

APPLICATION NOTE 3883

Practical Considerations for Advanced Current Sensing in High-Reliability Systems

Abstract: The simplest method for monitoring and measuring electrical current uses Ohm's Law: the voltage across a resistor in the current path is directly proportional to the current. This article describes practical design issues for resistor-based current sensing and shows practical applications such as current protection, hot-swap controllers, fuel gauging, and fault protection.

Basic High-Side Current-Sense Amplifiers

Resistor-based current sensing is simple, easy to use, low-cost, extremely linear, and requires no calibration. Ohm's Law states that voltage across a resistor is directly proportional to the current through it: $V = IR$. As a caveat, however, note that all resistors dissipate power when current passes through them. Because the dissipation produces heat that, in turn, affects the resistance, power dissipation in a sensing resistor must be carefully assessed.

A larger sense-resistor value yields better accuracy, but dissipates more power:

$$P = I^2R$$

Eq. 1

where I is the measured current and R the sensing resistance. The magnitude of the measured current is application-specific rather than a design parameter. Consequently, the sensing-resistor value should be as low as possible to minimize 'joule heating'.

Choosing a small-valued sensing resistor yields a low-level sensing voltage across it. An amplifier is required to boost that voltage to a level suitable for interface to a comparator, analog-to-digital converter (ADC), or other external circuit. Low sensing voltages are, moreover, vulnerable to the measurement error induced by the inherent bias current and input offset voltage of amplifiers. For example, a practical full-scale sensing voltage might range from 50mV to 200mV. If the amplifier's maximum input offset voltage is $\pm 5\text{mV}$, the measurement error is $\pm 10\%$ at 50mV (full-scale) and even worse at lower currents.

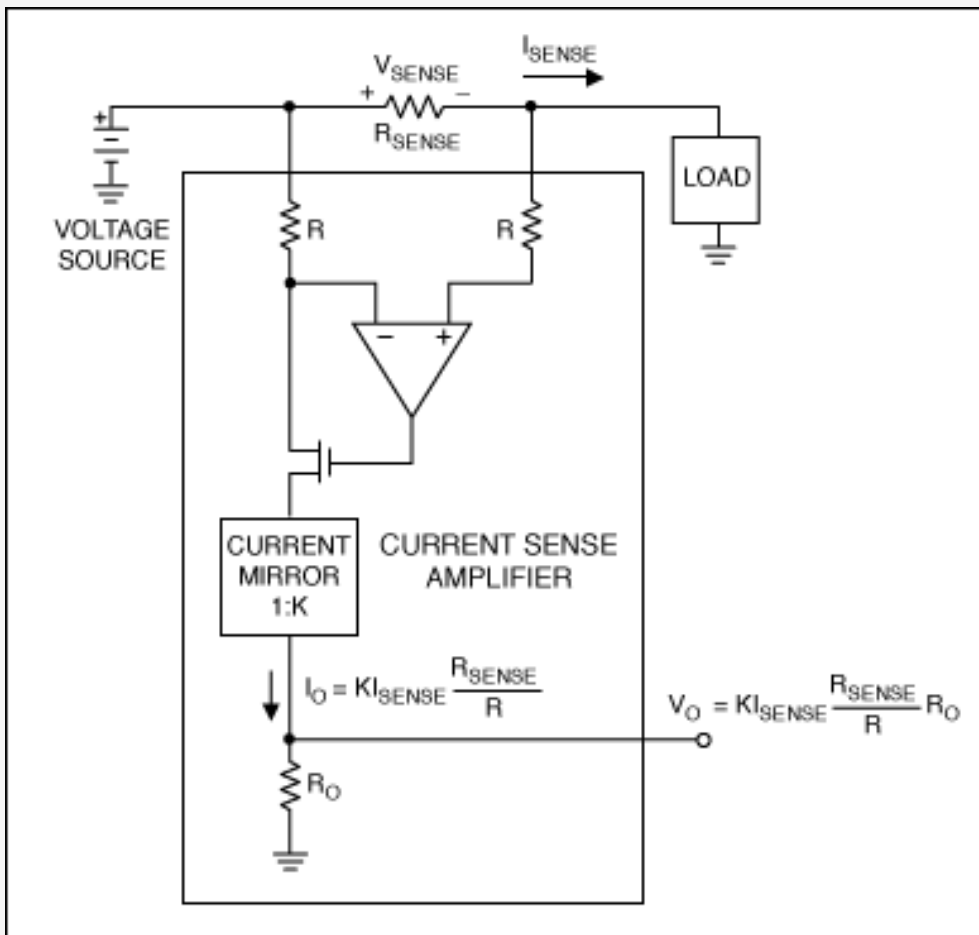


Figure 1. This high-side current sensor exploits Ohm's Law for current measurements.

The current-sensing amplifier must have both low-input offset voltage and low input bias current. A dedicated high-side current-sense amplifier (**Figure 1**) places a current-sensing resistor between the voltage source (a battery, for instance) and the load. By avoiding extraneous resistance in the ground plane, that arrangement greatly simplifies the board layout and generally improves the overall circuit performance. Current passing through the sense resistor (R_{SENSE}) develops a voltage drop, which is sensed by the op amp and drives the MOSFET transistor to sink current through R . The voltage drop across R equals the voltage across the sensing resistor:

$$K I_{SENSE} R_{SENSE} = I_O R, \therefore I_O = K I_{SENSE} (R_{SENSE} / R) \quad \text{Eq. 2}$$

Thus,

$$V_O = K I_{SENSE} (R_{SENSE} / R) R_O \quad \text{Eq. 3}$$

The sensor output current is proportional to the load current. Typically, a current mirror is included to increase the output current by a factor of K . If you require a voltage output, convert the current to voltage by placing an output resistor (R_O) between the current output and ground. Resistors R and R_O can easily be factory-trimmed to achieve a current-sensing accuracy of 1% or better.

Current Monitor and Protection

High-reliability power-supply circuits often incorporate short-circuit or overload protection (**Figure 2a**). The IC shown (a [MAX4373](#) current sensor) integrates a reference, comparator, and latch. R_1 and R_2 set the trip current. The comparator compares the current-sensor output voltage with the reference voltage. When load current reaches the allowed maximum, the comparator output turns off the p-channel MOSFET switch by latching to logic high. No current flows to the load. The p-MOSFET remains off until a reset is applied or the power supply is toggled.

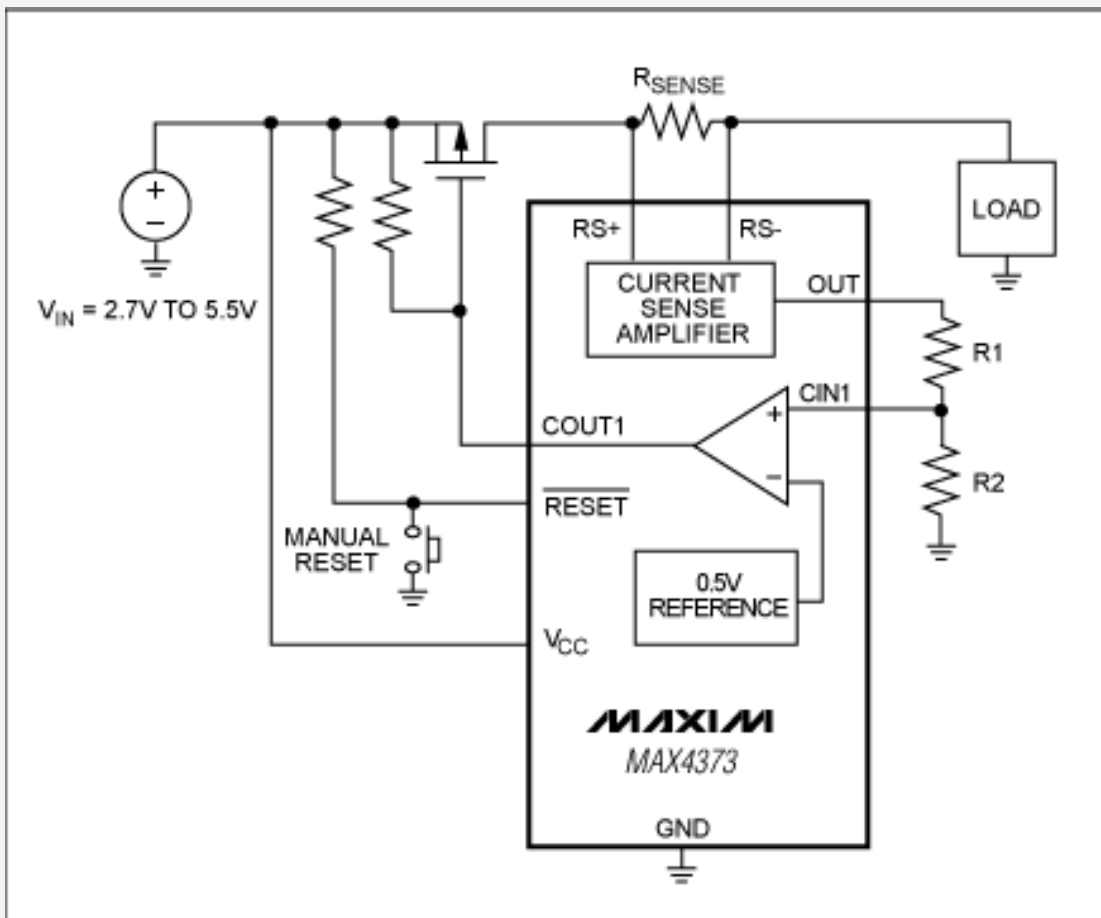


Figure 2a. When the IC detects an overload fault, its short-circuit protection circuit turns off the p-channel MOSFET and disconnects the load.

Battery chargers and other applications must guard against overcurrent from short circuits and undercurrent from open circuits. For this purpose, the current-window detector of **Figure 2b** is similar to the Figure 2a circuit, but includes a second comparator for monitoring undercurrent. The two comparator outputs are open-drain, and can therefore be 'wire-ORed' together or remain separate outputs. When the monitored current falls outside the window, the IC alerts the system by asserting a fault condition.

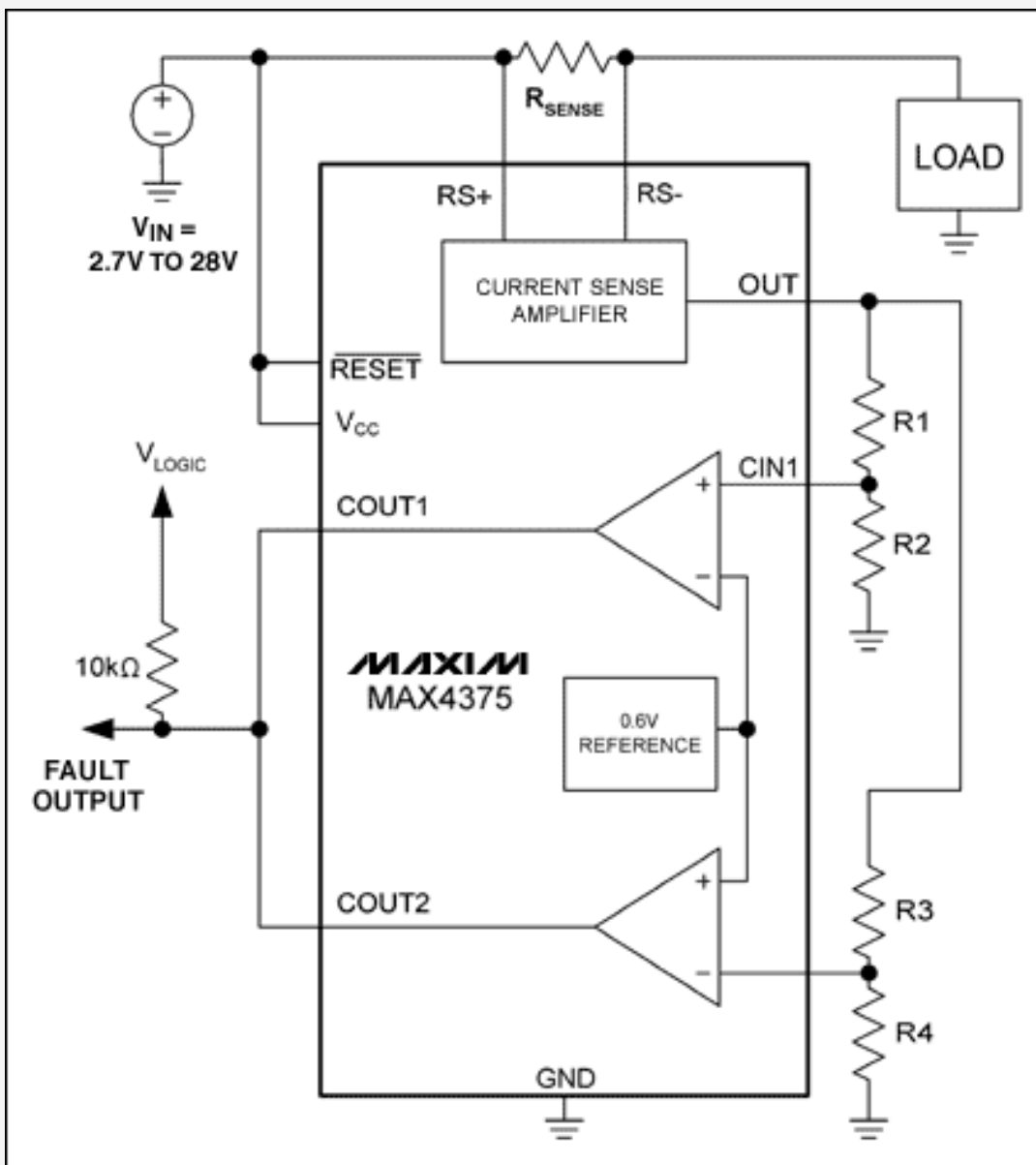


Figure 2b. A current-window circuit (comprising R1-R4, the comparators, and reference) detects open- and short-circuit faults.

Hot-Swap Controller

The hot-swap controller is a specialized and more sophisticated current sensor, intended for use with system cards such as the I/O cards on a server. It allows you to insert or remove a card while the system is running and without interrupting the system. Without a hot-swap controller, inserting or removing a card can short-circuit the system power supply and disrupt system operation. Without a hot-swap controller, furthermore, the on-board capacitors are charged very quickly when a card is inserted. The resulting in-rush current can temporarily pull the system supply voltage below the critical level.

The hot-swap controller (**Figure 3**) is designed to overcome these problems. It incorporates a soft-start capability to reduce the in-rush current to a safe level. When a fault occurs (overload or short circuit), the controller isolates the card from the rest of the system.

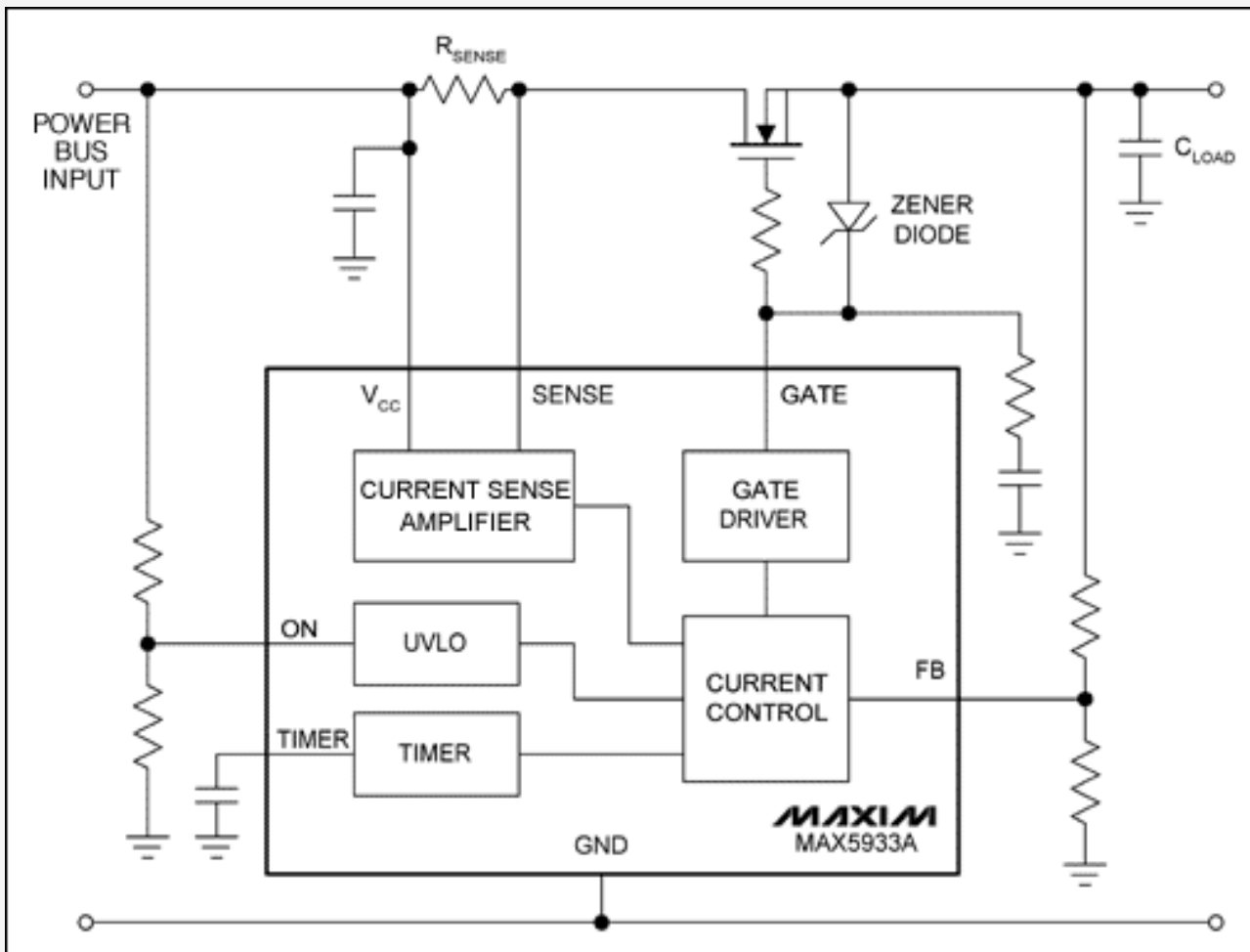


Figure 3. The MAX5933 hot-swap controller protects the power bus against in-rush current spikes and short-circuit faults.

As an example, hot-swap controllers of the [MAX5933A](#) family allow you to safely insert and remove circuit cards from a live backplane without causing glitches on the backplane power-supply rail. During startup the controller acts as a current regulator, using an external sense resistor and MOSFET to limit the amount of current drawn by the load. Internal circuitry slowly increases the monitored current, thereby avoiding a large inrush.

The sense resistor also sets the current limit. If the FB input senses a short circuit, the IC reduces (folds back) the current limit by a factor of 3.9. Using a 25mΩ sense resistor, for example, sets the normal operating current limit at 1.88A, but a short circuit suddenly reduces that limit to 480mA. Hot-swap controllers often include a timer that shuts off the MOSFET and protects the power bus when the current limit is not reduced within a given time period. Other hot-swap features include protections against undervoltage, overvoltage, and excessive temperature.

Fuel Gauges and Battery Management

The current-sensing amplifier shown in Figure 1 is a relatively simple and general-purpose device. Specific applications, such as fuel gauging and battery management, however, require that additional functions and features be integrated on-chip (**Figure 4**). Fuel gauging is important for battery applications, where battery capacity is monitored precisely to optimize system performance and prolong battery life.

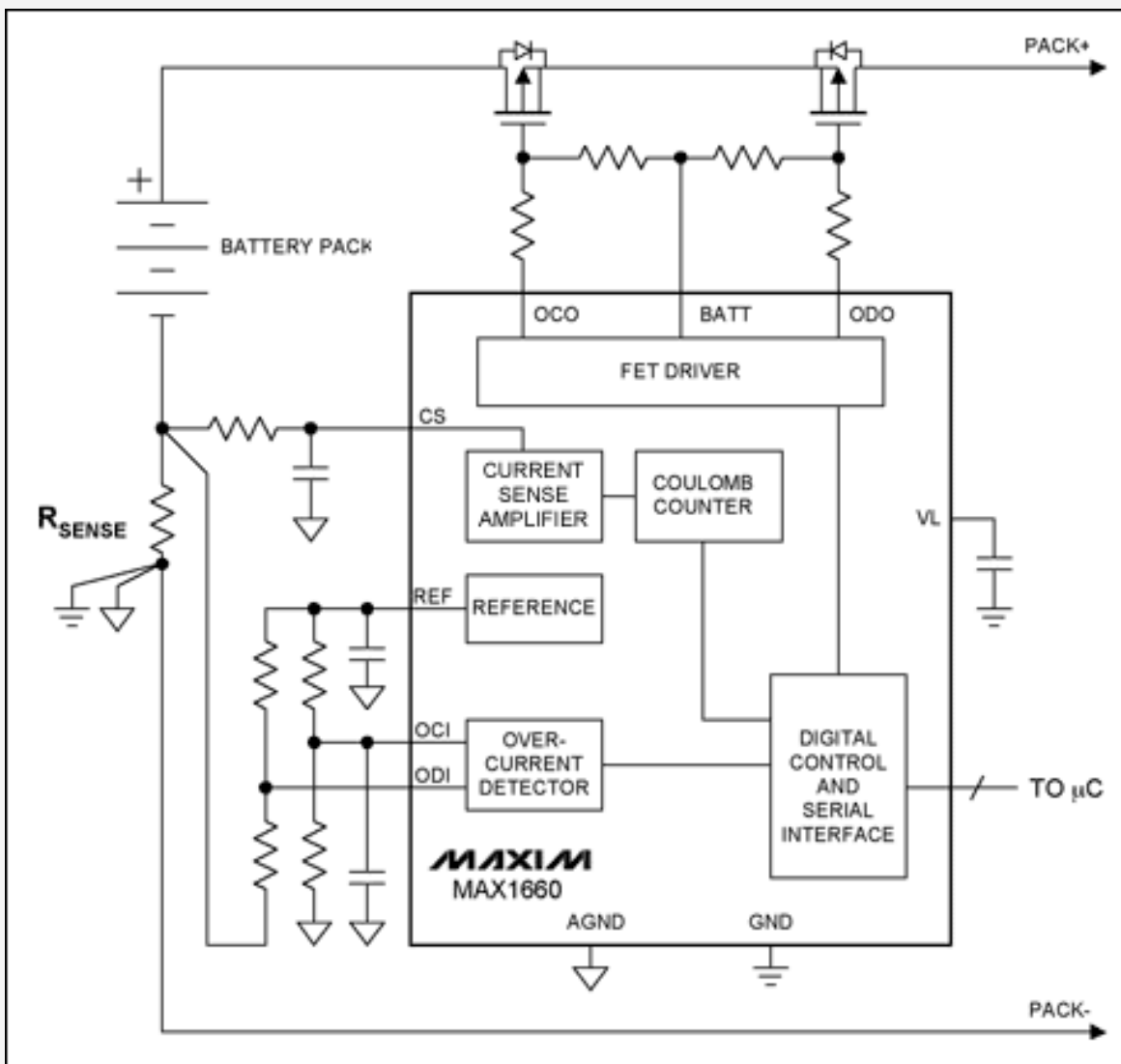


Figure 4. Fuel-gauging devices like the [MAX1660](#) track charge/discharge currents by monitoring the charges that flow in and out of the battery pack.

The battery pack in a laptop computer, for example, often integrates a 'smart' fuel gauge for monitoring and supervising the charging and discharging. Such gauging devices usually have a digital coulomb counter that tracks the accumulated charge and discharge actions. Thus, a given battery is fully charged when it accepts a certain amount of charge (in coulombs). Similarly, a battery is empty (discharged) when a given amount of charge is taken from it. Remember that one ampere of current equals one coulomb per second. Thus, the time integral of current equals the total charge. A current-sensing amplifier measures battery current, and the coulomb counter acts as a time integrator that accounts for the total charge flow during a charge or discharge cycle.

The current sensor for fuel-gauging applications requires a bidirectional current-measurement capability. When charging a given battery pack, the maximum charge is set by the user. When the coulomb counter reaches the set value, it alerts the microcontroller to stop charging because the battery is fully charged. Similarly, during discharge due to normal battery use, the gauge functions as a fuel gauge that informs the user how much battery capacity remains. When the coulomb counter reaches a set minimum limit, it prevents overdischarge by alerting the microcontroller that the battery is empty. Thus, the coulomb counter prolongs battery life by preventing excessive charging or discharging.

The current sensor also provides overload and short-circuit protection by continuously monitoring current flow. By shutting off the MOSFETs in response to a short circuit, the current-sense amplifier disconnects the battery to protect it from short-circuit faults.

Dynamic Power-Supply Controller

Power amplifiers (PAs) are routinely used in handset applications. Accurate control of the PA supply current maximizes battery usage and talk time. When the handset is near a base station and, therefore, does not require high transmitting power, you can reduce the PA supply current and still maintain a good transmitting signal. When the handset is far

away from the base station or too much interference is present, however, the transmitter requires high-output power and high supply current. Thus, dynamic adjustment of the PA supply current minimizes the power consumption while maximizing talk time.

Though similar to the current sensor in Figure 1, a PA current controller like the [MAX4473](#) (Figure 5) incorporates an error amplifier and operates in a closed loop. Its operation is like a current source. The error amplifier (A3) compares and integrates any voltage difference between the IR drops across R_{SENSE} and R_{G1} , and feeds that output to the gain control (GC) input of the power amplifier. A3 increases the gain and the PA output power, and consequently the supply current, until the two IR drops are equal. The voltage-to-current converter comprising A2, Q1, and R_{G3} controls the voltage drop across R_{G1} ; users control the PA supply current externally, with the PC input:

$$I_{CCPA} = \frac{V_{PC} \times R_{G1}}{4 \times R_{G3} \times R_{SENSE}} \quad \text{Eq. 4}$$

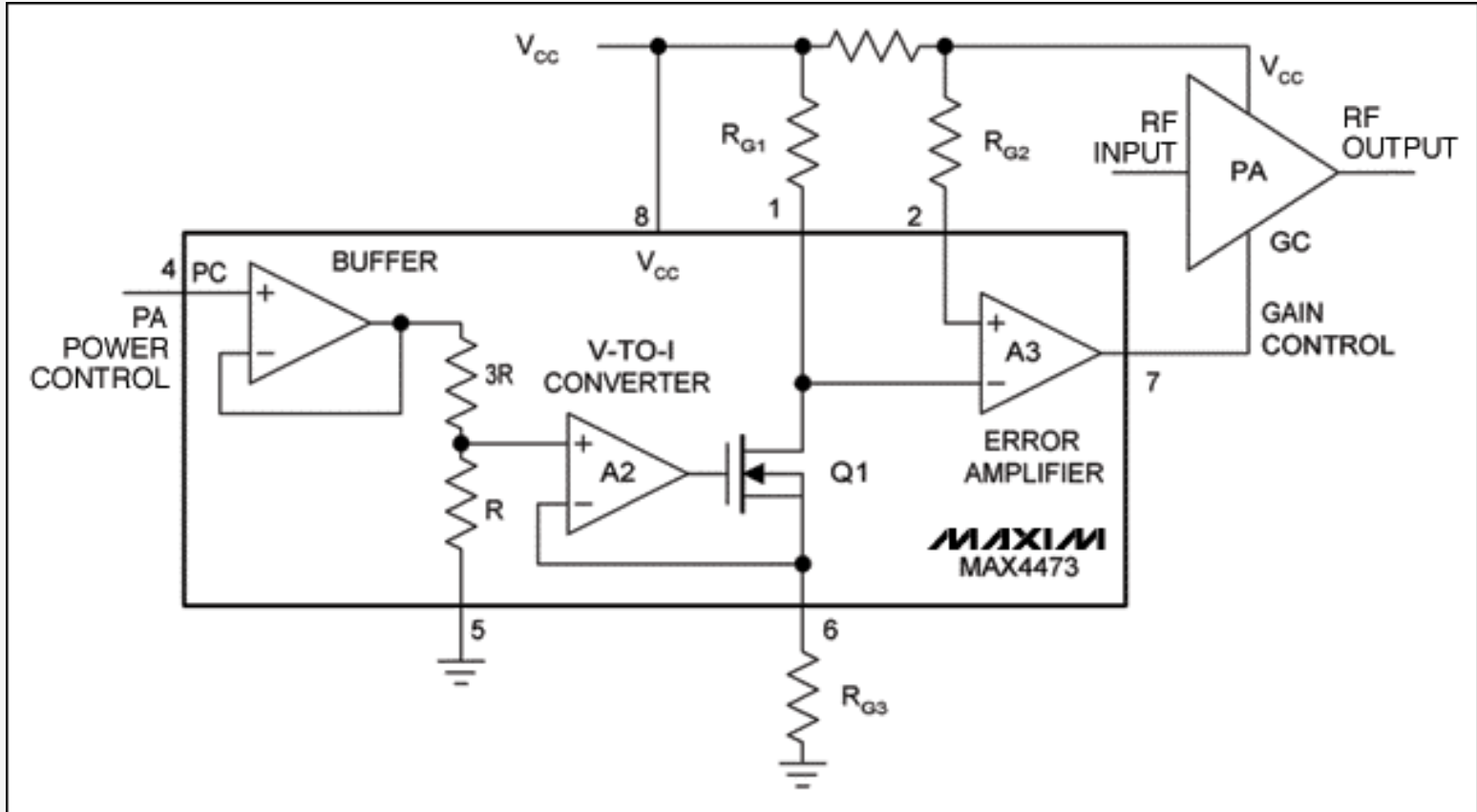


Figure 5. This current controller (MAX4473) dynamically adjusts the supply current to minimize power consumption while maintaining good signal integrity.

Advanced Power Sensing

For the battery in a notebook computer, whose terminal voltage varies as the battery discharges, power monitoring is safer than current monitoring and preferable to it. Power delivered to a load is defined as the load voltage multiplied by the load current. A power-monitoring integrated circuit must, therefore, include a current-sensing circuit with voltage output and an analog multiplier. The high-side current sensor provides an output voltage proportional to the load current. That voltage is multiplied by a fraction of the load voltage to obtain an output voltage proportional to load power.

The [MAX4210](#) power-monitor IC, for example, is designed to monitor the battery in a notebook computer. Its common-mode voltage range (4V to 28V) accommodates a variety of battery voltages. To measure current, you insert a sense resistor in the path between power source (battery) and load. The current-sense amplifier then feeds a voltage proportional to load current to one input of the analog multiplier. The other multiplier input connects to a voltage-divider connected to the load. (Load voltage must be reduced by a divider, because the multiplier's maximum input voltage is only 1.1V.) Multiplying these two voltages produces an output voltage proportional to load power. Like the current sensor, this analog multiplier is factory-trimmed to achieve good accuracy.

A solid-state, power-sensing circuit breaker (**Figure 6**), useful for protecting batteries from short circuits and overpower faults, blocks current to the load when it detects an overpower fault. When it detects a fault, the p-channel MOSFET (M1) turns off and stays off until you press the manual reset button or apply a logic-high to the CIN2- input. You can also reset the circuit breaker by cycling the input power, which causes the LE pin to go low and unlatch the comparator output OUT1. The RC network connected to the comparator (R3-R4-C1) prevents false transitions during the power-up voltage transient.

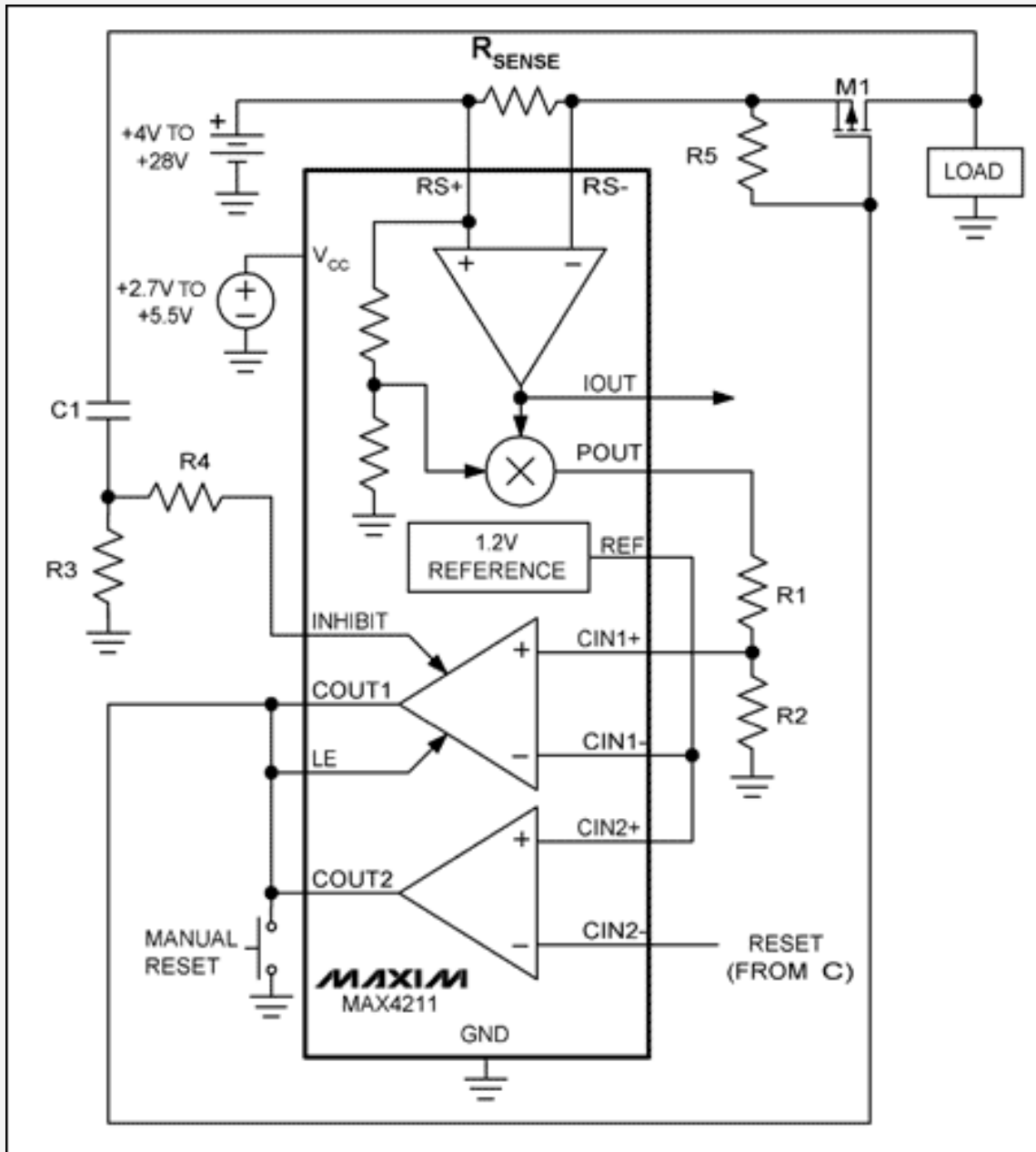


Figure 6. This solid-state, power-sensing circuit breaker shuts off current to the load in response to an overpower fault. Pressing the Manual Reset button or applying a logic-high to CIN2- resets the circuit breaker. If a voltage transient occurs during power-up, the INHIBIT input prevents false overpower alarms by temporarily suspending comparator COUT1.

Summary

Current sensors based on Ohm's Law are simple yet effective circuits for a variety of applications: power-supply protection, battery fuel gauging, and dynamic power supply control. Modern ICs integrate most of the components needed to implement a low-cost, high-performance, all-silicon current-sensing system. Factory-trimmed to better than 1% accuracy, such ICs improve system performance, reliability, and safety.

A similar article appeared in the August, 2005 edition of *Power Electronics Technology*.

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