# Application Note AN2267a

## *Single Cell Li+ Battery Charger using CY8C21xxx*

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**Associated Project**: Yes
**Associated Part Family**: CY8C21xxx
**PSoC Designer Version**: 4.2 + SP2
**Associated Application Notes**: AN2107

## Abstract

A CY8C21xxx-based 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 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 recommendation), the charge is processed with constant current (about 0.5-1 CA, depending on battery manufacturer recommendation). When the battery voltage reaches the predefined level, the charge source switches to constant voltage mode (4.1-4.2V). 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.

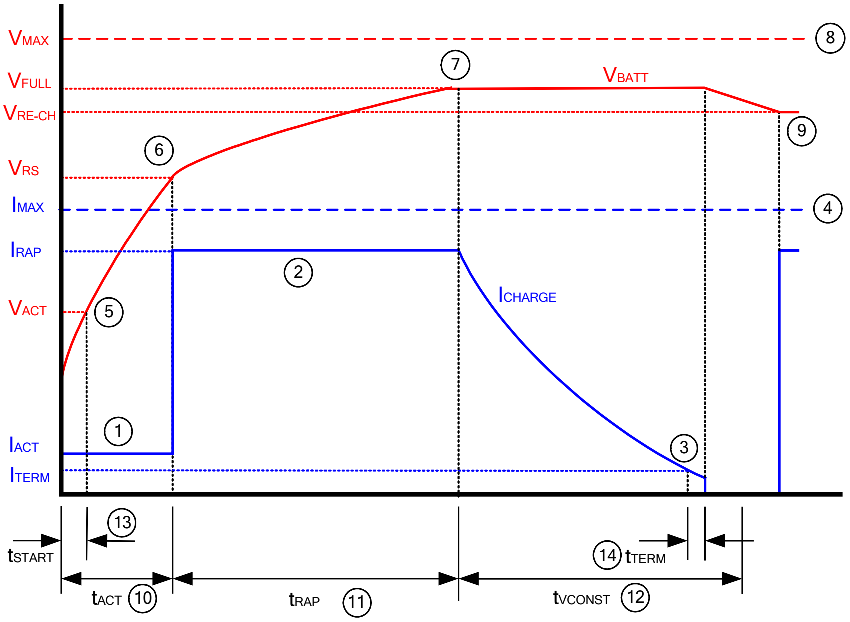


Figure 1. Li+ Battery Charging Profile

**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 completion (when $I_{CHAVG} \leq I_{TERM}$) | 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°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.

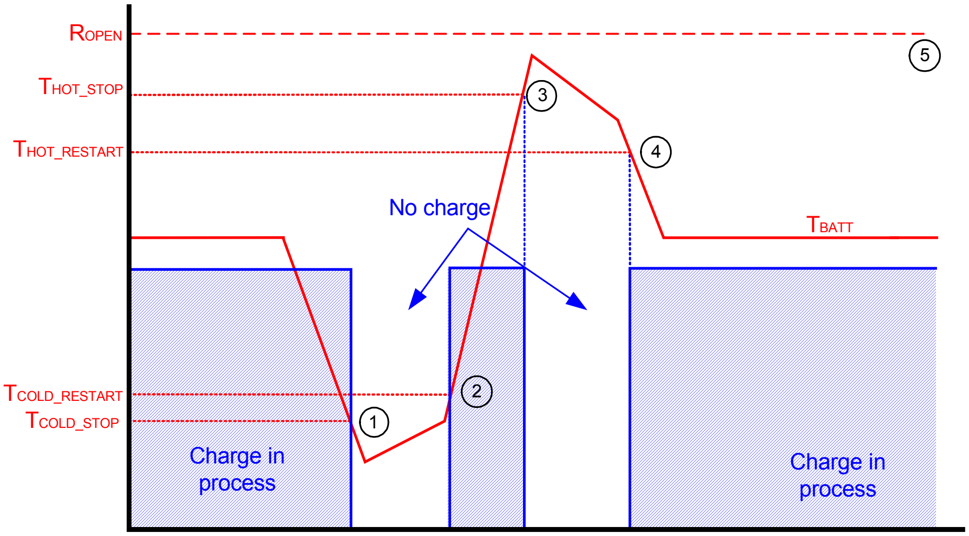


**Figure 2. Temperature Profile**

**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. A constant voltage signal that is proportional to the PWM duty cycle value forms on the gate, Q1. 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 transform the battery current, voltage and temperature into a signal, all of which are suitable for the PSoC$^{TM}$ device.

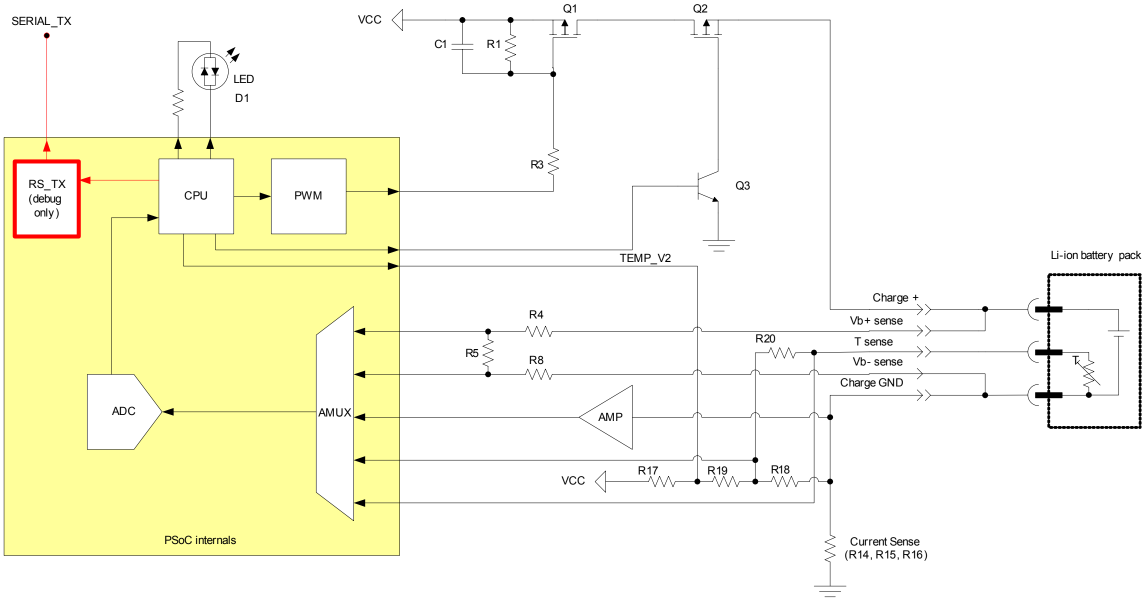


**Figure 3. Charger Structure**

As the voltage drops on the corresponding resistors, all parameters are measured using the internal 10-bit ADC. All measurements are performed by ADC offset compensation methods. 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.

For all measurements, the ADC is configured to provide maximal code (1024) at $2V_{ref}$ (2.6V).

The battery voltage is measured as a voltage drop on R5. The voltage is measured in two steps. First, the voltage is measured from the positive side of the battery lead. Then the voltage is measured from the negative side of the battery lead. Finally, the difference between the two measured values is calculated. Such a method compensates for the ADC offset in a way that is constant for both measurements.

$$\Delta n_V = \frac{n_{cal}}{V_{ref}}\left(V_{ADC}^{P} - V_{ADC}^{N}\right) = \frac{n_{cal}}{V_{ref}}\beta_V V_{bat} \qquad \textbf{(1)}$$

- $\Delta n_V$ is the ADC code without influence of the ADC offset voltage.
- $n_{cal}$ is the code value used under ADC calibration that corresponds to the $V_{ref}$ (1.3V) voltage measured by ADC (512).
- $V_{bat}$ is battery voltage.
- $V_{ref}$ is bandgap reference voltage (1.3V).
- $V^{P}_{ref}$ is voltage measured from R5 at the positive side of the battery lead.
- $V^{N}_{ref}$ is voltage measured from R5 at the negative side of the battery lead.
- $\beta_V$ is the resistive divider coefficient (equal to 0.48387 for R4=150 kΩ, R5=150 kΩ, R8=10 kΩ divider resistors).

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 the resistive voltage divider is 1 percent. These error sources 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.

Current measurements are implemented by measuring the voltage drop on the 0.333-ohm resistor, which is placed in the negative battery lead path. Because the current sense resistor signal is too small to be handled directly by the ADC, it is amplified by using the external amplifier with gain 8.4. The current value measured at the Initialization stage (see Figure 6), when current is not yet flowing through the current sense resistor, is stored as an ADC and AMP offset. After every measurement, the ADC and AMP offset is subtracted from the measured value. Therefore, all measured current values are free from ADC and AMP offset.

$$\Delta n_I = \frac{n_{cal}}{V_{ref}} V_{ADC} - n_{bias} =$$

$$= \frac{n_{cal}}{V_{ref}} G_{AMP} R_{sense} I_{bat} \qquad \textbf{(2)}$$

- $\Delta n_I$ is the ADC code without influence of the ADC and AMP offset voltage.
- $n_{bias}$ is the ADC code measured when no current is flowing through the current sense resistor.
- $n_{cal}$ is the code value used under ADC calibration that corresponds to the $V_{ref}$ (1.3V) voltage measured by ADC (512).
- $I_{bat}$ is battery charge current.
- $G_{AMP}$ is AMP gain (8.4).
- $V_{ref}$ is bandgap reference voltage (1.3V).
- $R_{sense}$ is current sense resistor value (0.333 ohm)

Temperature measurement is implemented via the Temp Sense, R20 (see Appendix 1). The voltage-drop measurement is done by applying, in series, two different voltages to the battery temperature sense resistor path. The first voltage is set by applying the logical high value to the TEMP_V2 wire. The second voltage on the temperature sense resistor forms when TEMP_V2 stays in High-Z mode. To determine the temperature, voltage measurements should be taken for voltages $V_1$, $V_2$, $V_{t1}$, and $V_{t2}$. This technique allows compensation of both the ADC offset and the possible offset caused by the voltage drop on the current sense resistor. These potential differences must be cancelled out in order to improve accuracy of temperature measurement. Figure 4 and Equation (3) illustrate how this works.

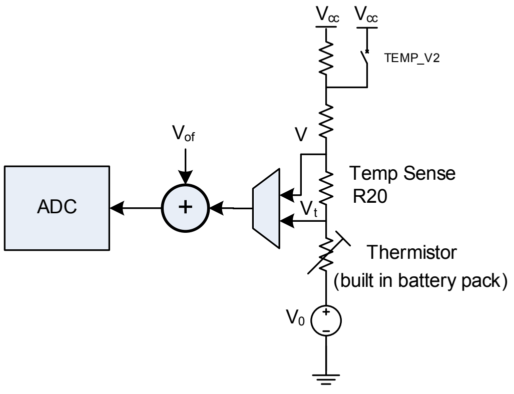


**Figure 4. Temperature Measurement**

$$V_{t1} = V_0 + V_{of} + \frac{R_{term}}{R_{20} + R_{term}}\left(V_1 - V_0\right);$$

$$V_{t2} = V_0 + V_{of} + \frac{R_{term}}{R_{11} + R_{term}}\left(V_2 - V_0\right); \qquad \textbf{(3)}$$

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

- $V_1$ and $V_2$ are the voltages measured in $V$ point when the switch TEMP_V2 is turned ON and turned OFF, respectively.
- $V_{t1}$ and $V_{t2}$ are the voltages measured from the temperature sense resistor when $V_1$ and $V_2$ are applied, respectively.
- $V_{of}$ and $V_0$ are offset voltages.
- $R_{term}$ 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 differences ($V_{t1}$-$V_{t2}$ and $V_1$-$V_2$). A hysteresis is added for the lower 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,<br>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 5.

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.

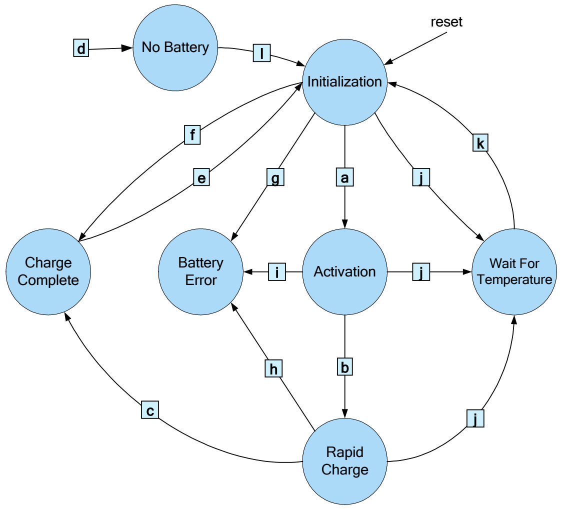


**Figure 5. Charger State Diagram**

**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 mode until current falls below $I_{TERM}$.

**Charge Complete**: Turns 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**: Turns on red LED and turns 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 limit. Wait for temperature to return within the limit. Then move to the Initialization state.

State Transition Descriptions:

**a)** IF VACT < VBATT ≤ VRE-CH
THEN Activation Current

If the battery is detected and 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 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 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 a 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 6 illustrates the regulator operation.

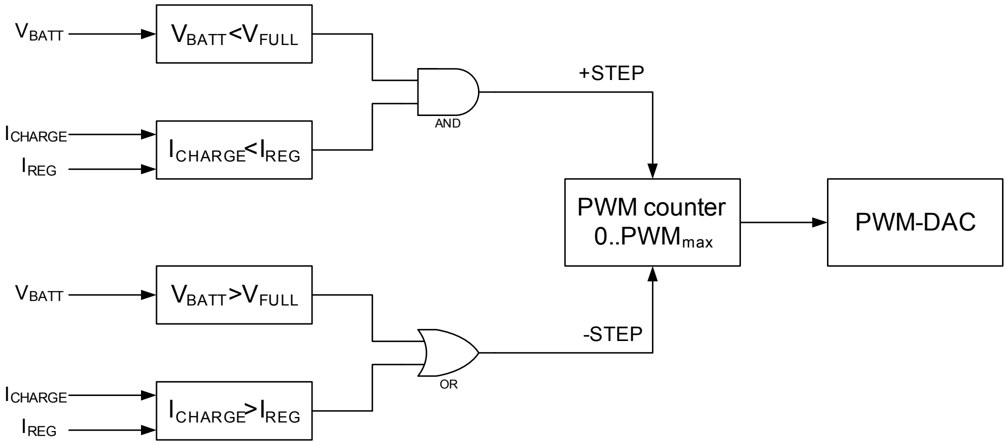


**Figure 6. Charger Regulator Operation**

To obtain faster current regulation, the scheme with an adaptive step regulator is used (see Figure 7). 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.

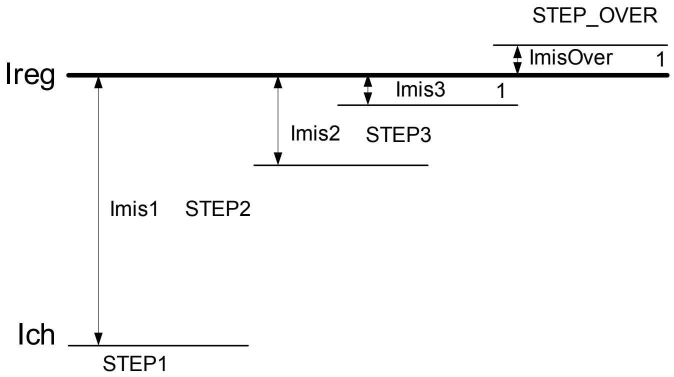


**Figure 7. Adaptive Step Charge Regulator**

## 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 the 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 (4). These values are stored in Flash for future reference.

$$V_X = K_X \cdot V_{pr4.2V} \tag{4}$$

$V_X$ 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 (5).

$$\begin{aligned}
V_{FULL}^{specification} &= 4.2V; & V_{FULL}^{actual} &= V_{pr4.2V};\\
V_{RE-CH}^{specification} &= 4.0V; & V_{RE\_CH}^{actual} &= V_{FULL} - \frac{V_{FULL}}{32} - \frac{V_{FULL}}{64};\\
V_{ACT}^{specification} &= 2.0V; & V_{ACT}^{actual} &= \frac{V_{RE-CH}}{2};\\
V_{RS}^{specification} &= 3.0V; & V_{RS}^{actual} &= V_{RE-CH} - \frac{V_{ACT}}{2};\\
V_{MAX}^{specification} &= 4.35V; & V_{MAX}^{actual} &= V_{FULL} + \frac{V_{FULL}}{32} + \frac{V_{FULL}}{256};
\end{aligned} \tag{5}$$

The advantage of this method is efficient code. The disadvantage is that it is largely dependent on specific values. If $V_{RE\text{-}CH}$, $V_{ACT}$, $V_{RS}$ or, $V_{MAX}$ changes, Equation (5) must be recreated and the corresponding firmware code fragment must be rewritten.

The charger connection used for calibration is shown in Figure 8.

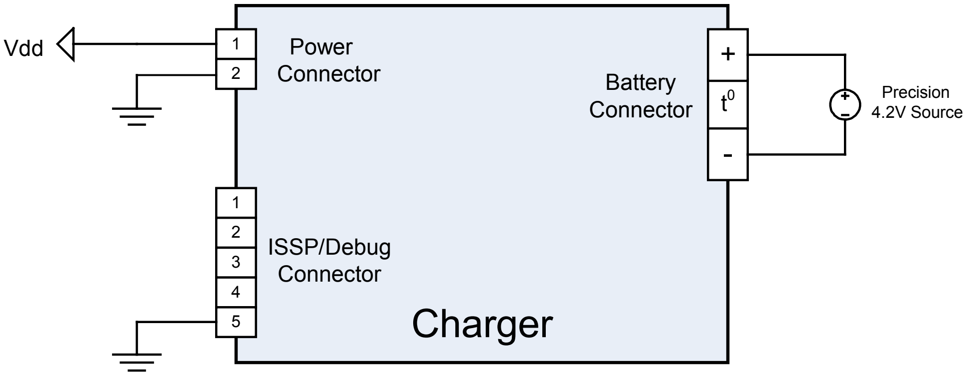
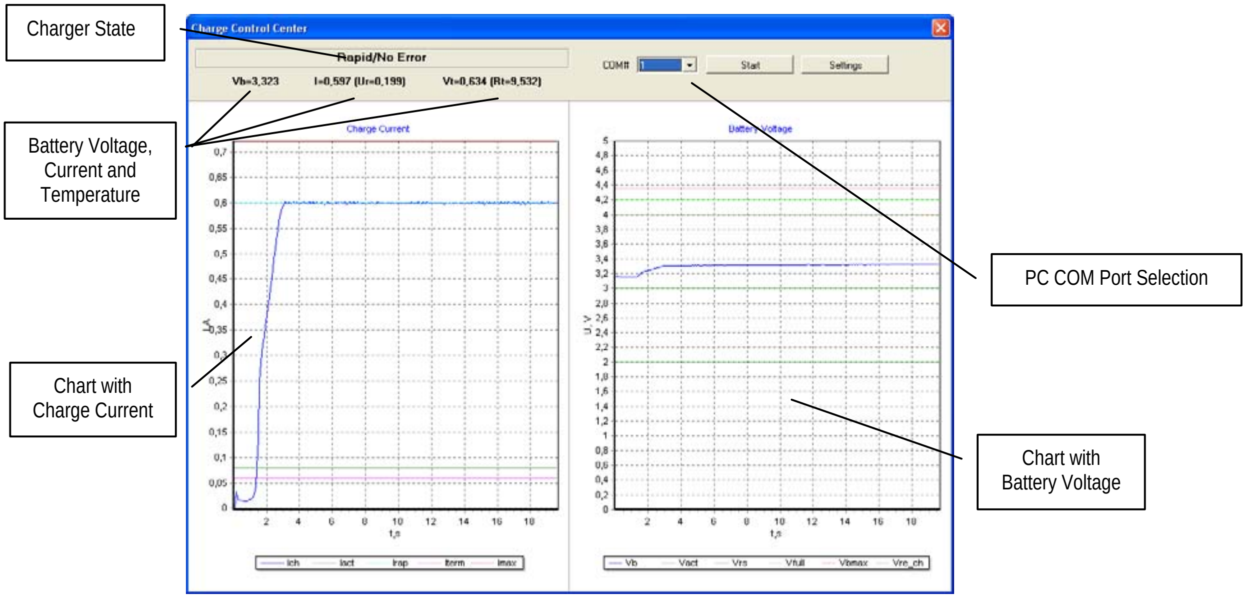


Figure 8. Charger Connection Used for Calibration

## PC Utilities and Debug Information

The charger control software was developed to monitor the charge process. The program interface is very simple (Figure 9). The user sets the COM#, clicks the Start button and turns on the charger. The software then presents the charger state and builds graphs with charge current and voltage (see Figure 9).

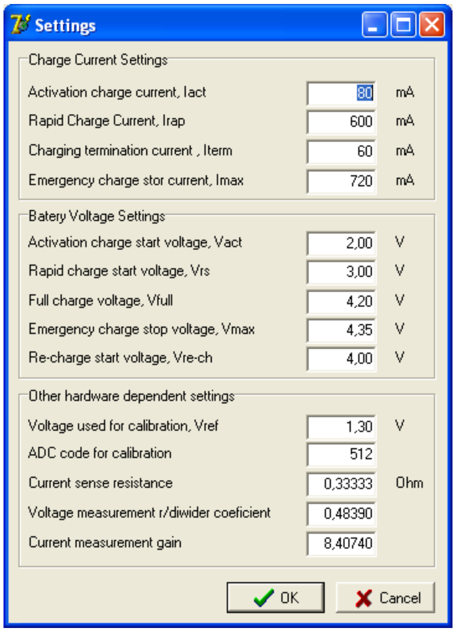

Rapid/No Error

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

COM# 1

Figure 9. PC Charger Monitoring Software

If the user changes the battery parameters in the charger project, then similar changes can be made in the Settings utility window (Figure 10), which is accessed by pressing the Settings button (Figure 9).



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 used for calibration, Vref | 1,30 | V |
| ADC code for calibration | 512 | |
| Current sense resistance | 0,33333 | Ohm |
| Voltage measurement r/diwider coeficient | 0,48390 | |
| Current measurement gain | 8,40740 | |

**Figure 10. Settings Window**

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 11.

**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 |

| 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 |

**Figure 11. Initialization Package Structure**

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 20 bytes. Packet details are represented in Table 5. The packet's structure is shown in Figure 12.

**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<br>0 – Initialization<br>1 – Battery Activation<br>2 – Rapid Charge<br>3 – Charge Complete<br>4 – Error<br>5 – Temperature Outrange<br>6 – No Battery Charger |
| 3 | 1 | Errors<br>0 – No Error<br>1 – Voltage Error ($V_{BAT} \geq V_{MAX}$)<br>2 – Current Error ($I_{CH} \geq I_{MAX}$)<br>3 – Activation Timeout<br>4 – Constant Current Rapid Charge Stage Timeout<br>5 – Constant Voltage Rapid Charge Stage Timeout<br>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 ($V_1$-$V_2$) used to determine thermistor resistance |
| 7 | 4 | 4-digit hexadecimal value of ($V_{t1}$-$V_{t2}$) used to determine thermistor resistance |
| 8 | 1 | Character with ASCII code 13 (CR) as marker of end of packet |

| 0 | 1 | 2 | 3 6 | 7 10 | 11 14 | 15 18 | 19 |
|---|---|---|---|---|---|---|---|
| LF | State | Error | $I_{CHARGE}$ | $V_{BATT}$ | $V_1$-$V_2$ | $V_{t1}$-$V_{t2}$ | CR |

**Figure 12. Information Package Structure**

## 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 13). The disadvantage of a step-down regulator is the large size of its components, especially the inductor.

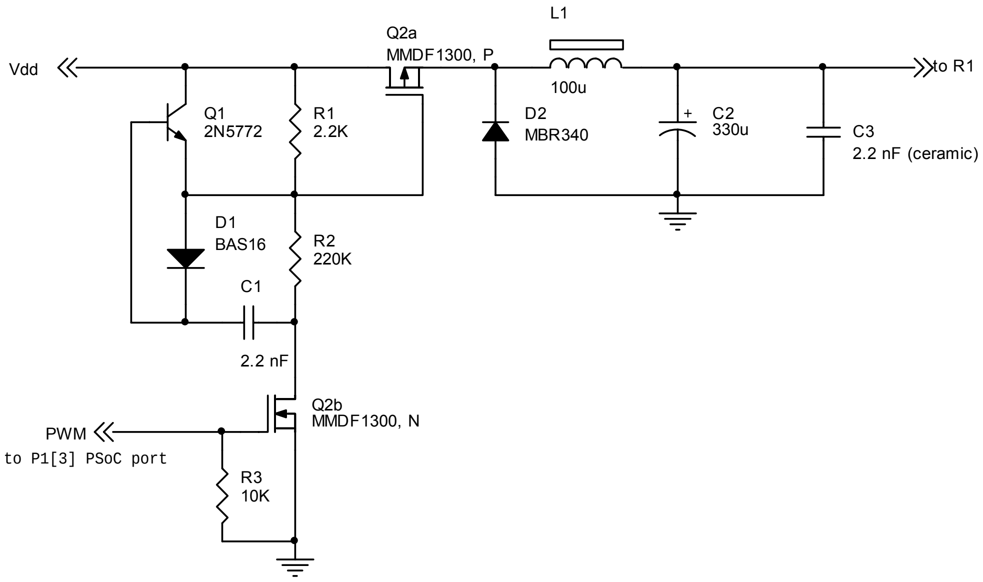


**Figure 13. Step-Down Current Regulator**

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 two possible variants of current-sense resistor placement and connection (Figure 14). 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 an expensive instrumentation amplifier dedicated for current sense signal conditioning.

In variant B, the current sense resistor in placed in the negative battery lead path. This allows use of a low-cost opamp rather than a special instrumentation amplifier. Variant B cannot be used in some designs because the battery “-“ is not connected to system ground. This is the current design.

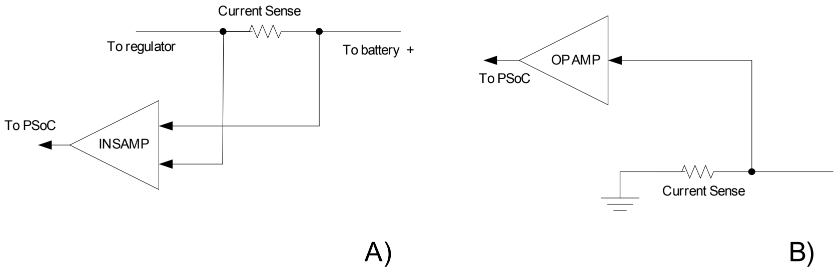
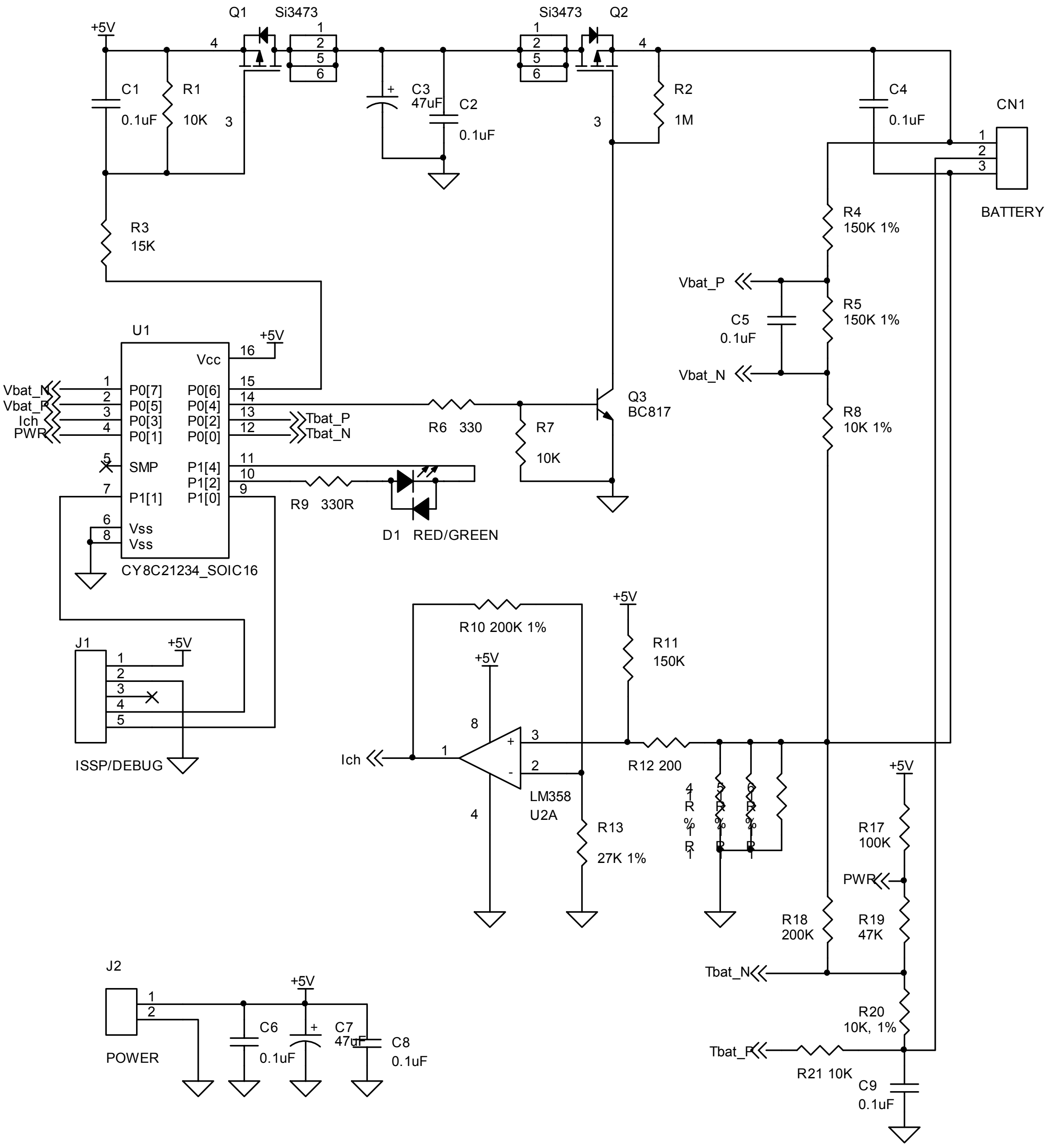
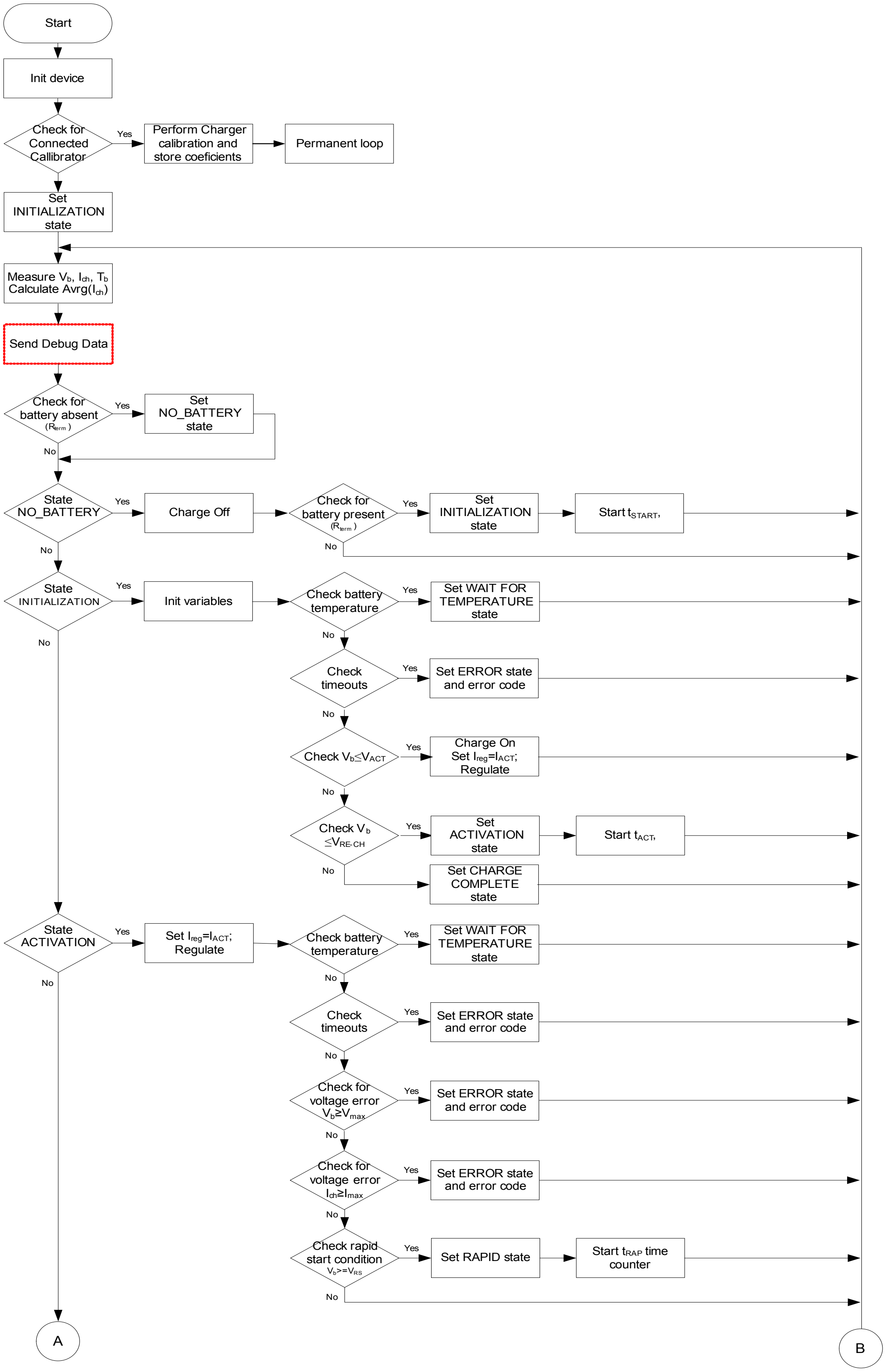


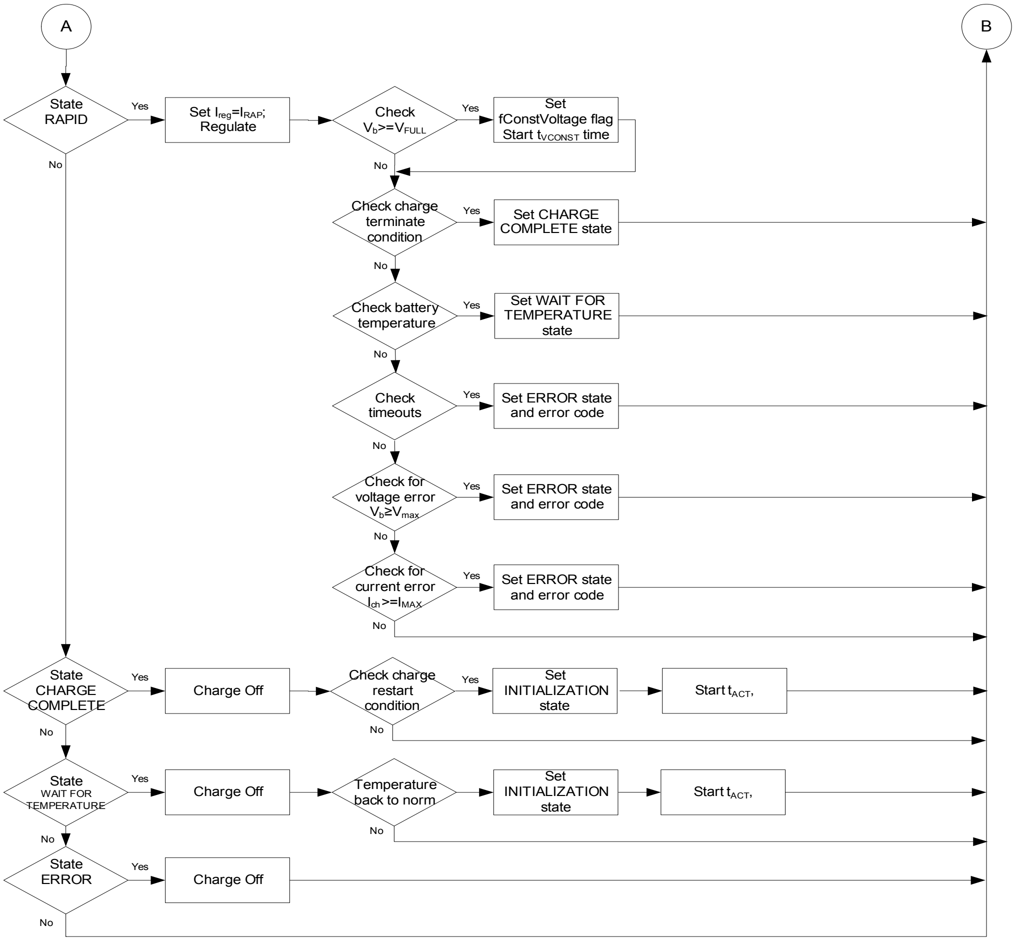
**Figure 14. Variants of Current-Sense Resistor Placement and Connection**

# Appendix 1. Charger Schematic

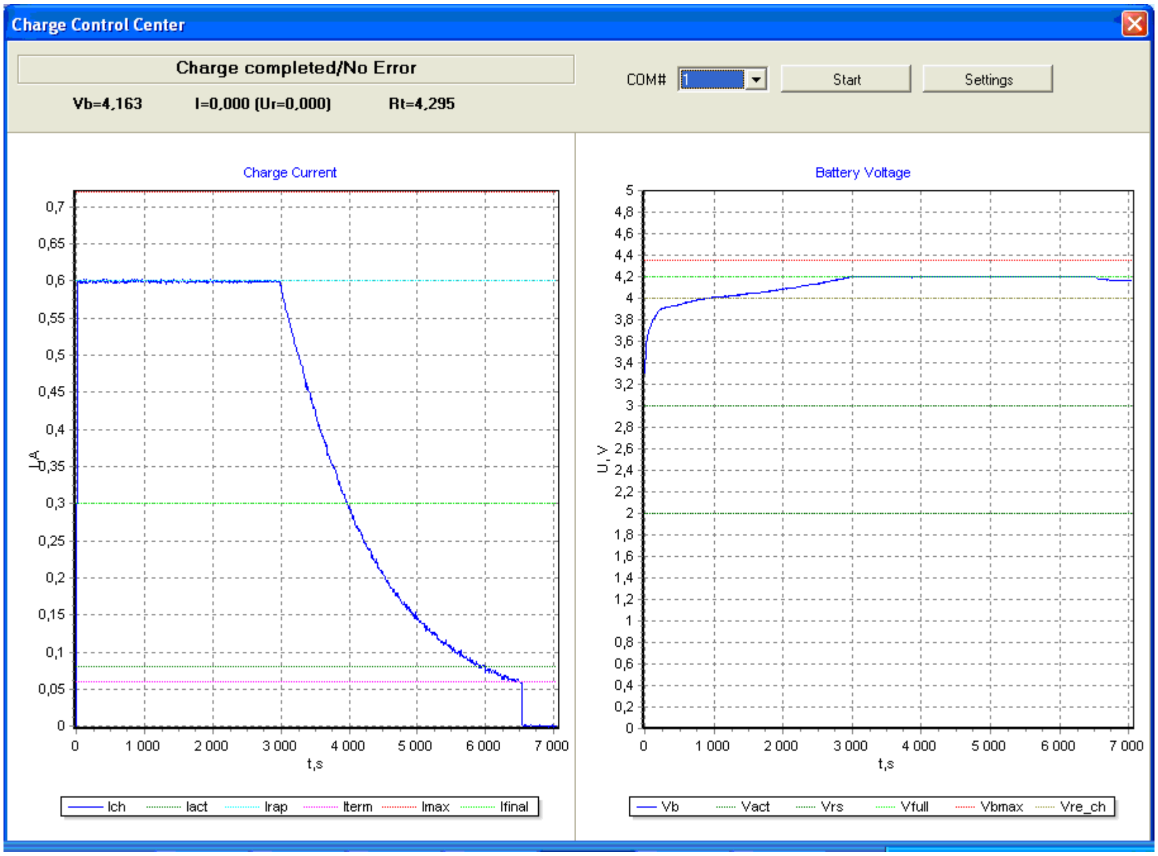


# Appendix 2. Firmware Flowchart




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≥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 3. Charge Process Example



Charge Control Center

Charge completed/No Error

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

## About the Author

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