

"Developing Affordable Mixed-Signal Power Systems for Battery Charger Applications"

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INTRODUCTION

As battery-powered electronic devices continue to become more common and more powerful, easily adaptable battery charger designs are needed. Using standard components, battery charger designs can be made simultaneously more flexible and more cost-effective. Mixed-signal designs simplify the addition of new, unique features to the system, and they allow the addition of differentiating features.

BATTERY CHEMISTRIES

Many different battery chemistries are used for rechargeable portable applications, including Lithium-Ion (Li-Ion), Nickel Metal Hydride (NiMH), Nickel Cadmium (NiCd), and Lead Acid batteries. This article will focus on two of the more popular chemistries, Li-Ion and NiMH, although the topics discussed apply to the other chemistries, as well.

Li-Ion batteries have the highest energy density of all battery types, making them the most portable of all rechargeable technologies. NiMH batteries are popular because they are safe and environmentally friendly. It is possible to design a mixed-signal, universal battery charger to charge both of these battery chemistries.

BATTERY CHARGING TERMINOLOGY

The rate of charge or discharge is expressed in relation to battery capacity. Known as the "C-Rate," this rate of charge equates to a charge or discharge current, and is defined as:

$$I = M \times C_n$$

Where:

I = charge or discharge current, A

M = multiple or fraction of C

C = numerical value of rated capacity, Ah

n = time in hours at which C is declared.

A battery discharging at a C-rate of 1 delivers its nominal rated capacity in one hour. For example, if the rated capacity is 1000mAh, a discharge rate of 1C corresponds to a discharge current of 1000mA. Similarly, a rate of C/10 corresponds to a discharge current of 100mA.

PREFERRED CHARGE PROFILE (Li-Ion and NiMH)

Li-Ion battery chemistries utilize a constant, or controlled, current and constant voltage algorithm that can be broken-up into four stages: (1) trickle charge, (2) constant current charge, (3) constant voltage charge and (4) charge termination. Figure 1 illustrates these four stages of Li-Ion battery charging.

The preferred algorithm for NiMH consists of the following stages: (1) trickle charge, (2) constant current, (3) top-off charge and (4) charge termination. Figure 2 illustrates these four stages of NiMH battery charging.

Stage 1: Trickle Charge -- Trickle charge restores charge to deeply depleted cells. For Li-Ion batteries, when the cell voltage is below approximately 3V, the cell charges with a constant current of 0.1C maximum. For NiMH batteries, trickle charge conditions weak batteries, when the cell voltage is greater than 0.9V per cell “fast” charge, or constant current charge can begin.

Stage 2: Constant Current Charge – For Li-Ion and NiMH batteries, after the cell voltage has risen above the trickle charge threshold, the charge current increases in order to perform constant current charging. The constant current charge should be in the 0.2C to 1.0C range.

Stage 3: Constant Voltage – For Li-Ion batteries only, constant current charge ends and the constant voltage stage begins when the cell voltage reaches 4.2V. In order to maximize performance, the voltage regulation tolerance should be better than $\pm 1\%$.

Stage 4: Charge Termination – For Li-Ion batteries, the continuation of trickle charging is not recommended. Instead, charge termination is a good option. For NiMH batteries, a timed trickle charge ensures 100% of battery capacity use. When the timed trickle charge is complete, charge termination is then necessary.

For Li-Ion batteries, one of two methods -- minimum charge current, or a timer (or a combination of the two), typically terminates charging. The minimum charge current approach monitors the charge current during the constant voltage stage and terminates the charge when the charge current diminishes in the range of 0.02C to 0.07C. The timer method determines when the constant voltage stage begins. Charging then continues for two hours, and then the charge terminates.

Charging in this manner replenishes a deeply depleted battery in roughly 2.5 to 3 hours.

Advanced chargers employ additional safety features. For example, with many advanced chargers, the charge stops if battery temperature is less than 0°C or greater than 45°C.

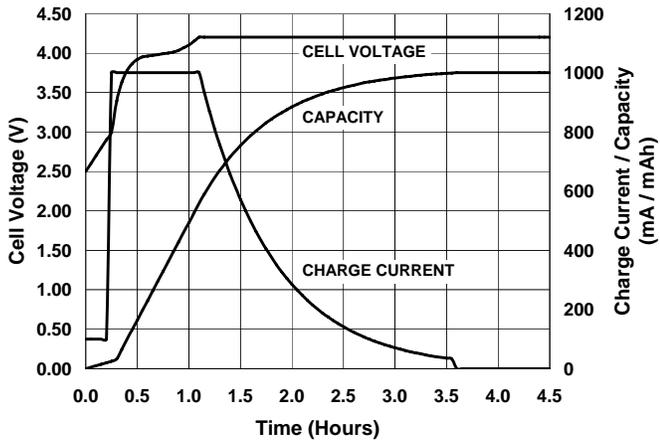


Figure 1: Li-Ion Charge Profile

For NiMH batteries, charge termination is based on a $-dV/dt$ reading of the battery pack, a $+dT/dt$ (delta temperature versus time), or a combination of both. In this case, temperature sensing is a possible safety precaution, as well as a termination method.

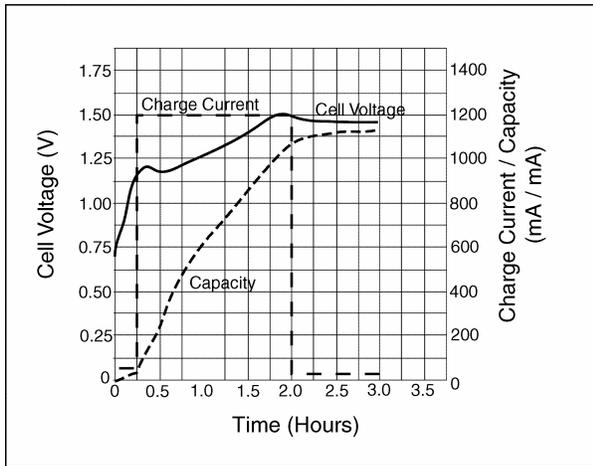


Figure 2: NiMH Charge Profile

BATTERY CHARGING -- SYSTEM CONSIDERATIONS

To recharge any battery quickly and reliably, a high-performance charging system is required. The following system parameters ensure a reliable, cost-effective solution:

1. Input Source

Many applications use very inexpensive wall cubes for the input supply. Output voltage is highly dependent on the wide-ranging ac input voltage, as well as the load current drawn from the wall cube.

Applications that charge from a car adapter can experience a similar problem. The output voltage of a car adapter will typically have a range of 9V to 18V.

2. Output Voltage Regulation Accuracy

For Li-Ion batteries, output voltage regulation accuracy is critical to maximizing battery capacity usage. A SMALL decrease in output voltage accuracy results in a LARGE decrease in capacity. However, the output voltage cannot be set arbitrarily high because of safety and reliability concerns. Figure 3 depicts the importance of output voltage regulation accuracy.

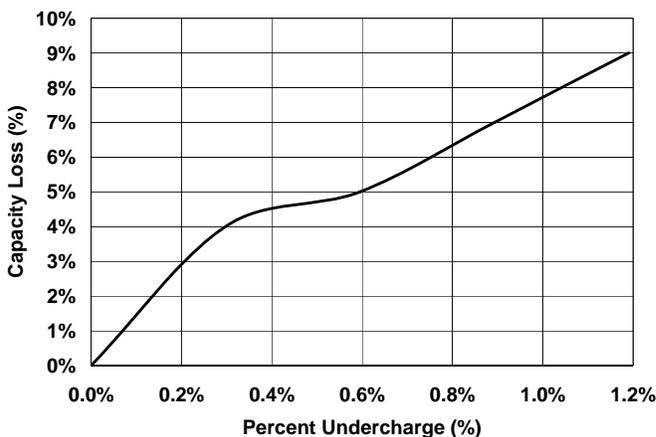


Figure 3: Capacity Loss vs. Undercharge Voltage

3. Charge Termination Method

Over-charging is the Achilles' heel of Li-Ion and NiMH cells. Accurate charge termination methods are essential for a safe and reliable charging system.

4. Cell Temperature Monitoring

The temperature range over which a rechargeable battery should be charged is typically 0°C to 45°C. Charging the battery at temperatures outside of this range may cause the battery to overheat. During a charge cycle, pressure inside the battery increases, causing it to swell. As temperature and pressure are directly related, the combination of high temperature and high pressure inside the battery can lead to mechanical breakdown or venting inside the battery. Charging the battery outside of the 0°C to 45°C temperature range may also harm battery performance, or reduce its life-expectance.

5. “Battery Discharge Current” or “Reverse Leakage Current”

In many applications, the charging system remains connected to the battery, even in the absence of input power. The charging system minimizes current drain from the battery when input power is not present. Maximum current drain should be less than a few microamperes and, ideally, below one microampere.

DESIGNING BATTERY CHARGERS

Given the aforementioned system considerations, an appropriate charge management system can be developed.

Linear Solutions

Linear charging solutions are employed when a well-regulated input source is available. An example of a linear charging solution is Microchip Technology’s MCP738xx Linear Battery Charger family. Linear solutions, in these applications, offer advantages such as ease-of-use, size, and cost.

Switch Mode Charging Solutions

For a wide input voltage range, such as the unregulated ac-dc wall cube or the automotive dc input, switching regulators lower the internal battery charger power dissipation to an acceptable level.

Selecting Topology

Switching regulator topology defines the organization of the regulator’s switches and passive filtering components. This difference in organization distinguishes topologies, offering a trade-off between complexity, efficiency, noise, and output voltage range. Many converter topologies exist, while only a few are popular to battery chargers in the 5-Watt to 50-Watt range.

Buck Regulator

The buck or “step-down” regulator is one popular topology for battery charging applications. The buck regulator, like other solutions, has the following advantages and disadvantages:

Advantages

- 1) Low complexity, single inductor topology.
- 2) For Synchronous applications, conversion efficiency can reach 90%.

Disadvantages

- 1) The buck regulator MOSFET switch integral body diode creates a path to discharge the battery when input voltage is not present. An additional blocking diode is therefore necessary, adding an additional component and, hence, voltage drop to the system.
- 2) Buck regulator input current is pulsed or “chopped.” This topology generates high electromagnetic interference (EMI) at the input of the power supply. Most buck regulators require additional input EMI filtering.

- 3) The buck regulator can only regulate output voltages that are lower than the input voltage. Some applications have a wide input voltage range that spans the necessary output voltage range. This is more common for multiple cell Li-Ion charger applications.
- 4) A single fault mode (buck switch short) creates a short circuit from input to battery. For NiMH applications where there is no internal battery protection, this poses a safety concern.
- 5) The buck regulator requires a high side drive (for N-Channel MOSFET switches). This is more complex when compared to low-side topologies.
- 6) External switch current sensing in pulse width modulation (PWM) controller applications is complex. Limiting switch current is important for fault modes such as shorted batteries or load. Without a high-speed switch current limit, the battery charger can be destroyed during a shorted condition.

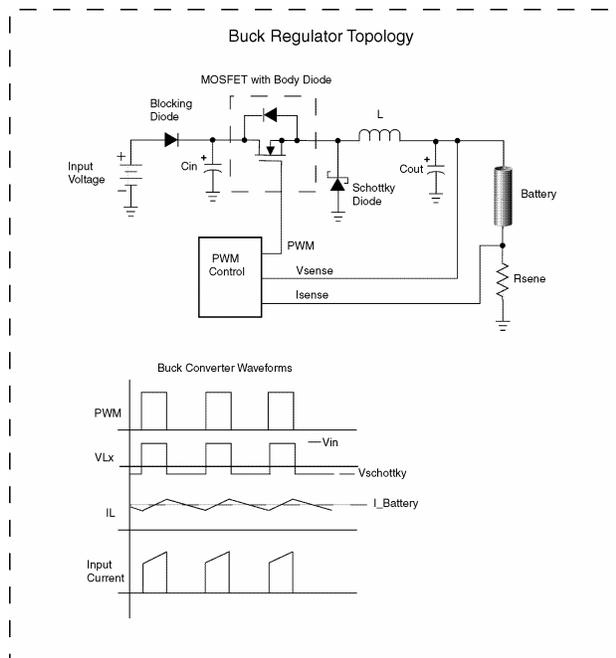


Figure 4: Buck Regulator Topology

SEPIC (Single-Ended Primary Inductive) Regulator

The SEPIC regulator is also a popular topology used for battery charging applications. SEPIC regulators have advantages over buck regulators and other topologies, and a few disadvantages.

Advantages

- 1) The blocking diode is built-in to the battery system topology, so no additional components or losses occur.
- 2) The input current pulled from the source is continuous (smooth) when compared to the “choppy” input currents of buck regulators.
- 3) Input to output is isolated, protecting the load or battery from a switch short.

- 4) The SEPIC regulator topology has step-down or step-up (buck-boost) capabilities.
- 5) The SEPIC switch is low side, simplifying the gate drive and current sensing in the switch.
- 6) The secondary side average inductor current is equal to battery current, enabling the sensing of current not in series with the low side of the battery.

Disadvantages

- 1) Requires two inductors or a “coupled” inductor.
- 2) Requires a single coupling capacitor, which can be expensive for high power (> 50 Watts, or high voltage ($V_{IN} > 100V$) applications.

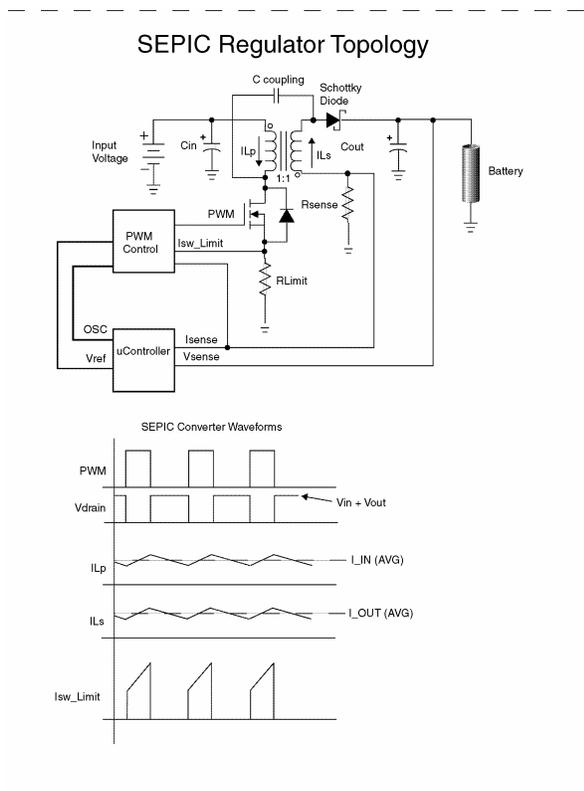


Figure 5: SEPIC Regulator Topology

SWITCHING BATTERY CHARGER DESIGN

By partitioning the design into two parts, it is possible to develop affordable, “intelligent” power systems. Battery chargers are, by nature, mixed-signal systems. For example, the power train (in this case, the SEPIC regulator) is analog. Turning the power switch on and off at high frequency requires some type of analog driver circuit. On the other hand, charge termination timers, fault management, and on/off control are typically digital functions that use timers and programmable capability.

BATTERY CHARGER SPECIFICATIONS

| | |
|------------------------------|---|
| Input Voltage | 6V to 20V |
| Output Voltage | 0V to 4.2V for single cell, 0V to 8.4V for two cell |
| Preconditioning Current | 200 mA |
| Preconditioning Threshold | 3V |
| Constant Current Charge | 2A |
| Charge Termination Threshold | 100 mA (current at which charge cycle is completed) |

Features:

Over-Voltage Protection (Battery Removal)

Over-Current Protection (Battery or Load Shorted)

Sense Battery Temperature for Charge Qualification

STRATEGY

Using a two-part approach to the mixed-signal design, first select a microcontroller that is capable of reading the state of the battery pack (voltage and temperature) and programming the SEPIC regulator output current. For our example, we will use the PIC[®] PIC12F683 8-pin Flash microcontroller.

Next, add a high-speed, analog PWM with a built-in MOSFET driver such as the MCP1630 to develop the “analog” programmable current source.

DESIGNING A SEPIC-PROGRAMMABLE CURRENT SOURCE

As with all switching regulator designs, the output is controlled by varying either the duty cycle, or the percentage of switch on-time (Q1, Figure 6). To regulate current going into the battery, charge current must be sensed. As shown in Figure 6, there is no sense element in series with the battery. The SEPIC regulator secondary winding, L_s , carries the average output current. The primary winding, L_p , carries the average input current. Secondary resistor R_s senses battery charge current. The high-speed, analog PWM reference input programs the desired battery charge current.

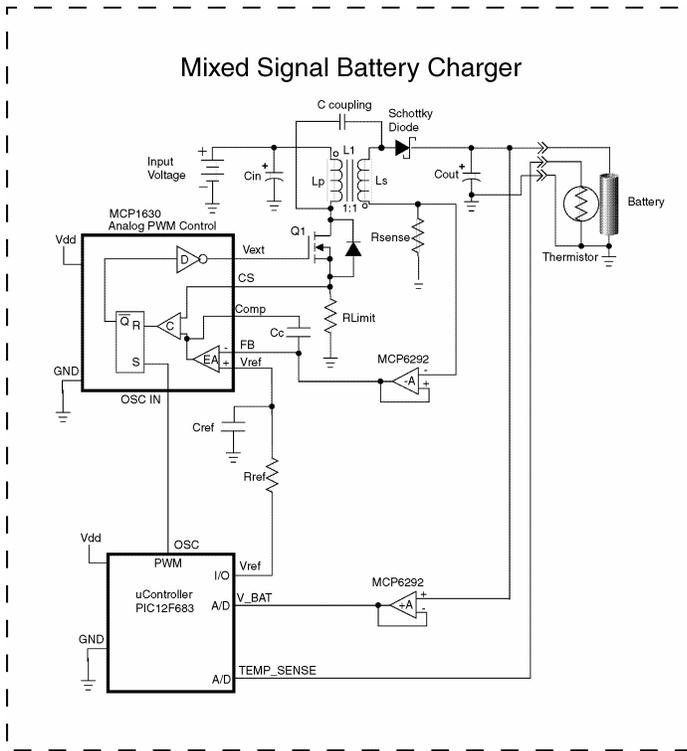


Figure 6: Mixed Signal Battery Charger Block Diagram

MIXED-SIGNAL DESIGN

By using the MCP1630 as an analog PWM and driver, a “programmable” SEPIC current source is achieved. The PWM and driver provide the analog current regulation, MOSFET gate drive, and high speed over current protection. The PIC12F683 microcontroller sets the SEPIC power train switching frequency (500 kHz) and programs the SEPIC constant current.

The PWM and driver utilize the microcontroller hardware PWM to set the SEPIC switching frequency and maximum duty-cycle. The hardware PWM frequency is equal to the SEPIC power train switching frequency, while the hardware PWM duty cycle sets the maximum SEPIC power train duty cycle. A 500 kHz pulse with a 25% duty cycle out of the microcontroller hardware PWM sets the SEPIC switching frequency to 500 kHz with a maximum duty cycle of 75%. A standard microcontroller I/O pin generates a software-programmable reference voltage using a simple R, C filter. This programmable reference programs the constant current SEPIC converter to a precise charge current.

At the non-inverting input (Vref), the programmable reference voltage sets the amount of battery charge current. The MCP1630 PWM output duty cycle (Vext) adjusts until the voltage at the Vref input is equal to the voltage at the FB input of the error amplifier. By adjusting the voltage at the Vref input, the battery current adjusts accordingly.

The PWM and driver are capable of driving the MOSFET at frequencies greater than 500 kHz, while monitoring the SEPIC switch current using an internal high-speed (12 ns typical) comparator. If the switch current is too high, the PWM duty-cycle will terminate, limiting the battery current.

Finally, the charge current is adjusted based on information such as battery voltage and temperature, received from an analog-to-digital converter (ADC).

To develop a constant voltage charge phase, the microcontroller A/D converter reads the battery voltage and updates the programmable current source (SEPIC) to maintain the battery voltage at 4.2V. This occurs at a rate much faster than the rate at which the battery voltage changes when subject to a constant current.

For Li-Ion applications, the charge cycle terminates when the current necessary to maintain the battery voltage at a fixed 4.2V reduces to some percentage of the battery C-rate (100 mA). This is set using firmware and is easily changed for different battery manufacturers' recommendations. In a typical analog charger, this termination charge current is a percentage of the charge cycle current, so that it cannot easily be changed.

For NiMH applications, the fast charge cycle terminates when one or both of two conditions occur -- either the battery voltage remains constant or drops with time, or the battery pack temperature rise is higher than a predetermined value. When fast charge terminates, a slow, timed trickle charge can begin.

The development of cost-effective, "intelligent" power systems is possible by combining an analog PWM and driver with a standard microcontroller.

An ADC input and battery pack thermistor together sense battery temperature. By reading the voltage at the "TEMP_SENSE" input, battery temperature can be determined.

The interruption of the PIC12F683 code when the sensed battery voltage is too high achieves over voltage protection (OV). The SEPIC converter shuts down in less than 1 us, with minimal voltage overshoot occurring at the battery terminals.

The SEPIC converter diode prevents any path for battery discharge back to the system charger. The only quiescent current draw on the battery is from a battery voltage-sensing path, typically less than 5 uA.

OPTIONAL FEATURES

In addition, the use of a single microcontroller and multiple high-speed analog PWM modules enables the addition of charger bays for multi-bay applications, as well as out-of-phase switching techniques and input power budgeting features.

Firmware such as the items listed here increase system precision because they enable the calibration of the Li-Ion termination voltages and charge currents.

CONCLUSION

By using a mixed-signal approach to developing battery chargers, battery charger designs can take advantage of the best of both the analog and digital worlds. Employing a mixed-signal approach enables high frequency operation (500 kHz), high-speed protection (12ns current sense to output), and minimizes the size of filtering components. In addition, the programmable digital features of the system enable appropriate determination of stage of charge and set charge current.

Because it facilitates the programming of settings and currents, firmware enhances new battery charging methods. This approach differentiates one mixed-signal design from another. This type of design is not limited to Li-Ion and NiMH batteries, and it leaves the door open for the programming of future rechargeable technologies into the system.

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