THIS SPEC IS OBSOLETE

Spec No: 001-32899

Spec Title: POWER MANAGEMENT - SINGLE CELL LI-ION BATTERY CHARGER - AN2267

Sunset Owner: Sachin Gupta (SGUP)

Replaced by: None

Power Management – Single Cell Li-Ion Battery Charger

AN2267

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Application Note Abstract

An Li+ battery charger design is presented in this Application Note. The dedicated PC-based software was developed to perform real-time charge process monitoring and analysis. The charger can be embedded into consumer and home appliances or industrial applications.

Introduction

Lithium-Ion (Li-Ion) and Lithium-Polymer (Li-Pol) batteries are characterized by the greatest capacity/volume ratio and can be found in notebooks, pocket PCs, cell phones and other newer-technology consumer applications.

This Application Note describes the single cell Lithium-based (Li+) battery charger on an example of a 600 mA/h battery. (Battery capacity and other battery parameters can easily be changed by modifying corresponding constants.)

Battery Charging Method

Lithium-based batteries use a two-stage charge profile: activation and rapid-charge stages. If battery voltage is less than 2.9-3.0 volts, it means the cell is completely discharged and the battery must be activated. In the activation stage, the battery is charged with a small constant current (typically 0.05-0.015 CA, where CA is the nominal battery capacity) until battery voltage reaches the desired level. The battery activation time is limited to approximately 1.5-3.0 hours depending on battery manufacturer recommendation. If, during activation time, the battery voltage cannot rise above 2.9-3.0 volts, the battery cell is considered damaged.

The rapid-charge stage starts after the activation stage. Rapid-charge consists of two modes: constant voltage and constant current.

When the battery voltage is less than the predefined level (4.1-4.2V, depending on battery manufacturer recommendations), the charge is processed with constant current (about 0.5-1 CA, depending on battery manufacturer recommendations). When the battery voltage reaches the predefined level, the charge source switches to constant voltage mode (4.1-4.2 V). If the charge current drops below the predefined limit, the charge process terminates; the battery manufacturer recommends users set the rapid termination current to 0.07-0.2 CA.

The rapid-charge stage must be protected by a timeout. The constant current time is estimated to provide 100-120 percent of the battery charge because during this mode the battery is charged up to 70-80 percent. The constant voltage charge time is limited to 2 hours, according to the manufacturer recommendations.

Figure 1 depicts the Li+ battery charge profile. Table 1 contains descriptions of the charge profile parameters and default values used in this design.

Please note that Li+ batteries are very sensitive to the charge voltage, current, and discharge limit. Therefore, they are assembled with a built-in thermistor and protective circuit. This circuit protects the battery from overcharge and overdischarge, and limits the load and charge current to safe values. Without this circuit, the battery can explode under adverse conditions. The charge source voltage-limit accuracy must be more than 1 percent.

Figure 1. Li+ Battery Charging Profile

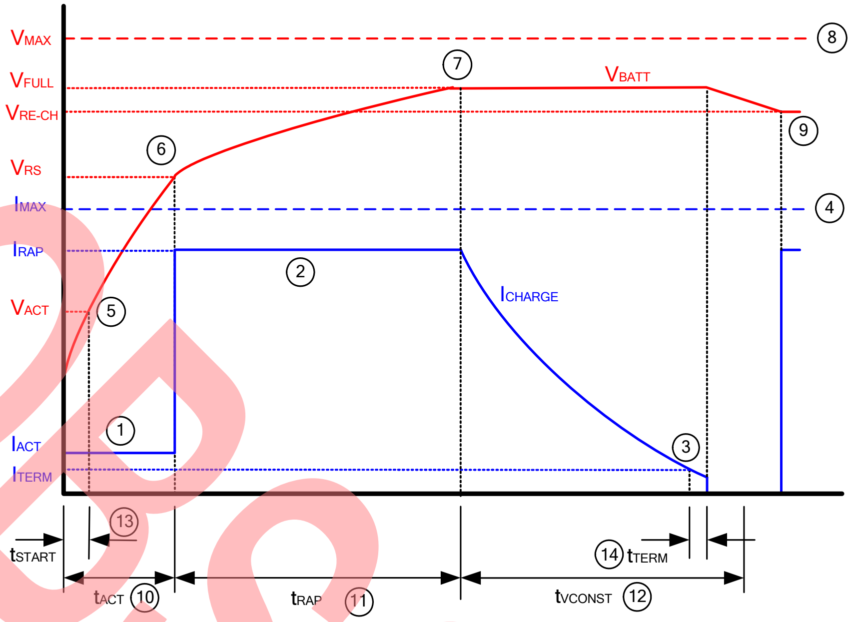


Table 1. Example of Charge Profile Parameters and Values

Marker	Parameter	Description	Value
Charging Parameters			
1	I_{ACT}	Activation charge current	80mA ±30mA
2	I_{RAP}	Rapid charge current	600mA ±40mA
3	I_{TERM}	Termination current (use average of I_{CH} over 1 sec)	60mA ±15mA
4	I_{MAX}	Emergency charge stop current	720mA ±70mA
5	V_{ACT}	Activation charge start voltage	2.0V ±0.1V
6	V_{RS}	Rapid charge start voltage	3.0V ±0.1V
7	V_{FULL}	Full charge voltage	4.2V ± 0.03V
8	V_{MAX}	Emergency charge stop voltage	4.35V ± 0.1V
9	$V_{RE\text{-}CH}$	Re-charge voltage	4.0V ± 0.1V
Timing Requirements			
10	t_{ACT}	Time limit for battery activation period	140 min
11	t_{RAP}	Time limit for constant current rapid charge period	80 min
12	t_{VCONST}	Time limit for constant voltage charge period	120 min
13	t_{START}	Maximum time for battery activation (while $V_{BATT} < V_{ACT}$)	20 sec
14	t_{TERM}	Minimum time for charge complete (when $I_{CHAVG} \le I_{TERM}$)	10 sec
Additional Parameters			
15	I_{MIN}	Minimum current for battery health test	25 mA
16	V_{CC}	Charger power supply voltage	5V ± 0.25V

Temperature Control

The charge process can be activated only if the battery temperature is within the predefined limit. Typical temperature values are +2 to +40^{0}C.

Figure 2 depicts the temperature profile. Table 2 contains descriptions of the temperature profile parameters and default values used in this design.

Also, thermistor resistance is used to check for battery presence. The battery is considered disconnected when the measured thermistor resistance is greater than R_{OPEN}. That means there is no thermistor; therefore, no battery pack is connected.

Figure 2. Temperature Profile

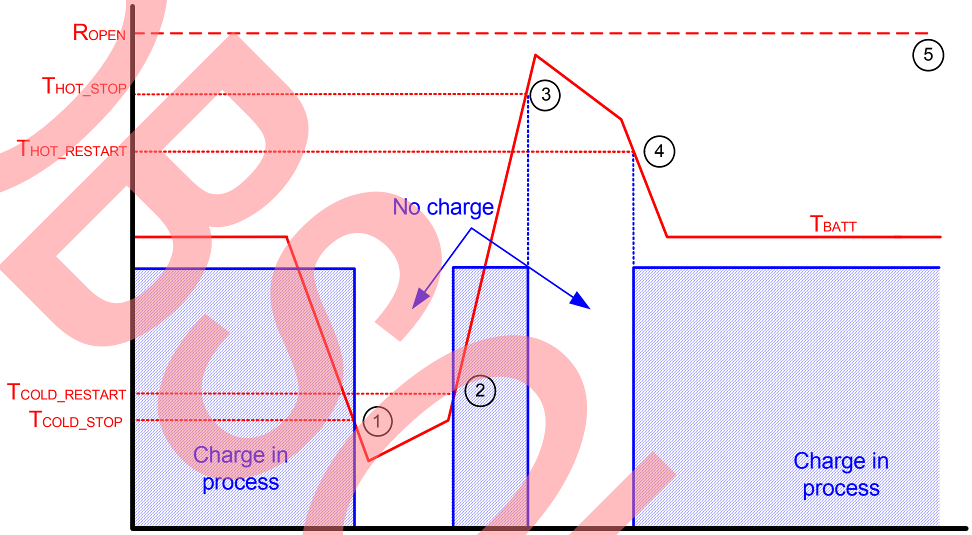


Table 2. Temperature Related Parameters

Marker	Parameter	Description	Value
1	T_{COLD_STOP}	Stop temperature measured from battery thermistor	2°C
2	$T_{COLD\_RESTART}$	Re-start temperature measured from battery thermistor	T_{COLD_STOP} +1°C
3	T_{HOT_STOP}	Stop temperature measured from battery thermistor	50°C
4	$T_{HOT\_RESTART}$	Re-start temperature measured from battery thermistor	T_{HOT_STOP}-2°C
5	R_{OPEN}	Thermistor resistance limit for determining open circuit	35 kΩ

Charger Hardware

Figure 3 shows the general structure of the charger. The following abbreviations are used:

RS_TX – EIA-232 (RS-232) transmitter for debug purposes (uses external translator). It monitors temperature, voltage and current using the PC. RS_TX is used only in the debug stage and may be removed in the released product.

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

PWM – Pulse width modulator for driving the regulator.

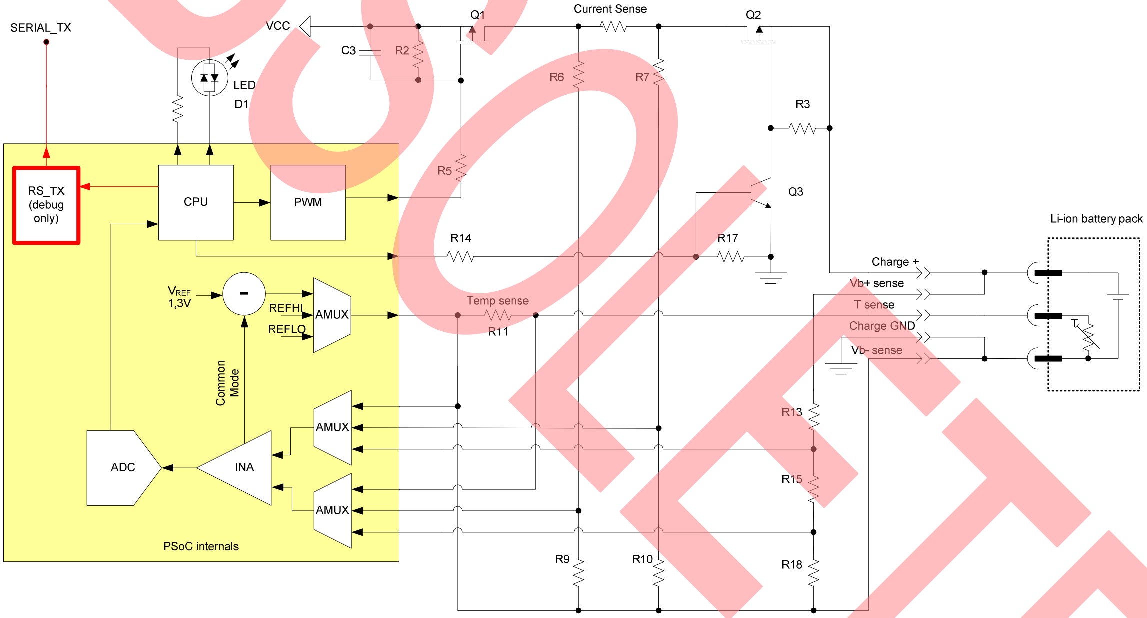
ADC – Incremental analog-to-digital converter for digitizing the analog signals.

INA – Instrumentation amplifier (with common mode out) for measuring charge voltage, current and temperature.

AMUX – Analog multiplexers.

The signal from the PWM goes to the RC-filter, which consists of 2 resistors and 1 capacitor. On the Q1, the gate forms the constant voltage signal proportional to the PWM duty cycle value. Therefore, the PWM with an RC-filter is a PWM-DAC. The MOSFET Q1 is driven by an analog signal from the PWM DAC and regulates battery charge current. The PWM period was set to 2048 for accuracy, and can easily be adjusted in the firmware. Q2 and Q3 were used to prevent a reverse current, which can discharge the battery when it is still connected and the charger is turned off from the supply voltage. There is a 0.33-ohm resistor at the current sensor. Other resistors form the battery interface to allow transformation of the battery current and voltage and temperature into a signal. All of which are suitable for the PSoC® device.

Figure 3. Charger Structure

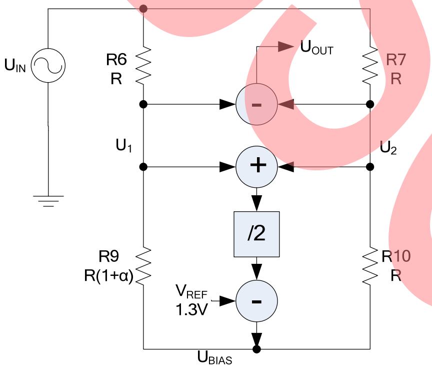


To correctly implement charge algorithms, the following must be measured accurately: charge current, battery voltage, and temperature. As the voltage drops on the corresponding resistors, all parameters are measured using the instrumental amplifier INA. The measurements of all parameters are implemented as a two-stage procedure to eliminate voltage offset of the instrumentation amplifier and ADC input. The INA inputs are shorted together in the first stage. This position is used to measure the INA offset voltage. Next, the real signal is measured.

Then, the difference between ADC code, which corresponds to first and second stage, is directly proportional to the battery measurement parameter without influence of the INA and ADC offset voltage. To limit current flow from the battery through the interface resistors for current and voltage measurement, we use precision resistor dividers with large resistor values.

The small imprecision of R6, R7, R9 and R10 can cause a current measurement error and dependency between measured current value and battery voltage. You can accurately measure current and greatly decrease the dependency between current measurement and battery voltage by reducing the influence of the resistors' tolerance on current measurement accuracy. We formed reference voltage by subtracting the INA common mode out (that is equal to the arithmetical mean of the INA input signals) and V_{REF}=1,3V. The common mode voltage is passed through the low-pass filter to a column analog buffer during current measurement. The internal switched capacitor low-pass filter is modified in such a way that Amux reference is set to RefHi. The filter input stage reduces the voltage and forms a resistive divider with the lower pin potential biased down. The common mode voltage is at 1.3V if the battery voltage is larger than 2.7V. Used this way, we partly compensate the difference between the divider resistors' values. Figure 4 describes an equivalent circuit to see how this compensation works.

Figure 4. The Current Measurement Bridge Resistors Imbalance Case Study



Suppose we have three equal resistors (R6, R7, R10) with value R and one additional resistor, R9, with value $R(1+\alpha)$. Equation (1) shows that U_{OUT} does not depend on U_{IN}. This is absolutely true when $U_{IN} \geq 2.7V$ because the PSoC device can potentially generate only a positive reference voltage ($U_{BIAS} \geq 0$). Note that during the activation stage (when battery voltage is less than V_{RS}), precise accuracy of current measurement is not required; therefore, it is not a problem.

$$\begin{cases} U_1 = \dfrac{(U_{IN} - U_{BIAS})(1+\alpha)}{2+\alpha} + U_{BIAS}; \\ U_2 = U_1 - U_{OUT} = \dfrac{U_{IN} + U_{BIAS}}{2}; \\ U_{REF} = U_1 - \dfrac{U_{OUT}}{2} - V_{REF}; \end{cases} \qquad \text{Equation 1}$$

$$\Rightarrow U_{OUT} = \frac{2\alpha V_{REF}}{4+3\alpha};$$

In the case where the U_{BIAS} is constant (not dependent on U_1 and U_2), the output voltage will be:

$$U_{OUT} = \frac{a(U_{IN} - U_{BIAS})}{2(2+a)}; \qquad \text{Equation 2}$$

The result of Equation (2) is proportional to input voltage U_{IN}. Therefore, the change in the battery voltage will be an error source for the current measurement.

Precise accuracy of current measurement is necessary when near the 4.2V battery voltage. Therefore, during the general calibration procedure (as follows), when the transistor Q1 is off, we measure voltage bias on the current sense resistor and store it in non-volatile memory. We subtract the memorized bias voltage from measurement values during the normal charge process. The following equation depicts this measuring scheme:

$$\Delta n_I = n_{\max} \frac{V_{ADC}}{V_{ref}} - n_{bias} = \qquad \text{Equation 3}$$

$$= n_{\max} \frac{G_{ina} \beta_I I_{bat} R_{sense}}{V_{ref}} - n_{bias}$$

- Δn_I is the ADC code without influence of the INA and ADC offset voltage.
- n_{bias} is the ADC code difference, which corresponds to the imbalance in current bridge resistors.
- ($\Delta n_I = n_{meas} - n_{offset} - n_{bias}$). n_{max} is full-scale ADC code and the value is equal to 2048 for a 12-bit incremental ADC in bipolar mode.
- I_{bat} is battery charge current.
- G_{ina} is INA gain (four times for current measurement).
- V_{ref} is bandgap reference voltage (1.3V).
- β_I is the resistive divider coefficient (0, 5 R6=R9=200 kΩ and R7=R10=200 kΩ):

$$\beta_I = \frac{1}{1+\dfrac{R_6}{R_9}} = \frac{1}{1+\dfrac{R_7}{R_{10}}}; \qquad \text{Equation 4}$$

The voltage measurement is also performed by an INA on the corresponding resistor and is shown in Equation (5):

$$\Delta n_V = n_{\max} \frac{V_{ADC}}{V_{ref}} = n_{\max} \frac{G_{ina}\beta_V V_{bat}}{V_{ref}} \qquad \text{Equation 5}$$

- Δn_V is the ADC code without influence of the INA and ADC offset voltage ($\Delta n_I = n_{meas} - n_{offset}$).
- n_{max} is full-scale ADC code and the value is equal to 2048 for a 12-bit incremental ADC in bipolar mode.
- V_{bat} is battery voltage.
- G_{ina} is INA gain (equal to 1 for voltage measurement).
- V_{ref} is bandgap reference voltage (1.3V).
- β_V is the resistive divider coefficient (equal to 0.17526 for R13=120 kΩ, R15=51 kΩ, R18=120 kΩ divider resistors):

$$\beta_V = \frac{1}{1 + \frac{R_{13} + R_{18}}{R_{15}}} \qquad \text{Equation 6}$$

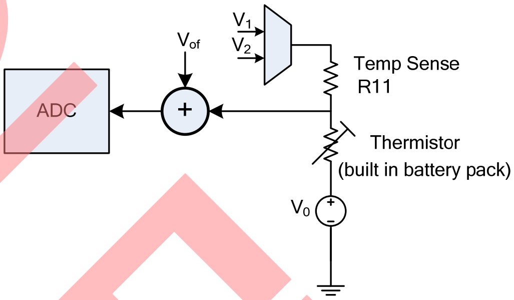
To obtain accurate voltage measurement, the calibration technique is used. The reason is that PSoC's bandgap reference voltage error is ±2 percent, ADC gain error ±1 percent, and INA gain error ±2-3 percent. These error sources will reflect in a non-calibrated voltage measurement error of up to 5-6 percent, which is not acceptable by the Li+ charge specifications. The calibration procedure with external voltage reference compensates for all gain errors.

All voltage thresholds are stored as calibrated ADC code. During the working process, the battery voltage (its ADC code) is compared to these stored values.

For this purpose, we use an external calibration device with a precise 4.2V source (it can be built using any high-precision analog reference, such as the AD780 from Analog Devices, and amplifier to gain output voltage to 4.2V). All devices must be calibrated during manufacturing process. The calibration process is described ahead.

Temperature measurement is implemented via the Temp Sense, R11 (see Appendix 1). The voltage-drop measurement is done by applying, in series, two different voltages to the Temp Sense pin and subtracting the results. The signal from the thermistor comes to the ADC via the INA with a unity gain. The bias voltage is formed by using the TestMux to apply the RefHi (2.6V) level and then AGND (1.3V). This technique allows compensation of both the ADC/INA offset and the possible offset caused by the potential differences between the Vss internal die connection and the lower thermistor pin. (The sources of potential differences between the Vss internal die connection and the lower thermistor pin are the device's internal die resistance, PCB voltage drop, battery pack voltage drop upon negative lead during charge, and so on. These potential differences must be cancelled out in order to improve accuracy of temperature measurement.) Figure 5 and Equation 7 illustrate how this works.

Figure 5. Temperature Measurement



$$n_{t1} = \frac{n_{\max}}{V_{ref}}\left[V_0 + V_{of} + \frac{R_{term}}{R_{11} + R_{term}}\left(V_1 - V_0\right)\right];$$

$$n_{t2} = \frac{n_{\max}}{V_{ref}}\left[V_0 + V_{of} + \frac{R_{term}}{R_{11} + R_{term}}\left(V_2 - V_0\right)\right]; \qquad \text{Equation 7}$$

$$\Delta n_t = n_{t2} - n_{t1} = \frac{n_{\max}}{V_{ref}}\left(V_2 - V_1\right)\frac{R_{term}}{R_{11} + R_{term}}.$$

- n_{t1} and n_{t2} are ADC code for resistive divider bias voltages V_1 and V_2, respectively (their difference is $V_{bandgap}$ or 1.3V).
- V_{of} and V_0 are offset voltages.
- Δn_t is ADC code.
- n_{max} is full-scale ADC code. The value is equal to 2048.
- R_{term} is battery pack thermistor resistance.

The thermistor transfer function is non-linear, but we do not need to obtain the temperature value in linear units for this design. Therefore, only the temperature thresholds during the charge need to be checked. This is done by analyzing the ADC code difference (Δn). A hysteresis is added for the bottom and upper bounds of the in/out temperature range to prevent multiple triggers when the temperature is close to the preset range (see Figure 2).

A bi-color (green/red) LED is used to indicate charger state. All of the possible states displayed by the LED are described in Table 3.

Table 3. LED States

#	Charger State	Led State
1	Charge (Activate, Rapid States)	GREEN
2	Charge Complete, No Battery States	OFF
3	Temperature Over Range	GREEN, BLINKING
4	Battery Error	RED

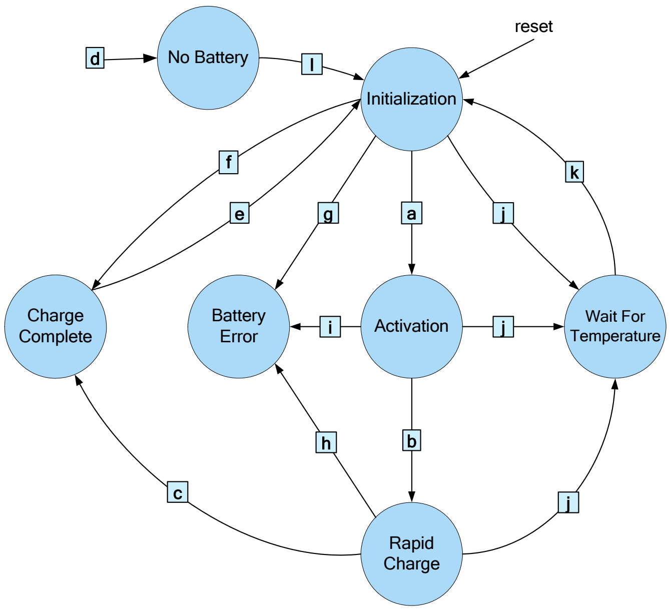
Charger Firmware

The charger firmware consists of two parts. The first part is the main part and is used for charging. The second part is intended for the calibration charger after manufacturing.

The main part of the firmware is built as a state machine. The diagram of the various states of the state machine is shown in Figure 6.

The order of connecting and disconnecting the three battery terminals is random. The physical ordering of the signals on the connector can vary from design to design. Therefore, all the possible sequences of **Battery+**, **Battery-** and **Thermistor** connections and disconnections are allowed when a battery is installed or removed. There is no ordering that will result in a lock-up condition, or result in false error detection.

Figure 6. Charger State Diagram



No Battery: LED = off, no charge. Waits for battery be connected.

Initialization: LED = off. Determines battery presence and its state. If thermistor is present but battery voltage value is below V_{ACT}, try short-time battery initiation by I_{ACT} current.

Activation: Turns on green LED. Charge by constant I_{ACT} current until voltage reaches V_{RS}.

Rapid Charge: LED = green. Constant current mode at I_{RAP} until voltage reaches V_{FULL}. Then changes to constant voltage until current falls below I_{TERM}.

Charge Complete: Turn off LED, done charging. Wait for battery to be removed, or for voltage to drop below $V_{RE\text{-}CH}$ to restart charge.

Battery Error: Turn on red LED and turn off charge. Error condition. Wait for battery to be removed, or power cycled.

Wait For Temperature: Blink green LED, stop charge. Temperature is outside of the desired range limits. Wait for temperature to return within the limits. Then move to the Initialization state.

State Transition Descriptions:

a) IF VACT < VBATT ≤ VRE-CH

THEN Activation Current

If the battery is detected and the battery is not already charged, then turn the LED on and transition to Activation.

b) IF VRS ≤ VBATT < VMAX

THEN Rapid Charge

If the battery voltage rises above the Rapid Charge start voltage, then transition to Rapid Charge.

c) IF VFULL ≤ VBATT < VMAX

AND ICHARGE ≤ ITERM

for tTERM Seconds

THEN Charge Complete

When the battery voltage has reached VFULL, change to Rapid Charge. If charge current falls below ITERM for tTERM seconds, turn off charge current and turn off status LED and transition to Charge Complete.

d) IF RTHERMISTOR ≥ ROPEN

THEN Wait for Battery

If a battery is disconnected, then transition to No Battery.

e) IF VBATT ≤ VRE-CH

THEN Initialize the Charging Process

If the battery voltage falls below the re-charge voltage, then transition to Initialization.

f) IF VRE-CH < VBATT

THEN Charge Complete

If the battery is detected and is fully charged then turn off the LED and transition to Charge Complete.

g) IF VBAT < VACT for tACT Seconds

THEN Battery Error

If the battery voltage is less than VACT after tSTART seconds of activation current, then turn off charge current, turn on red LED and transition to Battery Error.

h) IF VBATT ≥ VMAX

OR ICHARGE ≥ IMAX

OR Constant Current

Charge Duration > tRAP

OR Constant Voltage

Charge Duration > tVCONST

THEN Battery Error

When battery voltage exceeds VMAX, the charge current shuts off and turns on the red LED, which leads to Battery Error.

If the charge current is greater than IMAX, turn off charge current, turn on red LED and transition to Battery Error.

If the constant current charge time is longer than tRAP, or constant voltage charge mode lasts longer than tVCONST seconds, then turn off charge current, turn on red LED and transition to Battery Error.

i) IF VBATT ≥ VMAX

OR ICHARGE ≥ IMAX

OR after tACT seconds: VBATT < VRS

THEN Battery Error

When battery voltage exceeds VMAX, turn off charge current, turn on red LED and transition to Battery Error.

If charge current is greater than IMAX, turn off charge current, turn on red LED and transition to Battery Error.

If the activation mode lasts longer than tACT seconds, then turn off the charge current, turn on red LED and transition to Battery Error.

When charge and battery voltage exceeds VMAX and charge current is less than IMIN (indicating battery lead path is broken), then turn on red LED and transition to Battery Error.

j) IF TBATT ≤ TCOLD_STOP

OR TBATT ≥ THOT_STOP

THEN Temperature Outrange

When temperature reading from thermistor is out of range, turn off charge current, blink the status LED and transition to Wait For Temperature.

k) IF TBATT > TCOLD_RESTART

AND TBATT < THOT_RESTART

THEN Resume Charging

When temperature reading returns to operation range, re-start charge in Initialization.

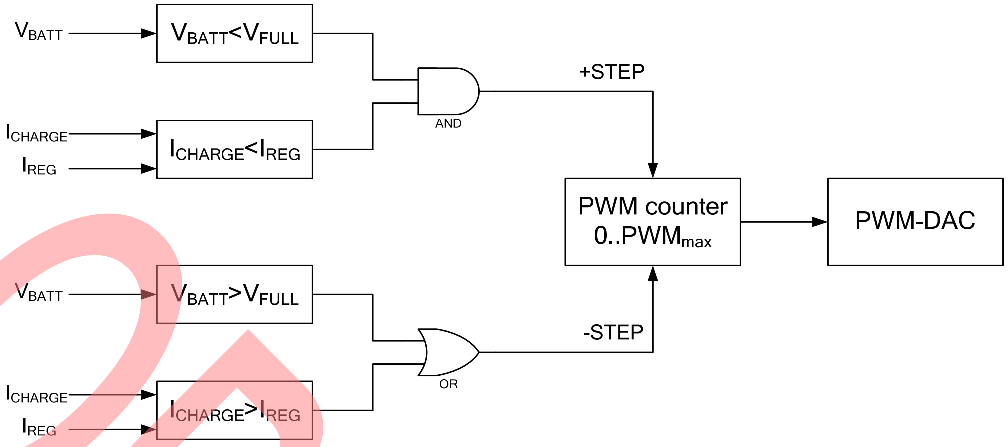
l) IF RTHERMISTOR < ROPEN

THEN Initialize the Charging Process

If a battery is detected, then transition to Initialization.

To build an Li+ battery charger, the regulator must be capable of regulating both charge current and voltage. This charger employs a simple adaptive regulator. The regulator operation is based on increasing PWM counter value if the charge voltage and current are smaller than the predefined value. If the charge voltage or current are greater than the predefined value, the PWM counter will be decreased. The counter values are limited both from below and above by 0 and the PWM maximum value. Figure 7 illustrates the regulator operation.

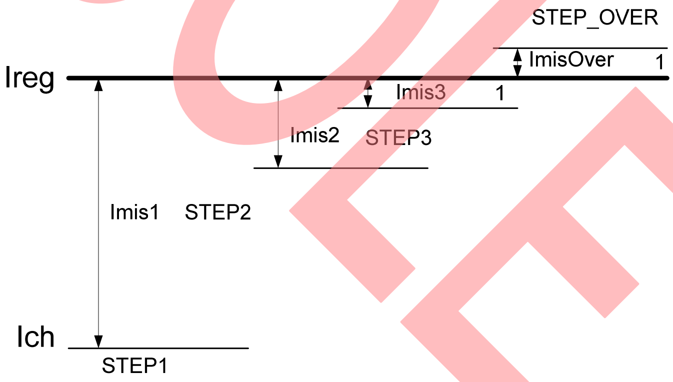
Figure 7. Charger Regulator Operation



To obtain faster current regulation, the scheme with an adaptive step regulator is used (see Figure 8). If the regulator current is greater than the charge current on the Imis1 predefined value, the regulator step is set equal, STEP1. Current differences, Imis2 and Imis3, correspond to STEP2 and STEP3.

If the difference between target charge current and the measured current is smaller, Imis3, then the PWM step is set to equal 1. Current difference ImisOver with STEP_OVER is used for a fast reaction in the event of current overflow. When the battery voltage rises above 4.2V and the *FConstVoltage* flag is set, the regulator step is set to 1 and there is no change during the constant voltage charge period.

Figure 8. Adaptive Step Charge Regulator



Production Calibration Procedure

As previously mentioned, all devices must be calibrated during the manufacturing process. Calibration is an easy procedure but needs a precise 4.2V source, instead of a battery, connected to the charger connector. It also needs pin 5 of the ISSP connector connected to ground. After start, the charger is used to check the P1[0] pin. If P1[0] is externally pulled down, then the charger goes to calibration mode. P1[0] is then connected to pin 5 of ISSP connector (J2, see schematic in Appendix 1). In this mode, MOSFET Q1 is on, MOSFET Q2 is off, and the charger measures the constant 4.2V.

The charger measures the 4.2V external voltage. The obtained ADC code is used to calculate threshold values for other voltages (see Equation 8). These values are stored in Flash for future reference.

$$V_X = K_X \cdot V_{pr4.2V} \qquad \text{Equation 8}$$

V_X is the required voltage threshold, individual scale coefficient. One way to calculate these thresholds is by using mathematical multiplication and division routines, but in this Application Note, the threshold values can only be obtained using simple operations of addition, subtraction, and shifts as shown in Equation 9.

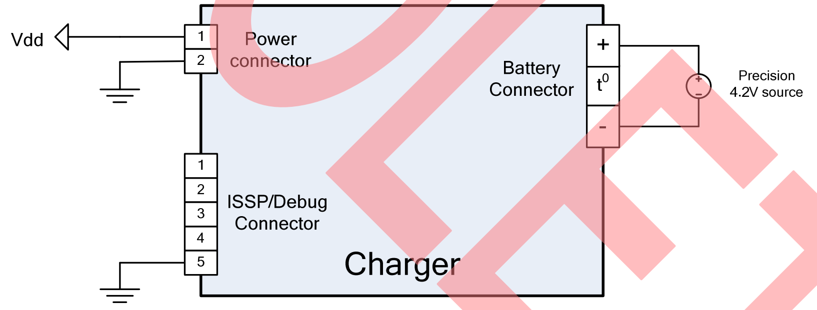
$$
\begin{aligned}
V_{FULL}^{specification} &= 4.2V; & V_{FULL}^{actual} &= V_{pr4.2V};\\
V_{RE-CH}^{specification} &= 4.0V; & V_{RE\_CH}^{actual} &= V_{FULL} - \frac{V_{FULL}}{32} - \frac{V_{FULL}}{64};\\
V_{ACT}^{specification} &= 2.0V; & V_{ACT}^{actual} &= \frac{V_{RE-CH}}{2};\\
V_{RS}^{specification} &= 3.0V; & V_{RS}^{actual} &= V_{RE-CH} - \frac{V_{ACT}}{2};\\
V_{MAX}^{specification} &= 4.35V; & V_{MAX}^{actual} &= V_{FULL} + \frac{V_{FULL}}{32} + \frac{V_{FULL}}{256};
\end{aligned}
$$

Equation 9

The advantage of this method is efficient code. The disadvantage is that it is largely dependent on specific values. If V_{RE-CH}, V_{ACT}, V_{RS} or, V_{MAX} changes, Equation (9) must be recreated and the corresponding firmware code fragment must be rewritten.

The charger connection used for calibration is shown in Figure 9.

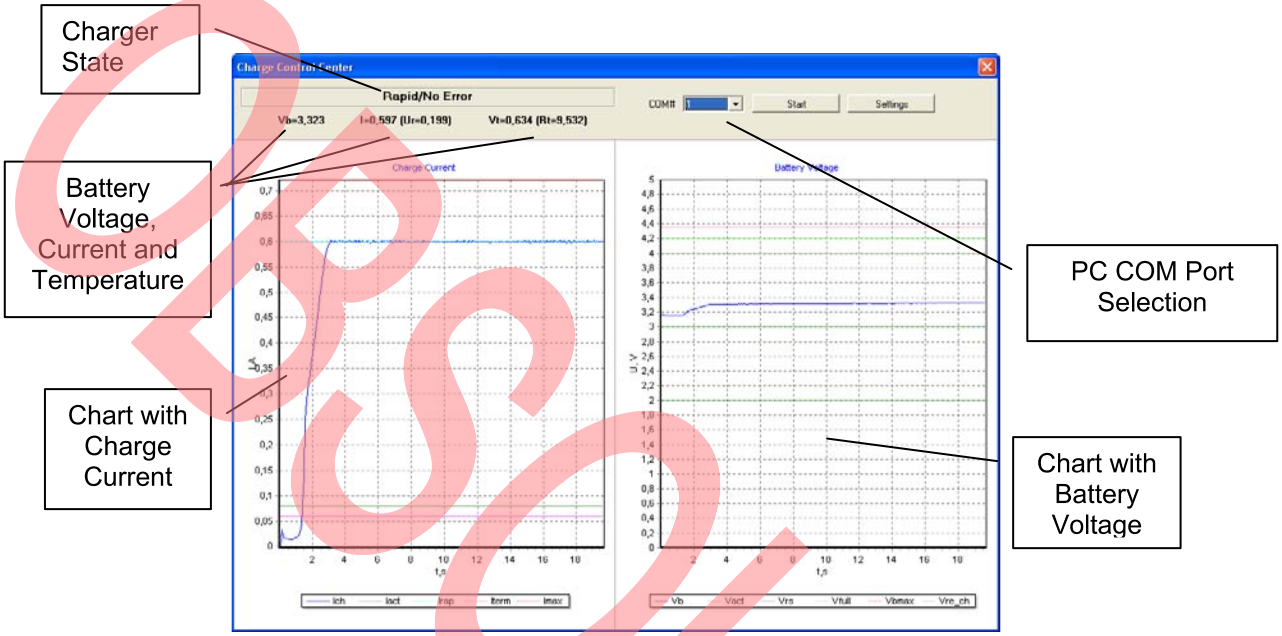
Figure 9. Charger Connection Used For Calibration



PC Utilities and Debug Information

The charger control software was developed to monitor the charge process. The program interface is very simple (Figure 10). The user sets the COM# and presses the Start button. Then turns on the charger. The software then presents the charger state and builds graphs with charge current and voltage (see Figure 10).

Figure 10. PC Charger Monitoring Software

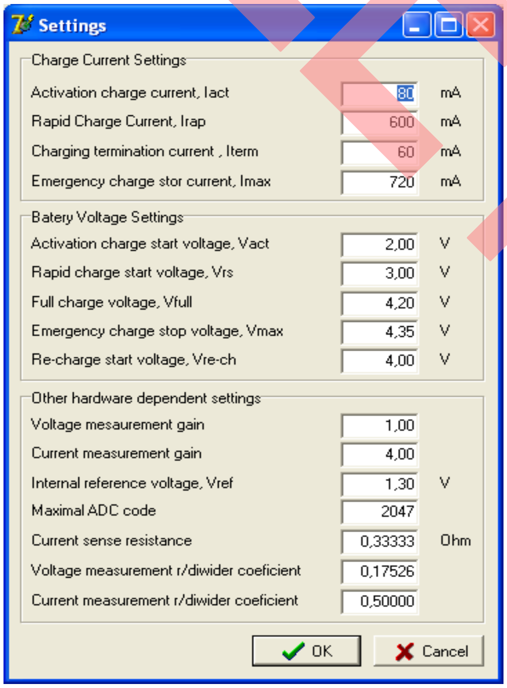


Rapid/No Error

Vb=3,323 I=0,597 (Ur=0,199) Vt=0,634 (Rt=9,532)

If the user changes the battery parameters in the charger project, then similar changes can be made in the Settings utility window, which is accessed by pressing the Settings button (see Figure 11).

Figure 11. Settings Window



Charge Current Settings

Activation charge current, Iact	80	mA
Rapid Charge Current, Irap	600	mA
Charging termination current , Iterm	60	mA
Emergency charge stor current, Imax	720	mA

Batery Voltage Settings

Activation charge start voltage, Vact	2,00	V
Rapid charge start voltage, Vrs	3,00	V
Full charge voltage, Vfull	4,20	V
Emergency charge stop voltage, Vmax	4,35	V
Re-charge start voltage, Vre-ch	4,00	V

Other hardware dependent settings

Voltage mesaurement gain	1,00	
Current measurement gain	4,00	
Internal reference voltage, Vref	1,30	V
Maximal ADC code	2047	
Current sense resistance	0,33333	Ohm
Voltage measurement r/diwider coeficient	0,17526	
Current measurement r/diwider coeficient	0,50000	

The charger can send two kinds of packets to the PC utility. Both packets are text format and all values are hexadecimal. The first packet is an initialization packet that is sent one time after the charger is powered on.

This package has a length of 22 bytes and contains the stored non-volatile memory voltage thresholds that were obtained during charger calibration. Packet details are represented in Table 4. The packet's structure is shown in Figure 12.

Table 4. Initialization Package

Item #	Length in Bytes	Reference	Description
1	1		Character 'I' as start marker of initialization packet
2	4	V_{FULL}	4-digit hexadecimal value of full-charge voltage (ADC code after calibration)
3	4	V_{ACT}	4-digit hexadecimal value of activation start voltage (ADC code after calibration)
4	4	V_{RS}	4-digit hexadecimal value of rapid start voltage (ADC code after calibration)
5	4	V_{MAX}	4-digit hexadecimal value of emergency stop voltage (ADC code after calibration)
6	4	V_{RE_CH}	4-digit hexadecimal value of re-charge start voltage (ADC code after calibration)
7	1		Character with ASCII code 13 (CR) as marker of end of packet

Figure 12. Initialization Package Structure

0	1 4	5 8	9 12	13 16	17 20	21
'I'	V_{FULL}	V_{ACT}	V_{RS}	V_{MAX}	V_{RE-CH}	CR

The second packet is sent regularly and contains the current state of the charger battery voltage, charger current, temperature values and errors. Using this packet, the PC utility builds charts and displays actual battery parameters.

This packet has a length of 16 bytes. Packet details are represented in Table 5. The packet's structure is shown in Figure 13.

Table 5. Information Packet

Item #	Length in Bytes	Description
1	1	Character with ASCII code 10 (LF) as packet start marker
2	1	Charger State 0 – Initialization 1 – Battery Activation 2 – Rapid Charge 3 – Charge Complete 4 – Error 5 – Temperature Outrange 6 – No Battery Charger
3	1	Errors 0 – No Error 1 – Voltage Error ($V_{BAT} \geq V_{MAX}$) 2 – Current Error ($I_{CH} \geq I_{MAX}$) 3 – Activation Timeout 4 – Constant Current Rapid Charge Stage Timeout 5 – Constant Voltage Rapid Charge Stage Timeout 6 – Battery Initialization Timeout
4	4	4-digit hexadecimal value of charge current (I_{CHARGE}) ADC code
5	4	4-digit hexadecimal value of battery voltage (V_{BATT}) ADC code
6	4	4-digit hexadecimal value of voltage drop on R12 code used for temperature control
7	1	Character with ASCII code 13 (CR) as marker of end of packet

Figure 13. Information Package Structure

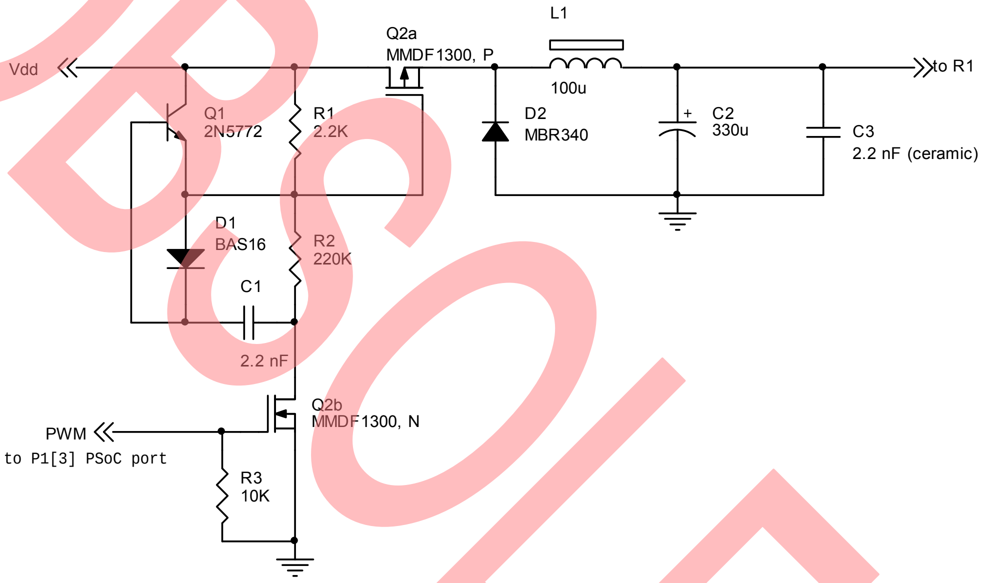
0	1	2	3 … 6	7 … 10	11 … 14	15
LF	State	Error	I_{CHARGE}	V_{BATT}	t^0	CR

Further Design Modifications

The proposed charger in this Application Note is based on a linear current regulator. The advantages of this regulator are its low-cost and small size.

The switch regulator is recommended from an efficiency point of view for batteries with over 1000 mA/h capacity. In this case, a step-down regulator is preferred (see Figure 14). The disadvantage of a step-down regulator is the large size of its components, especially the inductor.

Figure 14. Step-Down Current Regulator



The MOSFET Q2 (see Appendix 1) acts as a diode, preventing the battery from discharging when no power is applied to the charger. When Q2 is on, the on-resistance voltage drop is 0.02 to 0.05V, depending on the charge current. When minimum charger supply voltage is greater than battery maximum voltage, of more than 0.5V, the Schottky diode can be used instead of Q2 and Q3.

The **Current sensing** technique can also vary. There are four possible variants of current-sense resistor placement and connection (Figure 15). Each variant has its own benefits and drawbacks.

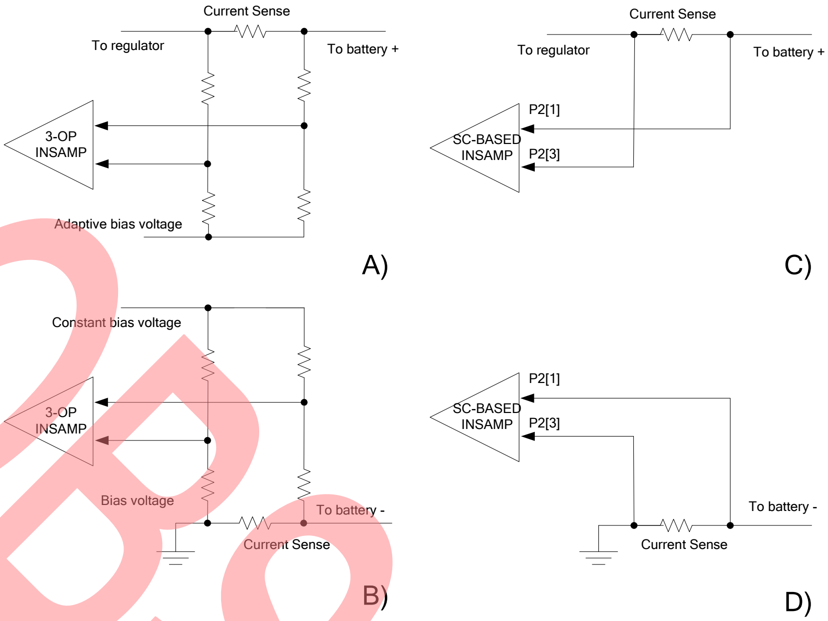
In variant A, the resistor is placed in the positive wire. The disadvantage of this placement is the need of adaptive voltage bias to avoid the influence of battery voltage to measured current due to the deviation in resistive divider values. This is the current design.

In variant B, voltage bias is constant. An adaptive voltage bias is not needed. But in this case, the negative lead of the battery is not directly connected to system ground. In some designs, this type of connection is unacceptable.

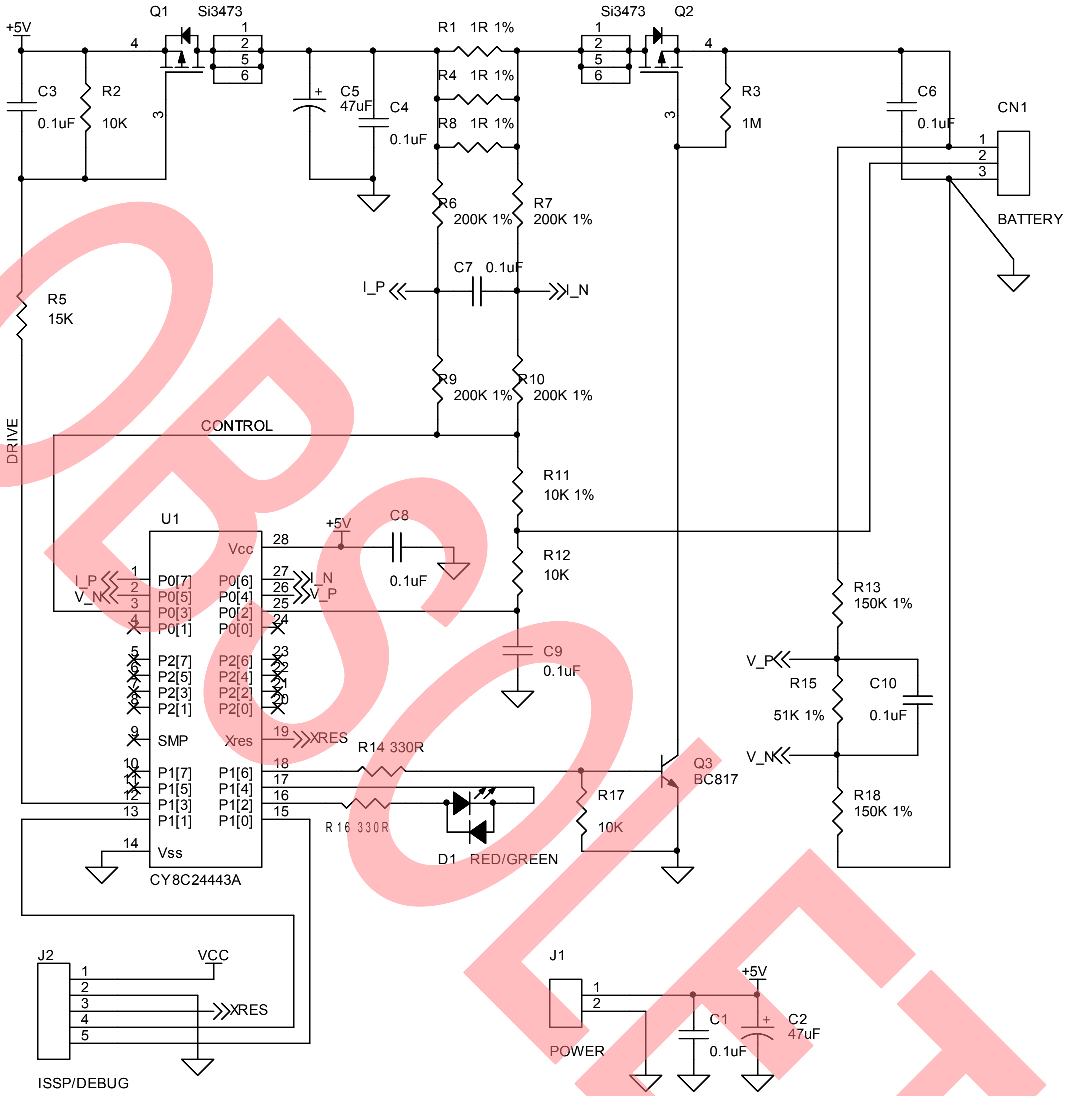
In variant C, a switched-capacitor-based instrumentation amplifier is used instead of a 3-opamp instrumentation amplifier, which is used in variants A and B. The advantage of this implementation is clear in the rail-to-rail input range. For the configuration, please see Application Note AN2041 – Standard – "Understanding Switched Capacitor Analog Blocks." This will require a 28-pin part (variants A and B can use a 20-pin part). Variants C and D must use parts with port 2 inputs (28-pin packages) and use more complicated offset compensation schemes. Also, variant C is unable to measure current when battery voltage is greater than PSoC power voltage.

In variant D, the same setup is used as in variant C except that the current-sense resistor is placed in the negative wire. This variant is not dependent on the battery voltage but, like variant B, it cannot be used in some designs because the battery "-" is not connected to system ground.

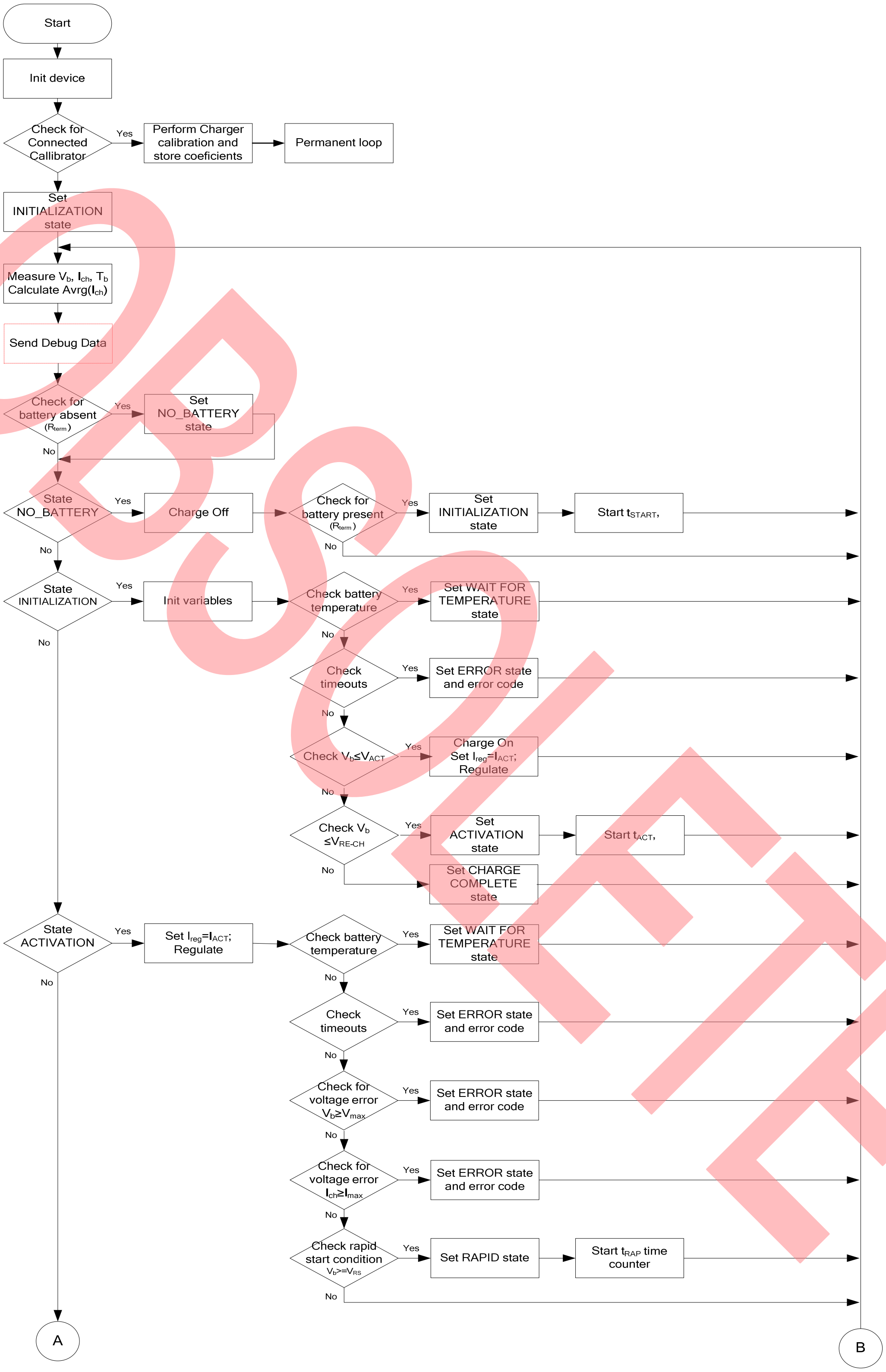
Figure 15. Variants of Current-Sense Resistor Placement and Connection

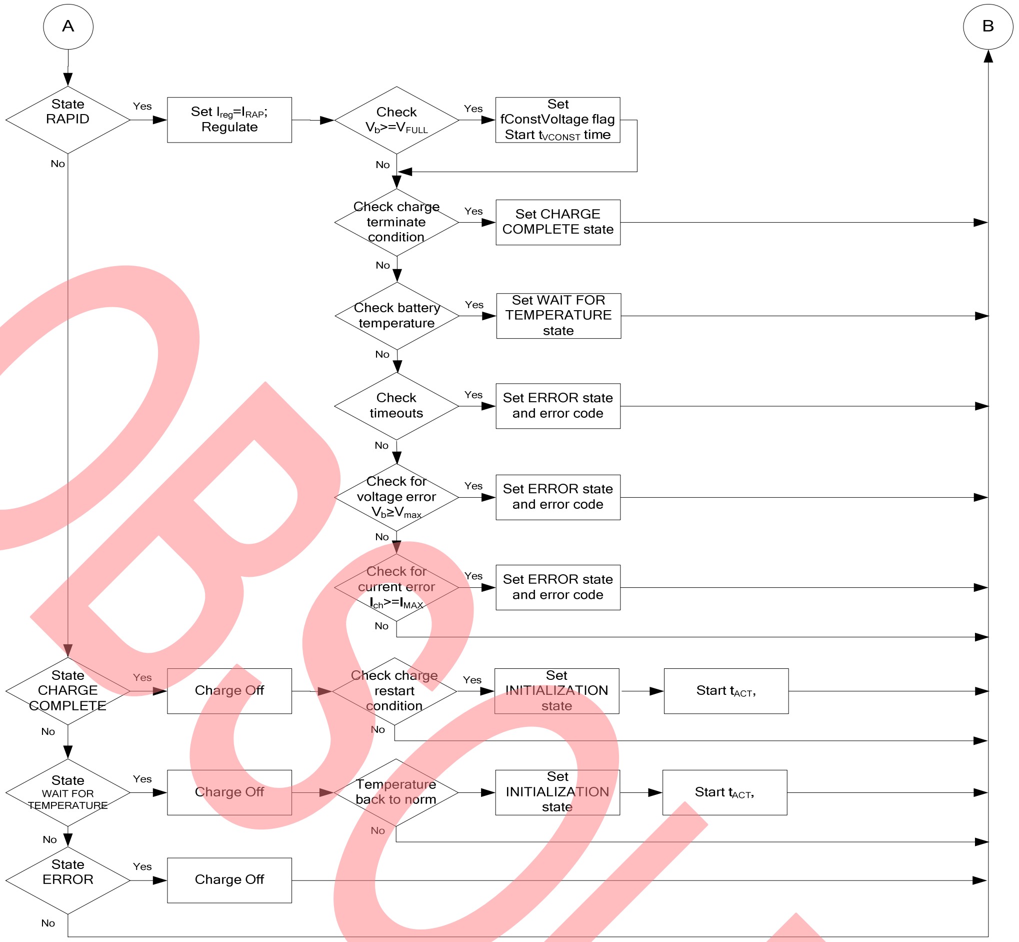


Appendix A. Charger Schematic

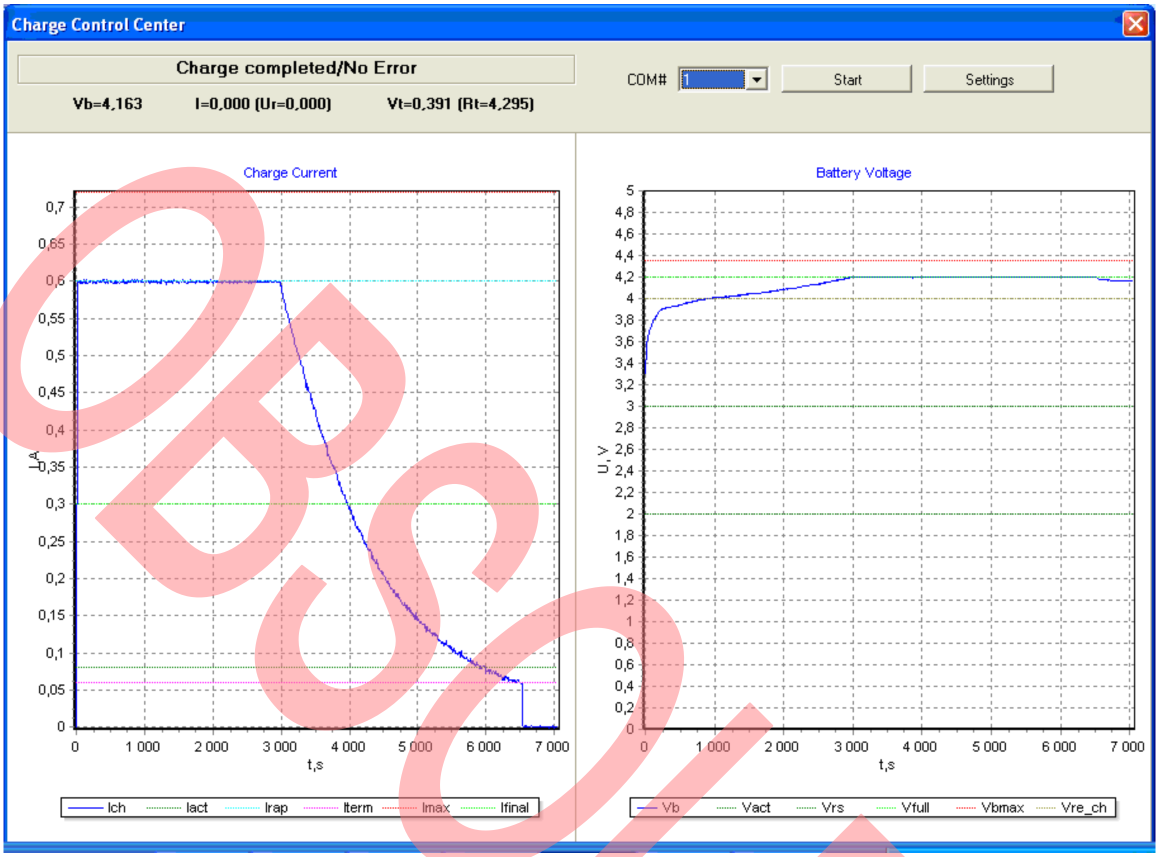


Appendix B. Firmware Flowchart




A
B
State RAPID
Yes
No
Set $I_{reg}=I_{RAP}$; Regulate
Check $V_b>=V_{FULL}$
Yes
No
Set fConstVoltage flag Start t_{VCONST} time
Check charge terminate condition
Yes
No
Set CHARGE COMPLETE state
Check battery temperature
Yes
No
Set WAIT FOR TEMPERATURE state
Check timeouts
Yes
No
Set ERROR state and error code
Check for voltage error $V_b \geq V_{max}$
Yes
No
Set ERROR state and error code
Check for current error $I_{ch}>=I_{MAX}$
Yes
No
Set ERROR state and error code
State CHARGE COMPLETE
Yes
No
Charge Off
Check charge restart condition
Yes
No
Set INITIALIZATION state
Start t_{ACT},
State WAIT FOR TEMPERATURE
Yes
No
Charge Off
Temperature back to norm
No
Set INITIALIZATION state
Start t_{ACT},
State ERROR
Yes
No
Charge Off

Appendix C. Charge Process Example



Charge Control Center

Charge completed/No Error

Vb=4,163 I=0,000 (Ur=0,000) Vt=0,391 (Rt=4,295)

COM# 1

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Revision	ECN	Orig. of Change	Submission Date	Description of Change
**	1494923	YJI	09/21/07	New Application note.
*A	3088791	YARA	11/17/10	No change to spec. Sunset ECN – added doc history table.
*B	4207653	SGUP	12/02/13	Obsolete Spec.

OBSOLETE

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.

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