Introduction

This app note describes how to implement a monolithic battery charger with a GreenPAK mixed-signal integrated circuit. This application note comes complete with design files which can be found in the References section.

Contents

1. Terms and Definitions ............................................. 1
2. References ..................................................................... 1
3. Introduction ................................................................... 2
4. Battery Charging Schemes ........................................... 2
5. Battery Charger Design Diagram and Schematic .............. 5
6. Implementation and Configuration of the Battery Charger ........................................................................ 7
7. Tests and Conclusion .................................................... 14

1. Terms and Definitions

IC Integrated circuit
IR Infrared
LED Light-emitting diode
Li-ion Lithium-ion battery
Li-Polymer (LiPo) Lithium-ion polymer battery
LiFePO4 Lithium iron phosphate batteries

2. References

For related documents and software, please visit:


Download our free GreenPAK Designer software [1] to open the .gp files [2] and view the proposed circuit design. Use the GreenPAK development tools [3] to freeze the design into your own customized IC in a matter of minutes. Find out more in a complete library of application notes [4] featuring design examples as well as explanations of features and blocks within the GreenPAK IC.

[2] AN-CM-337 Monolithic Battery Charger.gp, GreenPAK Design File
[5] SLG47105 Datasheet
3. Introduction

Battery-powered electronic devices have become one of the key elements of everyday life. These devices include mobile phones, multimedia players, navigation devices, remotely operated sensors, and actuators, to name a few. It is more practical and cost-effective to use rechargeable battery cells instead of batteries which require frequent replacement.

The use of battery cells has also promoted the development of battery chargers as an important part of the power management system of such devices. The battery charging process has evolved, including the procedure by which the battery is charged, and the circuit implementation of this procedure.

There are several battery cells available for supplying electronic devices, each of them with different advantages and disadvantages. This portfolio of battery types, however, is reduced when considering portable devices that must be also lightweight. With this constraint, Li-ion, Li-Polymer (LiPo), and LiFePO4 batteries are the most used cells in real applications, with LiPo batteries being the most used.

Li-Polymer batteries are rechargeable batteries that use Li-ion technology with a polymer electrolyte instead of a liquid electrolyte. The polymer electrolyte is formed by a high conductivity semisolid (gel) which allows this battery type to be made in almost any size or shape. Li-Po batteries provide higher specific energy than other lithium battery types. They have a nominal cell voltage of 3.7V which is converted to a standard voltage for battery-based applications. When higher voltages are required, such as 7.4V, two LiPo cells are connected in series.

The second parameter that is usually analyzed is the battery capacity. Battery capacity is a measure (typically in amp-hours) of the charge stored by the battery, and it is determined by the mass of active material contained in the battery. Li-Po batteries have been developed for different capacities, from 80mAh for small-sized low-power applications to 8Ah for motor-based portable devices such as drones and RC cars.

One of the key features that must be controlled to obtain better battery performance, in terms of available capacity and battery life, is the charging process. This is the main reason why battery chargers for these battery types have evolved in recent years. The charging process has evolved to obtain better performance, and the electronic hardware has been miniaturized to obtain smaller chargers that can be included in portable devices without a large increase in weight and size. In this context, miniaturizing the battery charger is a main objective for device development and the main reason why several commercial ICs with different levels of integration are available.

In this application note, we'll design the charging process and power stage of a Li-ion, Li-Polymer (LiPo), and LiFePO4 battery charger using a High Voltage GreenPAK SLG47105. The result is a small monolithic battery charger that only requires passive components.

4. Battery Charging Schemes

Batteries can be charged with different processes involving different current and voltages regulations. Usually, the process applied to charge a battery is called a charging scheme. For lithium-based batteries, there are two main schemes that are applied in real applications: the pulse charging scheme and the Constant Current Constant Voltage (CCCV) scheme. These schemes are designed to extend battery lifetime.

Over the course of many electrochemical reactions, the internal structure of a battery gradually depletes, and the battery life decreases. In addition, each charge cycle stresses the battery structure and causes battery degradation. This puts a limit on the number of recharge cycles. To extend the number of recharge cycles, different battery charging schemes follow a profile designed to ensure safety and long life without compromising performance.

The simplest charging scheme is pulse charging. In this scheme, a high-peak short duration current pulse is applied to the battery. The high current level initially generates a battery voltage spike higher than the battery’s rated maximum voltage. The battery voltage recovers normal levels when it can fully absorb the injected charge, after which the battery voltage reaches a level higher than before applying the current peak. This process is repeated several times until the battery voltage reaches the nominal battery voltage. This sequence is shown in Figure 1.
The pulse charging scheme is one of the most popular charging schemes due to its simple and cost-effective implementation. However, there are many disadvantages of the pulse scheme. The battery voltage spikes are usually lower than the maximum voltage that the battery can tolerate without damage. This is always true for batteries such as lead acid batteries, but not always in lithium-based ones. Lithium-based batteries are highly sensitive to voltage, so the spikes can damage them.

The high peak current pulses can also generate excessive heat, causing temperature overloads. This can be quite dangerous as it can cause the battery to explode or catch fire. Therefore, the pulse charging scheme is undesirable for lithium batteries, and other charging schemes are needed.

The Constant Current Constant Voltage (CCCV) charging scheme is based on four phases as shown in Figure 2.

![Figure 1. Pulse Charging Current and Voltage](image1)

![Figure 2. Constant Current Constant Voltage (CCCV) Phases](image2)
The first phase, usually called the Trickle Charge phase, is designed to test if the battery is working properly or is damaged without applying voltages or currents that could otherwise be dangerous. This is accomplished by applying a constant charging current to the battery until the battery voltage reaches a minimum level, usually called $V_{\text{bat(short)}}$. The constant current level used in this phase ($I_{\text{bat(short)}}$) is normally 5% of the full charging current (called $I_{\text{chg}}$) to avoid excessive heating if the battery is damaged.

Once the battery shows proper operation by increasing its voltage over $V_{\text{bat_short}}$, the second charging phase, Precharge is started. The constant current level $I_{\text{prechg}}$ used in this phase is usually 10% of the full charging current $I_{\text{chg}}$. This phase continues until the battery voltage reaches the minimum operational voltage, called $V_{\text{bat_low}}$, which typically corresponds to about 70% of battery nominal voltage.

When battery voltage is over $V_{\text{bat_low}}$, the Constant Current or Fast Charge phase is started, applying the fast charge current ($I_{\text{chg}}$) in order to reach 100% of battery capacity. This constant current is applied until the battery voltage increases to the battery regulation voltage $V_{\text{batreg}}$. This is done to avoid applying high constant-current phase which can cause the battery voltage to increase over its maximum rated level, which damages the battery and causes excessive heating.

When the battery regulation voltage is reached, the Fast Charge phase is stopped, and the fourth phase is started, the Constant Voltage phase. In this phase, a constant voltage equal to the rated regulation voltage of the battery is applied. In this case, the battery auto regulates its current, absorbing as much charge as needed to continue the charging process. As the battery continues to charge, its current starts to decrease. When the current drops to the Precharge current level (10% of $I_{\text{chg}}$), the voltage regulation phase finishes and the battery can be considered fully charged.

With the battery in a charged condition, its voltage can be controlled by the charger automatically. In this case, when the voltage drops to the recharging voltage $V_{\text{bat_rchg}}$, usually 96% of nominal voltage, the charging process is started again.

The Constant Current and Constant Voltage phases are why this charging scheme is called CCCV. The accurate control of voltage and current makes this scheme very popular for batteries sensitive to voltage and current levels, such as lithium-based batteries.

The CCCV charging scheme involves multiple phases with different start and end conditions and different current or voltages levels, so it requires a more complex implementation. There are several commercial ICs from different vendors that implement this charging scheme. These usually require several external components, not only for the configuration and voltage and current regulation, but also for implementing the power output stage.

In this application note we'll use this scheme for the monolithic battery charger with an integrated power output stage. This charger is externally configurable, so all voltages and currents are selectable by the user.
5. Battery Charger Design Diagram and Schematic

The monolithic battery charger using the SLG47105 is shown in Figure 3.

**Figure 3. Monolithic Battery Charger Block Diagram**

The battery power supply is generated with a high frequency PWM switching the internal HV GPIOs of the SLG47105 configured as a half bridge. As the current drivers for the battery charging process, these pins switch the output inductor to generate the desired regulated output voltage.

The PWM, generated with the internal PWM module of the GreenPAK IC, is controlled internally based on voltage and current feedback via the analog comparators and current sense modules. The voltage and current references for regulation are controlled internally, generating the reference level for the corresponding charging phase.

The entire process, including all the phases of the CCCV charging scheme, are controlled with internal LUTs and ripple counters configured to implement a state machine that generates all the signals required.

The block diagram shown in Figure 3 is represented in the schematic circuit shown in Figure 4. It includes the required external components for voltage and current level configuration and the output filters for battery charging.

**Figure 4. Monolithic Battery Charger Schematic Circuit**
As shown in the circuit diagram, the system output connected to the battery is filtered with a 10μH inductor and a 100μF non-polarized capacitor. These values are selected to filter the high frequency component of the 98.04kHz PWM output.

The circuit shown in Figure 5 (the Iref network) is used to configure the Trickle Charge current $I_{\text{bat\_short}}$, the Precharge current $I_{\text{prechg}}$ and the Fast Charge current $I_{\text{chg}}$. The values of the three resistors are determined by the following equations.

![Figure 5. Current Level Configurations](image)

\[
R_{I_{\text{bat\_short}}} = \frac{8000xI_{\text{bat\_short}}}{3.3 - 0.08xI_{\text{bat\_short}}}
\]
\[
R_{I_{\text{prechg}}} = \frac{800xI_{\text{chg}}}{3.3 - 0.008xI_{\text{chg}}}
\]
\[
R_{I_{\text{chg}}} = \frac{8000xI_{\text{chg}}}{3.3 - 0.08xI_{\text{chg}}}
\]

By selecting these resistors, all current levels for battery charging can be configured so the charger can adapt to the battery charging requirements. The charger can drive up to 2A output current.

Similar concepts can be applied for battery voltage feedback. The battery voltage feedback is controlled by the charger to reach the conditions of each charging phase, and finally, in the last step, to regulate it. To implement this control, the system requires a voltage signal that must be obtained with the resistor divider network shown in Figure 6.

![Figure 6. Voltage Level Configuration and Feedback](image)
The network shown in previous figure also allows the user to configure the battery’s nominal voltage. The battery charge voltage is configured with the following equation:

\[ V_{\text{batreg}} = 1.1x \left( 1 + \frac{R_1}{R_2} \right) \]

Resistor \( R_1 \) is the high side resistor from the battery to the current feedback pin, and \( R_2 \) is the low side resistor from the feedback pin to GND. The recommended value for resistor \( R_2 \) is 200kΩ or lower. Also, 1% or higher accuracy is needed for both resistors to obtain the best resolution.

The state pin is a digital output indicating the charging state. When this pin is high, the battery is charging. When this pin is low, the battery is charged, and the process has finished.

This implementation results in a battery charger with the following characteristics:

**Table 1: Battery Charger Electrical Characteristics**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Input Charge Voltage</td>
<td>12V</td>
</tr>
<tr>
<td>Input Control Voltage</td>
<td>3.3V</td>
</tr>
<tr>
<td>Input Current</td>
<td>2A</td>
</tr>
<tr>
<td>Output Fast Charge Current</td>
<td>2A</td>
</tr>
<tr>
<td>Battery regulation voltage</td>
<td>3.4 - 9.0V</td>
</tr>
</tbody>
</table>

6. **Implementation and Configuration of the Battery Charger**

The monolithic battery charger is implemented on a SLG47105V GreenPAK. This CMIC contains internal PWM generators, analog comparators, current sensors, and high-voltage integrated dual H-Bridge/quad Half-Bridge functionality. These can be used for generating the charging voltage and current required for battery charging with the corresponding signals for voltage and current regulation.

The CCCV phase control is implemented by using the internal ripple counter and the voltage and current feedback signals, as shown in Figure 7.
The Trickle Charge phase is represented internally as state zero of the ripple counter, and it is the first state of the control. In this state, ACMP1H controls the battery voltage continuously until it goes lower than $V_{bat\_rchg}$. When this condition is met, the start control 3-bit LUT5 enables the entire system to start the charging process, also activating the voltage output.

Each phase has a LUT, located in the upper side of the figure, waiting for the predefined conditions that must be reached to move on to the next phase. These conditions depend on the voltage or current levels that are compared with the comparators ACMP0H and CCMP1.

As an example, when the charger is in the first phase, the voltage must increase above $V_{bat\_short}$ to go to the Precharge phase. This is made by a pulse generated from the 3-bit LUT0 that only sets high when the counter is zero and the feedback voltage is higher than the reference voltage connected to ACMP0H. In this condition, the generated pulse increases the ripple counter to the next step, and the 3-bit LUT1 takes the control. This dynamic is repeated over the entire charging cycle.

The configuration of both analog comparators and the current sensor can be seen in Figures 8, 9, and 10.

Figure 7. Phase Control and Sensing
As mentioned previously, the battery voltage charging is generated and regulated by a PWM connected to the HV GPIOs of the GreenPAK configured as half bridge. This configuration is required to obtain the desired voltage with a high current output without converting the battery in a floating charge (as it would be if an H-Bridge were used). This requirement disables the option of using the current sense connected to the HV GPIO port used for the battery, as the current could not be sensed in the half-bridge branch.

As current must be measured to regulate it, the current sensor of the second HV GPIO SLG47105 is used. The second port was configured in High-Z so there is no current over it and the external shunt resistor of its current sensor can be used as the shunt resistor of the battery current.

The HV GPIO port connections and configurations are shown in Figures 11, 12, and 13.
To generate the PWM signal for voltage and current regulation, the PWM0 module is used. PWM is configured to 98.04kHz, which can be generated with the high frequency 25MHz internal oscillator. The duty cycle control is configured as a duty cycle counter, which can be incremented or decremented with an external control signal. This control signal is obtained from the voltage and current sensors, so depending on the current phase of
Monolithic Battery Charger

charging, one of those signals controls the output. When current must be regulated, the current sensor comparator output determines if the PWM duty cycle must be higher or lower to regulate the desired current. When voltage must be regulated, the analog comparator controls the PWM in a same way. The PWM is connected to HV OUT0 to control the half bridge output.

The configuration of the PWM0 module is shown in Figure 14.

![PWM0 Configuration](image)

Figure 14: PWM0 Configuration

As shown previously, voltage control is implemented with the analog comparator ACMP0H connected to the voltage feedback and an external reference voltage. To generate the reference, the PWM1 module is used filtered with an external first order RC low pass filter. The PWM 1 module is configured to generate a 98.04kHz PWM output signal with a configurable duty cycle from the internal register file. Each time the system advances to the next phase, the PWM receives a control pulse to increment the register pointer, so the next required voltage reference is generated. The PWM output is connected to PIN 15, filtered, and connected to Pin 3 as reference input voltage.

The connection of both PWM 0 and PWM1, and the configuration of the PWM1 module, are shown in Figures 15 and 16.
Figure 15: PWM0 and PWM1 Connection

<table>
<thead>
<tr>
<th>PWM1</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>PWM</td>
<td>Reg File</td>
</tr>
<tr>
<td>PWM period:</td>
<td>10.2 us</td>
</tr>
<tr>
<td>PWM frequency:</td>
<td>98.0392 kHz</td>
</tr>
<tr>
<td>Resolution:</td>
<td>8-bit</td>
</tr>
<tr>
<td>Duty Cycle source:</td>
<td>RegFile 8 LSB</td>
</tr>
<tr>
<td>Initial byte #:</td>
<td>0 (Range: 0 - 7)</td>
</tr>
<tr>
<td>Initial duty cycle:</td>
<td>11.76%</td>
</tr>
</tbody>
</table>

Figure 16: PWM1 Configuration
Similar ideas of voltage reference control can be applied to current reference control. Current control is implemented with the current sense comparator CMP1 connected to the shunt resistor and an external reference voltage related to current levels. To generate the reference, three resistors connected to a resistor network are used, as shown in Figure 5. Each time the system advances to the next phase, the system connects the corresponding resistor by enabling the corresponding pin (PIN 2, PIN 14, or PIN 20) and configuring the others as High-Z. With this implementation, one of the three resistors is connected to the resistor divider circuit while the others are disabled. This requires the pins named above to be configured as Digital Input/Output with the data output connected to GND and the Output Enable input controlled by the internal system logic.

Figures 17 and 18 show the connection of each pin and the configuration of PIN 2.

![Figure 17: Current Reference Control](image)

![Figure 18: PIN 2 Configuration](image)

The entire battery charger implementation diagram is shown in Figure 19.

![Figure 19. Monolithic Battery Charger Implementation](image)
7. Tests and Conclusion

To test the implementation, the entire system was assembled and analyzed with a waveform recorder to analyze battery current and voltage. A fully discharged LiPo battery was used. This battery, with a nominal voltage of 4.1V, was charged with a fast charge current of 1A. For this configuration, R1 and R2 of the voltage feedback network were 560kΩ and 200kΩ respectively, while \(R_{\text{chgl}}\), \(R_{\text{prechg}}\) and \(R_{\text{bat\_short}}\) were 2482Ω, 242.7Ω and 84.7Ω respectively. The entire system can be seen in Figure 20.

![Figure 20. System Implementation](image)

To analyze the results, we logged the voltage and current waveform at the battery, the reference voltage output used for voltage regulation at different charge phases, and the PWM output duty cycle.

Figure 21 shows the reference voltage output generated by the GreenPAK that is compared with the battery voltage feedback obtained from the resistor divider network shown in Figure 6.

In Figure 22, the duty cycle of the PWM output signal for CCCV battery charging is shown. Note that the duty cycle spike corresponds to the change from the Fast Charge phase to the Constant Voltage phase, and the charger changes from constant current regulation to constant voltage regulation.

![Figure 21: Reference Voltage](image) ![Figure 22: PWM Output Duty Cycle](image)

These images show the expected dynamic on both signals for a CCCV based battery charger.

Figures 23 and 24 show the output voltage applied to the battery and its current. The output voltage and the current have the expected shape of the CCCV charging scheme.
In this application note, we implemented a monolithic battery charger for lithium-based batteries using the CCCV charging scheme and implemented it on the GreenPAK SLG47105V.

Miniaturized and efficient battery chargers like this one are extremely important in today's electronics market. The size of the entire measurement system is smaller than many other implementations and highlights where GreenPAK can be used to replace other commercial devices.

**Revision History**

<table>
<thead>
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<th>Revision</th>
<th>Date</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.00</td>
<td>Mar 3, 2022</td>
<td>Initial release.</td>
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