

BATTERY POWER PRODUCTS & TECHNOLOGY

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How to Design a Safer Battery Charging System

Jinrong Qian, Applications Engineering Manager

Mao Ye, Applications Engineer

Texas Instruments

The Lithium-Ion (Li-Ion) battery is widely adopted in portable devices because of its high-energy density on both a gravimetric and volumetric basis. However, Li-Ion batteries are very sensitive to over-charging and over temperature, which may cause thermal run-away and battery explosion. How to design a safer battery charging system has become one of the critical factors for rechargeable battery-powered devices. This article talks about the main system design considerations for Li-Ion battery safety, charger design and safety monitoring, as well as charging system level safety.

Battery-Operated Charging System

Figure 1 shows a typical battery charging system. System input is either a DC power supply from an AC wall adapter, or a DC power source such as USB interface. This typical battery charging system includes a charge front end (CFE), battery charger and battery pack. The CFE protection integrated circuit (IC) can improve the battery-operated system's safety by integrating input over-voltage, over-current and battery over-voltage protections. Battery charger ICs regulate battery charge voltage current and monitor battery temperature to improve life cycle and safety. It is very helpful to understand the Li-Ion battery characteristics for designing a safer charging system.

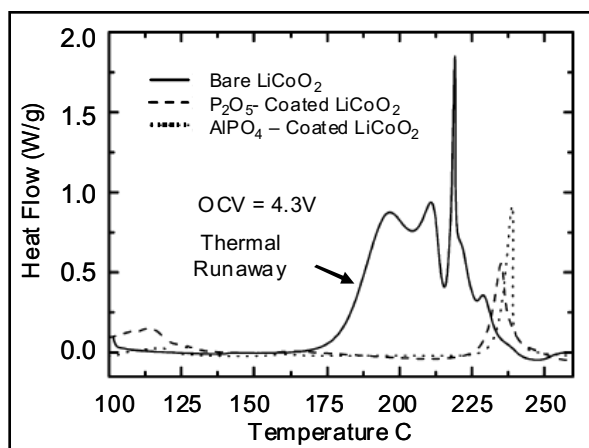


Figure 1. Typical Battery Charging System

Li-Ion Battery Safety

Excessively high operating temperatures accelerate cell degradation, causing thermal run-away and Li-Ion batteries to explode. This is a specific concern for Li-Ion batteries because of its highly aggressive active material. Rapid temperature increases can occur if a battery is overcharged at high current or shorted. When overcharging a Li-Ion battery, active metallic lithium is deposited on anode. This material dramatically increases the chance of fire because it can explode from being in contact with electrolyte and cathode material. For example, Li/carbon intercalated compound reacts with water. The released hydrogen can be ignited by heat generated from the reaction. Cathode material, such as LiCoO₂, reacts with electrolyte when temperatures exceed its thermal run-away threshold of 175°C with 4.3V cell voltage (see Figure 2) [1]. Li-Ion cells use thin, micro-porous films such as polyolefin to electrically isolate the positive and negative electrodes. These electrodes provide excellent mechanical properties and chemical stability. They are also reasonably priced. The low melting point of polyolefin, 135°C to 165°C, makes it suitable for thermal fuse use. As the temperature approaches the polymer's melting point, porosity is lost. This is deliberate to shutdown the cell since lithium ions no longer can flow between electrodes.

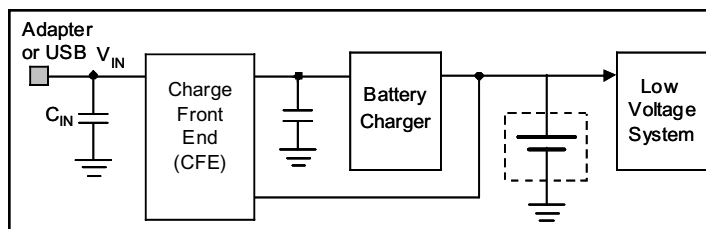


Figure 2. Battery Thermal Runaway

Also, there is a positive temperature coefficient (PTC) device and a safety vent to provide additional protection in Li-Ion cells. Typically, the case commonly used as the negative terminal is Ni-plated steel. When the case is sealed, metal particles can contaminate the cell's interior. Over time, these particles can migrate into the separator, degrading the insulating barrier placed between the cell's anode and cathode sides. That creates a micro-short between anode and cathode, allowing electrons to flow freely, ultimately causing the battery to fail. Usually, this type of failure leads to little more than the battery powering down and ceasing to function properly. In rare instances, howev-

er, the battery may overheat, melt, catch fire or even explode. This was reported as the main root cause of some recent battery failures that resulted in mass recall by different manufacturers.

Safer Battery Charger Design

Figure 3 shows a widely used Li-Ion battery charge profile. Charging a Li-Ion battery consists of three phases: pre-charge, fast-charge constant current (CC) and constant voltage (CV). During pre-charge, the battery is charged at a low rate. Typically, this is one-tenth the fast charge rate when the battery cell voltage is below 3.0 V. This allows the passivating layer to recover, which might be dissolved after prolonged storage in the deep discharge state. It also prevents overheating at 1°C charge rate (the current which can completely discharge the battery in one hour) when partial copper decomposition appears on anode-shortened cells on over-discharge.

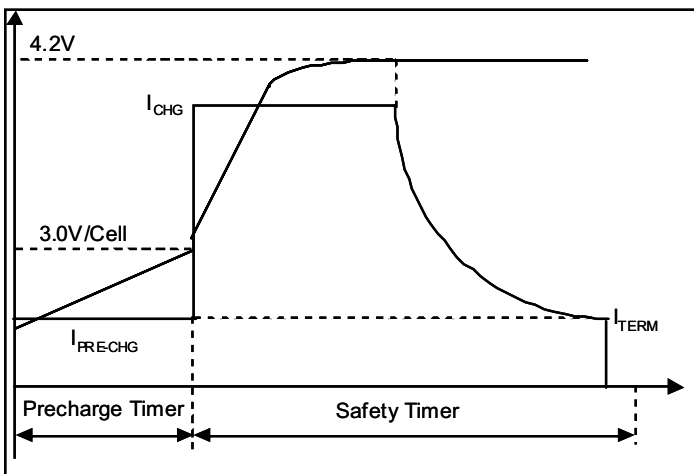


Figure 3. Li-Ion Battery Charge Profile

A pre-charge safety timer prevents charging a dead battery over a long time period. Typically, when the battery cell voltage reaches 3.0 V, the charger enters the CC phase. Fast-charge current usually is limited from 0.5 to 1C rate to prevent overheating, resulting in accelerated degradation. Rates should be selected so that the battery temperature does not exceed 45°C. Charge the battery at the fast-charge rate until it reaches a voltage regulation limit (typically 4.2 V/cell for LiCoO₂-based cathode). The charger begins regulating the battery voltage and enters CV phase, while the charge current exponentially drops to a pre-defined termination level where battery charging is terminated.

Battery charge voltage accuracy is critical for battery life cycle and safety. Higher battery charge voltages offer more capacity, but result in shorter battery life [2] as shown in Figure 4. For the battery charge voltage with ±2.5 percent tolerance, the charge voltage could reach 4.3 V, which may cause thermal runaway and safety issues. To prevent charging the battery at high temperatures and improve safety, charger ICs must monitor the battery pack temperature. Only when the battery temperature is within the safety region, typically between 0 to 45°C, will the battery be charged. Usually a thermistor inside the battery pack is used for this purpose. Moreover, a fast charge safety timer is often required to prevent charging a dead battery for an excessively long period. The battery charger must be terminated when the safety time expires, even if the battery does not reach the termination current.

Highly integrated linear battery chargers are widely used to charge a single-cell Li-Ion battery due to their design simplicity, low cost, and small size for portable devices. One design challenge is to remove and minimize the heat generated, while maintaining the battery charger within a safe thermal operating region. A newly developed battery charger with thermal regulation alleviates thermal concerns while maximizing charge rate and minimizing charge time.

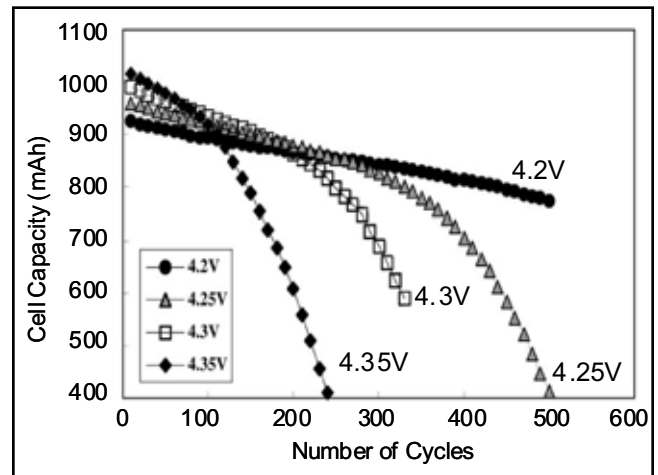


Figure 4. Relation Between Charge Voltage and Cycle Life for a Li-Ion Battery with LiCoO₂ Cathode

The linear charger simply drops the adapter's DC voltage down to the battery voltage. The power dissipation in the linear charger is given by:

$$P_{\text{CHGR}} = (V_{\text{IN}} - V_{\text{BAT}}) \times I_{\text{CHG}} \quad (\text{Equation 1})$$

There is a large difference between the input and battery voltage when the charger transitions from pre-charge to fast-charge mode when power dissipation reaches the maximum. For example, if a 5 V adapter is used to charge a 1,200 mAh Li-Ion battery, maximum power dissipation is 1.8 W with 1 A charge current, and 3.2 V battery voltage. This power dissipation results in 85°C temperature rise for a 3 by 3 mm QFN package with 47°C/W thermal impedance. The junction temperature exceeds the maximum allowed operating temperature of 125 at 45°C ambient temperature. It is difficult to have a good thermal design for maintaining a junction temperature within a safe region when initiating the charge. As the battery voltage rises during the charge, power dissipation drops. How can we maintain the charger functioning in a safe thermal operating region while improving thermal design? The more advanced battery chargers such as bq2408x and bq2403x have introduced a thermal regulation loop to prevent the charger from over-heating. When the internal chip temperature reaches a pre-defined temperature threshold, for an example 110°C, any further IC temperature increase reduces the charge current. This limits power dissipation and extends thermal protection to the charger. The maximum power dissipation causing the IC junction temperature to reach the thermal regulation depends upon the PCB layout, the number of thermal vias, and ambient temperature (see Figure 5).

When the thermal loop is active, the charging current may reach the charge termination threshold. This falsely terminates charging since thermal regulation usually happens during the

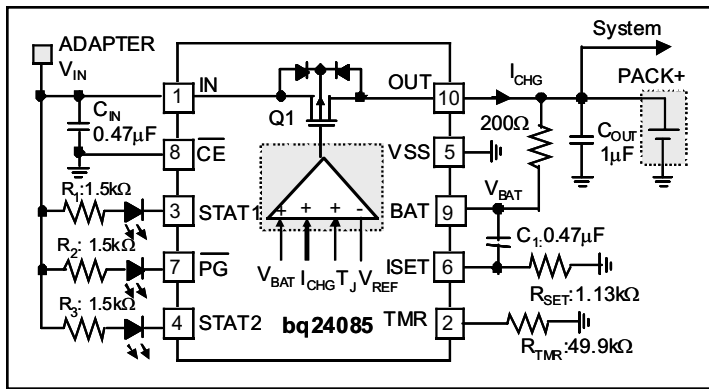


Figure 5. Typical Application Circuit for the bq24085

early stages of fast charge. To prevent false charge termination, battery charge termination is disabled whenever the thermal regulation loop is active. Additionally, the effective charge current is reduced. This increases battery charge time. Thus, the charge safety timer may falsely expire for a fixed safety timer. The bq24085 employs the dynamic safety timer which automatically slows down the safety timer's clock frequency. The dynamic timer control circuit effectively extends the safety timer duration. This minimizes the chance of a safety timer fault due to the thermal regulation.

System Level Charge Front End (CFE) Safety Design

How can we improve system level charging safety and reliability? Many different adapters are available to power portable devices, but their electrical specifications usually differ from one manufacturer to another. This provides technical challenges for system designers building a portable device to meet safety requirements when different adapters are used. Challenges include input over-voltage, input over-current, battery over-voltage and reverse input voltage, all of which can damage the system.

Input over-voltage can be caused by adapter hot plug-in, wrong adapter, transient or a steady state over-voltage condition. During adapter hot-plug in, over-voltage occurs due to resonance between the cable inductance and the system's input decoupling capacitor. Input over-current may not be an issue with stand-alone chargers, since the constant-current mode limits the amount of current delivered to the output or battery. However, with power path management battery chargers such as the bq24070, which have a direct power path from the input to the system, often have no protection from pulling excessive current. Lately, there has been some concern with operating adaptors in their current-limit mode, and a desire for a programmable input current-limit circuit to assure the adaptor does not get into this mode. Li-Ion/Li-Poly battery packs are known for the potentially dangerous "flaming" condition if over-charged under high temperature. The key indication for an over-charge is the higher cell voltage. More manufacturers are looking for safety measures to ensure pack safety and compliance. To improve battery safety, a second level over-voltage protection is added to remove the input power source. This is accomplished by turning off CFE power MOSFET when battery over-voltage is detected.

Figure 6 shows a typical system level CFE circuit. The high-voltage protection CFE isolates the high input voltage from low

voltage charger and system, so that the system will not see high voltage. This IC integrates all these safety features including input current limiting and protection, input voltage protection, and battery over-voltage protection. Whenever either fault condition exists, the CFE turns off the MOSFET to achieve proper protection, which in turn improves overall system safety.

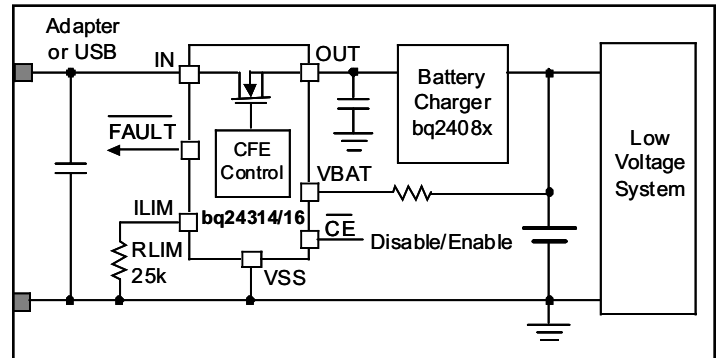


Figure 6. Typical System Level CFE Circuit

Summary

It is critical to design a safer battery charging system from battery characteristics, charger IC design, and system level safety considerations. Together with the CFE, battery charger IC, and safety protection in the battery pack, the charging system can achieve more robust safety performance. The fully-integrated CFE improves charging system level safety, while the safer battery charger design improves battery life cycle, and prevents the hazard from overcharging.

Reference

1. Jaephil Cho, Joon-Gon Lee, Byoungsoo Kim, and Byungwoo Park, "Effect of P2O5 and AlPO4 Coating on LiCoO2 Cathode Material", Chem. Material, Vol. 15, No. 16, 2003, pp 3190 – 3193.
2. Soo Seok Choi and Hong S. Lim, "Factors that affect cycle-life and possible degradation mechanisms of a Li-ion cell based on LiCoO2", Journal of Power Sources, Volume 111, September 2002, pp 130-136.

Jinrong Qian is an Applications Engineering Manager and Distinguished Member of the Technical Staff for the Portable Power Battery Management group at Texas Instruments. He has published a myriad of peer-reviewed power electronics transactions and power management papers, and holds 20 U.S. patents. Dr. Qian earned a BSEE from Zhejiang University, and a Ph.D. from Virginia Polytechnic Institute and State University. Jinrong can be reached at ti_jinrongqian@list.ti.com.

Mao Ye is an Applications Engineer with Texas Instruments where is he responsible for portable power battery management. Mao received his MSEE and BSEE from Zhejiang University, China.