Application Note   AN2361

Power Management - USB-Powered Battery Charger for NiCd/NiMH Batteries

Abstract

This Application Note describes a USB-powered battery charger for NiCd/NiMH batteries that permits rapid recharging. Dedicated PC-based software has been developed to monitor and control the charging process in real time, and display data in a graphical user interface. The charger can be embedded into consumer, office and industrial applications. It needs no drivers and starts working immediately when plugged into a USB port. A battery can be left in the charger for any length of time without risk of overcharge.

Introduction

The growing popularity of wireless computer peripherals such as the wireless mouse, keyboard, and similar devices is likely to spur demand for a device that can be recharged rapidly. Rechargeable batteries are also widely used in peripheral and non-computer related appliances.

The charger described in this Application Note can easily be incorporated into computer peripherals. For example, one battery can be located in a mouse or another wireless device, and a second battery inserted into a combination host/charger that is connected to the USB port of a computer. When the battery in the peripheral device is drained, the user can simply swap the two batteries. Moreover, this charger can charge or discharge user batteries under manual charge control. The user can control the charger from PC software, immediately stopping or starting the charge process. As an added option, it is possible to discharge the battery before charging. This lets the user train batteries using a discharge-charge cycle.

In the following sections, this Application Note describes how the charger works, its various aspects, and how it can be modified:

- o Rapid Battery Charging
- o Charger Hardware
- o Charger Firmware
- o USB Connection
- o PC Utilities and Debugging
- o Design Modifications
- o Appendixes

Rapid Battery Charging

This charger uses the pulse method for nickel-based batteries, which makes rapid battery charging possible and preserves battery health.

The battery is charged by means of constant current impulses of 5-second duration, alternated with 0.5-second latent periods during which no charge is applied. Then the charger measures the battery voltage. When the battery voltage stops increasing or starts decreasing, the battery is fully charged. The charge termination criteria and the battery voltage upon full charge are shown in Figure 1. A more detailed description of NiCd/NiMH battery charge termination criteria is available in AN2260, "Rapid NiCd/NiMH Battery Charger and DC Brushed Motor Controller for Autonomous Appliances."

Figure 1. NiCd/NiMH Battery Pack Voltage in Time Graph
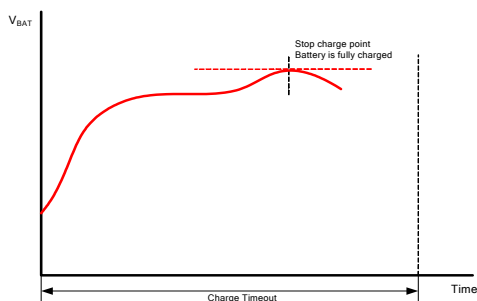
The charge stage should be limited by a time-out that should extend for approximately 120-150 percent of the estimated time required to charge NiCd/NiMH batteries with expected maximal capacity.

Table 1. Main Charger Characteristics

No.	Parameter Name	Two Cells	Three Cells
1	Voltage indicating battery presence, V	0.5	0.75
2	Re-charge voltage level, V	1.8	2.7
3	Emergency charger stop voltage, V	3.5	5.25
4	Discharge stop voltage, V	1.0	1.5

Charger Hardware

The charger structure is shown in Figure 2. The acronyms in the figure are defined as follows:

USB – Full-speed universal serial bus engine used for receiving control data from the PC and sending data about charger status and battery states to the PC.

CPU – Central processor core for implementing charge algorithms and performing charge control functions.

**INA** – Switched capacitor-based instrumentation amplifier.

INT – Differential integrator built on the base of a switched capacitor block.

DSM – Delta-sigma modulator used for current regulator control output.

ADC – Incremental analog-to-digital converter for digitizing the analog signals.

AMUX – Analog multiplexer used for switching between two analog signals for measurement.

Figure 2. Charger Structure
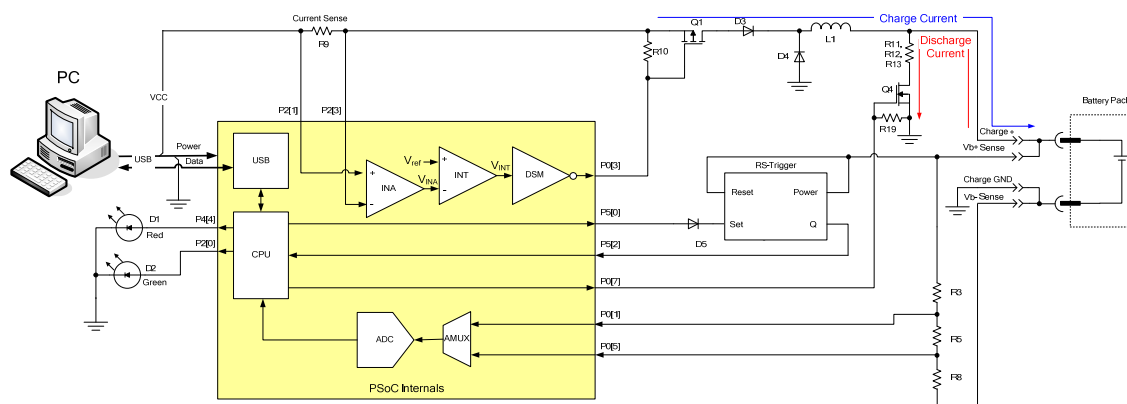
The main task of the charger is efficient use of the maximum allowed current from the USB bus (0.5A) in order to minimize charge time. Because the current from a USB is insufficient for a fast battery charge, the battery is charged with a fixed current. It is the current drawn from the USB that is controlled rather than the charge current. The battery charge current is determined by the battery voltage; regulator input power is maintained at a constant level.

The current regulator uses a hardware control loop. The hardware control loop consists of an instrumentation amplifier (INA) to handle a current sense resistor (R9) signal, a differential integrator (INT), which acts as a

difference amplifier, and a delta-sigma modulator (DSM) as a voltage-to-duty cycle converter. This loop controls the MOSFET gate duty cycle to keep the input current constant. This method enables the greatest use of available USB power. This implementation uses three configurable switched capacitor blocks: one for the instrumentation amplifier, one for the differential integrator and one for the delta-sigma modulator. The configuration of parameters of the switched capacitor block is described in AN2041, "Understanding Switched Capacitor Analog Blocks." The following equations describe the operation of the regulator:

$$V_{INA} = \frac{C_A^{INA}}{C_F^{INA}} V_{P2[1]} - \frac{C_B^{INA}}{C_F^{INA}} V_{P2[3]}; \tag{1}$$

$$V_{INA} = \frac{C_A^{INA}}{C_F^{INA}} R_{sense} I_{bus}; \quad C_A^{INA} = C_B^{INA};$$

$$V_{INT} = \int \left[\frac{C_A^{INT}}{C_F^{INT}} V_{ref} - \frac{C_B^{INT}}{C_F^{INT}} V_{INA} \right] dt; \tag{2}$$

V_{INA} is instrumentation amplifier output, and C_A^{INA}, C_B^{INA}, C_F^{INA}, C_A^{INT}, C_B^{INT}, and C_F^{INT} are values of the capacitors that correspond to generic switched capacitor blocks. For correct operation, C_A^{INA} must be equal to C_B^{INA}. The $V_{P2[1]}$ and $V_{P2[3]}$ values are voltage on the PSoC® pins P2[1] and P2[3], respectively. The value R_{sense} is the current sense resistor value. The value I_{bus} is the current drawn from the USB. The value V_{INT} is the differential integrator output. The value V_{ref} is the bandgap reference voltage. In the steady state, the integrated (V_{INT}) average value should be equal to zero. Thus, the target value of the regulator current can be calculated as follows:

$$I_{bus} = \frac{C_F^{INA} \cdot C_A^{INT} \cdot V_{ref}}{C_B^{INT} \cdot C_A^{INA} \cdot R_{sense}}; \tag{3}$$

If C_F^{INA} = 16, C_A^{INT} = 2, V_{ref} = 1.3V, C_B^{INT} = 14, $C_A^{INA} = C_B^{INA}$ = 31, and R_{sense} = 0.2Ω, the USB drawing current is equal to 0.479A. By modifying the capacitor values, the user can alter the current consumption from the USB supply. However, the USB specification enforces a 0.5A current limitation.

Operation of the regulator is shown in Figure 3.

Figure 3. Integrator Output (Upper Trace) and Delta-Sigma Modulator Output (Lower Trace)
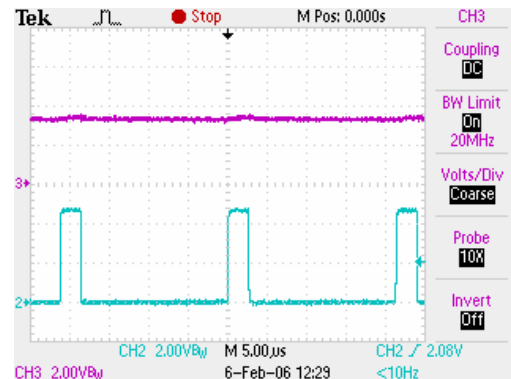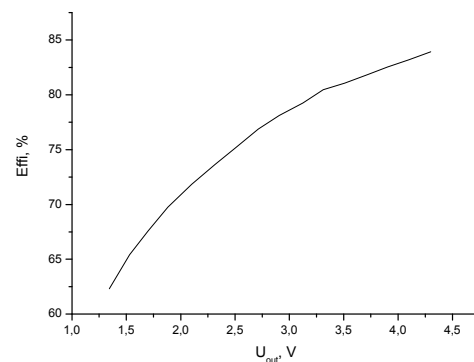

a) When Battery Voltage is 3.9V
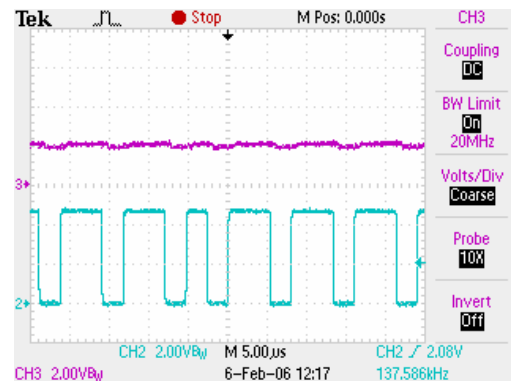
b) When Battery Voltage is 1.3V

The battery charge current is determined by input current, battery voltage, and regulator efficiency. Regulator efficiency based on real measurements is shown in Figure 4.

Note that low efficiency at low voltage output is caused by voltage drops on diodes D3 and D4.

Figure 4. Regulator Efficiency

The battery voltage is measured by an ADC using a resistive divider to condition the signals to the allowed level. This is combined with a correlated double sampling method. ADC and input amplifier offsets are thus eliminated. The

ADC first measures voltage on pin P0[1] and then on pin P0[5]. The battery voltage is calculated as the difference between the voltages of P0[1] and P0[5]. The derived voltage measurement is shown in the following equation:

$$\Delta n_V = n_{max} \frac{G_V \left(V_{P0[1]} - V_{P0[5]} \right)}{V_{ref}} = n_{max} \frac{G_V \beta_V V_{bat}}{V_{ref}} \ (4)$$

$V_{P0[1]}$ and $V_{P0[5]}$ are the voltages on pins P0[1] and P0[5], respectively. The value Δn_V is the ADC value without the amplifier and ADC offset voltages. The value n_{max} is the maximum ADC code, with a value equal to 2047 for an 11-bit incremental ADC. The value V_{bat} is battery voltage, and G_V is the input amplifier gain, equal to 1. The value V_{ref} is the bandgap reference voltage (1.3V), and β_V is the resistive divider coefficient, which is equal to 0.25 for R_3=150 kΩ, R_5=100 kΩ, and R_8=150 kΩ divider resistors:

$$\beta_V = \frac{1}{1 + \frac{R_3 + R_8}{R_5}} \quad \textbf{(5)}$$

The ADC and regulator share *Comparator Bus 1*. Because the regulator and ADC never work simultaneously, the comparator bus reconnects by firmware to the ADC to provide measurement. The comparator bus reconnects to the delta-sigma modulator for hardware control of the charge state. See **Charger Firmware** later in this Application Note.

The MOSFET Q4 allows the battery to be discharged before a charge. If Q2 is activated, the current from the battery flows though R11, R12, and R13, which are connected in parallel to provide greater thermal dissipation. This battery-discharge feature can be activated only from the PC software as an option for battery training; it is not automatic.

The charger can be used in applications that require leaving the battery in the charger after the charge cycle, even if the PC power is turned off. Overcharging the battery can cause permanent damage or decrease battery capacity. To prevent battery overcharge, battery charging is only initiated after PC start when the battery voltage falls below a predefined limit. This limit is called the charge restart condition. But if the user inserts the battery in the charger, the charger starts immediately, without testing the voltage. To detect that a battery was changed when the charger was not powered from a USB, a simple RS-trigger, powered from the battery, is used. The RS-trigger automatically enters the reset state after the power goes on. Thus, changing the battery automatically resets the trigger. If the battery is not replaced in the charger, the recharge starts only if the battery voltage has fallen below a predefined limit. When the battery is changed, a charge is initiated regardless of battery voltage. The RS-trigger is built from two bipolar transistors, Q3 and Q4. As a result of nonsymmetrical resistances in bases (R4 vs. R5) and collector circuits (R1 vs. R2), a reset state is always triggered upon power-up. Refer to Appendix 1.

One digital block and interrupt-based firmware are used for charge-time control. The PSoC Timer8 User Module generates an interrupt with a frequency of 20 Hz and clocks from VC3 (5,859 kHz).

Two LEDs, green and red, are used to indicate the charger state. When the charger is connected to the USB, both LEDs are switched on. After device enumeration, the LEDs indicate the charger state. A green LED means a charge is in process. When both LEDs are turned off, everything is functioning properly but no charge is being applied to the battery at this time, possibly because the battery is fully charged or there is no battery in the charger. A red light indicates an error condition. More detailed charger state information is provided with the PC software.

Charger Firmware

The firmware is constructed as a state machine. The state diagram is shown in Figure 5.

The active charge states are marked in green. Error states are marked in red.

Figure 5. Charger State Diagram
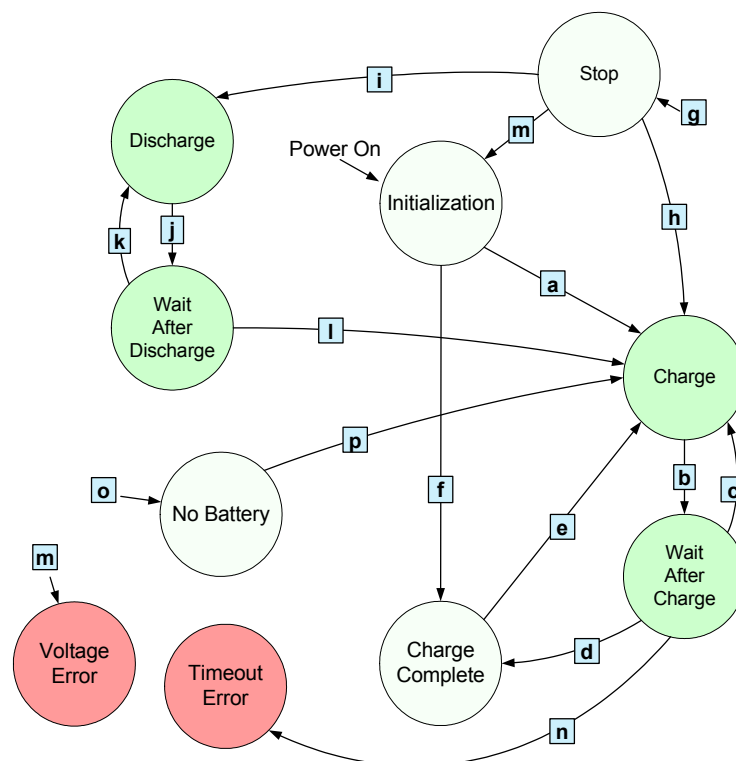
In Figure 5, state transitions are indicated by lines and squares labeled with letters. See **State Transition Descriptions** ahead for explanations of the transitions. The states in circles in Figure 5 are defined as follows:

Initialization – Both LEDs are off. Test for battery presence and state based on battery voltage.

Charge – Green LED is on. Charge uses hardware current regulator for 5 seconds.

Wait After Charge – Green LED is on. No charge, wait 0.5 seconds.

Charge Complete – Both LEDs are off. No charge. Battery is fully charged.

Stop – Both LEDs are off. No charge. This state occurs when the device gets a stop command from the PC. Wait for the next command.

Discharge – Green LED is on. Discharge is in progress for 5 seconds.

Wait After Discharge – Green LED is on. No charge, no discharge, wait 0.5 seconds.

No Battery – Both LEDs are off. Charge is turned off. Wait for battery to be inserted.

Voltage Error – Red LED is on. Stop charging. Battery voltage has reached the permitted safe level. The battery or charger may be damaged. Wait for battery to be removed.

Timeout Error – Red LED is on. Charging is stopped. Charger has attempted to charge the battery for a predefined period but detects that the battery has failed to take a full charge. The battery may be damaged. Wait for the battery to be removed.

State Transition Descriptions

The state transitions shown in Figure 5 are described as follows:

a) IF $V_{NO-BATT} < V_{BATT} \leq V_{RE-CH}$

or fBatteryChanged flag is set

THEN Charge

If a battery is detected and the battery is not already charged, then the green LED is turned on, and transition to the Charge state occurs.

b) IF 5 sec has elapsed

THEN Wait after charge

Charge the battery for 5 seconds.

c) IF battery voltage increasing

THEN Charge Complete

The charge termination criteria are that the voltage is decreasing during a charge, or that the voltage remains constant (no longer increasing) during a charge. If either criterion is not met, then the battery charge continues.

d) IF battery voltage not increasing

THEN Charge Complete

If termination criteria are met, the green LED is turned off and the charge is stopped. Transition to the Charge Complete state occurs.

e) IF $V_{NO-BATT} < V_{BATT} \leq V_{RE-CH}$

THEN Charge

If the battery voltage has fallen below the re-charge voltage level (possibly because the battery is self-discharging), the battery charge is resumed.

f) IF $V_{RE-CH} < V_{BATT}$

THEN Charge Complete

If a battery is detected and is fully charged, transition to the Charge Complete state occurs.

g) IF Stop command received

THEN Stop

If a stop command has been received from the PC, a stop occurs immediately, regardless of the current state.

h) IF Charge command received

THEN Charge

If a charge command has been received from the PC, then charging starts immediately, regardless of the battery voltage.

i) IF Discharge command received

THEN Discharge

If the discharge command is received from the PC, then discharging starts immediately. This is the only way to discharge the battery.

j) IF $T_{BATT} \leq T_{COLD\_STOP}$

THEN Wait after discharge

Permits discharge of the battery for 5 seconds.

k) IF $V_{BATT} > V_{DISCH}$

THEN Discharge

If batteries are not discharged, the discharge continues.

l) IF $V_{BATT} \leq V_{DISCH}$

THEN Charge

If the battery is fully discharged, transition to the Charge state occurs.

m) IF $V_{BATT} > V_{ERR}$

THEN Voltage Error

If battery voltage exceeds the V_{ERR} level, transition to the Voltage Error state occurs regardless of the present state.

n) IF duration of charge exceeds predefined limit

THEN Timeout Error

If the battery charge exceeds a predefined limit, the charge stops. The battery may be damaged.

o) IF $V_{BATT} \leq V_{NO-BATT}$

THEN No Battery

Exit from the current state and transition to No Battery if the battery has been removed.

p) IF $V_{BATT} > V_{NO-BATT}$

THEN Charge

If a newly inserted battery is detected, a charge starts. A charge always starts after a battery is inserted.

Note that if a battery is removed, then the charger goes to the No Battery state from any other state except the Stop state.

A time-based interrupt handler is used to implement sleep mode (Suspend state of the USB). The interrupt handler checks the bus activity bit. If the bus enters USB Suspend mode, the charger goes into CPU sleep mode. The CPU stays in sleep mode until it receives a wake-up event from the USB. Sleep mode support is required for full compliance with USB standards.

USB Connection

The charger uses USB for two purposes:

- To receive and manually control data that relates to the charge process.

- As a power source for the charger.

Logically, the charger is represented as an HID device. The charger requires only a low data rate. An HID is very useful in this case. The advantage of an HID is that no special driver is needed and software support is simplified.

The supporting documents (see supporting files in the project .zip) contain tables of the USB descriptors and HID report descriptors. Both descriptors are represented in PSoC style, corresponding to the USB Setup Wizard tables.

PC Utilities and Debugging

Dedicated charger control software has been developed to monitor the charge process. The user interface (UI) is very simple, as shown in Figure 6.

The UI consists of a chart that displays battery voltage, labels indicating the present charger state (Stopped, in Figure 6), battery voltage (2.79V), and four buttons to manually control the charge process.

The software is optional and not required for charger operation.

Figure 6. Charger Monitoring Software
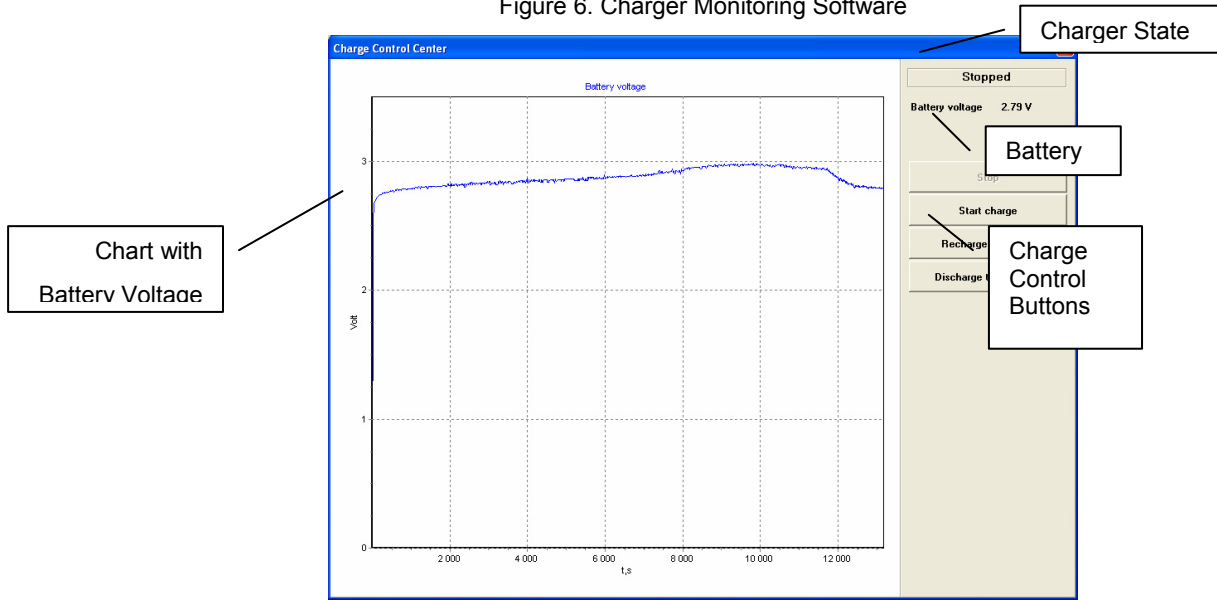
The data packets that are sent from the charger to the PC and from the PC to the charger are shown in Table 2. The data packet from charger to PC contains the charger state and battery voltage. Using this data, the software builds a chart and prints the actual battery voltage. This package has a length of 3 bytes.

The battery voltage is calculated in Equation (6) from the returned ADC code by the inverse function of Equation (4):

$$V_{BATT} = \frac{V_{ref} \Delta n_{V_{BATT}}}{G_V \beta_V n_{max}}; \qquad \textbf{(6)}$$

$\Delta n_{V_{BATT}}$ is the battery voltage in ADC code from the data packet.

The data packet from PC to charger contains a single 1-byte command.

Table 2. Data Packets

Item #	Length in Bytes	Reference	Description
a) Data Packet from Charger to PC			
1	1	State	Charger State • INITIALIZATION = 0 • CHARGE = 1 • WAIT AFTER CHARGE = 2 • CHARGER COMPLETE = 3 • NO BATTERY = 4 • DISCHARGE = 5 • WAIT AFTER DISCHARGE = 6 • STOP = 7 • VOLTAGE ERROR = 8 • TIMEOUT ERROR = 9
2	2	$\Delta n_{V_{BATT}}$	Battery voltage in ADC code
b) Data Packet from PC to Charger			
1	1	Cmd	Command to Charger • STOP = 1 • CHARGE = 2 • RECHARGE = 3 • DISCHARGE = 4 • SET TIMEOUT = 5

Design Modifications

It is possible to decrease the cost of the charger by eliminating the coil and Schottky diode and substituting a pulse regulator with a linear current source. However, this alternative increases the charge time because if a linear regulator is used, the charge current is not greater than 0.5A. The constant current source consists of an instrumentation amplifier to sense the current and a differential integrator. The current source is similar to that described in AN2203 "Programmable Analog High Current Source. PSoC Style."

The structure of a charger with a linear current source is shown in Figure 7. The delta-sigma modulator (DSM) is eliminated and the differential integrator directly drives the MOSFET gate. The differential amplifier inputs are swapped to obtain an inverted signal on the output. The inverted signal is required to form negative feedback in order to drive a P-channel MOSFET. In contrast to a switching regulator, the MOSFET in a linear regulator operates in linear mode. As a result, the power dissipation on the MOSFET is higher, so a small heat sink may be necessary. A PCB plane is suitable for this role.

Figure 7. Charger Structure with Linear Regulator
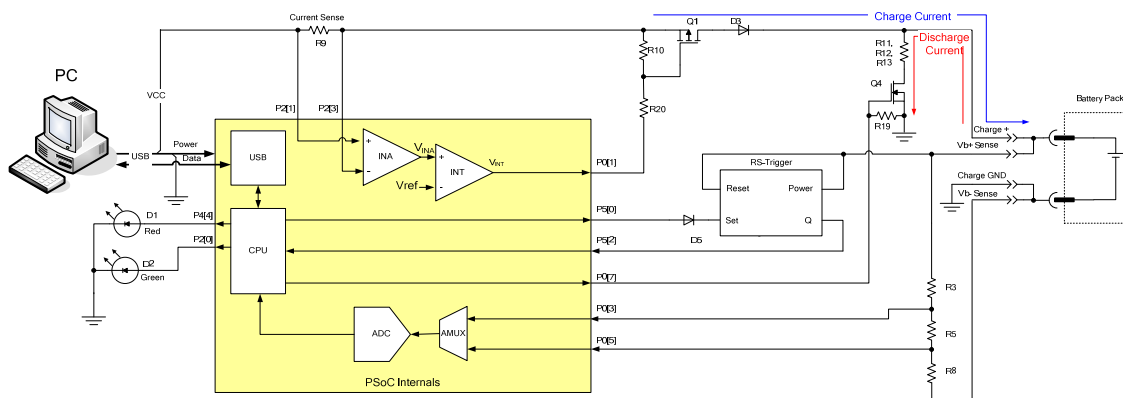
The charge current vs. battery voltage for the switching regulator is shown in Figure 8

Figure 8. Charge Current vs. Battery Voltage
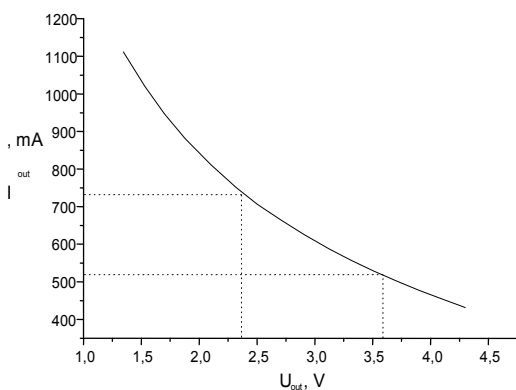
For the linear regulator, the current is constant and does not exceed 0.5A. So when a switching regulator is used to charge two batteries (2.6V in a charged state) the charge current is significantly greater than the charge current when a linear current source is used. For three batteries with 3.9V in a charged state, the charge current is about the same for both kinds of regulators. For deeply discharged batteries (2.4V), the charge current is greater.

However, the overall benefit is not great when a switching regulator is used to charge three NiCd/NiMH batteries. So in this case, a linear regulator can be used with a very small loss of efficiency. Switching and linear regulator efficiencies against battery voltage are shown in Figure 9.

Figure 9. Switching and Linear Regulator Output Power vs. Battery Voltage
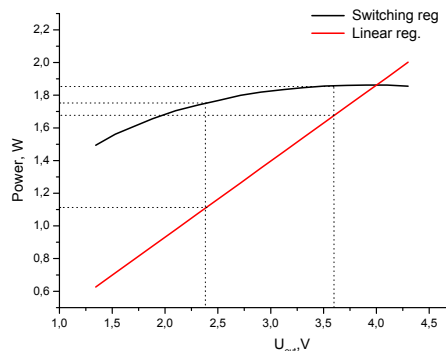

The time required to charge different batteries when the two regulator types are used is shown in Table 3.

Table 3. Charge Time Examples with Different Regulator Types

No.	Case	Time
1	Two cells by 1400 mAh using switching regulator	189 min
2	Two cells by 1400 mAh using linear regulator	323 min
3	Three cells by 1800 mAh using switching regulator	384 min
4	Three cells by 1800 mAh using linear regulator	426 min

The USB charger is designed to be part of a more complex system. Additional resources can be allocated to the unused digital blocks. For example, the SPIM User Module can be added for communication with the WUSB User Module. The size of the firmware code is small, about 4.5 KB (less than 30 percent of Flash). A total of 104 bytes of SRAM is used for variables (13 percent using the large memory model (LMM), 40 percent without). Resources are thus available to combine this charger onto one PSoC device with the user's own design.

Appendix 1. Charger Schematic
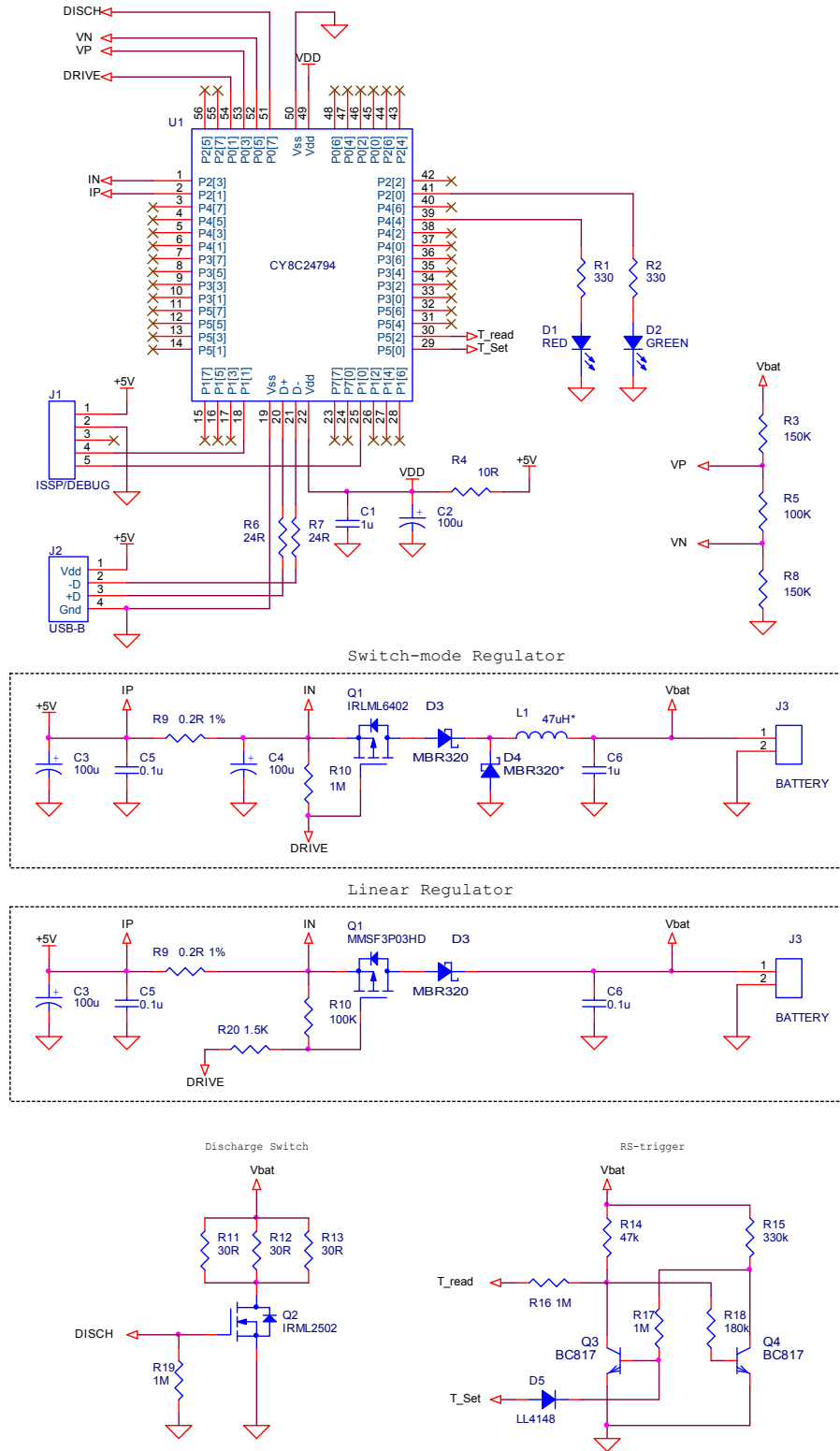
Appendix 2. Board Photo

About the Author

Name: Svyatoslav Paliy

Title: Application Engineer

Background: Svyatoslav earned a Master of Science degree from Lviv Polytechnic National University (Ukraine) in 2000. His interests include the various aspects of embedded systems design, and Windows and Linux programming.

Contact: svt@isto.lviv.ua

In March of 2007, Cypress recataloged all of its Application Notes using a new documentation number and revision code. This new documentation number and revision code (001-xxxxx, beginning with rev. **), located in the footer of the document, will be used in all subsequent revisions

[+] Feedback