

## ***A Multi-Chemistry Battery Charger***

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**Associated Project:** Yes  
**Associated Part:** CY8C26xxx

### **Summary**

The multi-chemistry battery charger design is presented. The charger is capable of charging the Ni-Cd, Ni-MH, Li-Ion, Li-Pol and SLA batteries without any hardware/software modifications. The dedicated PC-based software has been developed to configure the charger and perform real-time charging process visualization and analysis. This charger can be used as a standalone application to charge various battery types or embedded into consumer, home appliances or industrial applications. Alternative charger applications are studied as well.

### **Introduction**

Modern applications use various battery types. Sealed Lead-Acid (SLA) batteries are used typically in cost-sensitive applications where cost is more important than capacity/volume ratio. The typical application examples include Un-interruptible Power Supplies, back-up power in security or surveillance systems, and stationary lighting systems. Nickel-Cadmium (Ni-Cd) and Nickel-Metal-Hydride (Ni-MH) batteries are characterized by moderate capacity/volume ratio and are widely used in various consumer electronics. The Lithium-Ion (Li-Ion) and the Lithium-Polymer (Li-Pol) batteries are characterized by the greatest capacity/volume ratio and can be found in notebooks, pocket PCs, cell phones and newer consumer applications.

Each battery type needs a dedicated charging scheme to properly charge a battery. Despite the chipmaker's suggestions that there are various integrated circuits to implement battery chargers, these circuits are designed to charge only predefined battery types and cannot easily be retuned to interact with other battery types or implement additional features.

Each feature implementation needs dedicated components thus increasing the device complexity and price. The unique architecture of PSoC allows building the multi-functional battery charger with minimal external components and a universal, multifunctional system at a very affordable price. When a user wants to implement additional functions or support a new battery type, only the firmware needs to be modified. The PSoC in-circuit and self-programming capabilities make these operations simple.

This Application Note describes the universal battery charger that can process various battery types without hardware and firmware modifications. Users must select an appropriate battery type and battery parameters via PC-based software. These settings are then uploaded into non-volatile memory and the charger is ready to operate as a standalone application. Alternatively, the charger can be controlled via a PC as a slave device to provide real-time, battery-charging process information.

Table 1. Battery Charger Technical Data

Item	Item Value
<b>Supported Battery Capacity</b> (Determined by Step-Down Converter Parameters)	0.1-1.5 A*h
<b>Maximum Battery Voltage</b> (Determined by External Resistor Divider)	7.8 V
<b>Battery Temp. Measuring Range</b> (Re-configurable in Charger-Control Software)	0 ... 64°C
<b>Maximum Total Charge Time</b>	18 h
<b>Battery Current Measuring Error</b> (After Calibration)	1-3%
<b>Battery Voltage Measuring Error</b> (After Calibration)	0.5%
<b>User Interface</b>	2 Buttons and 3 State LEDs
<b>PC Communication Interface</b>	RS232
<b>PC Communication Speed</b>	19200 baud

## Battery Charging Methods

The following section describes the battery charge methods for various battery chemistries. Detailed information concerning battery chemistry, operation and charging methods can be found in the online resources at the end of this note [1-5]. Reference [1] provides excellent information concerning batteries and various aspects of use. The reader must see this reference first. Fast-charge methods, which allow users to fully charge a battery within several hours, are described briefly.

Note that during this section the symbol CA, [h<sup>-1</sup>] will be used to mark charge current to battery-capacity relation. If not otherwise defined, all battery voltages are related to a single cell. Please note that all numerical values are given for reference purposes only. The exact data must be found in the battery's data sheet or obtained from the manufacturer.

### *Ni-Cd and Ni-MH Batteries*

The rapid charging process of these batteries can be separated into three distinct stages: activation charge, rapid charge, and trickle charge. The constant current source must be used to provide battery charging during these phases.

First of all, the battery temperature must be analyzed. If the battery temperature does not fall into a predefined range, typically +10°...+ 50°C, only a small-current trickle charge is allowed. The activation and rapid charge stages can be permitted in an opposite case scenario.

If the battery was excessively discharged, the activation charge stage must be used first. During this stage the battery is charged with current 0.2-0.3 CA until the battery voltage reaches 0.8-1 V/cell or activation charge timeout elapses. If the activation charge stage is terminated by timeout, the battery is considered as inoperative and the charge process is terminated with an error. This can happen if the battery was irreversibly discharged or contained shorted cells.

The rapid charge stage replaces activation charge after battery voltage reaches the rapid start threshold. The battery charge current is set to 0.5-1 CA in this stage. This stage continues until rapid termination conditions are true or timeout elapses. If rapid charge stage was terminated by timeout, the charging process is terminated with an error similar to activation charge timeout termination. This happens typically when a battery is damaged or the charge current was not selected in compliance with battery capacity. Rapid charge timeout can be calculated to transfer 150% of the nominal battery charge; it corresponds to 90 min at 1 CA rapid charge current. The rapid charge stage must be switched to trickle charge stage if even one of the following events has happened:

- The battery voltage dropped from its maximum value. The battery voltage drop level,  $\Delta V$ , must be set equal to 15-20 mV/cell for Ni-Cd batteries and 5-10 mV/cell for Ni-MH. Please note that if the battery was left unused for a long period of time or excessively discharged, the battery voltage can start dropping before the battery is completely charged. This false termination phenomenon must be blocked by initial delay to prevent the incomplete rapid charge termination. Typical timer interval is 5-10 minutes.
- The battery voltage reached its upper threshold limit. This limit must be set to 1.8-1.9 V/cell and prevents the battery from overcharging at the end of battery life when cell resistance rises.
- The battery temperature-raising speed increased. Some portion of the electrical energy is converted into battery chemical energy and the rest is dissipated into heat during the charging process. This useful portion is maximized during the initial rapid charge phase and minimized when the battery is completely charged. In this case virtually all the electrical energy is converted into heat, causing a speedy increase in battery temperature. The temperature derivate must be set to 1-2 °C/min to detect rapid charge completion.
- Note that Ni-Cd battery charging is an endothermic reaction, which causes the battery temperature to decrease during the initial rapid charge phase. The Ni-MH charge reaction is exothermic as opposed to the Ni-Cd charge reaction. For Ni-MH batteries, temperature increases constantly with derivate rising in the final rapid charge phase.
- Battery temperature leaves the allowed temperature range. If the battery was placed in a very hot or cold ambient space during charge (for example, under direct sunlight), the battery temperature can leave the safe rapid charge range. If this happens the rapid charge must be suspended until the battery temperature returns to the predefined range. Only the trickle charge current is allowed in this situation.

The trickle charging stage is characterized by a much smaller current charge; 0.02-0.05 CA is the typical value. The timer terminates the trickle stage. Trickle charge time is 15-20 hours for these batteries.

**Note:** Some Ni-Cd batteries have memory issues due to decreasing battery capacity after several charging cycles in which the battery was not discharged completely before the charge started. To eliminate this phenomenon, the battery must be discharged completely in the Ni-Cd battery charger.

Figure 1 illustrates the battery-charging process previously described.

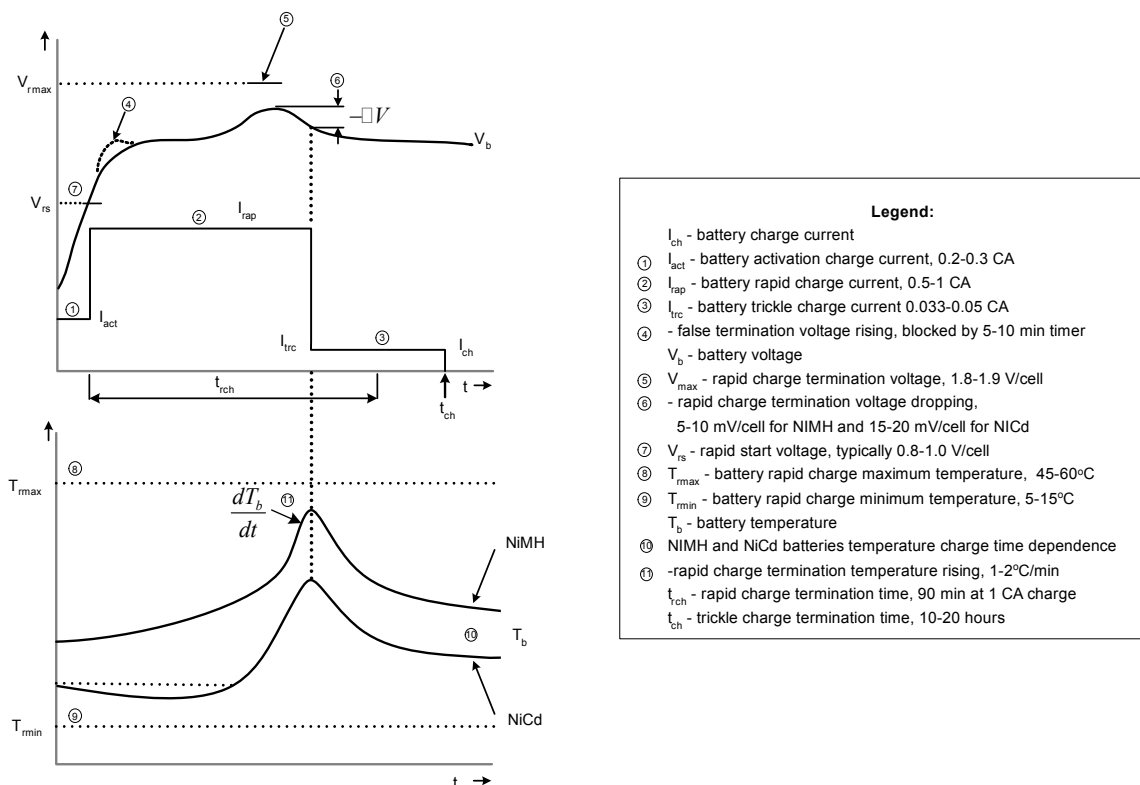


Figure 1. Ni-Cd/Ni-MH Battery Charge Profile

### SLA Batteries

The SLA battery charging process can be separated into three different stages (activation, rapid, trickle) too. Each stage must be protected by the timer, similar to the Ni-Cd and Ni-MH batteries. The battery charge is allowed if the battery temperature falls into a predefined range; typical values are +5°C...+45°C.

If the battery is over discharged, the activation stage must be used first. This stage is useful to detect shorted or damaged cells. The battery is charged by constant current source at 0.1-0.2 CA until cell voltage reaches 1.8-2.0 V for SLA. The timeout for activation stage can be set to 3-5 hours. Once battery voltage reaches rapid-charge starting level, the rapid charge is started.

Rapid charge is provided by the regulated source that operates in constant current mode until just before the battery voltage reaches the predefined value. When the battery voltage reaches this level, the charge source operates as constant voltage source. Rapid charge terminates when the charge current drops below predefined value; typically 0.05-0.2 CA.

The battery manufacturer recommends that the rapid-charge current limit for SLA batteries be set to 0.3-1 CA and voltage limit set to 2.2-2.45 V/cell. The trickle charge stage follows the rapid charge stage. In trickle charge the battery voltage and current limitation levels are lower than in the rapid charge; typical values are 2.25 V/cell and 0.1 CA. The timer terminates the trickle stage.

Note that other charge algorithms can be used with SLA batteries. The algorithms use constant charge current and analyze the absolute value of the battery voltage and its second derivative to rapid charge termination, pulse-charging methods etc. Please see [1] for details. This SLA charge method is most recommended by battery manufactures.

Figure 2 illustrates the SLA battery-charging process previously described.

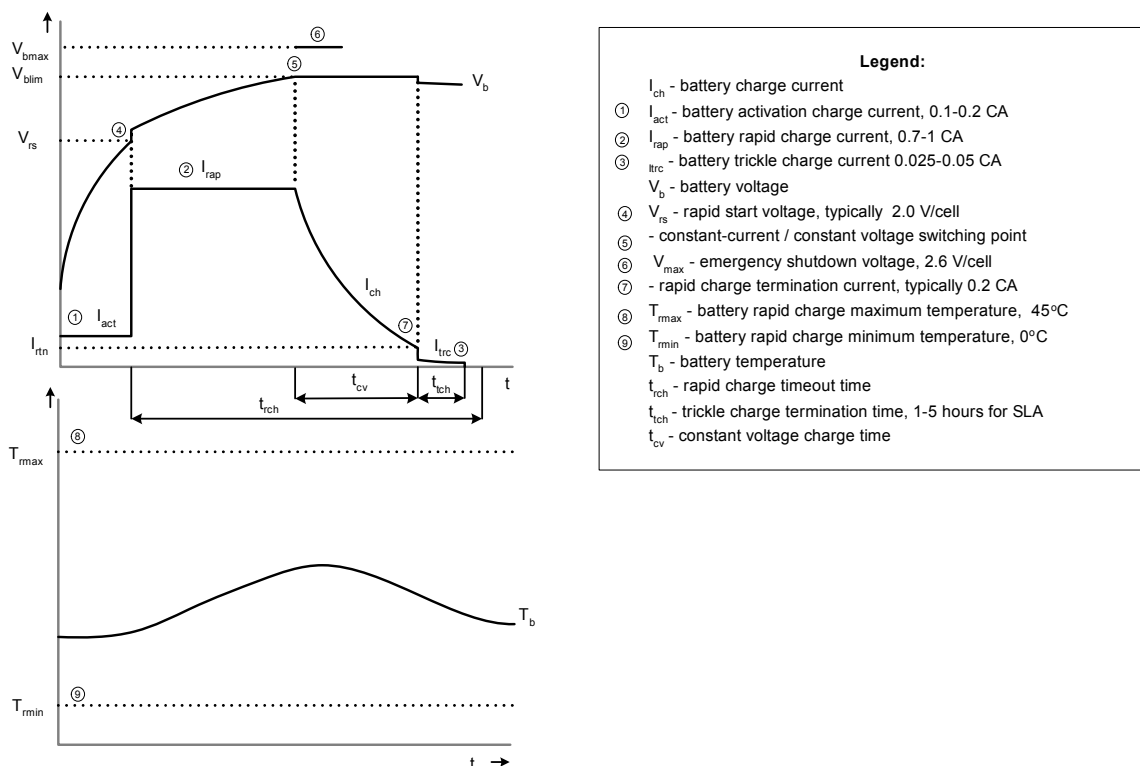


Figure 2. SLA Battery Charge Profile

### The Li-Ion and Li-Pol Batteries

Despite principal differences in battery chemistry, the battery charging principles of Li-Ion and Li-Pol are similar to SLA batteries. The main differences lie in the charge-parameter values and the demand for accuracy in the charge settings. Please note that the Lithium-based batteries are very sensitive to the charge voltage and current, discharge limit, and are assembled into special battery packs with built-in thermistor and protective circuit. This circuit protects the battery from over charge and over discharge, and limits load/charge current to safe values. Without this circuit, the battery can explode under adverse conditions. The charge source voltage limiting accuracy must be not be less than 1 %, which causes additional challenges in the Li-Ion/Li-Pol battery's charger design.

Li-based batteries use a two-stage charge profile (activation, rapid). The long trickle charge mode is eliminated because batteries that contain Lithium cannot accept additional charge without battery degradation. The charge process can be activated only if battery temperature is within predefined limits.

The typical temperature values are +5...+50°C. If the battery voltage is less than 2.9-3.0 V/cell, the battery must be activated first. In the activation-charge stage, the battery is charged with constant current (0.05 - 0.15 CA) until battery voltage reaches the level given above. The activation charge timeout is set to 1.5-2 hours. The activation charge can diagnose battery health and identify troubles such as damaged or shorted cells.

The rapid-charge stage starts after the activation charge finishes without error. The rapid charge consists of two modes. When the battery voltage is less than the predefined level (4.1 or 4.2 V, depending on battery type), the charge is processed with constant current. When the battery voltage reaches this level, the charge source switches to constant-voltage mode and the charge process is terminated when the current drops below some predefined limit. The battery manufactures recommend use of the rapid-constant current at 0.5-1.0 CA and rapid-termination current at 0.07-0.2 CA.

The rapid charge must be protected by timer implementation. The rapid charge timeout consists of the sum of the constant current and constant voltage times. The constant current time is estimated to provide 100-120% of the battery charge because during this stage the battery is charged up to 70-80%. The nominal value is 60-75 minimum at 1 CA rate. The constant voltage charge time is limited to two hours according to the manufacturer recommendations.

As described early, there is no trickle charge for Li-Ion batteries.

Figure 3 depicts the charge profile for Li-Ion/Li-Pol batteries:

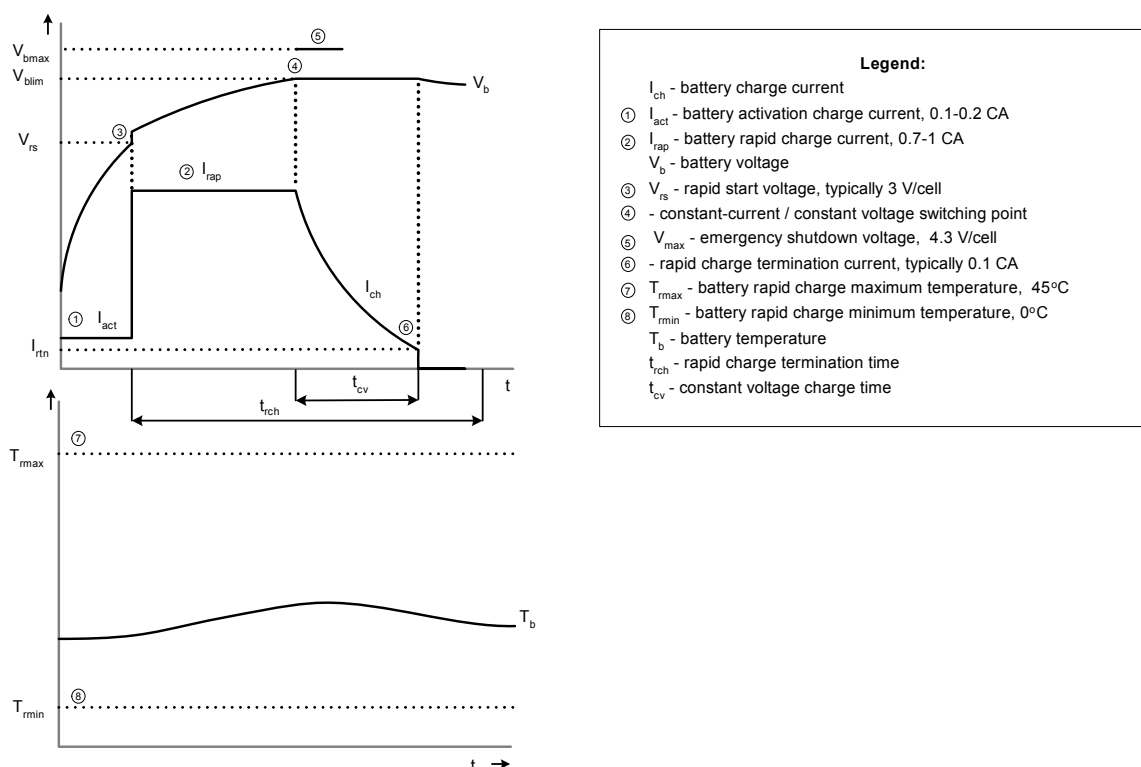


Figure 3. Li-Ion/Li-Pol Battery Charge Profile

### Conclusion

In spite of the fact that various battery types are characterized by different charging strategies and rapid charge termination criteria, here are some common characteristics of the battery-charge profiles:

- Regardless of battery chemistry, the battery charging process can be separated into several distinct regions with different charge currents and voltages.
- For safety reasons, a timer must guard each charge stage.

- There are different charge modes depending on if the battery temperature falls into a defined region or not. For some batteries the charging process is completely prohibited when the temperature is outside a defined range. Others tolerate only a small-current charge.
- To provide battery charge, the programmable source with both constant current and constant voltage operational modes must be used to satisfy various charge stages.

The primary differences in the charge process lie in termination conditions, programmable source current and voltage values, and how they relate.

## The Charger Hardware

Figure 4 illustrates the general charger flow-chart. The device consists of:

- Power supply **PS** to power all charger modules
- Step-down converter **SDC** to provide the battery charge energy
- Battery interface **BI** to transform battery current and voltage for suitable processing by PSoC signals
- Switching matrix **SWM** to switch battery interface signals
- Instrumentation amplifier **INA** to measure charge current
- Programmable gain amplifier **PGA** to measure battery voltage and temperature
- Multiplexer **MUX** for **PGA/INA** output-signal switching
- Analog-to-digital converter **ADC** to digitize the analog signals
- Central processor **CPU** to implement the charge algorithms and perform charger control functions
- Pulse-width modulator **PWM** to drive step-down converter
- **RS232** level translator for remote control and monitoring
- User interface **UI** to allow user interaction with device
- **SMBUS** interface is intended to interact with smart battery packs or can be used as an alternative data exchange channel

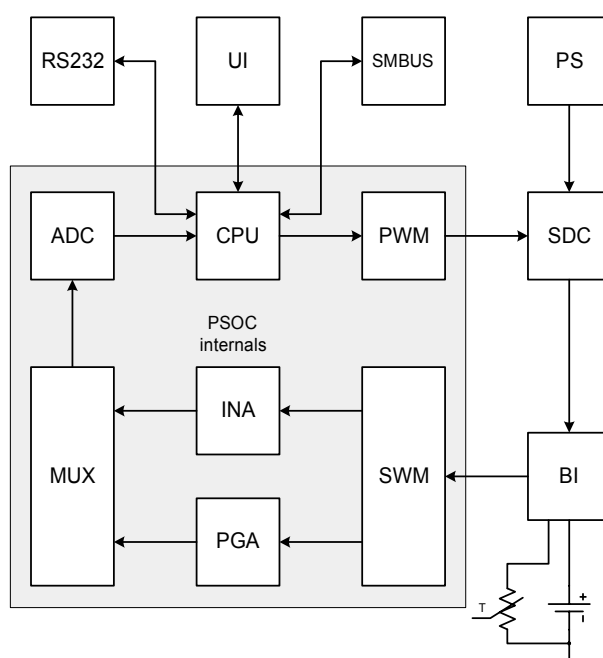


Figure 4. Charger Flowchart

## The Schematics

The Figures 5 and 6 depict charger schematics. Note that the charger only consumes ports P0 and P1.

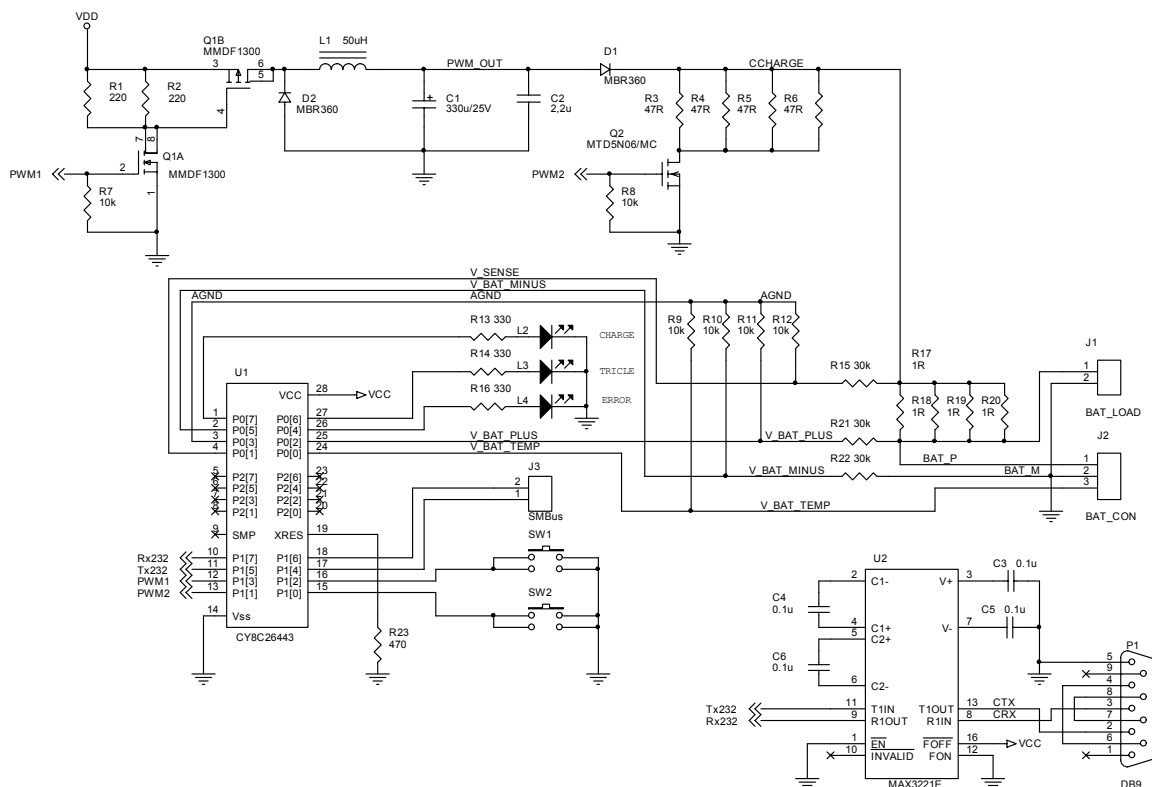


Figure 5. Charge Part Schematic

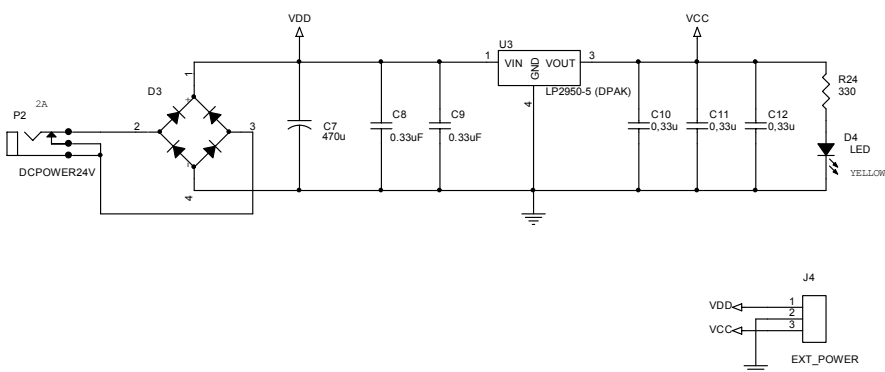


Figure 6. Charger Power-Supply Schematic

The dual MOSFET Q1 is a step-down converter current switch. Q1A acts as a level translator and Q1B has current switch role. The step-down converter operation frequency was set to 100 kHz, but easily can be adjusted in the firmware. MOSFET Q2 is a battery discharge switch used in the processor-controlled battery discharge for Ni-Cd batteries to eliminate the battery memory effect that was previously described.

Note that excellent information concerning the switch-mode converter design and customization can be found in [8].

The resistive network (R9-R12, R15, R17-R20-R22) forms the battery interface that allows transformation of the battery current and voltage into suitable signal levels for PSoC.



This interface allows users to accurately measure battery voltage, charge/discharge current and temperature.

The current-sense resistor assembling R17-R20 was moved from the battery load current loop to eliminate current sensing resistor loss when the battery serves load.

Note that for applications with large battery voltage it is better to move current sense resistor into negative battery lead path to eliminate large common-mode voltages. Only minor changes must be done in the firmware to support this modification.

Battery pack is connected via 3-pin connector J2. The thermistor must be connected to negative battery lead (battery manufacturers connect the thermistor in this way only). The connector J1 is intended for battery load connection. J3 is the SMBUS data connector.

The charger user-interface part is implemented via two buttons, SW1 and SW2, to charge process START/STOP control and three LEDs to display charge status.

The LED L2 indicates ACTIVATION or RAPID charge. L3 indicates the TRICKLE or the WAITING states and L4 displays the charger ERROR conditions. The lighting of both L2 and L3 corresponds to the battery discharge process. The level translator U2 converts RS232 signals into CMOS-compatible levels. The analog ground bias was set to  $2V_{ref}$ , or 2.6V.

The power supply consists of the linear regulator U3 to power processor and level translator. Note that the external DC power supply must be used to charge power supply. The modern low-cost high voltage switching power regulators from many manufacturers [6] can be used to build AC main charger power supply.

### The PSoC Internals

Most charger functions are implemented by user modules in the project's main configuration but dynamic re-configurable blocks are used to perform some measurements. Figure 7 depicts processor internals:

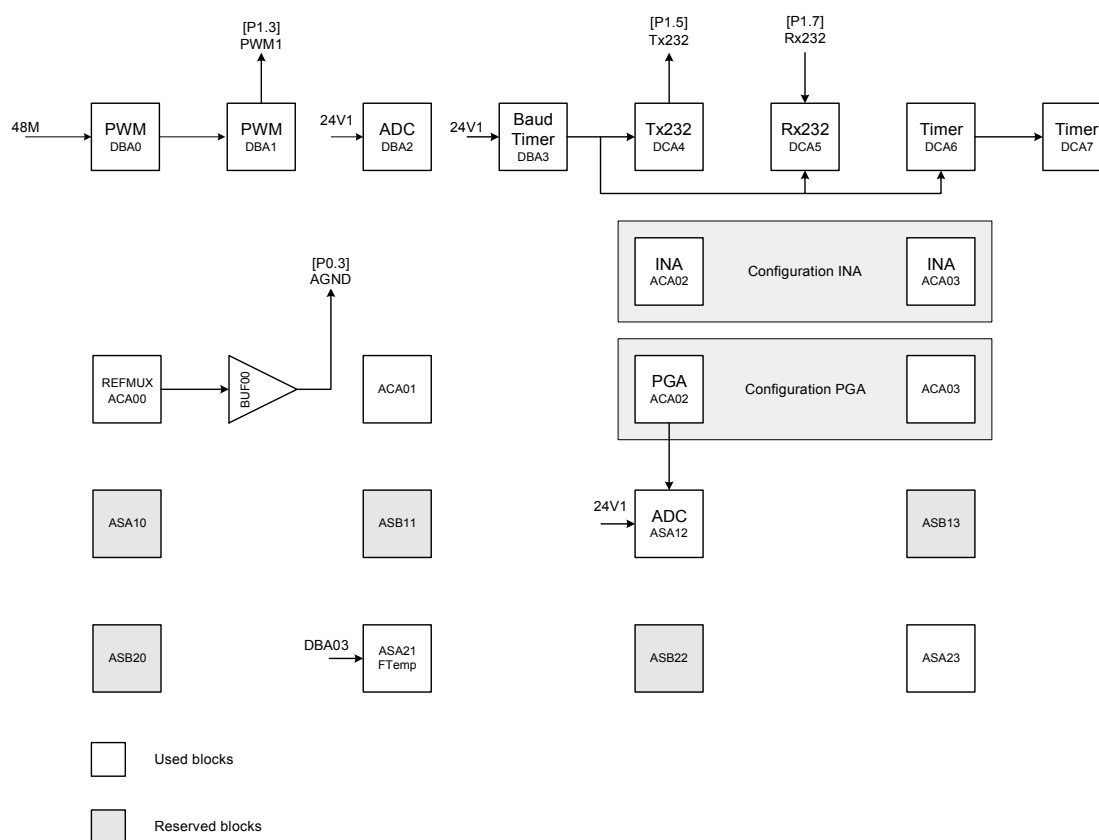


Figure 7. PSoC Internals

The pulse-width modulator has been placed in DBA00 and DBA01. The module is configured in the software as 9-bit PWM unit, which is allowed to provide enough regulation steps. The PWM switching frequency is set to 100 kHz. The serial port baud-rate timer is placed into DBA03. This timer output is used as clock source for the UART. The UART is comprised from separately placed serial transmitter and receiver, which have been placed into DCA04 and DCA05 respectively. Notwithstanding the fact that PSoC Designer suggests the UART User Module but it is unsuitable for this design because current API version does not provide routines to disable/enable receiver/transmitter interrupts separately. The default exchange speed is set to 19200 baud.

The baud-rate timer output is used for additional purposes. First of all, it drives the interval timer, which is used as a real-time clock. It may be curious to use the baud-rate timer as a real-time clock source because the low-speed internal oscillator exists. But PSoC data sheet currently does not provide any time/temperature frequency dependence information concerning this oscillator. It is known that the generated frequency can be varied into several times. But the high-speed oscillator provides guaranteed frequency stability. So, the only way to use digital PLL is to tune the low-speed oscillator during charger operation or employ a high-frequency signal as real-time clock. The last solution has been implemented in this design.

The timer generates interrupts with a 0.25s rate that is used to calculate other time intervals.

The delta-sigma ADC is placed into ASA12 and DBA02 blocks. Despite the fact that other ADC types provide better resolution, dynamic range and signal-to-noise ratio (SNR), this ADC was selected because ADC results have no dependence on interrupt latency. The following software digital filtering and averaging saw an increase in delta-sigma ADC SNR and an improvement in measurement accuracy. The user can test other ADC types for performance by replacing this ADC in PSoC Designer.

The baud-rate timer output serves as the clock source for the temperature sensor, which is used for measuring die temperature before self-programming internal memory to store charger settings. When the charger is used at room temperature this unit can be considered redundant, but it is useful for extreme use conditions.

### Battery Measurements

To provide correct implementation of the charge algorithms and battery voltage, the charge current and temperature must be measured accurately. The charger performs the dynamic re-configuration to implement these functions. Because the battery current is determined by measuring the voltage drop in sense resistor with presence of the large common-mode signal, the best way to measure current is to use the instrumentation amplifier (INA) to amplify this small sense resistor signal. But the PSoC instrumentation amplifier has minimum gain of 2 and limits battery voltage range, which can be measured accurately in this way. The programmable-gain amplifier (PGA) is ideal for measuring battery voltage because it provides gain levels as low as 1. An additional PGA is needed to buffer the output if the PGA is set for attenuation. Input voltage is only limited by the input-stage acceptance levels of PSoC.

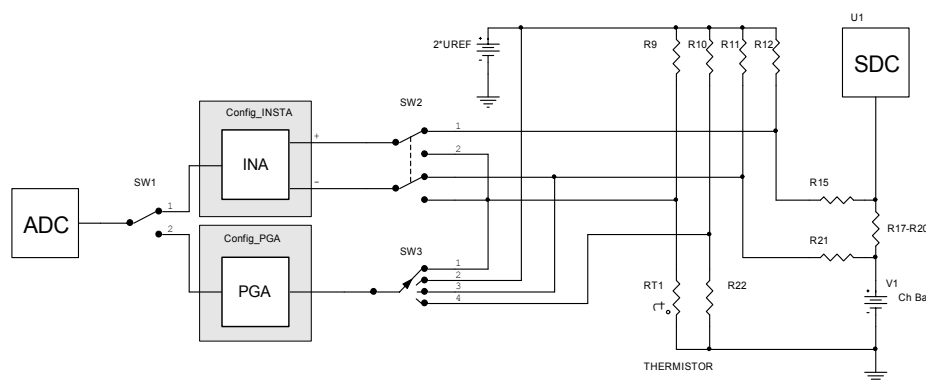


Figure 8. Battery Measurement Implementation

This amplifier can effectively be used to measure battery temperature because PGA suggests wide range of gain levels (useful values are from 0.5 to 16).

Note that the thermistor resistance decreases exponentially with a rise in temperature, so the thermistor voltage can be varied in the wide range [7].

Figure 8 illustrates implementation of the measuring configuration. The measurement of battery current is implemented as a two-stage procedure to eliminate voltage offset of the instrumentation amplifier and ADC input.

The switch SW2 is placed in position 2 and INA inputs are shorted together in the first stage. Note that the current routing scheme does not allow connecting the INA inputs to AGND. This position is used to measure INA offset voltage. The switch SW2 goes to position 1 and the current sense resistor signal is measured. If  $R_{10}=R_{11}=R_{12}$  and  $R_{15}=R_{21}=R_{22}$ ,  $R_{17} \ll R_{15}$  then the difference between ADC code, which corresponds to the SW2 position 1 and 2, is directly proportional to the battery current without influence of the INA and ADC offset voltage. The following formulas depict current measuring scheme:

$$\begin{aligned} n_1 &= n_{\max} \frac{V_{ADC_1}}{V_{ref}} = n_{\max} \frac{G_{ina} V_{os}}{V_{ref}} \\ n_1 &= n_{\max} \frac{V_{ADC_2}}{V_{ref}} = n_{\max} \frac{G_{ina}}{V_{ref}} (V_{os} + \beta \cdot I_{bat} R_{17}) \\ \Delta n &= n_2 - n_1 = n_{\max} \frac{G_{ina} \beta \cdot I_{bat} R_{17}}{V_{ref}} \end{aligned} \quad (1)$$

Where  $n_{\max}$  is the maximum ADC code and the value is equal to 1024 for 11-bit sigma-delta ADC in bipolar mode.  $n_1$ ,  $n_2$  are the ADC code during first and second measurements.

$V_{os}$  is INA offset voltage,  $I_{bat}$  is battery current,  $G_{ina}$  is INA gain,  $V_{ref}$  is bandgap reference voltage, 1.3 V, and  $\beta$  is the resistive divider coefficient:

$$\beta = \frac{1}{1 + \frac{R_{15}}{R_{12}}} \quad (2)$$

Note that the influence of the INA input current is small for selected resistive divider values (the parallel value is less than 10k) and can be ignored in this case. The most important thing is to use the precision resistors in the resistive divider to obtain high-value common mode signal rejection.

The recommended  $R_{10}$ - $R_{12}$  and  $R_{15}$ ,  $R_{21}$  and  $R_{22}$  tolerances are 0.1%. The maximum battery voltage,  $V_{bat\ max}$ , battery current,  $I_{bat\ max}$ , and resistive divider values must be selected to satisfy the following:

- INA maximum input voltage must be lower than allowed instrumentation amplifier common-mode voltage  $V_{cm\ max}=4V$  for 5V supply, or;

$$2V_{ref} + \beta(V_{bat\ max} + I_{bat\ max} R_{17} - 2V_{ref}) < V_{cm\ max} \quad (3)$$

- to prevent ADC saturation by current sense resistor differential voltage, the following equation must be true:

$$G_{ina} \frac{I_{bat} R_{17}}{V_{ref}} \beta < 1 \quad (4)$$

Note that there must be an ADC input range reserve of approximately 15-20% caused by possible large INA offset voltage.

The battery voltage is also measured by using PGA into two stages.

First, SW3 is placed into position 4. The negative battery lead voltage is measured. Second, SW3 is placed into position 3 and the positive battery lead potential is measured. The difference between these measurements allows the program to calculate the exact battery voltage without influence of the PGA/ADC input voltage offset errors. The following question set illustrates this:

$$n_1 = \frac{n_{\max} G_{PGA}}{V_{ref}} (-2V_{ref} \beta + V_{os}) \quad n_2 = \frac{n_{\max} G_{PGA}}{V_{ref}} (\beta(V_{bat} - 2V_{ref}) + V_{os})$$

$$\Delta n = n_2 - n_1 = n_{\max} G_{PGA} \frac{V_{bat}}{V_{ref}} \beta \quad (5)$$

Where  $G_{PGA}$  is PGA gain.  $V_{os}$  is PGA input voltage offset.  $V_{ref}$  is reference voltage.  $n_{\max}$  is maximum ADC code value.  $n_1$  and  $n_2$  are in ADC code during first and second measurements.

To prevent ADC saturation during voltage measuring, the following disparity must be true:

$$\frac{G_{PGA}}{V_{ref}} \beta (V_{bat} - 2V_{ref}) < 1 \quad (6)$$

Note that the default gain value is 16 for INA and 1 for PGA. The following versions of the charger firmware/PC-based software will support automatic gain selection and resistive divider optimization for exact battery type and cell count. The resistive divider values must be correctly selected in equations (3), (4) and (6) for given battery voltage and charge current. The rule to calculate suitable resistor values is very simple. For given maximum charge battery voltage, calculate  $\beta$  values from (3), (4) and (6). Then select the minimal value among these three numbers and calculate  $R_{15}$  value according to Equation (2) using the fixed value of the  $R_{12}$ .

The temperature is measured by measuring the voltage drop across  $R_9$  and  $R_{10}$ . The PGA has been used to extend the measuring range. The measuring process is separated into three stages. The PGA input offset is measured first by switching SW3 into position 2. Second, the switch SW3 turns to position 1 and the  $R_9$  lower-pin potential is measured. Third, the switch SW3 turns to position 4 and the  $R_{10}$  lower pin is measured. Using these three values, the resistance of the thermistor can be obtained by the following equation:

$$n_{AGND} = n_{\max} \frac{G_{PGA}}{V_{ref}} V_{os}$$

$$n_1 = n_{\max} \frac{G_{PGA}}{V_{ref}} \left( V_{os} - 2V_{ref} \frac{R_9}{R_9 + R_{th}} \right), \quad n_2 = n_{\max} \frac{G_{PGA}}{V_{ref}} \left( V_{os} - 2V_{ref} \frac{R_{10}}{R_{10} + R_{22}} \right)$$

$$\frac{n_{AGND} - n_2}{n_{AGND} - n_1} = \frac{n_{\max} \frac{G_{PGA}}{V_{ref}} 2V_{ref} \frac{R_{10}}{R_{10} + R_{22}}}{n_{\max} \frac{G_{PGA}}{V_{ref}} \left( 2V_{ref} \frac{R_9}{R_9 + R_{th}} \right)} = \frac{R_{10}}{R_{10} + R_{22}} \frac{R_9 + R_{th}}{R_9} \quad (7)$$

$$R_{th} = R_9 \left( \frac{n_{AGND} - n_2}{n_{AGND} - n_1} \frac{R_{10} + R_{22}}{R_{10}} - 1 \right)$$

Where  $G_{PGA}$  is PGA gain during temperature measuring.  $G_{PGA}$  is set to 1 or 8 automatically, depending on the current ADC code value.  $n_{max}$  is the maximum ADC code value.

As easily seen in (7), the temperature code has no dependence on the reference voltage value,  $V_{ref}$ . To provide ADC saturation-free temperature measurement, the thermistor value at maximum expected temperature must satisfy the following disparity:

$$\frac{R_{th}(t_{max})}{R_9} > 2G_{PGA} - 1 \quad (8)$$

Because  $G_{PGA \min}=1$ , then  $R_{th}(t_{max}) > R_9$ . The PSoC column 2 and 3 multiplexers serve the SW2 and SW3. Switching is done by direct modification to the AMX\_IN register in the charger firmware.

## The Charger Firmware

The charger firmware is separated into several modules that serve distinct functions, such as performing measurements, regulating battery charge process and timer functions, implementing charge algorithm, checking charge termination-conditions, storing selected charger parameters and calibration settings into PSoC Flash memory, remote control and data exchange.

### Battery Charge Algorithm

The following battery-charge algorithm performs charge-profile analysis for various battery types. First of all, the battery discharge setting is analyzed. If the battery needs to be discharged, the discharge switch is turned on. Now the charger continuously measures the battery voltage and waits until this voltage drops below discharge-stop threshold. When the battery is discharged, the charge process can begin. Note that the timer protects the total discharge time. When the timer timeout elapses, the discharge process terminates with a timeout error.

The battery-charge process is started by resetting the charge termination flag and setting the idle values of the battery current and voltage. These values will be put into the charge regulator when the battery temperature is outside the allowed range. Note that the Ni-based batteries allow a small charge-current charge when the battery temperature is outside the predefined range, but other types do not. So, for SLA, Li-Ion and Li-Pol batteries, idle mode-charge values must be set to zero, which prohibits any charge current.

When the regulator voltage and current values are determined, it is time to measure the current battery voltage and charge current, and update the step-down converter PWM value according to the selected regulation law.

After updating the PWM value, the series of conditional tests will be completed. The total charge time will be checked first and the charger will be stopped with timeout error when the total charge timeout has expired. Next, the battery charge voltage must be checked. When this voltage is higher than the allowed maximum value, the charge process must be terminated with the battery voltage error flag. This situation happens typically when the battery is removed during the charge process and the regulator does not have enough time to reduce the charge current. Alternatively, this condition test can be used to detect damaged batteries with high internal resistance.

Then, the battery temperature must be checked. If the battery temperature is not in the specified range, the idle values of the battery charge voltage and the current are sent to the charge regulator and the operation timer is suspended. This timer counts the rapid, activation or trickle charge time. The charger returns to the battery charge voltage, current measurements and PWM regulation.

If battery temperature is good, the termination flag is checked. If this flag was set, the trickle charge values are sent to the regulator and operation timer is resumed. The total trickle time is then checked. If the trickle timeout elapses, the process terminates with no errors. If the termination flag was not set, the battery voltage is analyzed. If this level is bigger than the rapid-charge start voltage, the rapid charge mode is selected (activation charge in the opposite case). The operation timer is resumed for both activation and rapid charge modes and corresponding timeouts are checked. If any timeout expires, the charge process terminates with timeout error.

When the termination criterion is true, setting the termination flag terminates the rapid charge. The different battery types are characterized by various termination criteria. For example, the rapid charge of the SLA batteries terminates when the charge current drops below the predefined level.

When these condition tests completed, the charger started the battery measurements and PWM regulation.

Figure 9 illustrates the proposed algorithm:

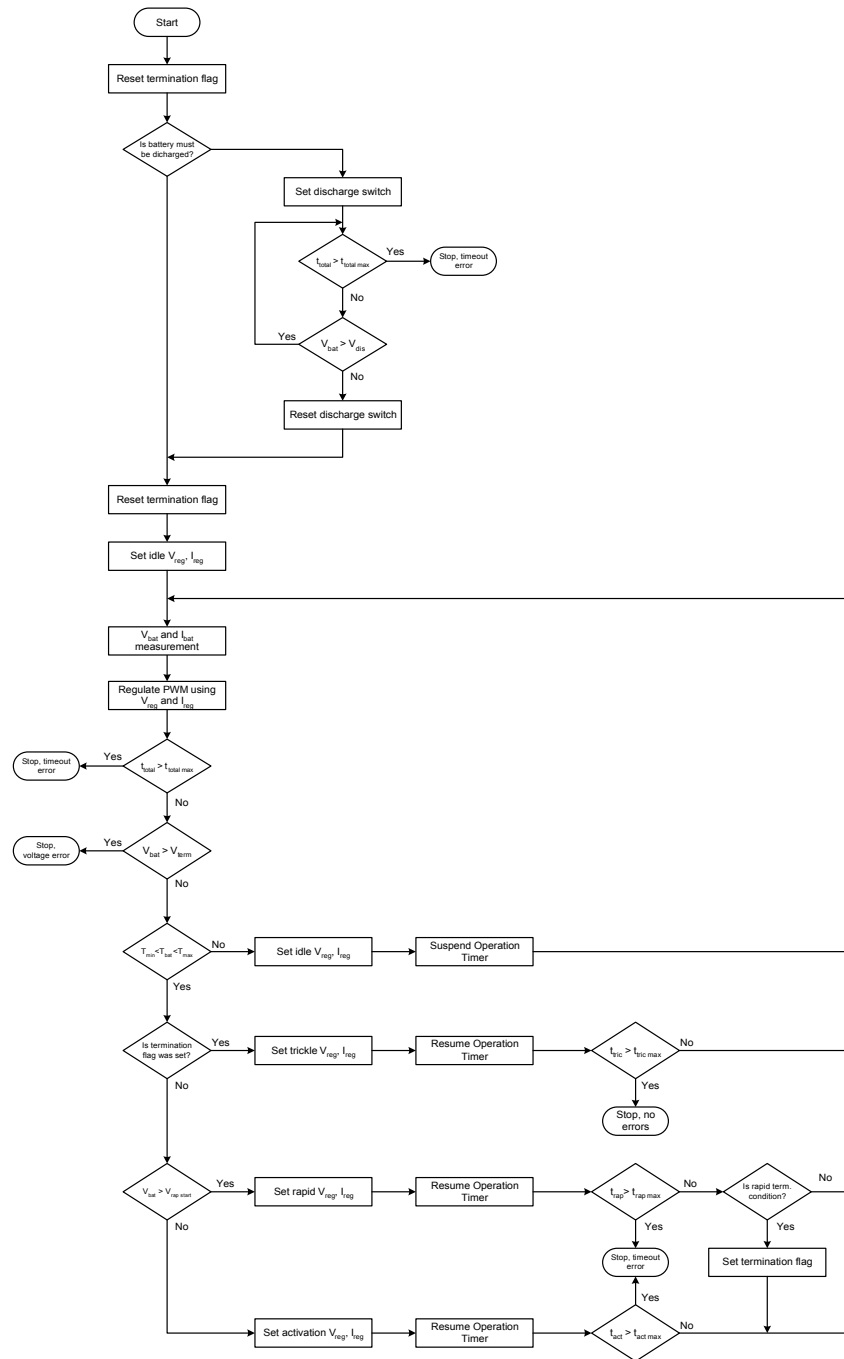


Figure 9. Universal Battery Charge Algorithm

Note that by varying algorithm settings and modifying charge-termination criterion, new battery types can also be supported.

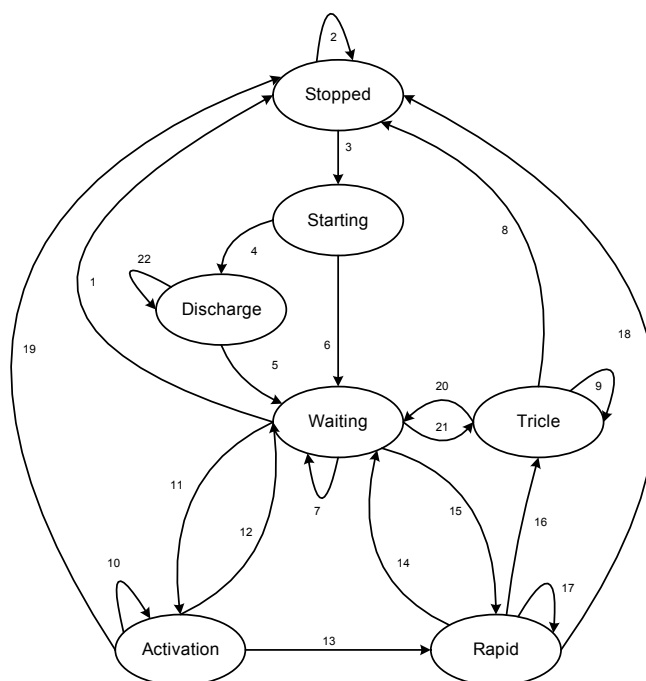
This algorithm was implemented in the charger firmware as a state machine.

The following states were used:

- STOPPED marks the charged initial state;
- STARTING indicates charge process initialization;

- DISCHARGE marks the battery discharge process;
- WAITING is used for the idle state depicting when battery temperature is outside allowed temperature range;
- ACTIVATION, RAPID and TRICKLE depict the battery activation, rapid and trickle charging.

Figure 10 illustrates the charger state diagram:



**Figure 10. Charger State Diagram**

Initially the charger is in STOPPED state and preserves this state until just before an external (from user interface or serial port) event is received (2). If the charge starting command is issued, the charger goes to the STARTING state (3). If the battery must be discharged first, the charger jumps to DISCHARGE (4) state, and to WAITING state directly in the opposite case (6). The charger preserves the DISCHARGE state when battery is not discharged completely (22).

The charger will preserve the WAITING state until just before the battery temperature falls into the predefined range (7). If the battery temperature is good, the ACTIVATION or RAPID states can be switched.

If the battery voltage is lower than the rapid start voltage, the charger goes to ACTIVATION state (11) and to RAPID state (15) in the opposite case.

When the battery voltage reaches the rapid start voltage, the charger leaves the ACTIVATION state and switches to the RAPID state (13). If termination criterion is satisfied, the TRICKLE state replaces the RAPID state (16). When the TRICKLE state timeout has elapsed, the charger moves into STOPPED state (8). From the RAPID, ACTIVATION or TRICKLE states the charger can temporarily return to WAITING state if the battery temperature leaves the allowed range (12), (14), (20).

The charging process can be terminated with an error if total or operation charge timeout elapses or the battery voltage is higher than the charge termination voltage (1), (8), (18), (19).

### **The Timers**

As explained above, the charger uses 0.25s interrupts as the primary real-time clock. The double-byte variable is being incremented by each timer tick and is used as a time counter. The counter overflows each 4.5 hours but this phenomenon has no influence on the charger operation. Successive time intervals are generated by this counter analysis. The current firmware release employs three software count-down timers to calculate various time intervals.

$$\frac{1}{T_k} = A + B \cdot x + C \cdot x^3, x = \ln(R_t) \quad (9)$$

Where A, B, C are approximation coefficients.  $R_t$  is thermistor resistance and  $T_k$  is thermistor absolute temperature, K. The direct calculations from Equation (9) need complex, float-point calculations and are not suitable for this charger implementation. Because the temperature range is limited to 60°C (no batteries are allowing activation/rapid charge outside 0..60°C), a better way lies in using a lookup table to calculate battery temperature. To eliminate any complex mathematical calculations, this table must contain an array of the ADC code, which will correspond to the concrete temperatures. The search algorithm is looking at the table value, which is nearest to the measured ADC code. The table index will reflect battery temperature linearly.

The lookup table code can be calculated from a reverse function for Equation (9) (by using Cardano formulas) to find thermistor resistance at a particular temperature and Equation (7) to calculate corresponding ADC code. This code can be stored in the PSoC Flash memory after charger calibration. The charger uses 256-point lookup table with starting point at 0°C in 0.25°C increments. The table consumes 512 bytes of Flash memory and does not create any size problems because PSoC has more than enough Flash memory. So, the maximum temperature, which when measured by using this lookup table is 63.75°C, is completely enough for this application.

Each timer has different resolution and serves different purposes. Timer<sub>1</sub> has a resolution of 1s and is intended to provide battery temperature measurement intervals. The battery temperature is being measured every 4s. Timer<sub>2</sub> is intended to provide operation timeouts, has a resolution of 64s and supports suspend/resume operations without resetting. Timer<sub>3</sub> is used to calculate total charge time and has a resolution of 256s.

### **Battery Temperature Calculation**

The thermistor, which is widely used in modern battery packs, has a non-linear transfer function. The resistance temperature dependence can be calculated using the following formula [7]:

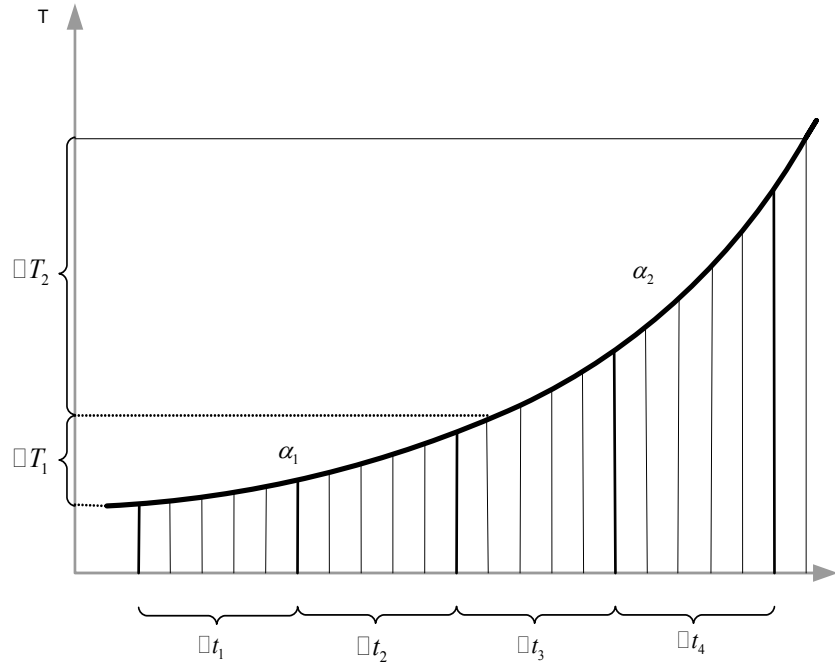
### **Charge Completion Checking**

Various battery types employ different rapid charge termination strategies. For SLA and Li-Ion batteries, rapid charge terminates when the charge current drops below the predefined level. It is very simple to implement this criterion in software. The Ni-Cd and Ni-MH batteries use two complementary termination criteria: detection of temperature derivate rising or detection of battery voltage dropping from its maximum value. Most chargers measure the temperature periodically and calculate the difference between adjacent temperature points. In spite of the simplicity of algorithm implementation, this method is characterized by poor noise immunity and can mistakenly terminate the charge process in a noisy environment<sup>1</sup>. The proposed integral method is free from this drawback.

The method is based on calculation and comparing integration sums for adjacent time intervals. Figure 11 depicts implementation of this algorithm:

<sup>1</sup> Author observed this effect in some commercial chargers when thermistor wires were too long and noise was introduced by other system parts.





**Figure 11. Battery Temperature Derivate Integral Analysis**

Let us suppose that the temperature is rising linearly within two accumulation intervals.

It is completely true if the accumulation interval is small in comparison to the temperature derivate change time. So, the temperature change law can be written in the following form:

$$T_i = T_0 + \alpha \cdot i \quad (10)$$

Where  $i$  is the sample-point number and  $T_0$  and  $\alpha$  are approximation coefficients.

The two adjacent integral sums will be estimated. The index  $i$  changes within from 0 to N-1 for the first sum and from N to 2N-1 for the second integration sum.

$$\begin{aligned} S_1 &= \sum_{i=0}^{N-1} T_i = \sum_{i=0}^{N-1} (T_0 + \alpha i) = NT_0 + \frac{\alpha N \cdot (N-1)}{2} \\ S_2 &= \sum_{i=N}^{2N-1} T_i = \sum_{i=N}^{2N-1} (T_0 + \alpha i) = NT_0 + \frac{\alpha N \cdot (3N-1)}{2} \end{aligned} \quad (11)$$

Note that the formula for the arithmetical proportion sum calculation was used here and no quantization effects were taken into account during this estimation.

The difference between the two sums is as follows:

$$\Delta S = S_2 - S_1 = \alpha N^2 \quad (12)$$

The difference between the two sums has no dependence on the initial temperature,  $T_0$ . To practically use this criterion, the parameter  $\alpha$  can be estimated via temperature growth.

Let us suppose that within accumulation time,  $\Delta t$  collected N points and observed the temperature growth  $\Delta T$ . By substituting these values into Equation (10), the  $\alpha$  can be calculated by the following formula:

$$a = \frac{\Delta T}{N} \quad (13)$$

The charger periodically measures the battery temperature and calculates the sum of the N temperature values. After this process has been completed, the comparison between adjacent integration sums is done. If the difference between these two integration sums is greater than the predefined threshold value, it is determined that the battery temperature derivate reached the charge termination threshold and the charger must switch to the next state. In this firmware release, the temperature measurement is being initiated each 4s and the integration sum accumulation time is 64s, which takes into account 16 temperature samples.

Decreasing battery-voltage detection is implemented by continuously updating the maximum value of the charge voltage and estimating the difference between this maximum value and the latest charge voltage. If this difference reaches the predefined threshold, this termination criterion is considered true. To improve detector noise resistance and charger reliability, the voltage samples are filtered first by the IIR LPF. The filter transfer function is determined by the following equation:

$$y_j = (1 - \gamma)y_{j-1} + v_j \quad (14)$$

Where  $y_j$  is the filter output signal j sample,  $v_j$  is the input voltage sample, and  $\gamma$ ,  $\gamma < 1$  is the filter coefficient. This filter is characterized by the gain  $\gamma^{-1}$  and the voltage threshold value is multiplied by  $\gamma^{-1}$  in proportion to the filter gain. This filter implementation allows decreasing the influence of fixed-point rounding errors and improving accuracy of small voltage drop detection. Instead, dividing/multiplying the binary shift has been done, the  $\gamma = 2^{-K}$ , where  $K=1..3$ .

This charger employs a simpler regulator, which has worse dynamic characteristics but does not demand estimation of regulator coefficients. 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 12 illustrates the regulator operation:

### ***The Charge Regulator***

In the first section of this Application Note the battery charging algorithms were considered. To implement a universal charger, the regulator must be capable of regulating both charge current and voltage and stay stable for loading various dynamic characteristics. The traditional digital proportional-integrate derivate control (PID) regulator provides excellent regulation characteristics for properly selected regulator coefficients. These coefficients must reflect the step-down converter/load dynamic behavior and desired sample frequency. To provide optimum regulation, the regulator coefficients must be dynamically updated to reflect load property changes [2]. An alternative approach lies in using fuzzy-logic systems.

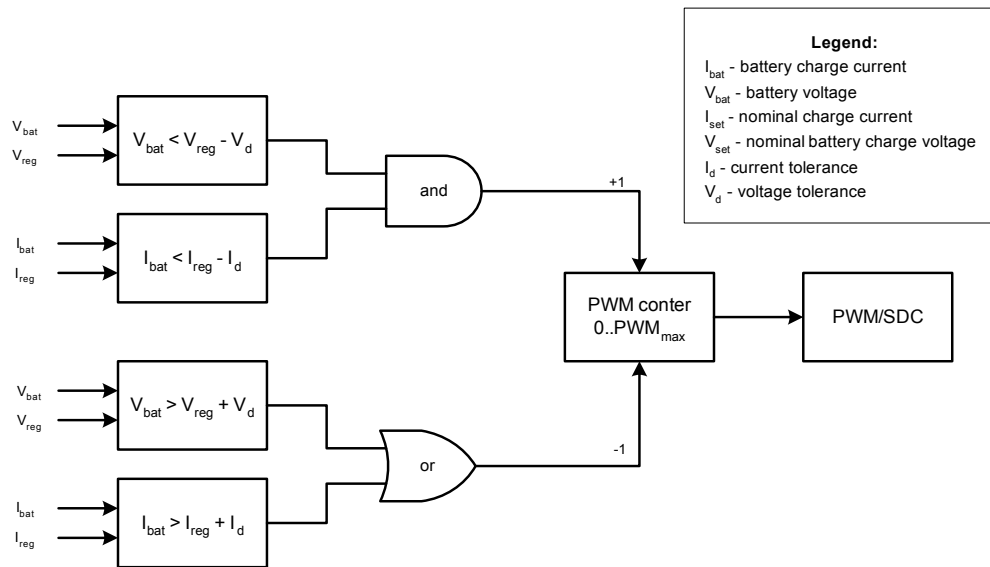


Figure 12. Charge Regulator Operation

**Data Exchange Protocols**

The charger uses serial port communication for remote control and charge-process monitoring. It can operate as a standalone application with two control buttons, but the thermistor lookup table and battery settings must be uploaded first. These settings are stored in nonvolatile PSoC Flash memory. The communication model is based on master-slave approach. Under dedicated control, the PC acts as master and the charger acts as slave. Any host controller with UART can remotely control the charger.

The PC or host controller is sending the predefined commands and the charger is returning a reply for each command. The current firmware release supports the following commands:

- test data link to detect charger connection;
- measure PSoC die temperature and set Flash memory starting block number;

- write Flash memory block (used for uploading both thermistor lookup table and battery settings);
- start and stop charging;
- request charger state information; reply includes state machine state, error code, current time, battery temperature, charge current and voltage.

The data communication protocol is trivial. Each packet consists of the start byte 'S', data bytes and stop byte 'P'. The messages are different lengths, depending on command type. The data bytes are encoded into hex format, so each data byte needs two bytes to be transmitted or received. The 100 % overhead does not cause any problems because the data exchange rate is typically very low (several ten bytes per second) and bytes are encoded or decoded on-the-fly, without additional memory use.

Figure 13 illustrates data packet structure:

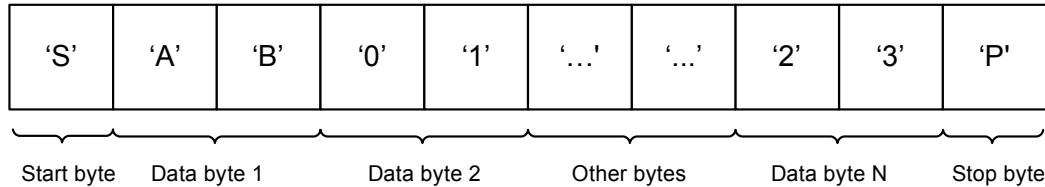
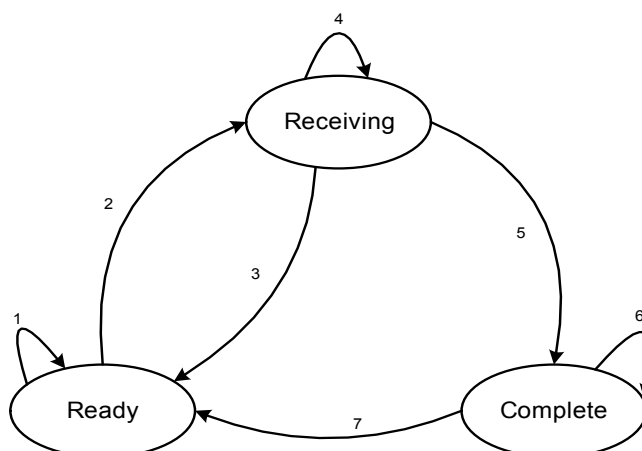


Figure 13. Data Packet Structure

The serial receiver and transmitter operation is completely interrupt-driven to eliminate UART polling. The receiver contains the state machine. Figure 14 illustrates the receiver operation:



**Figure 14. Serial Receiver State Machine**

Initially, the receiver is in READY state. The receiver preserves this state until just before the start byte is received (1). The receiver moves to the RECEIVING state after receiving the start byte (2). This state will be preserved until just before the stop byte is received (4). If this happens, the receiver went to COMPLETE state (5). The receiver can transit from RECEIVING to READY state if any of the following events occur (3):

- The new start byte was received.
- The received symbol cannot be decoded or was received with error.
- More buffer size data bytes were received without stop byte.

The receiver preserves COMPLETE state until just before data packet is read and processed (6). The receiver will be reset (7) in the main program loop by calling the corresponding routine after incoming data processing.

## The Charger Control Software

The dedicated charger control software has been developed to simplify charger configuration and monitor charge process. Software features include:

- Dialog-based battery-parameter settings with disk load/store capability.
- Voltage, current calibration.
- Battery voltage, current, and temperature visual representation with disk load/store/append capabilities.

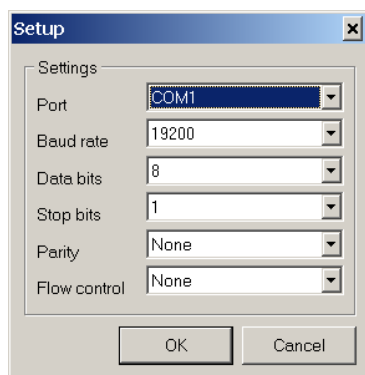
- Automatic battery settings and thermistor lookup table generation with uploading into PSoC Flash memory.

The software is a multi-thread Win32 application and runs under Microsoft Windows 98, NT, 2000, or XP.

The program interface is very simple; user must carry out several steps to complete charger setup. These steps include the following:

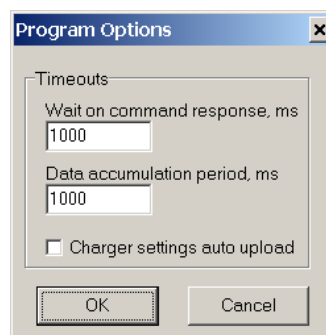
### **Setting Program Options and Serial Port Settings**

After program installation, the serial port settings must be checked. From main program menu, select "Settings -> Serial Port Settings," choose free serial port and select 19200 baud 8-data bits, 1 stop bit and no flow control and parity. Press "OK" to close window. You can test serial port settings by pressing the "Query" button. You must see "The diagnostic message was received" in the Messages window, Output tab. If you see red text "The charger is not responding," please check serial port connection and charger power.



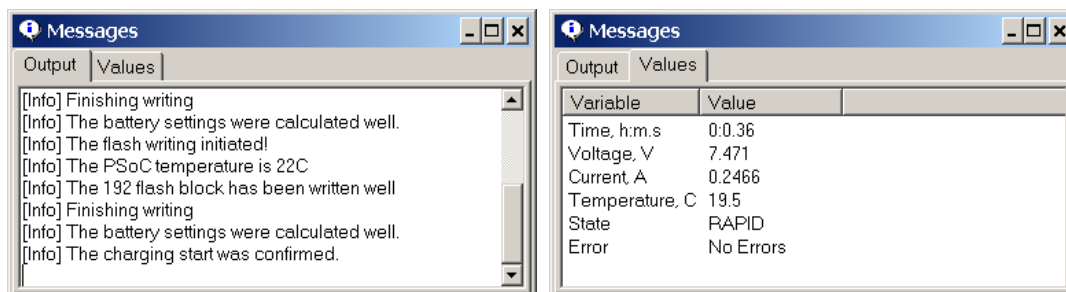
**Figure 15. Serial Port Dialog Window**

The program options window (Settings -> Program Options) allows you to select charger query period and charger response-wait timeout. All values are in milliseconds. You can select the checkbox to automatically upload the new battery settings into charger Flash memory (but to upload thermistor lookup table you must press corresponding menu item manually).



**Figure 16. Program Options Dialog Window**

Note that the serial port settings and program options are automatically stored in the system registry, so they will be retrieved next time the program starts. All diagnostic messages are sent into the Messages window, which has two tabs. The "Output" tab displays various diagnostic messages, the "Values" tab displays current charger information such as the measured battery voltage, current, temperature, charger state machine state, error code... Here is a message example:



**Figure 17. Message Window Tabs**

### **Setting Battery Parameters**

Setting battery parameters must be done with care because invalid battery settings can damage the battery or even the charger.

The command is callable as "Settings -> Battery Settings" or via the speedup button. There are two tabs in this dialog. The first is intended to provide battery settings; the second selects charger hardware component parameters.

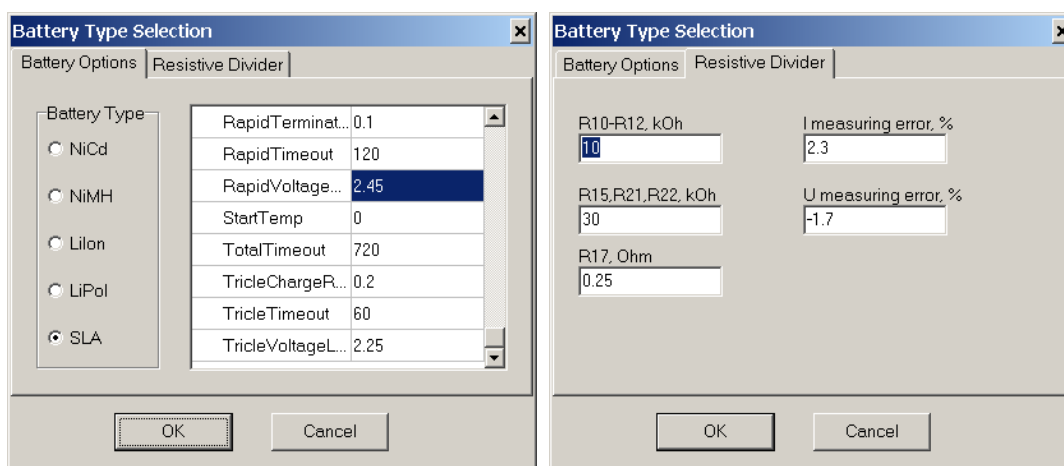


Figure 18. Battery Settings Dialog

Select battery type first. Later, fill in all the battery properties according to the following tables.

Table 2. The Ni-Cd and Ni-MH Battery Settings Table

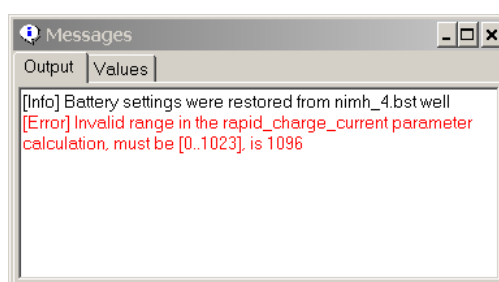
Parameter Name	Parameter Description and Dimension
ActivationChargeRatio	Relation between battery charge current during activation stage and capacity, $h^{-1}$
ActivationTimeout	Activation charge timeout, min
Alias	User-friendly battery name or model number, will be stored together with other parameters
Capacitance	Battery capacity, A*h
Cells	Battery cell count
CheckTempIncrease	Check if you want to use temperature derivate rising as rapid-charge termination criterion
CheckVoltageDecay	Check if you want to use the battery voltage dropping as rapid-charge termination criterion
DeactiveTime	Timeout to prevent false rapid-charge termination by initial voltage dropping, min
DischargeFirst	Check if you want the discharge to precede battery charging
DischargeStop	The discharge stop voltage, V/cell
MaxTemp	Upper limit of the allowed temperature interval, °C
RapidChargeRatio	Relation between battery charge current during rapid stage and capacity, $h^{-1}$
RapidStartVoltage	Switching threshold between activation and rapid charge, V/cell
RapidTimeout	rapid-charge timeout, min
StartTemp	Lower limit of the allowed temperature interval, °C
TempIncValue	Battery temperature rising speed to detect rapid-charge termination, °C/min
TotalTimeout	Total charge timeout, min
TrickleChargeRatio	Relation between battery charge current during trickle stage and capacity, $h^{-1}$
TrickleTimeout	Trickle charge timeout, min
VoltageDecay	Battery voltage dropping level to terminate rapid charge, V/cell

**Table 3. The Li-Ion, Li-Pol and SLA Battery Settings Table**

Parameter Name	Parameter Description and Dimension
ActivationChargeRatio	Relation between battery charge current during activation stage and capacity, $h^{-1}$
ActivationTimeout	Activation charge timeout, min
Alias	User-friendly battery name or model number
Capacitance	Battery capacity, A*h
Cells	Battery cell count
DischargeFirst	Check if you want the discharge to precede the battery charging
DischargeStop	The discharge stop voltage, V/cell
MaxTemp	Upper limit of the allowed temperature interval, °C
RapidChargeRatio	Relation between battery charge current during rapid stage and capacity, $h^{-1}$
RapidStartVoltage	Switching threshold between activation and rapid charge, V/cell
RapidTerminationCurrent	Relation between battery charge current and battery capacity to determine rapid-charge termination current, $h^{-1}$
RapidTimeout	Rapid charge timeout, min
RapidVoltageLimit	Maximum charge voltage during rapid charging, V/cell
StartTemp	Lower limit of the allowed temperature interval, °C
TotalTimeout	Total charge timeout, min
TrickleChargeRatio	Relation between battery charge current during trickle stage and capacity, $h^{-1}$
TrickleTimeout	Trickle charge timeout, min You can set zero for Li-based batteries
TrickleVoltageLimit	Maximum charge voltage during trickle charge stage

When you have finished setting the battery-charging parameters, press the “Ok” button. Please review the Messages window to make sure there were no errors during battery parameter calculation.

If you see messages similar to those shown in Figure 19, your battery settings do not reflect the resistive divider values. Please correct these values according to the equations given earlier.

**Figure 19. Error Message Example**

Secondly, select Resistive Divider tab and modify resistor values according to the equations, which were considered in the charger hardware section. The charger calibration possibility has been implemented as well. The bandgap voltage error, PSoC blocks' gain error, resistor divider resistance errors, and PCB voltage-drop tracking introduce the errors in battery voltage and current measurements that decrease accuracy of the charge process.

These errors can be reduced by comparing charger data to the values measured externally. The calibration can be done in the following way: set voltage and current measurement error to 0, close dialog box by pressing “Ok” and upload battery settings to the charger. Then, start the battery-charge process.

During the rapid charge stage, take measurements of the real battery current and voltage using precision external U-I meter and compare that with the charger-measured values, which are displayed in the Messages window, Values tab.

Calculate the percentage difference between them. These values must be put in the “U measuring error” and “I measuring error” edit boxes. Press the “Ok” button. Review the new voltage and current values in the Values tab. They must be very close to the value measured by the external meter. Upload the recalculated battery settings into the charger and save battery settings in the file for recall. The calibration process is now complete. To do this operation, the resistor can be used instead of a real battery. The resistor value can be calculated as relationship of nominal battery voltage to rapid charge current.

After setting battery parameters you can save all settings into a file. Use “File -> Save Battery settings” and open it later via “File -> Open Battery Settings.” Note that the charger resistive divider values and calibration data are linked with battery settings and will be saved/opened together because these values are battery dependent. When you properly select battery settings, you can upload these values to the charger by pressing “Action -> Upload Battery Data.” In this way the calibration correction will be taken into account for both charger setting calculations and data visualization.

### Entering Thermistor Calibration Data

The various battery packs are characterized by different thermistor temperature coefficients. To properly generate a charger lookup table, these coefficients must be estimated according to the thermistor temperature curve. The charger control software allows you to extract thermistor resistance approximation coefficients for any thermistor using experimental or passport data. Click “Settings -> Thermistor Calibration” and the following dialog window will appear.

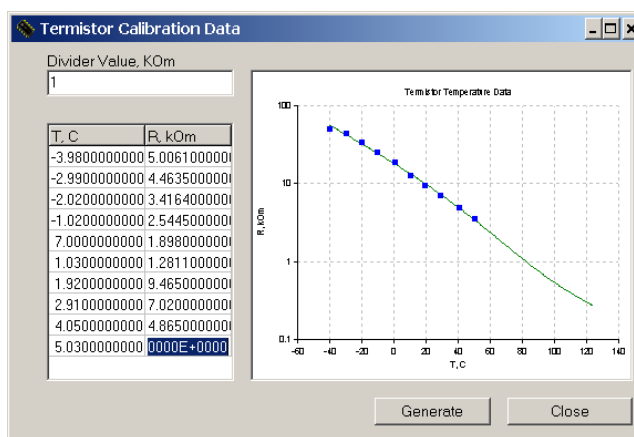


Figure 20. Thermistor Calibration Dialog Box

Enter the value of R9 in the upper edit box. As easily seen in Equation (8), the divider resistance must not be greater than the thermistor resistance for maximum temperature operation to prevent ADC saturation. The rule of thumb is to set the divider resistance equal to the thermistor value at 65°C. You will see the warning message in the Messages window if your R9 value was selected improperly.

Using the Insert, Arrow and Page Up, Page Down keys create new lines in the value editor and type numerical values for temperature and resistance. When all values are entered, you can save them to a text file from the value editor context-sensitive menu. You can open the file next time using this context menu. To find thermistor coefficients, use the measured data from the thermistor data sheet. User must provide a minimum of three resistance-temperature pairs. The software automatically calculates the thermistor coefficients and lookup table.



If your thermistor data are noisy, enter more than three points to improve estimation accuracy. Do not forget to include points near 0°C and 60°C. Press Generate button. You will see approximation graph and approximation coefficients with statistical information printed in the Messages window. If needed, set the Messages window to review approximation results.

Note that the graph Y-axis scale can be switched from log to linear and vice versa in the graph context-sensitive menu. When the thermistor coefficients are estimated and lookup table filled, you can upload lookup table into the charger by selecting "Actions -> Upload Thermistor Table."

### Start Charging

When the battery settings and thermistor lookup table are generated and uploaded into charger PSoC Flash memory, the user can start the charge process by pressing the "Start" button. You will see corresponding information in the Messages window, Output Tab. The Values Tab depicts the battery voltage, current, temperature, current charger state and decoded error codes.

This information is useful during battery evaluation or testing. Note the text in the Messages window can be cleared in the context-sensitive menu. You can abort the charge process any time by pressing the "Abort" button. The charger then returns to STOPPED state.

### Data Visualization

Once the charging process is started, the charger is periodically queried by software. This query interval can be adjusted in the Program Options dialog window on-the-fly. The software continuously updates the graph windows during charging, so you can view the battery charge time graphs in real-time. The possibilities to hide/show data points and graph zoom are implemented as well. To show/hide data points, use the graph context-sensitive menu. For graph zooming, press the [Shift] key together with left mouse button and draw a rectangle around interesting graph fragment. Release the left mouse button and your graph will be zoomed to the rectangled area. To restore the full graph view, press the [Shift] button and double-click the graph area.

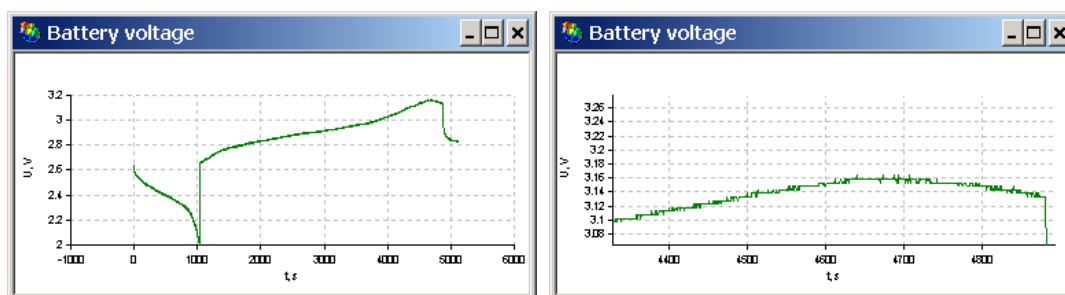


Figure 21. Graph Zooming

You can save graph data by pressing "File -> Graph data." The software allows you to open previously stored data by pressing "File -> Open Graphs Data" and append the other graphs to the existing graph for comparison and detail analysis.

To do this, use "Append Graph Data."

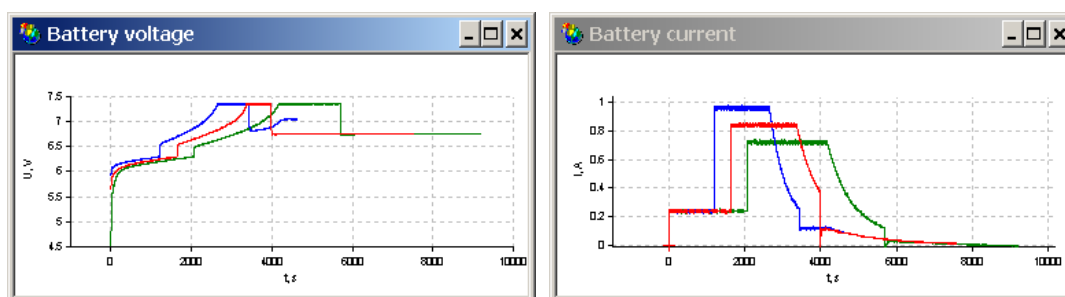


Figure 22. Several Charge Profiles in One Window

## To Probe Further

The proposed battery charger does not cover some advanced battery charging topics such as battery regeneration, advanced diagnostic and testing, fuel gas measuring and rest-capacity estimation, adaptive charging methods with charging parameters temperature correction, etc. These features can be added in the next firmware release. The CRC checking of the PSoC Flash self-programming memory blocks will be provided as well to detect damaged battery settings.

The possibility to generate 'C' header files for both battery settings and thermistor lookup table will be added in the charger control software. This feature will be very useful when the user has tested the charger well and wants to put the device into mass production with only one battery type, without serial interface. Secondly, more user-input checking will be implemented. And, lastly, the automatic calculation and optimization of all charger hardware coefficients depending on battery parameters will be added. These parameters include PGA/INA gain levels, resistive divider values, etc.

## Conclusion

The universal, multi chemistry charger has been considered. The charger reference design includes the full firmware sources, Orcad schematic and layout files. The charger control software sources can be obtained freely from <http://www.cypress.com/> under PSoC >> Reference Designs. This software has been written in Borland Delphi 7. But the charger applications are not limited to classic battery charge. Thanks to the flexibility of PSoC architecture, additional functions can easily be implemented. For example, the author's friends are using this charger to quickly charge the small electric racing cars during competitions, battery screening and diagnostic, etc. In this case, this \$10 design replaces very expensive battery diagnostic equipment.

## References

1. Isidor Buchmann, Batteries in a portable world. This excellent book concerning battery chemistry, operation, charging schemes is available freely online at <http://www.buchmann.ca/toc.asp>.
2. Benjamin Kuo, Digital Control Systems; The digital control systems questions are discussed here.
3. Charge Methods for Ni-Cd Batteries.
4. Charge Methods for Nickel Metal Hydride Batteries.
5. Charge Methods for Li-Ion Batteries. The last three references describe the chemistry-specific battery charge methods and can be downloaded at <http://www.panasonic.com/industrial/battery/>.
6. Components for AC-DC main power supply are produced by Power Integration, On-Semiconductor, International Rectifier, Infineon. Visit their sites for details.
7. The NTC/PCT Thermistors, A AVX-KYOCERA Reference manual, can be downloaded from <http://www.avxcorp.com/>.
8. P.P.K. Ghetty, Switch-mode power-supply design, TAB Books, 1986.

You can download full charger control software sources from Cypress site at <http://www.cypress.com/> under PSoC >> Reference Designs.

## Appendix A.

Following are charge profile examples for various battery types. The charger discharges battery then consecutively turns on the activation, rapid and trickle modes.

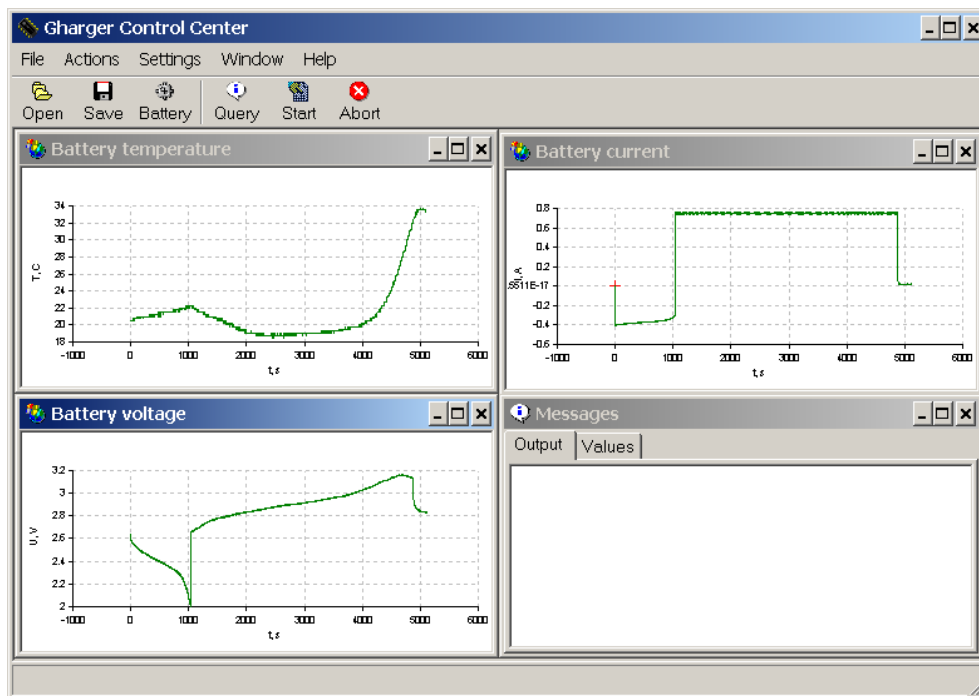


Figure 23. The 2 Cell Ni-Cd Battery Charge Profile

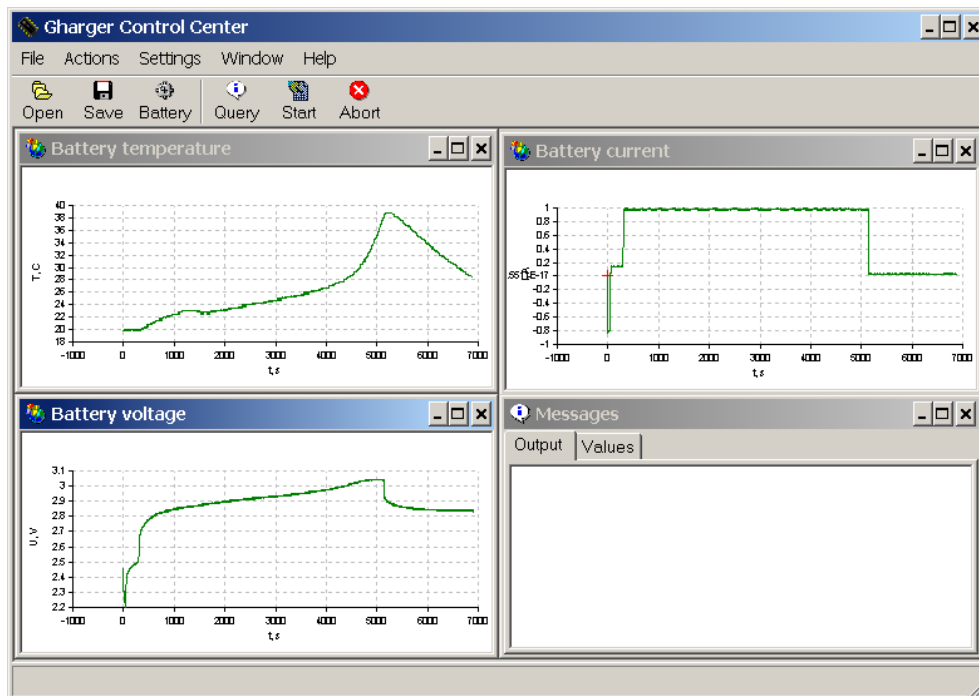


Figure 24. The 2 Cell Ni-MH Battery Charge Profile

Please see differences in the battery temperature time behavior.

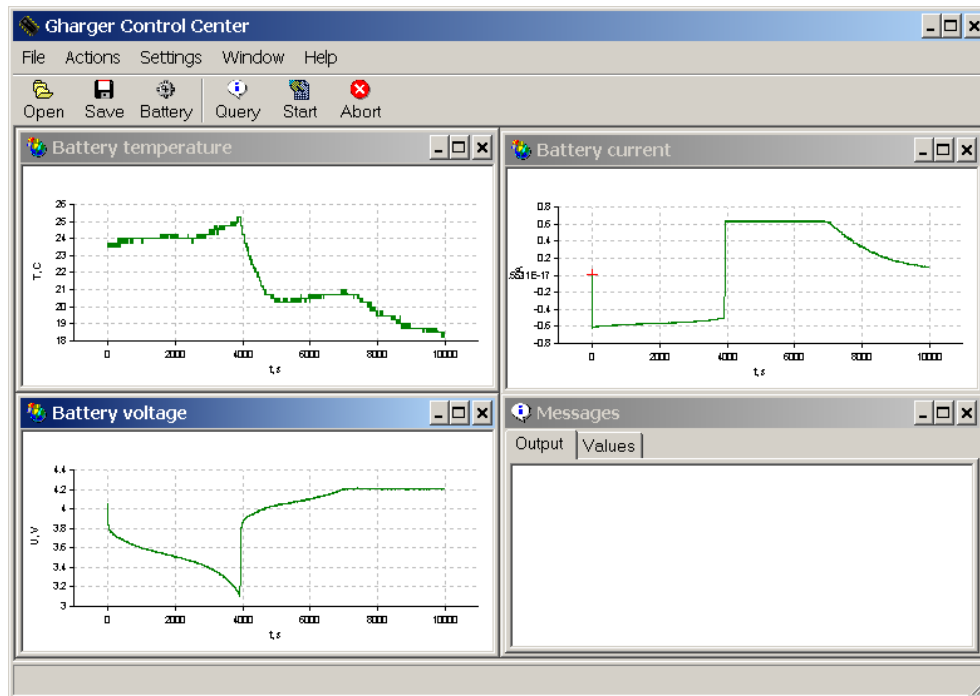


Figure 25. The Single Cell Li-Ion Battery Charge Profile

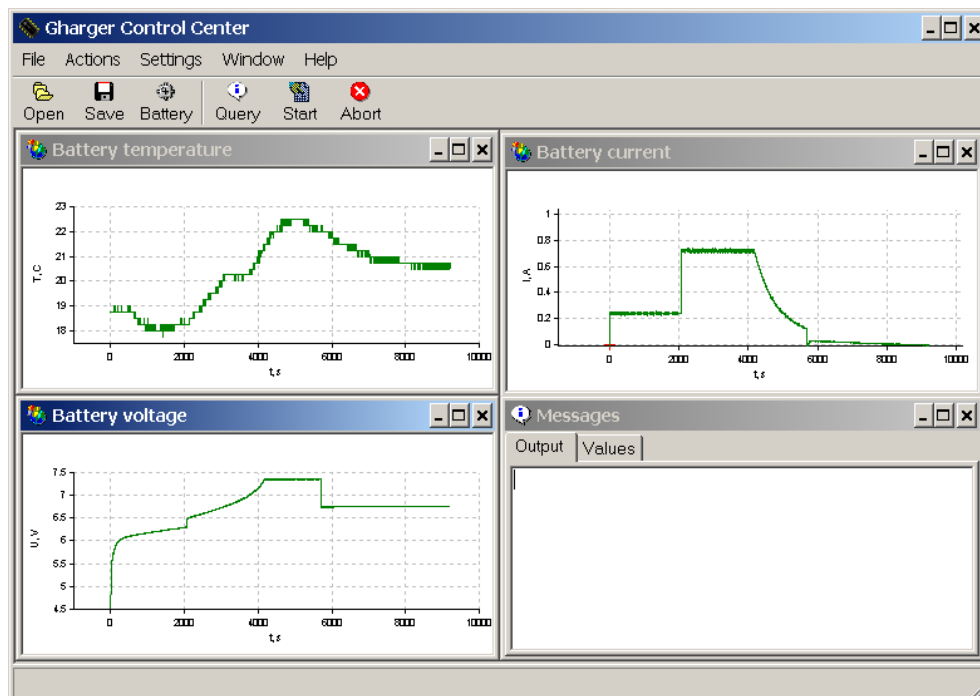


Figure 26. The 3 Cell SLA Battery Charge Profile

## Appendix B.

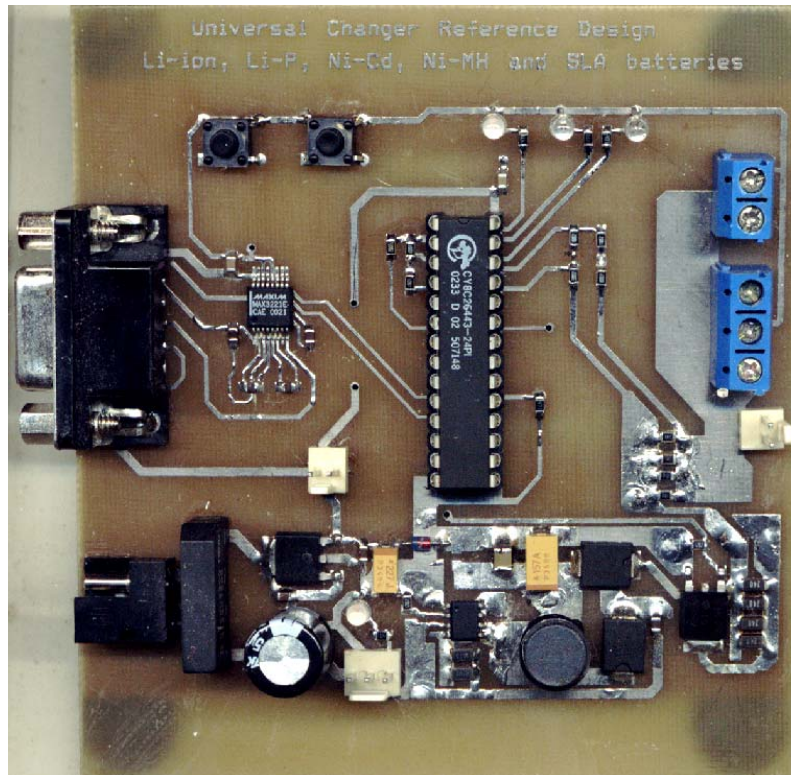


Figure 27. The Charger Photograph, Actual Size

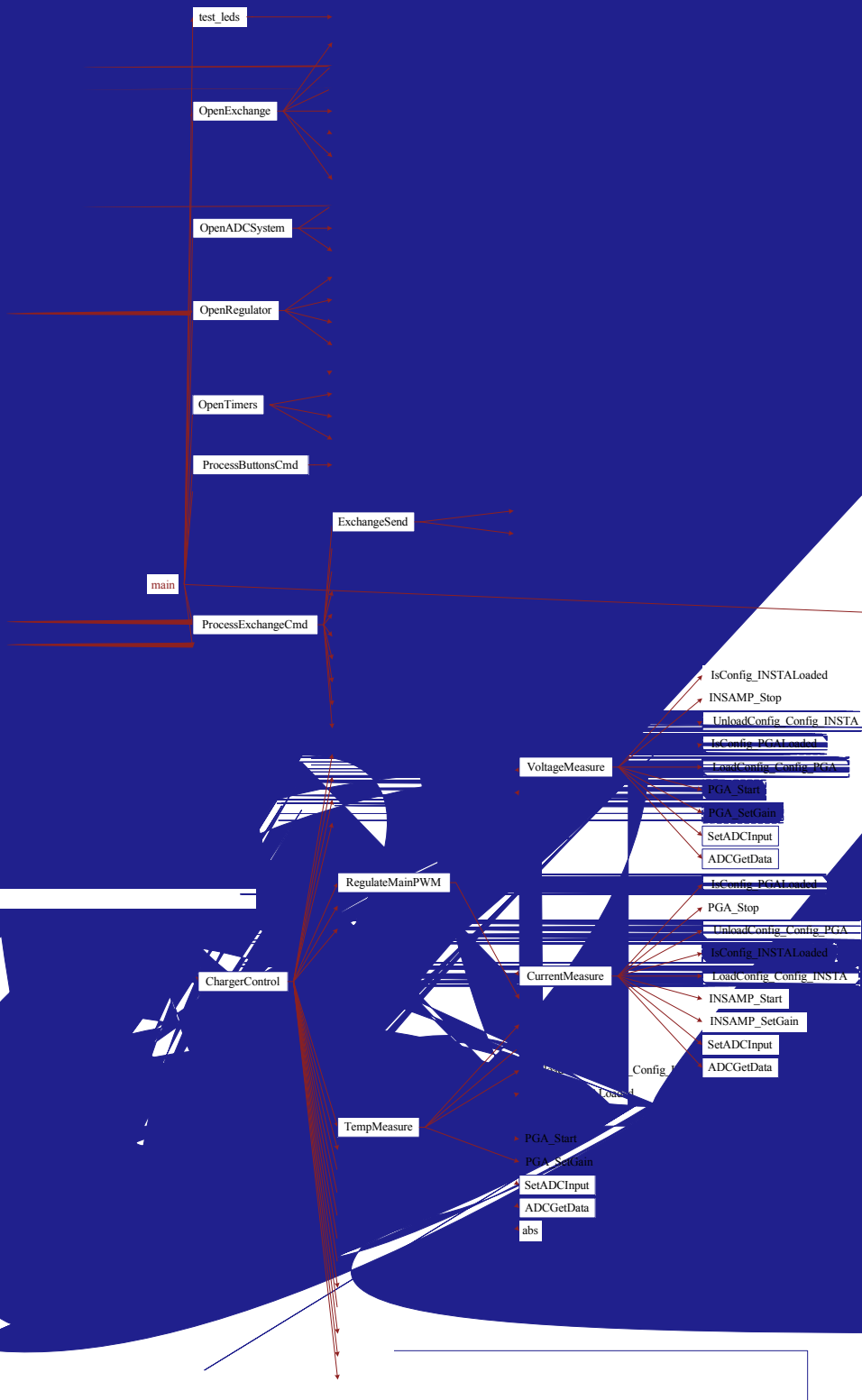


Figure 28. Charger Firmware Function Call Tree. (It is useful to understand how the firmware operates.)

## About the Author

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**Title:** Associate Professor

**Background:** Victor earned a radiophysics diploma in 1996 from Ivan Franko National Lviv University, PhD degree in Computer Aided Design systems in 2000 and is presently working as an Associate Professor at National University "Lvivska Polytechnika" (Ukraine). His interests include the full cycle of embedded systems design including various processors, operating systems and target applications.

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