4.5µA Li-Ion Battery Protection Circuit

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Li-Ion Battery Undervoltage Lockout

Figure 1 shows an ultralow power, precision undervoltage-lockout circuit. The circuit monitors the voltage of a Li-Ion battery and disconnects the load to protect the battery from deep discharge when the battery voltage drops below the lockout threshold. Storing a battery-powered product in a discharged state puts the battery at risk of being completely discharged. In a discharged condition, current to the protection circuitry continuously discharges the battery. If the battery is discharged below the recommended end-of-discharge voltage, overall battery performance degrades, the cycle life is shortened and the battery may die prematurely. In contrast, if the lockout voltage is set too high, maximum battery capacity is not realized.

The low-battery mode of operation is indicated when, for instance, a cell phone automatically powers down after the battery-low indicator has been flashing for some time. If the phone is misplaced in this condition and found months later, the protection circuitry shown in Figure 1 will not overdrain and damage the battery because the protection circuitry takes less than 4.5µA of current. At this low current, the time the Li-Ion battery takes to reach the end-of-discharge voltage is significantly extended. For other protection circuitry that typically requires higher current, the rate of discharge is faster, allowing the battery voltage to drop below the safe limit in a shorter time. Note that if the battery is allowed to discharge below the safe limit, unrecoverable capacity loss occurs.

The Micropower Voltage Reference and Op Amp

The LT1389 is not just another voltage reference. Its very low current consumption makes it the ideal choice for applications that require maximum battery life and excellent precision. It requires only 800nA of current and provides 0.05% initial voltage accuracy and 20ppm/°C maximum temperature drift, equating to 0.19% absolute accuracy over the commercial temperature range and 0.3% over the industrial temperature range. Operating at one-fifteenth the current required by typical references with comparable accuracy, the LT1389 is the lowest power voltage reference available today. The LT1389 precision shunt voltage reference is available in four fixed-voltage versions: 1.25V, 2.5V, 4.096V and 5.0V. It is available in the 8-lead SO package, in commercial and industrial temperature grades.

Low power (I_S < 1.5µA) and precision specifications make the LT1495 rail-to-rail input/output op amp the perfect companion to the LT1389. The extremely low supply current is combined with excellent amplifier specifications: input offset voltage is 375µV maximum with a typical drift of only 0.4µV/°C, input offset current is 100pA maximum and input bias current is 1nA maximum. The device characteristics change little over the supply range of 2.2V to ±15V. The low bias currents and offset current of the amplifier permit the use of megohm-level source resistors without introducing significant errors. The LT1495 is available in plastic 8-pin PDIP and SO-8 packages with the standard dual op amp pinout.

Consuming virtually no current, the LT1389 and the LT1495 are ideal choices for the UVLO circuit and many other battery applications.

Circuit Operation

The circuit is set up for a single-cell Li-Ion battery, where the lockout voltage—the voltage when the protection circuit disconnects the load from the battery— is 3.0V. This voltage, set by the ratio of R1 and R2, is sensed at node A. When the battery voltage drops below 3.0V, node A falls below the threshold at node B, which is defined as:

$$V_B = 1.25V + I \cdot R4 = 1.37V$$
where
$$I = (V_t - 1.25V)/(R3 + R4) = 800nA$$
$$V_t = \text{lockout voltage}$$

The output of U1 will then swing high, turning off SW1 and disconnecting the load from the battery. However, once the load is removed, the battery voltage rebounds and will cause node A to rise above the reference voltage. The output of U1 will then switch low, reconnecting the load to the battery and causing the battery voltage to drop below 3.0V again. The cycle repeats itself and oscillation occurs.

To avoid this condition, R5 is added to provide some hysteresis around the trip point. When the output of U1 swings high to shut off SW1, node B is bumped up 42mV above node A, preventing oscillation around the trip
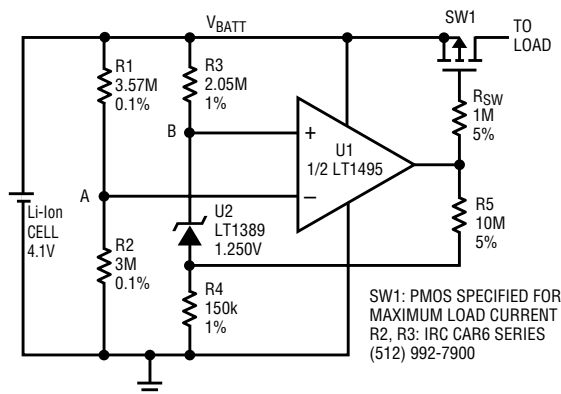

Figure 1. Undervoltage lockout circuit

point. Using the formula below, the amount of hysteresis for the circuit is calculated to be 92mV. Hence, V_{BATT} must climb back above 3.092V before the battery is connected.

Hysteresis = $V_B' \cdot R1/R2 + V_B - V_t$
where
$V_B' = (V_{OMAX} - I \cdot R4) \cdot R4/R5 + V_{REF} + I \cdot R4$
V_t = lockout voltage
V_{OMAX} = maximum output swing (high) of U1 at V_{BATT} is equal to the lockout voltage

Consult the battery manufacturer regarding the maximum ESR at maximum recommended discharge current. Multiply the two values to get the minimum hysteresis required.

Being Precise

The worst-case voltage-monitor accuracy is better than 0.4%. Interestingly, the battery's longevity and capacity are directly related to the depth of discharge. More cycles can be obtained by partially rather than fully discharging the Li-Ion battery, and, conversely, more use time can be obtained by fully discharging a Li-Ion battery. Cutting off the load at the perfect end-of-discharge voltage would ideally result in the best of both cases. To perform this task requires an accurate overall system. For example, if the optimum lockout voltage is to be set at 3.1V, a 5% overall accurate system would yield

Figure 2. V_{BATT} vs V_A with hysteresis

±155mV, cutting off at either at 2.945V or at 3.255V. At a lockout voltage of 3.255V, maximum capacity is not obtained. In addition, the operating range is reduced, with the fully charged battery voltage being 4.1V. For a 0.4% overall accurate system, the lockout voltage would be at 3.088V or at 3.112V, more than twelve times better accuracy and optimally achieving the highest capacity. Furthermore, the load is kept disconnected with only 4.5µA to the protection circuit. Thus, the protection circuit works by preventing deep discharge of the battery.

Conclusion

There need not be a trade-off between performance and current consumption. The LT1389 nanopower precision shunt voltage reference and the LT1495 1.5µA precision rail-to-rail input/output op amp deliver the 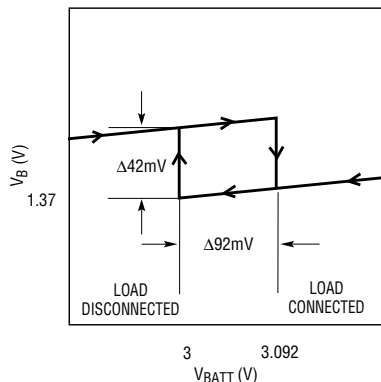highest performance with virtually zero current consumption. ⎍⎍