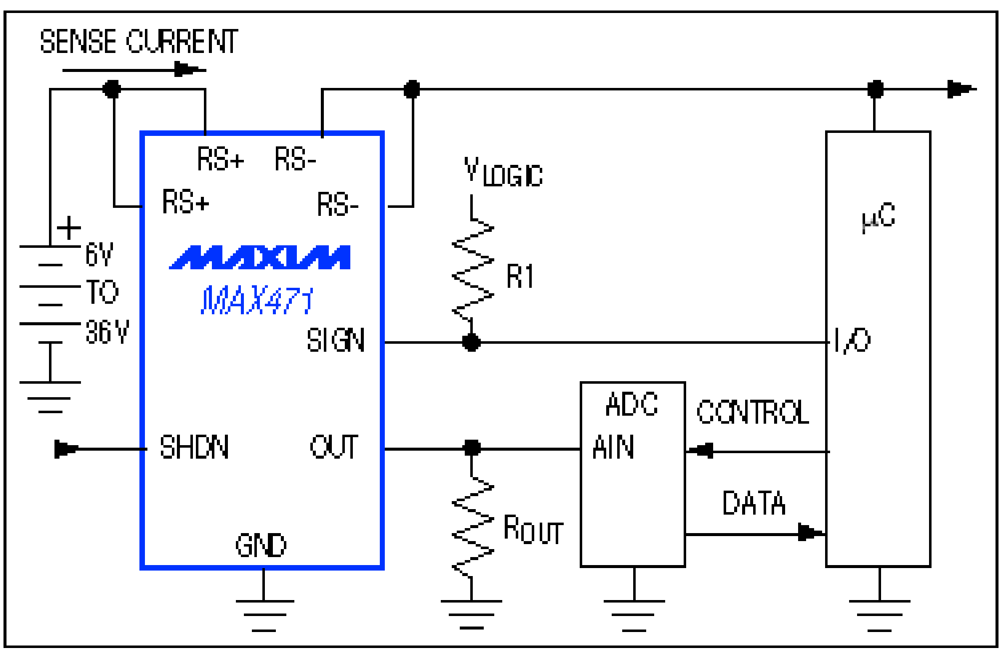

Figure 2. An A/D converter enables the µC to read the MAX471's current-source output.

If the measured current is not steady, you can integrate it by replacing ROUT with a capacitor. Knowing that IAVERAGE = CΔV/Δt, you can allow the capacitor to charge to a certain voltage, take a measurement, divide by the time between measurements, and then discharge the capacitor (with a shunt switch) and start over. Current flow during the capacitor-discharge interval (dead time) is lost to the measurement, but that effect is minimal if the discharge time is a small fraction of charge time.

A circuit with two charging capacitors (**Figure 3**) lets you integrate the current without creating a dead interval. The relationship ΔQ = CΔV lets you calculate the total charge removed from the battery or added to it. For a given comparator threshold voltage (1.182V in this case), you must balance the effects of capacitance needed (to store charge between sampling intervals), capacitor leakage, and the full-scale output current from IC3.

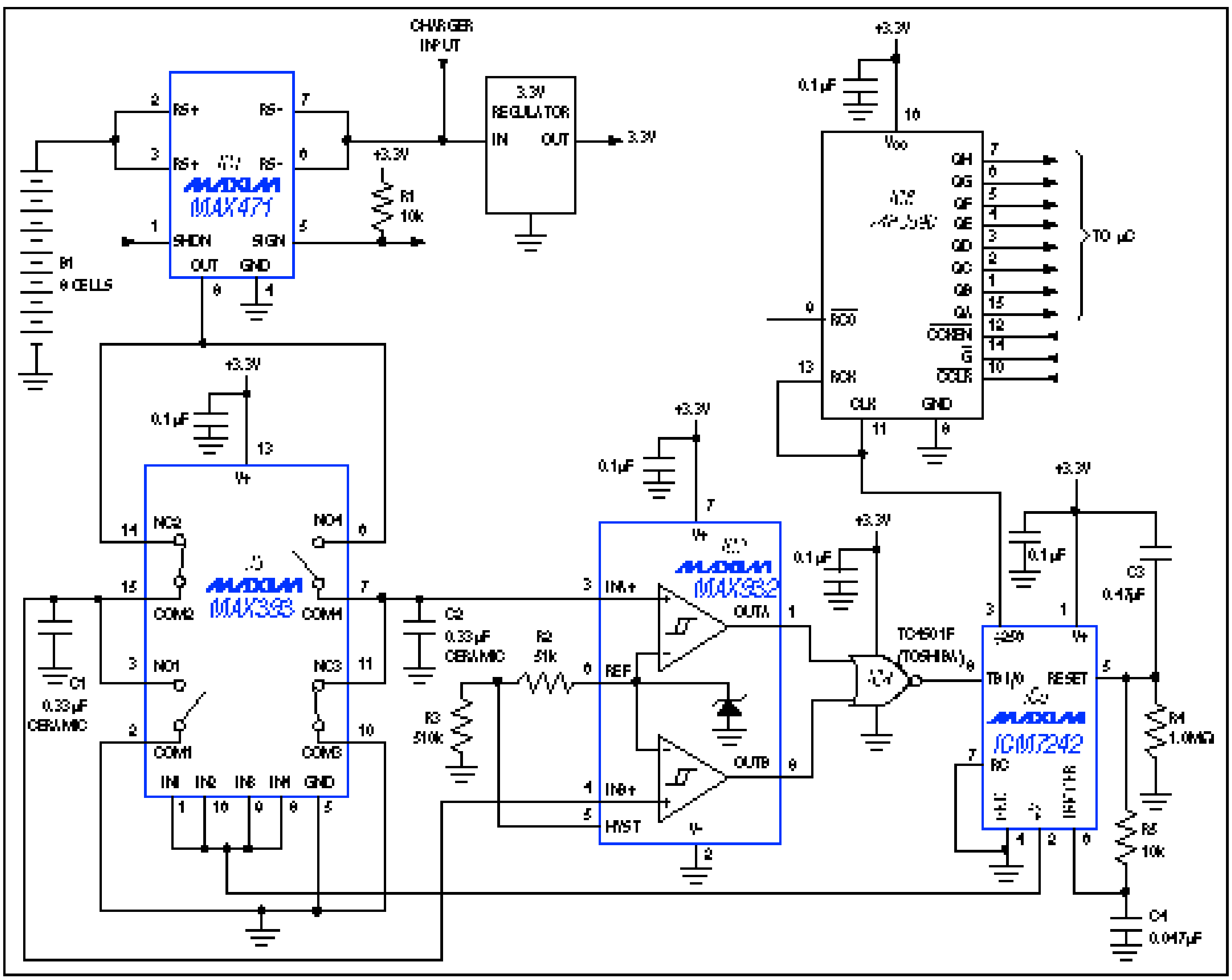

Figure 3. By switching between two integrating capacitors (C1 and C2) this battery fuel-gauge circuit monitors a continuous battery discharge with minimal error.

The Figure 3 circuit converts current to frequency and counts the resulting pulses. As an example, a full-scale current of 3A from the battery causes IC2's current-source output (pin 8) to source 1.5mA. Analog switches in IC3 steer this 1.5mA to one of two 0.33µF ceramic capacitors while discharging the other to ground. When the charging capacitor reaches 1.182V (the threshold voltage of dual comparator IC2) the corresponding comparator output goes high.

These low-to-high comparator transitions are summed by the NOR gate (IC4) and fed to IC5, whose divide-by-two output drives the analog switches to simultaneously discharge one capacitor and divert charging current to the other. IC5 serves as a prescaler, dividing the NOR gate output by 256 and feeding it to an 8-bit parallel counter (IC6). By periodically reading this counter's three-state outputs, the µP can track net cumulative charge taken from the battery:

$\Delta Q_C = C\Delta V$,

where ΔQ_C is the maximum charge accumulated by either capacitor C, and ΔV is the corresponding capacitor voltage (i.e., 1.182V, which triggers the capacitor's discharge). Then, ΔQ_C is proportional to charge taken from the battery (ΔQ_B) by the same factor that scales IC1's current-source output (0.5mA/A):

$\Delta Q_C = (0.5mA/A)x\Delta Q_B$.

Rearranging terms,

$\Delta Q_B = 2000\Delta Q_C = 2000C\Delta V$.

Each negative-going transition at the NOR-gate output represents Q_B of charge from the battery, and 256 of these transitions produce one clock cycle into IC6, representing:

$$
\begin{aligned}
256\Delta Q_B &= 256(2000C\Delta V) \\
&= 256(2000)1\mu F(1.182V) \\
&= 0.605 \text{ coulombs.}
\end{aligned}
$$

Thus, to assure a continuous monitoring of current from the battery, the system must read the three-state outputs of IC6 at least once during each of its 256-count cycles. These cycles vary according to the rate of battery discharge, but the maximum read interval is determined by the maximum anticipated discharge rate (3A in this case). The consequent 1.5mA output from IC3 charges each capacitor to 1.182V in CV/i = (0.33µF)(1.182V)/1.5mA = 260µs. This interval is multiplied by 256 in the IC5 prescaler and again by 256 in the IC6 counter: 260µs(256)(256) = 17 seconds maximum. You can extend this maximum interval with a larger value for the two capacitors.

Measurement linearity remains relatively constant for load currents between 100mA and 3A. Below 100mA, measurement errors increase due to the effect of offset current in the current-sense amplifier (**Figure 4**).

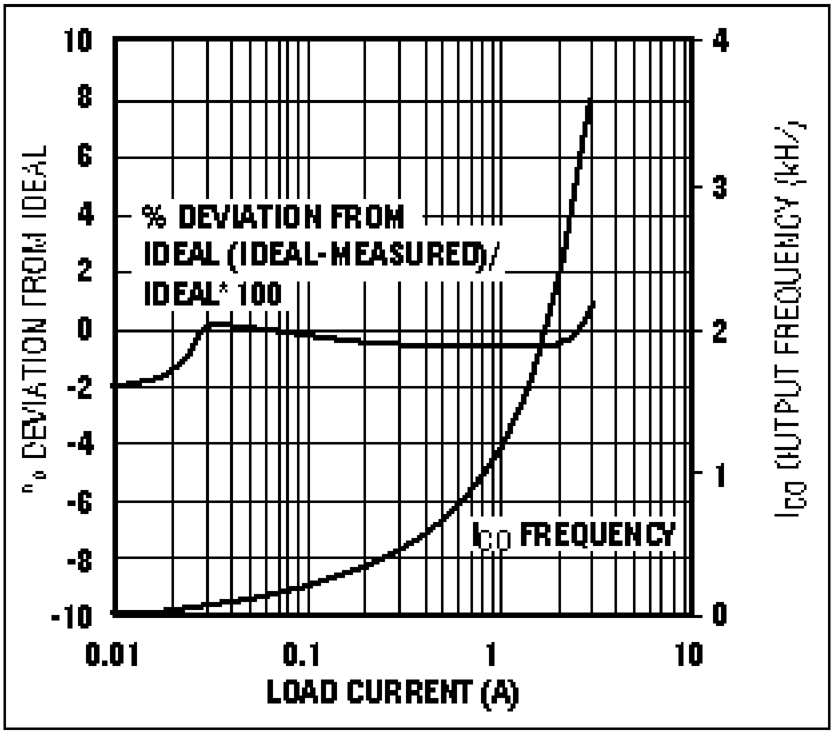

Figure 4. For low values of load current, the measurement error in Figure 3 deviates because of offset error in the current-sense amplifier (IC1).

Current control

Though designed primarily for current measurements, the MAX471/MAX472 amplifiers also lend themselves to current-control applications. These include current sources, overcurrent-protection circuits, and battery chargers. The circuit of **Figure 5**, for example, is a current-source battery charger capable of sourcing 2.5A with efficiency better than 90%. Again, the MAX471 senses current on the battery's high side, allowing use of a common ground as in automotive applications.

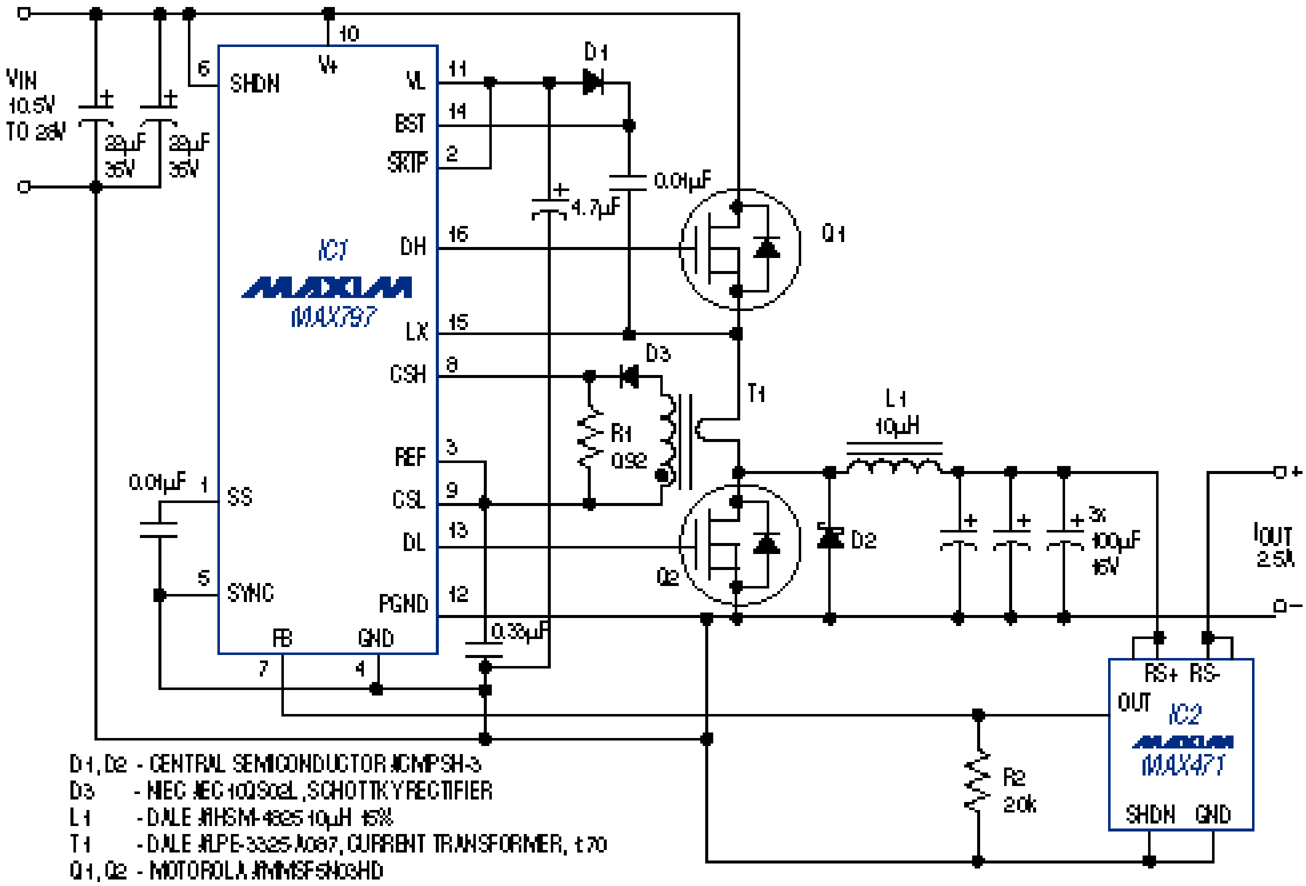

Figure 5. A high-side current-sense amplifier (IC2) enables this 2.5A, 90%-efficient, current-source battery charger to have a common ground with the battery.

IC1 is a current-mode buck-regulator controller whose drive outputs (DH and DL) control two external n-channel MOSFETs. Their on-resistances are lower than those of equivalent p-channel MOSFETs, so the n-channel devices dissipate less power for given amounts of channel current. Positive gate drive for the high-side MOSFET (Q1) is generated by a charge pump in IC1. Buck regulators limit their maximum output to V_{IN}, so removing the battery while this charger is operating will not cause a dangerous rise in V_{OUT}.

The current-sense amplifier (IC2) senses I_{OUT} via an internal sense resistor and produces a smaller but proportional output current. The external resistor R2 then produces the feedback voltage required by IC1. For digital control of I_{OUT}, you can switch to other output resistors using an analog-switch array, or one or more small FETs such as the 2N7002 (not shown). On-resistance errors contributed by these FETs are not significant because IC2 produces a low output current.

Current through Q1 flows through the primary of the current transformer (T1), whose secondary directs a reduced current through the sense resistor R1. The result (compared with a conventional sense resistor in series with Q1) is lower power dissipation and better efficiency. This circuit operates with efficiency as high as 96% (**Figure 6**). Efficiency decreases with output voltage, because at lower voltages the fixed power level required to drive the FETs and IC represents a larger percentage of the total.

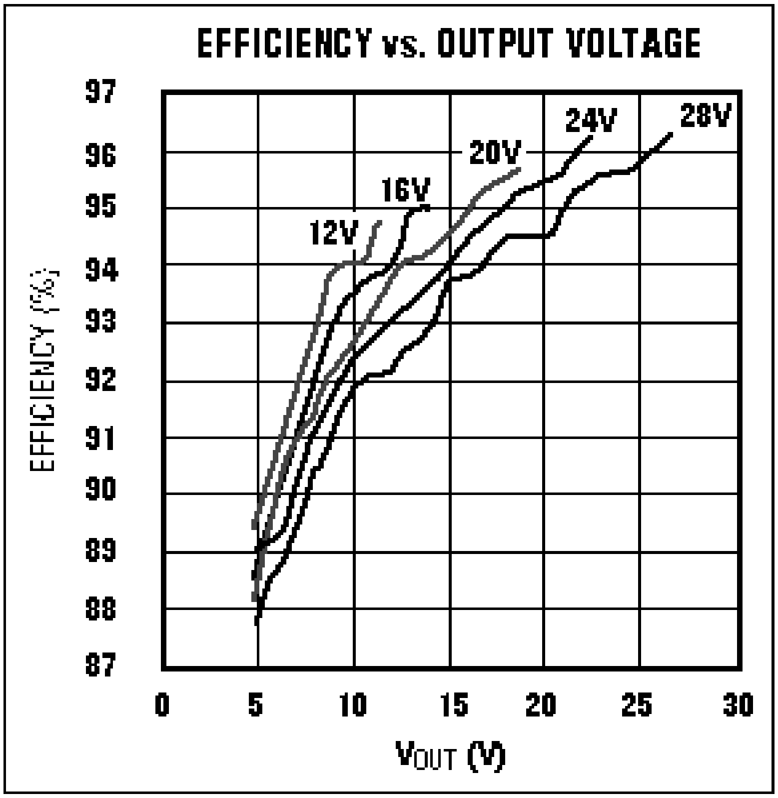

Figure 6. A fixed level of power dissipation in the battery charger of Figure 4 causes efficiency to decline with output voltage.

Step-up battery charger

Battery charging in many portable applications is controlled by a µP or µC (**Figure 7**). The processor issues CHARGE ON/OFF and FAST/TRICKLE CHARGE commands, and IC2 monitors the charging current. IC1 is a step-up switching regulator that boosts the applied 5V to a level necessary for supplying the combined charging current and system-load current. The 5V supply must include short-circuit protection for this application.

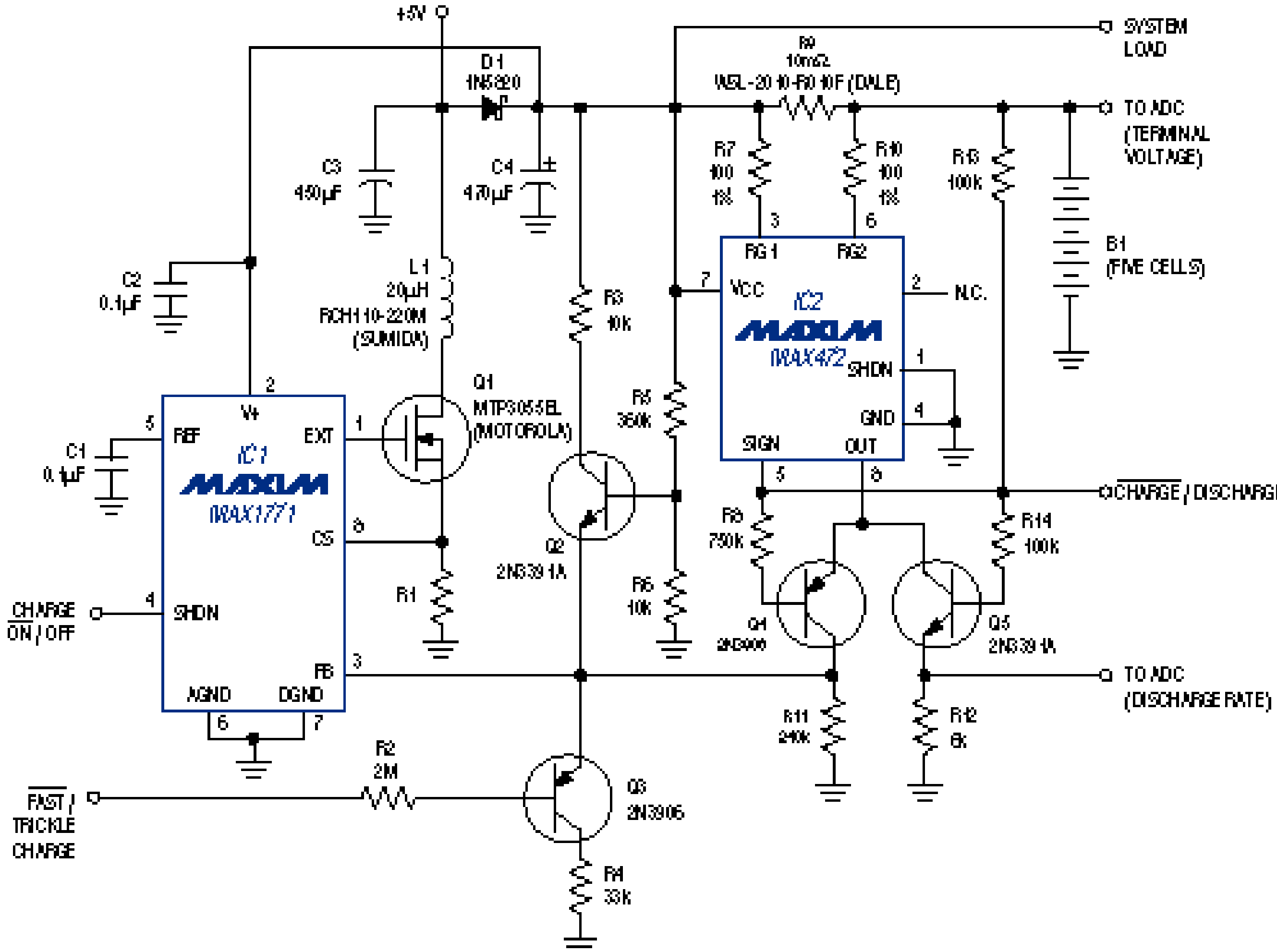

Figure 7. Under control of a microprocessor, this step-up battery charger delivers battery current and load current at the same time.

IC2's output current (pin 8) is proportional to the current through sense resistor R9, reduced by a factor of 10^{-4} (which equals the value of R9 divided by the value common to R7 and R10). Q3 and Q4 are on during a fast charge, so the output current flows through the parallel combination of R11 and (approximately) R4. The resulting feedback voltage to the boost converter (pin 3) maintains the R9 fast-charge current at 500mA. This feedback also enables the regulator to supply as much as 500mA of load current in addition to the charging current. Q2 limits the battery voltage to 10V (2V per cell).

An external processor and multi-channel A/D converter monitor the battery's terminal voltage during a fast charge. When the A/D senses a change of slope in this voltage, the processor terminates charging by asserting a high on FAST/TRICKLE CHARGE. Q3 turns off, causing a rise in the feedback (to IC1) that lowers the charging current to the trickle-charge rate of approximately 60mA.

If the boost converter shuts down, or if the sum of load current and charging current exceeds the boost converter's output capability, the charging current reverses as current flows out of the battery. IC2 indicates this reversal via its open-collector SIGN output, pulled high by R13, which turns off Q4 and turns on Q5. Current through R12 then produces a voltage proportional to the battery's discharge current: 5A through R9 produces a full-scale response of 3V across R12.

By integrating this voltage over time (sampling at fixed intervals and multiplying each sample by the associated time interval), the system can monitor energy removed from the battery. Based on this measurement and the terminal-voltage measurement, the processor can then re-initiate a fast charge (by asserting FAST/TRICKLE CHARGE low) before the battery reaches its end of life.

Switched, digitally controlled current source

The variable current source of **Figure 8** generates 0A to 5A outputs with a compliance range of 4V to 30V. It has two advantages over conventional current sources: the 12-bit D/A converter (IC2) makes it digitally programmable, and its switch-mode step-down regulator (IC1) is more efficient than the alternative linear pass transistor. Applications include battery charging and dc motor control.

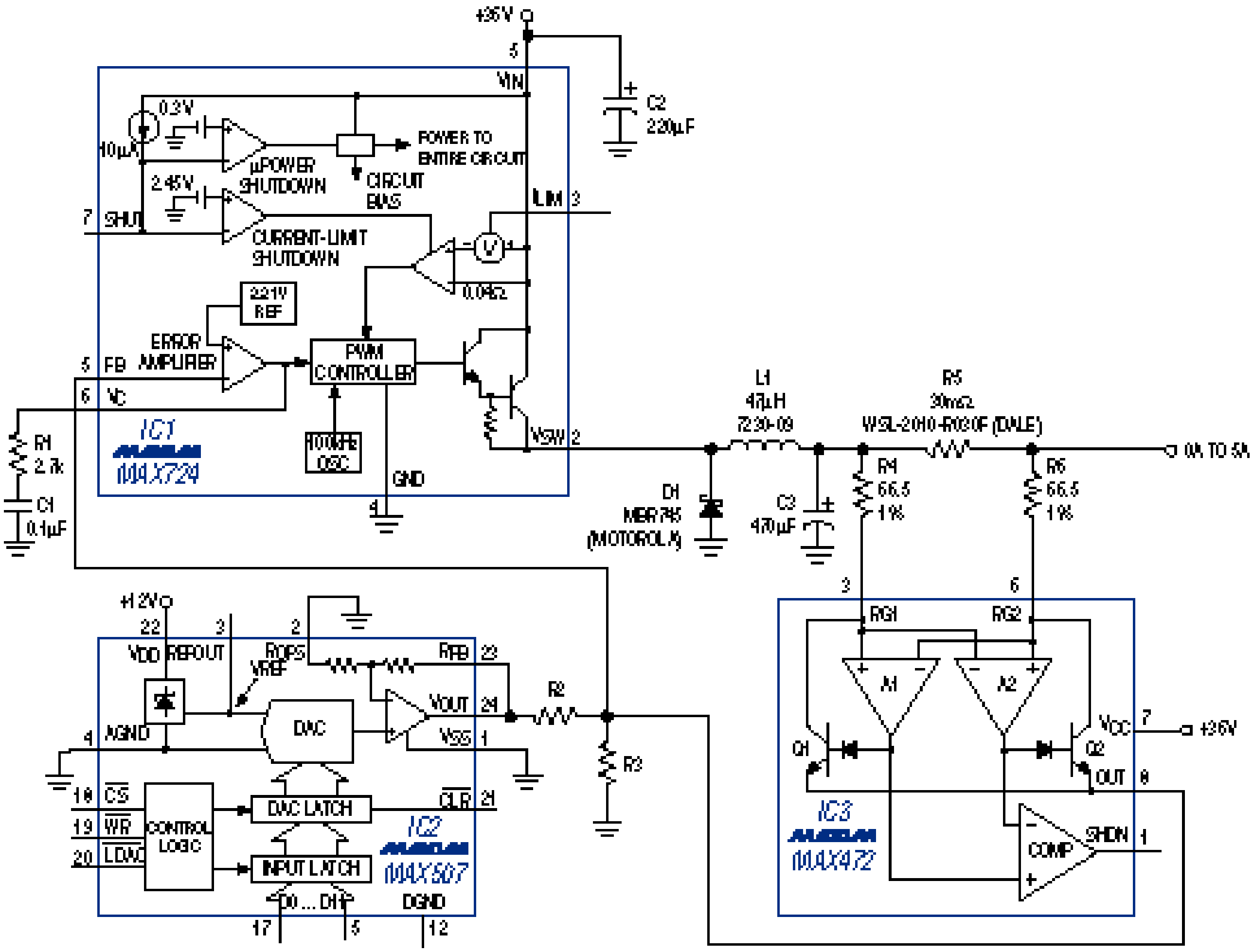

Figure 8. This 0A to 5A variable current source features an efficient, switch-mode step-down regulator (IC1). A 12-bit D/A converter (IC2) makes the source digitally programmable.

IC3 (the current-sense amplifier) senses output current as a voltage drop across R5 and produces a proportional signal current at pin 8. Thus, the regulator's feedback voltage (at pin 1 of IC1) is set by the D/A converter and modified by IC3's current feedback, which flows across the parallel combination of R2 and R3. This current feedback opposes any change in load current due to a change in load resistance.

The D/A converter generates 0V to 10V, producing a source current that varies inversely with code: FFFHEX (10V from the DAC) produces 0mA, and 000HEX (0V from the DAC) produces 5A. For a given programmed level, the actual output varies somewhat with load resistance and the corresponding compliance voltage. When tested at 1.5A, for instance, the output of the circuit deviates about 15mA (i.e., 1% of 1.5A) for compliance voltages between 10V and 20V (**Figure 9**).

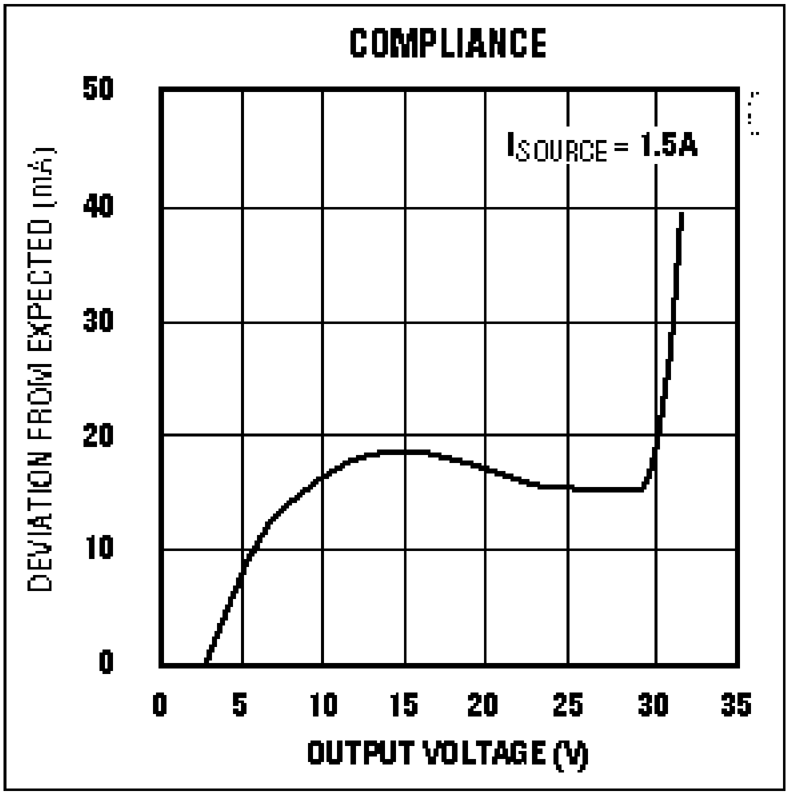

Figure 9. The Figure 8 current source varies only 2mA or so over the compliance range 10V to 20V.

You can easily reconfigure the circuit for other ranges of output current (I_{SOURCE}) by resizing R2 and R3:

$$I_{SOURCE} = \frac{2217\,[(V_{FB}(R2 + R3) - R3V_{DAC}]}{R2R3},$$

where V_{FB} = 2.21V and V_{DAC} ranges from 0V to 10V. Values for R2 and R3 are defined by the desired range for I_{SOURCE}: V_{DAC} = 0V for the high value of I_{SOURCE}, and V_{DAC} = 10V for the desired low value of I_{SOURCE}. Substituting these two sets of values in the equation yields two equations, to be solved simultaneously for the values of R2 and R3.

Variable linear current source

By converting current to a feedback voltage you can transform a low-dropout linear voltage regulator into a current regulator (**Figure 10**). The control input $V_{CONTROL}$ determines the output current: applying 5V sets this current to zero, and applying 0V sets it to 250mA. Intermediate voltages from a D/A converter (or the buffered output of a potentiometer) let you control the output current digitally or manually.

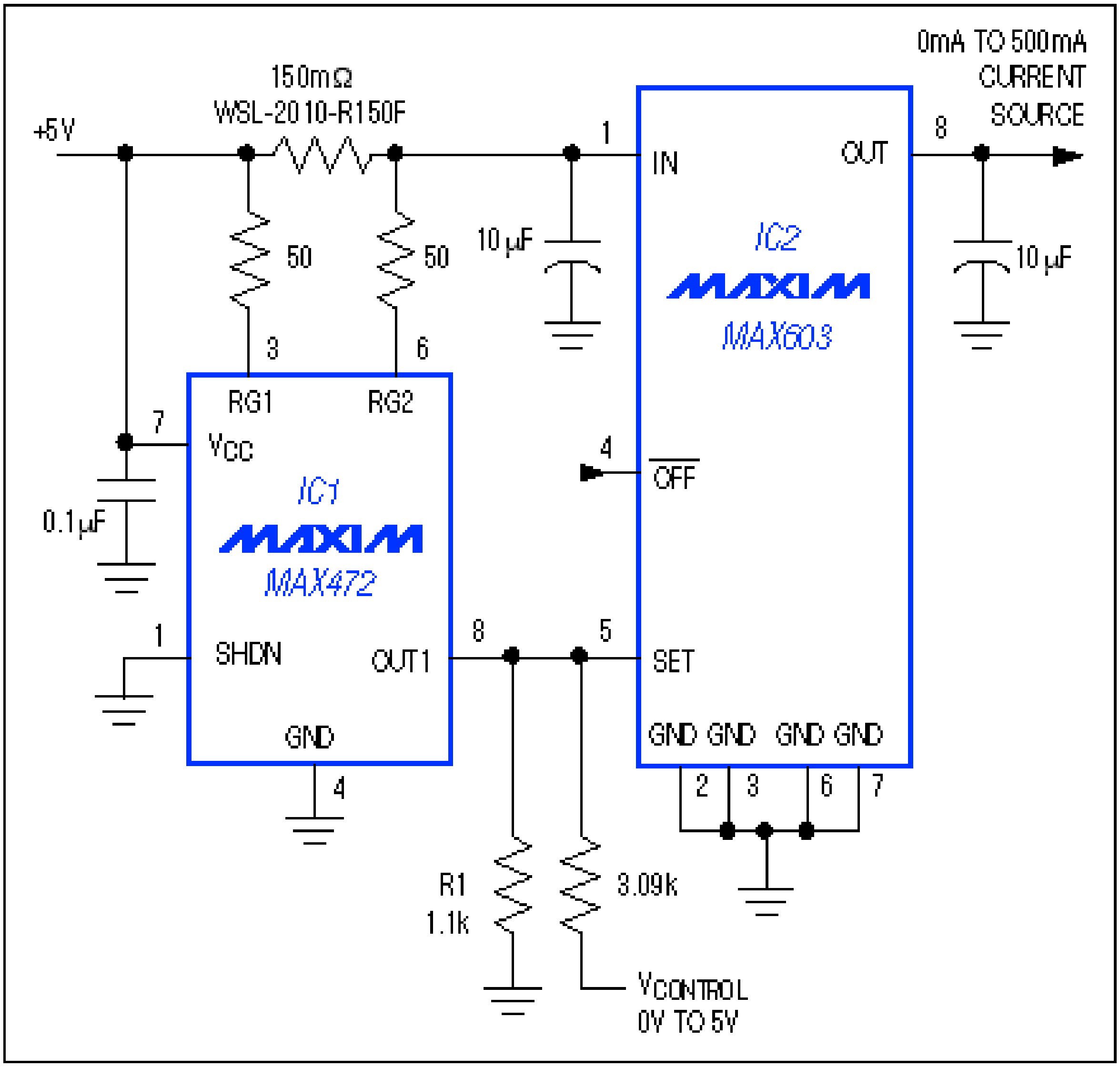

Figure 10. This current source (similar to that of Figure 8) varies linearly from 0mA to 500mA in response to the applied control voltage.

This circuit has a compliance range of 0V to 4.7V when powered from 5V, but it also operates from supply voltages as high as 11V, if you take care not to exceed the maximum power-dissipation rating for the regulator package. This rating is 1.8W at room temperature. Ignoring a tiny operating current, the chip dissipation equals the voltage drop from pin 4 to pin 6 times the current through the chip via these pins.

Under the worst-case conditions of 250mA output current, output shorted to ground, and a dissipation limit of 1.5W (the 1.8W package rating less a safety factor), the circuit's input voltage can be as high as 6V. (6V x 250mA = 1.5W.) Excessive power dissipation causes the thermal-protection circuitry to turn on and off, producing a pulsed output current as the internal temperature oscillates about the thermal trip point.

Polarity-reversal/forward-current protection

The **Figure 11** circuit protects a battery-operated system in two ways: Q1 prevents damage due to the flow of reverse current that otherwise occurs when the battery is installed backwards, and Q3 prevents the excessive flow that otherwise occurs with a sudden load increase or short circuit.

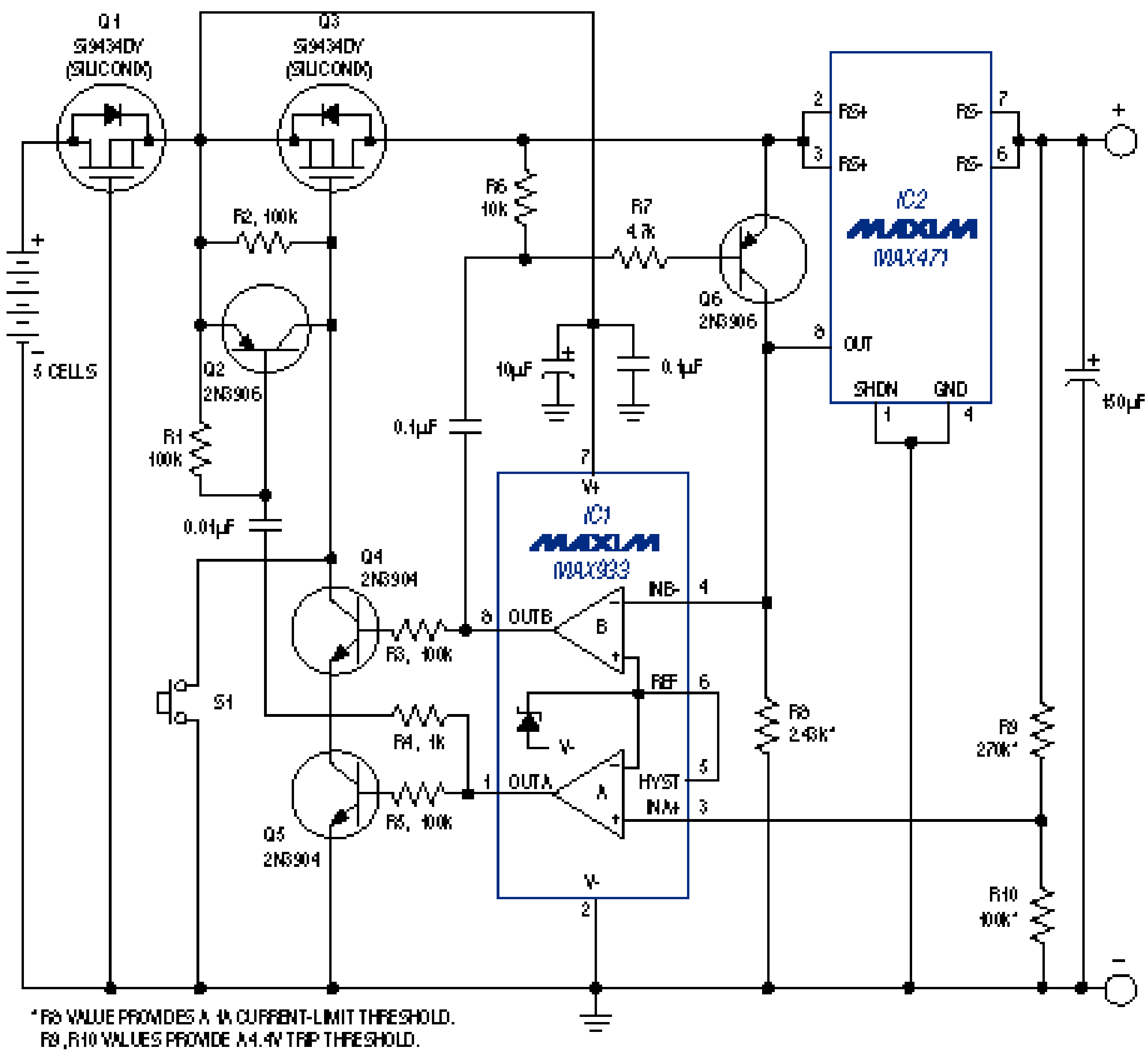

Figure 11. This load-protection circuit prevents current flow in response to excessive loads, output short circuits, and wrong-polarity connections to the battery.

A properly installed battery fully enhances Q1 by pulling its gate more than 5V below the source. If the battery is installed backwards, Q1 is off because the gate is positive with respect to the source. Regardless of battery polarity, the body diodes of Q1 and Q3 are oriented to assure that no current can flow when either device is off. Both FETs have low on-resistance.

Current-sense amplifier IC2 senses the load current flowing between its RS+ and RS- terminals and develops a proportional voltage across R8. During normal operation, the comparator outputs are high and Q3 remains on.

When the load current exceeds a limit set by R8 (i.e., $I_{LIMIT} = 2000V_{TH}/R8$, where 2000 is the sense amplifier's gain and V_{TH} is the comparators' input threshold (1.182V ±2%), the B comparator output goes low, turns off Q4, turns off Q3, and disconnects the battery from its load. At the same time, Q6 provides positive feedback by pulling the comparator input up to the collapsing supply rail, latching Q3 off as the supply voltage drops.

A short-circuited output turns off IC2 by removing the voltage at pins 6 and 7 (3V is the minimum for proper operation). IC1's B comparator loses control because the R8 voltage goes to zero, but comparator A is able to shut off Q3 by turning off Q5. Q2 speeds the Q3 turn-off time to about 10µs, and when Q3 is off, the circuit draws about 2µA. (To restore power, you press S1.) During normal operation the battery current varies with its terminal voltage: 200µA at 5V, 230µA at 6V, 300µA at 8V, and 310µA at 10V.

More Information

MAX1771: QuickView -- Full (PDF) Data Sheet -- Free Samples

MAX471: QuickView -- Full (PDF) Data Sheet -- Free Samples

MAX472: QuickView -- Full (PDF) Data Sheet -- Free Samples

MAX797: QuickView -- Full (PDF) Data Sheet -- Free Samples

MAX932: QuickView -- Full (PDF) Data Sheet -- Free Samples

MAX933: QuickView -- Full (PDF) Data Sheet -- Free Samples