Today’s preferred rechargeable battery chemistry for small, lightweight, portable applications is lithium-ion. When it comes to power management for mobile phones, portable media players or navigation devices, and other such equipment, design engineers work with a well-defined and understood set of voltage and current ranges. This includes the battery as the power source, the charger that accurately and reliably provides energy to the battery, and linear regulators or dc/dc converters for the power conversion to the system.

However, the power-management designer cannot control the actual power source being used with the device. The equipment can be plugged into many different types of power supplies such as regulated and unregulated ac/dc adapters, USB hubs and ports, as well as automotive and industrial power systems. These can cause a multitude of issues. As the external power source becomes the great unknown, care needs to be taken to protect the application from unknown and unforeseeable events.

Modern protection schemes protect sensitive charging electronics from high-voltage and overcurrent conditions, both at the circuit and battery level. This provides a safe and reliable charging front-end for the application through superior voltage and current capability with fast turn-off speeds.

**Single-cell lithium-ion charging systems**

A typical charging and power-management system in single-cell, lithium-ion applications usually consist of two components: a power source and power-conversion circuitry. The user plugs an ac/dc wall adapter or a USB cable from a computer into the portable device to supply a voltage of approximately 5V. In the equipment, a charge-management IC regulates the battery charge and powers the main system regulators. The charge-management IC may be a stand-alone charger used in conjunction with a highly-integrated power management unit (PMU) that contains a number of dc/dc and low dropout voltage (LDO) regulators. Alternatively, the charge functionality is integrated
Historically, equipment manufacturers controlled the type of power source being plugged into their application, assuring that the power adapter supplied with the electronic device met the specified operational performance. USB charging was not a widespread feature.

Today, however, given the enormous cost pressure in consumer electronics, suppliers try to shave pennies off their system costs by simplifying power adapters or eliminating them altogether and shipping only a cable for USB charging. Additionally, a large aftermarket allows consumers to source virtually any type of power adapter for their electronic gadgets. Due to its convenience, USB charging is quickly becoming the de facto standard for single-cell, lithium-ion applications. This also has been mandated by the Chinese government, which desires a universal charger interface for new portable electronic equipment.
With no control over the type of power source it is plugged into, the equipment is exposed to a wide variety of operating and failure modes that the power designer must anticipate. Inexpensive aftermarket ac/dc adapters may not be as tightly regulated, if regulated at all. This could allow spikes on the power line, or the open loop voltage of a simple, transformer-based adapter to reach the charging and battery system. The adapter electronics may fail, resulting in unforeseen overvoltage or overcurrent conditions. Inductive effects of long cables may pose additional voltage and current-transient problems. USB ports and dedicated USB chargers, while presumably following the USB specification, often are not as closely regulated to the 5V supply voltage they are supposed to provide.

So why are there potential reliability and safety problems? One would assume that the charging circuit provides sufficient safety mechanisms to withstand temporary or permanent abnormal operation conditions of a power supply. Unfortunately, the opposite is true. Most stand-alone charge ICs, and virtually all analog-baseband PMUs in the market today, use low-voltage semiconductor processes that often provide absolute maximum voltage ratings of 6 to 7V. This does not provide much of a safety margin for overvoltage conditions in a 5V system.

Process availability creates this situation. Few semiconductor companies possess the necessary process technology to combine high-voltage power transistors and highly integrated chip logic in order to manufacture high-performance charge ICs that meet economically viable price points. For integrated PMUs with functions that go beyond power management, such as audio-signal processing and touch-screen control, the need to achieve the highest possible integration while maintaining maximum audio performance and accuracy mandates the use of small-structure, low-voltage, CMOS processes. There is a trade-off, however. With increasing integration, the maximum allowable voltage rating decreases.

Circuit and battery protection considerations

In essence, three things can go wrong with voltage and current conditions at the front-end of the power-conversion system.

First, the power source input voltage may exceed a safe level of operation, defined as the level from which the circuits can be permanently operated without damaging the system. Second, through abnormal load conditions, the charging or power-conversion circuit may attempt to draw more current from the power source than is allowed in order to not damage the source, or be compliant with a given standard for the input current. And last, the charger could malfunction, allowing the lithium-ion battery regulation voltage to exceed a safe operating level, possibly leading to an explosion.

Overvoltage protection traditionally has been performed by transient voltage suppressors (transorbs), which are zener diodes engineered for high-power operation. But transorbs may be relatively slow to react and not particularly precise in regards to their protection threshold. Besides, they are relatively large components. A dedicated integrated input overvoltage (OVP) circuit may be faster to respond and more accurate. However, it is still insufficient to ensure total system safety and reliability because it only covers one potential case for potentially harmful operating conditions. A fuse can protect against an overcurrent condition, but as in the case of the transorb, its response time may be inadequate for fast voltage and current transients. Failing permanently requires the system to be shipped back in for service. Next to consumer safety, avoiding costly field returns is the No. 1 reason for equipment manufacturers to seek out more advanced protection approaches. Along with providing added layers of safety, their designs need to be small, cost-effective, and sufficiently intelligent to avoid permanent failure.
Figure 2: Multilayered system protection continuously monitors input voltage, current, and battery voltage.

The circuit in

Figure 2: Multilayered system protection continuously monitors input voltage, current, and battery voltage.

is designed to protect lithium-ion batteries from charging-circuit and power-supply failures. The IC continuously monitors the input voltage and current, as well as the battery voltage. In case of an input overvoltage condition, the IC immediately removes power from the charging circuit by turning off an internal switch. In the case of an overcurrent condition, it limits the system current at a pre-programmed threshold value. If the overcurrent persists, it switches off the pass element after a blanking period.
Additionally, the IC monitors its own die temperature and switches off if it becomes too hot. The input overcurrent threshold is user-programmable, allowing currents up to 1.5A. A processor can control the circuit, and the circuit provides status information to the host about fault conditions. Critical for space-constrained portable equipment, the circuit operates using two very small 1-µF capacitors. It is packaged in a space-saving $2 \times 2$ mm$^2$ package. This greatly reduces the form factor of a complete high-performance protection solution, compared with the previously described discrete approach of fuses and transorbs.

Figure 3: Overvoltage response for input step from 5V to 12V, $t_{\text{rise}} = 20\mu$s.
If the ac-adapter input voltage rises above a pre-programmed value ($V_{\text{OVP}}$), shown in green horizontal line, an internal FET that acts as pass element is turned off, removing power from the circuit. The FAULT pin is driven low. When the input voltage returns below $V_{\text{OVP}} - V_{\text{HYS-OVP}}$ (but still above $V_{\text{UVLO}}$), the FET is turned on again after a de-glitch time of $t_{\text{ON(OVP)}}$ to ensure that the input supply has stabilized. The voltage hysteresis is implemented to avoid ringing.

Figure 3: Over-voltage response for input step from 5V to 12V, $t_{\text{Rise}} = 20\mu s$. 

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The overcurrent threshold $I_{\text{OCP}}$ is programmed by a resistor $R_{\text{ILIM}}$ connected from the ILIM pin to ground. If the load current tries to exceed the $I_{\text{OCP}}$ threshold, the device limits the current for a blanking duration ($t_{\text{BLANK(OCP)}}$) as shown in Figure 4.
If the load current returns to less than $I_{OCP}$ before $t_{BLANK(OCP)}$ times out, the device continues to operate. However, if the overcurrent situation persists for $t_{BLANK(OCP)}$, the FET is turned off for a duration of $t_{ON(OCP)}$, and the FAULT pin is driven low. The FET is then turned on again after $t_{ON(OCP)}$, and the current is monitored all over again.

Each time an OCP fault occurs, an internal counter is incremented. If 15 OCP faults occur in one charge cycle, the FET is turned off permanently. The counter is cleared either by removing and re-applying input power, or by disabling and re-enabling the device with the CE pin controlled by a host processor. It is easy to see that a simple fuse/transorb combination cannot match this level of flexibility and system safety optimization.

Although a lithium-ion battery pack typically contains dedicated safety circuitry that protects the battery cell from being exposed to unsafe voltage levels, it may be best to add a second level of safety that ensures the battery is supervised and protected from abnormal operating conditions should the battery-pack-protection circuit fail.

The battery overvoltage threshold $B_{VOVP}$ shown in Figure 2 is set internally to 4.35V. If the battery voltage exceeds the $B_{VOVP}$ threshold, the FET is turned off, and the FAULT pin is driven low. The FET is turned back on once the battery voltage drops to $B_{VOVP} - V_{HYS-BOVP}$. Each time a battery overvoltage fault occurs, an internal counter is incremented. If 15 such faults occur in one charge cycle, the FET
is turned off permanently. The counter is cleared either by removing and re-applying input power, or by disabling and re-enabling the device with the CE pin, similar to clearing the OCP counter.

In addition to protecting the system from unwanted and unsafe external conditions, the design protects itself from malfunction due to overheating. If the junction temperature of the device exceeds $T_{J(OFF)}$, the FET is turned off, and the FAULT pin is driven low. The FET is turned back on when the junction temperature falls below the switch-off temperature $T_{J(OFF)}$ minus an amount allowing for hysteresis $T_{J(OFF-HYS)}$ to avoid a false voltage trigger.

Often it is desirable to signal abnormal conditions to a host system to take further action. The FAULT pin is an open-drain output that goes low during overvoltage, overcurrent, and battery-overvoltage events. If the application does not require monitoring of the FAULT pin, it can be left unconnected.

The IC has an enable pin that can be used to enable or disable the device. When the CE pin is driven high, the internal FET is turned off. When the CE pin is low, the FET is turned on, as long as other conditions are safe. The CE pin has an internal pull-down resistor and can be left floating. Note that the FAULT pin functionality is also disabled when the CE pin is high.

**Conclusion**

Modern portable equipment may be supplied by a multitude of power sources with operational and failure modes often unknown to the design engineer. While traditional protection circuitry consisting of fuses and transors provides some level of protection, it cannot address today's requirements of small footprint, low power dissipation, and fast, repeatable response. Fully integrated overvoltage, overcurrent, and battery-overvoltage circuits provide maximum safety and reliability while occupying the smallest possible board space and avoiding costly field returns.