



Application Note 30

MIC2179 Lithium-Ion Battery Charger

by Jeff Dixon

Introduction

The Micrel MIC2179 is a current-mode, 200kHz, synchronous, buck (step-down) regulator. In this application, the MIC2179 is configured to provide both constant-current and constant-voltage for a 2-cell lithium battery charger. The current is sensed on the high side to avoid ground-bounce noise and the associated problems usually found in ground referenced circuits. Voltage is sensed using a simple voltage controller to reduce the parts count and provide a 0.5% voltage tolerance. The MIC2179 operates from a 4.5V to 16.5V input and has the following value-added features: dual-mode (skip-mode, PWM-mode) operation for high efficiency (up to 96%), low quiescent current (1.0mA in PWM mode, 600µA in skip mode), internal current limit, thermal shutdown, undervoltage lockout (4.35V), low dropout (100% duty cycle) and simplified loop compensation (current-mode control).

Lithium-Ion Charge States

The three charge states for a lithium-ion battery are trickle charge, bulk-charge, and overcharge. Starting with a fully discharged battery, a lithium battery charger needs to change modes sequentially through these different charge states.

Trickle charge—a constant-current mode used to bring a battery up to the cutoff voltage (V_{CUTOFF}). The battery could be in deep discharge (2.5V to 2.7V per cell) for many reasons such as low state of charge, low ambient temperature, shorted cells, or high internal leakage. Also, to maintain full charge.

Bulkcharge—occurs while in constant-current mode and the charger is delivering the maximum allowable current to the battery (see manufacture's specification). This method replaces a majority of the battery's charge as quickly as possible until the overcharge voltage threshold is reached.

Overcharge—is a constant-voltage mode function that occurs consecutively after bulk charge. As the Li-ion battery nears full capacity, the current decreases, and the battery's terminal voltage increases until 4.2V per cell is reached. When the current becomes low enough, less than trickle-charge normally, the charging cycle is complete. Li-ion cells should not be float charged. After the charge cycle is complete, the charger should be shut down.

Theory of Operation

The lithium-ion battery charger can be divided in to four blocks: a constant-current source, constant-voltage source, a switching regulator and an end-of-charge circuit.

Constant-Current Block

To analyze this block, assume the constant-voltage block (U3 and supporting circuitry) are inactive. Starting with a dis-

charged battery connected to the charger, the circuit acts like a constant-current source. An MIC2179 synchronous buck regulator provides the regulated power. The constant-current source's feedback loop consists of R7 (current-sense resistor), U2 (MIC6211 op amp), Q3 (VN2222 N-channel MOSFET), and the internal 1.24V reference of U1 (MIC2179 synchronous buck regulator).

First, the lithium-ion battery charger starts up in trickle-charge mode. In trickle mode, the output of U2 (MIC6211) is on, biasing Q2 on, allowing the output of the MIC2179 to source 157mA of charging current to the battery. The intelligent system or microprocessor senses the low logic level at the output of U4 and places the charger into the bulk-mode charging state (1.5A). Sequencing from trickle mode to bulk mode is accomplished by applying a logic high on Q2's gate. In bulk-mode, current ramps up to 1.50A (for a 2-cell lithium application) through sense-resistor R7 (100mΩ) creating a 157mV drop.

Initially, the inverting input of U2 is lower than the noninverting input causing the output to go higher, increasing drive to Q3. This increases the current through the parallel combination of R3 and R4 until 1.24V is developed across them. The MIC2179 feedback pin senses the 1.24V and compares it to the internal 1.24V bandgap reference and reduces output duty cycle until 157mV is maintained across resistor R7. Finally, there is 157mV at both inputs of the MIC6211 (op amp), completing the negative feedback loop.

Trickle charge and bulk charge is calculated using:

$$\text{Trickle Charge Current} = \left(\frac{1.24V}{R3} \right) \left(\frac{R5}{R7} \right) = 157\text{mA}$$

$$\text{Bulk Charge Current} = \left(\frac{1.24V}{R3 \parallel R4} \right) \left(\frac{R5}{R7} \right) = 1.55A$$

Constant-Voltage Source

Once the battery's terminal reaches the 8.4V (2-cell lithium-ion battery overcharge threshold), the constant-current source circuit is biased off. As the output voltage of the charger tries to go higher than 8.4V, the output of U3 (open-emitter configuration) biases D3 on. The feedback pin of the MIC2179 is now pulled-up toward the 8.4V V_{OUT} rail, reducing duty cycle and maintaining output voltage regulation. The constant voltage feedback loop consists of U3 (LM3420A), D3, U1 (MIC2179), L1, R7, D2, and Q4.

Because overvoltage conditions greatly reduce the life span of a lithium battery, an LM3420A was chosen for the voltage feedback loop to help maintain terminal voltage to 0.5%.

In this charger design when the input supply is disconnected, diode D2 is reverse biased to prevent battery discharge. Q4

is bifunctional: it prevents the battery from being discharged when the input supply is removed; and it alleviates a race condition between the LM3420 and the start-up of the MIC2179 switching regulator. The LM3420 must be on before the output of the MIC2179 comes up.

End-of-Charge Circuit

The end-of-charge circuit is used to signal the microprocessor or another subsystem when the lithium-ion battery pack has reached the overcharge threshold. Again, in this 2-cell lithium-ion application, the overcharge threshold is 8.4V.

Starting with a discharged battery and the charger in bulk-charge mode, the constant-current is decreasing and the voltage across the battery is increasing over time. The change in current versus voltage is a function of the changing internal impedance of the lithium-ion battery under charge.

U5 is being used as a differential amplifier to monitor the output current by sensing the I-R drop across sense resistor R7. The gain of U5 is set to 82.5. The gain of U5 is set to maintain greater than 1.24V at its output down to a I_{OUT} of greater than 157mA. U4 compares the output of U5 against the 1.24V bandgap reference on its noninverting pin generated by the internal bandgap reference of MIC2179. In bulk-charge mode, the output of U5 is always higher than U4's reference voltage, thus maintaining a logic level low at the end-of-charge pin.

Once R7 has less than a 15mV drop across it, the output of U5 can no longer sustain greater than 1.24V at its output. Now U4 has 1.24V on both its inputs.

Next, the I_{OUT} drawn by the battery reduces even further due to charging. Now the voltage at U4's inverting pin is lower than the 1.24V reference producing a logic level high at the output of U4, signaling an end-of-charge.

The present industry-standard variable used to determine lithium-ion battery end-of-charge is the current draw at about 90% charge (see Figure 3). The end-of-charge current is typically about C/10. A simple countdown timer circuit (not shown) is usually started upon reaching the end-of-charge state. Based on the individual manufacture specification, this completes the charge cycle.

End-of-charge output current is calculated using a 1.24V reference:

$$\text{End-of-Charge Threshold} \leq (I_{\text{OUT}} \times R7) \frac{R9}{R6} = 1.24V$$

1.24V is the reference for U4 pin 3 which is the end-of-charge comparator.

Note: This circuit uses 157mA as an end-of-charge threshold. At the end of charge, the charging circuit should be shut down. It is not recommended to float charge Li-ion cells for long periods of time.

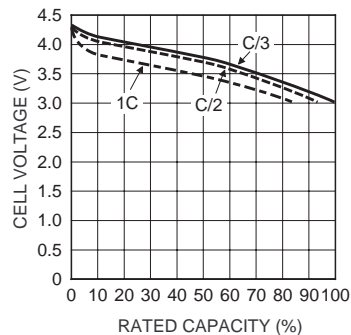


Figure 1. Typical Li-Ion Voltage vs. Capacity for C1-C3 Rates²

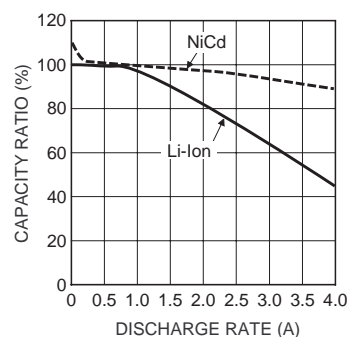


Figure 2. Typical Li-Ion and NiCad Capacity vs. Discharge Rate²

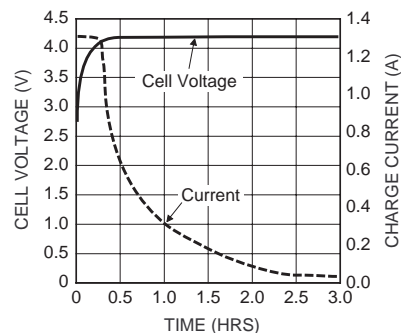


Figure 3. Typical Lithium Cell Voltage vs. Charging Current²

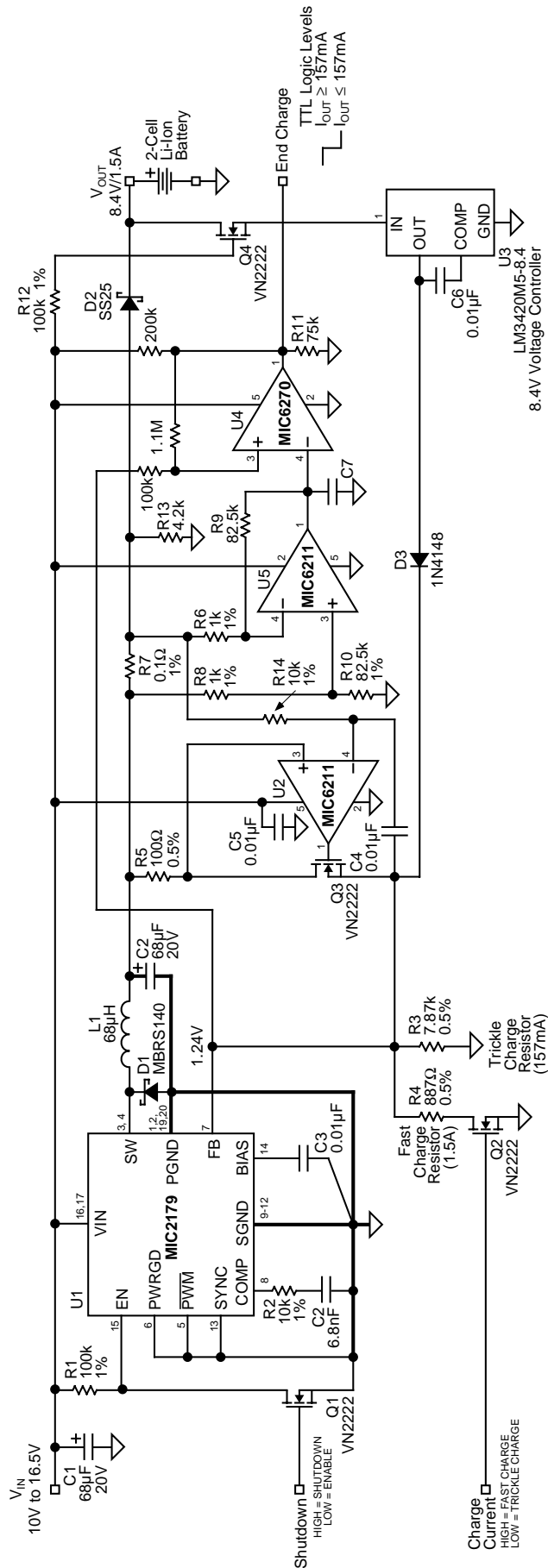


Figure 4. 2-Cell Lithium-Ion Battery Charger Utilizing the MIC2179 Synchronous Buck Regulator

Lithium-Ion Battery Charging Terms¹

Ampere-hours—product of current in amperes multiplied by time current is flowing through the battery.

Capacity—a designation by the battery manufacturer which helps identify a particular cell model and also provides an approximation of capacity. Manufacturers typically define capacity in terms of C/10 as a standard value when specifying capacity.

C rate—discharge or charge rate in amperes typically expressed in terms of capacity. Example: a 5.0Ah cell can sustain 500mA discharge rate for 10 hours. This example used a C rate of C/10.

Self-discharge rate—the spontaneous decomposition of the internal chemicals of the battery causes the battery to discharge at some manufacturer's specified rate when not in use. Determines shelf life.

Deep discharge—when a battery is discharged below the manufacturer's recommended cutoff voltage. Lithium-ion ranges from 2.7V discharged, 3.6V nominal, to 4.2V per cell when fully charged. For example, if a lithium-ion battery has a voltage between 2.5V and 2.7V, the cell is considered to be in a deeply discharged state.

Constant-voltage charger—a charging circuit used to maintain a regulated voltage across a battery but allows the current to vary depending upon the battery's state of charge.

Constant-current charger—a charging circuit used to maintain a regulated current to a battery's but allows the voltage to vary depending upon the battery's state of charge.

Trickle charge—a constant-current source used to slowly bring a battery up to its recommended cutoff voltage (lithium-ion 2.7V per cell) or to maintain full charge (4.2V per cell). In a typical trickle-charger lithium-ion battery application, a current of between C/50 to C/10 is used to maintain the cell(s).

References

1. *Battery Reference Book*, second edition (Terms)
2. *Typical Lithium-Ion Battery Curves/Charts*, Toshiba Battery Corporation

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