Fast Charging Overtemperature Protection for Smartphones


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INTRODUCTION

The global smartphone market is intensely competitive. Huge smartphone brands that were household names just a few years ago are now forgotten. Competition is no longer defined by brand loyalty but rather by technological new features. Multi-lens, high pixel cameras, 5G compatibility, foldable screens and ultra-fast charging are just some of the features vying to win over consumers.

The ability to power such high-end devices in ultra-thin form factors is the result of the steady evolution of the lithium-ion battery pack. The packs that first arrived on the market in the early 1990s have continued to improve with the development of new cathode, anode, electrolyte and separator materials. While lithium-ion battery technologies may not follow Moore's Law, they still have shown a relentless progression of improvements to energy capacity, power delivery and life span while costs have continued to decrease.

One of the most recent battery advancements is fast charging offering the ability to dramatically cut charging time. Fast charging works by increasing the amount of current sent to the battery in order for its capacity to refill quicker. Unfortunately, this performance comes with some safety and longevity concerns that require overtemperature protection. This white paper provides an overview of lithium-ion cell construction and possible fast charging conditions that threaten its safe, reliable and long operational life. The paper outlines some of the potential hazards that fast charging conditions can inflict on lithium-Ion battery cells and USB Type-C™ power delivery cables along with layout solutions to minimize these effects.

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LITHIUM-ION CELL OVERVIEW

The basic function of the lithium-ion cell is to transform chemical energy into electricity. The individual lithium-ion cell is comprised of an intercalating lithium compound cathode, a carbon based (typically graphite) anode as well as a liquated or gel type electrolyte with lithium salts through which ions travel, and a polymer separator to act as an internal insulator to the electrons. The use of the two intercalation electrodes has led to the lithium-ion batteries being called "rocking-chair" batteries as ions shuttle back and forth between the electrodes and through the electrolyte in a lithiation/delithiation process. The separator plays a critical role in cell safety by ensuring there is no physical contact between the cathode and anode.

LITHIUM-ION CELL HAZARDS

While separators have evolved from simple single-layer sheets to multilayer sheets with shutdown features, they alone cannot ensure complete cell safety. The lithium-ion cell is constructed with materials that are flammable and degradable where mechanical and electrical shock can lead to thermal runaway. The lithium-ion cell materials that are stable at lower temperatures start to breakdown when temperatures exceed 130 ˚C. If a cell starts to enter thermal runaway, the results can be catastrophic as seen in various news reports in recent years. Thermal runaway in a lithium-ion cell is a highly exothermic, self-propagating process that results in the venting of toxic and highly flammable gases and the release of significant energy in the form of heat, greater than 1000 ˚C. Some of the newest smartphones on the market now use multiple cells, therefore, the risk becomes even greater as failure can potentially daisy chain from one cell to the next.

THE MECHANICS OF FAST CHARGING

The shuttling back and forth of lithium-ions between the intercalating cathode and anode has a degrading impact on electrodes. Current research has highlighted how lithium concentration on the surface of the electrode closest to the separator experiences a higher State of Charge (SOC). SOC is defined as the ratio of current capacity to the maximum amount of charge that can be stored in the battery. Understanding the SOC is critical for regulating against over-discharging and over-charging batteries. Without such regulation, batteries are at a risk of having their operating life reduced or, in the worst case, catastrophic failure.

During fast charging operations, the highly concentrated lithium on the surface depletes at a faster rate than the lithium stored in the bulk of the electrode. This fast diffusion induces mechanical stresses, which can then result in cracks within the electrode and eventually electrode surface disintegration. When electrode surface material has disintegrated, it exposes material in the core of the electrode. This material then takes on the role of the surface electrode and the disintegration process starts all over again. It is believed that this process is a leading factor in lithium-ion batteries having a far lower lifespan when regularly fast charged.

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OPERATIONAL CHARACTERISTICS OF FAST CHARGING

Smartphone batteries charge in two phases. Phase one charges the cell within 70 % to 80 % of the cell capacity in a constant current mode. Phase two applies a trickle current in a constant voltage mode up to the remaining 100 % capacity. However, when fast charging is applied, the charging rates (C rates) are drastically increased, for example, up to 3 C (compared to a typical 0.8 C) during the constant current phase.

The high levels of current generate ohmic heating. Hence, fast charging is recommended at room temperature only. Elevated levels of temperature cause a further deterioration of battery life while excess heat (>130 ˚C) can result in catastrophic failure. For that reason, low ohmic overtemperature protection devices must be a required element of a fast charging cell design.

LITHIUM-ION CELL SAFETY

While lithium-ion pouch cells boast many desirable benefits such as low cost, ease of large-scale manufacturing, lighter non-universal sizes and high energy densities, the technology still has the same limitations as other types of lithium-ion cells. The requirement for protection circuits to maintain the voltage and current within safe limits is one of the primary limitations of a lithium-ion battery. The soft foil cell design also adds a further disadvantage causing the cells to visibly inflate (sometimes called pillowing) during over-charge because of internal delamination.

Considering such obvious hazards, cell designers should consider taking a multi-layered approach to protect against various potential hazards. Individual cells require mechanical, electrical and thermal protection and this becomes more complicated when cells are networked into various battery pack arrangements.

There are numerous standards that help govern battery pack safety, but for rechargeable batteries in smartphones, the IEEE 1725 standard (IEEE Standard for Rechargeable Batteries for Cellular Telephones) is a solid starting point. This standard and the standards it references help guide designers in their battery protection design by specifying that multiple levels of redundancy are built into a pack.

An integral part of maximizing battery pack efficiency and safe operation is the battery management system (BMS) that uses various primary and secondary protection devices as well as software and hardware elements to manage the State of Charge (SOC), current, voltage and ambient battery temperatures. Mini-breaker Thermal Cutoff (TCO) devices are key elements in the protection architecture that are being increasingly used in lithium-ion battery cell arrangements. TCO devices are designed to provide accurate and repeatable overcurrent and overtemperature protection.

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EFFECTIVE BATTERY PROTECTION SOLUTIONS

Meeting the changing protection demands in next-generation lithium-ion battery packs has led to the evolution of TCO technology as well. Today's TCO devices combine two common circuit protection technologies, a PTC and a bimetal switch. Figure 1 below provides a simple schematic of the construction of a TCO. The two terminals (arm terminal and base terminal) are connected in a normally closed position to allow current to flow through the device. The contact point between both terminals serves a critical function in supporting high precision contact resistance, which can be as low as 2 mΩ (max.) in some model families. This is critical to ensure low ohmic heating during fast charging.

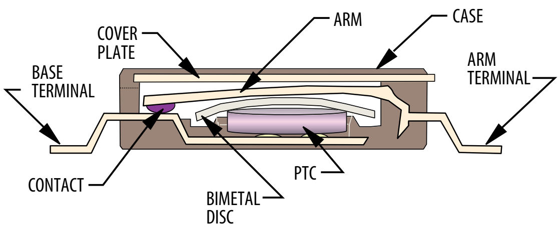

Figure 1. | *Construction of Bourns® Mini-breaker TCO Device*

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HOW TCO DEVICES WORK TO PROTECT A BATTERY CELL

Figures 2 and 3 illustrate how miniature TCOs mechanically provide protection to the circuit. Under normal conditions, current flows through the arm terminal, down through the very low resistance contact point and out through the base terminal. Key to any fast charging battery application is low resistance, hence, the need for the right contact resistance between the arm terminal and the base terminal.

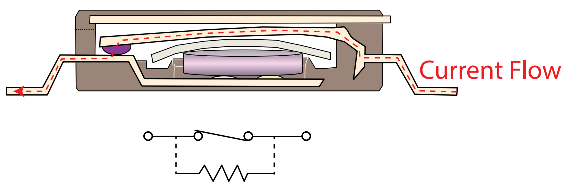

Figure 2. | *Miniature TCO Device in the Normally Closed Position*

The TCO device can be triggered by either an increase in the environmental temperature or by excessive current flows. Once the trip temperature has been reached, the bimetal disc flexes and this motion causes the arm to open (see Figure 3). If the TCO component used only a bimetal disc for its protection, the arm would quickly close as the temperature cooled. However, the benefit provided by a Bourns® miniature TCO device is that the PTC operates in parallel with the arm terminal. When the bimetal disc causes the arm to open, current flows through the bimetal disc and into the PTC. This current causes the PTC to act like a current-limiting heater, which provides sufficient heat to keep the bimetal disc flexed and the arm open. The combination of the bimetal disc and the PTC prevents oscillating between opening and closing of the TCO device's arm. Instead, this design allows the arm to remain open until a lower and safer temperature level is reached (between 40 °C ±10 °C,, which is below the lower specification limit of the TCO device), at which point the arm will reset. As part of UL 60730 testing, the opening and closing mechanism of most Bourns® miniature TCO devices is tested up to 6000 cycles.

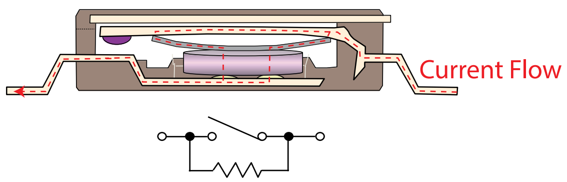

Figure 3. | *Miniature TCO Device Triggered Open*

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FAST CHARGING USB CABLES

Fast charging of smartphones requires that the charging cables be enhanced. Recent upgrades to the power delivery specifications from the USB Implementers Forum enables specially-designed cables to deliver up to 100 W of power (20 Volts, 5 Amps). The latest USB Type-C™ cables with 100 W power capabilities have plug openings of 21.35 mm^2 compared to the 64 mm^2 opening size of the USB Standard A plug. These miniature-sized USB Type-C™ plugs have 24 pins compared to just 9 pins in the much larger USB Standard A plugs.

The combination of small area, higher pin count and considerably higher power levels adds potential risks to these new cables. Fast charging over such cables can result in overheating and even fire damage if pins are damaged, the outer shell body is damaged or foreign material and liquids enter the plugs.

For that reason, it is advised that a protection solution such as a TCO device is embedded within such cables, (see Figure 4).

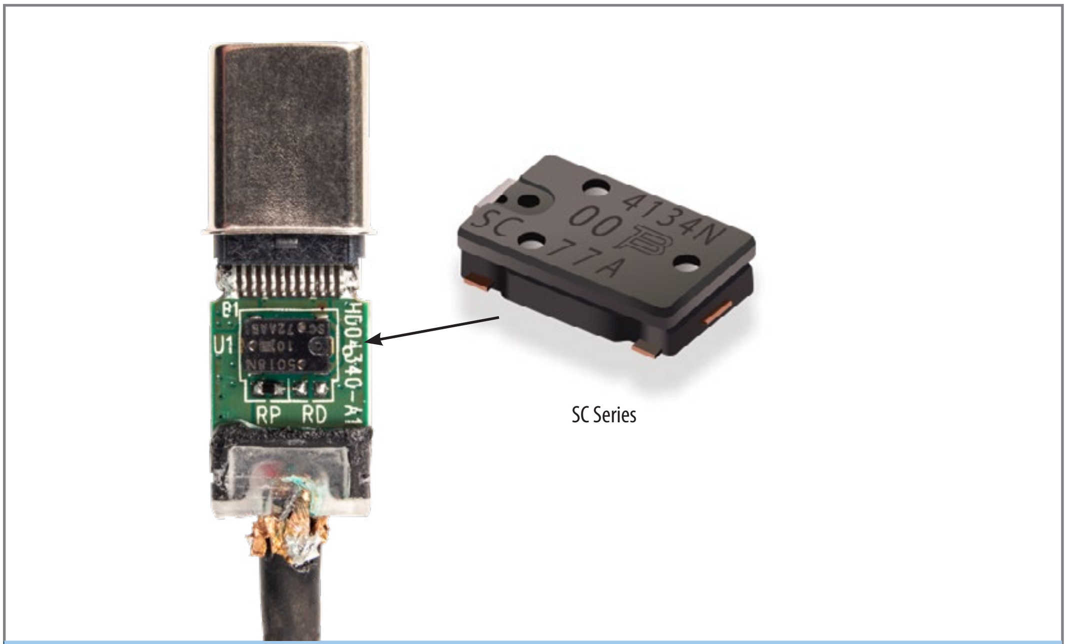

Figure 4. | Mini-breaker TCO Devices in USB Type-C™ Cable

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FAST CHARGING USB CABLES *(Continued)*

TCO devices have been proven to protect cables from damage from overheating by acting independently of any controller. By placing a TCO device on the USB V_{bus} line, it will react to an overheating condition, then quickly cut the current and allow the cable to cool. This is an optimal overtemperature solution. The performance of overheated cables with and without TCO protection is demonstrated in Figure 5 below. The cable without the TCO device continues to overheat from the fault and the temperature creeps up to 100 ˚C. The cable with TCO protection quickly trips and the cable surface does not overheat.

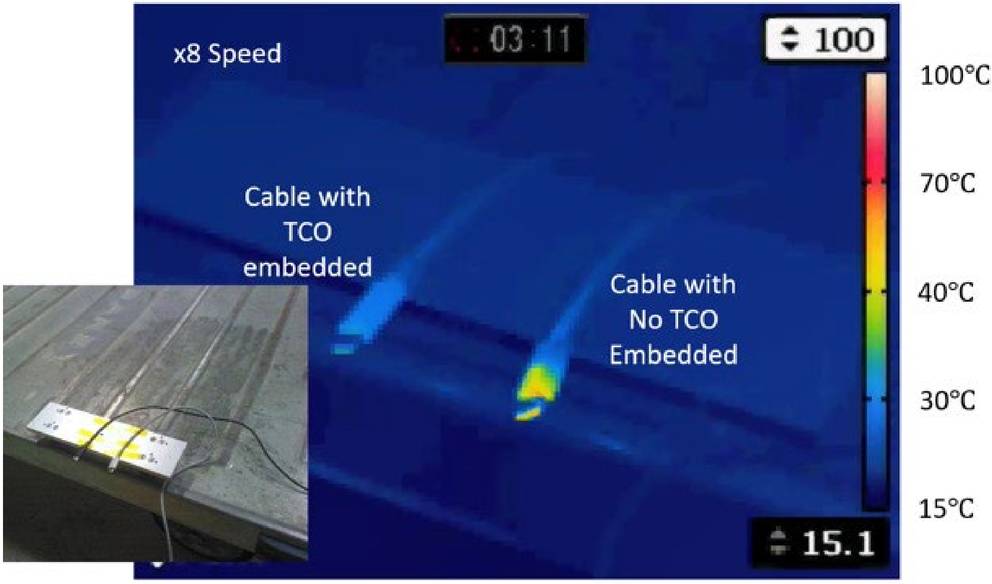

Figure 5. *USB cables under fault conditions.*
Cable on the left illustrates that the TCO device has protected against overheating.
The cable on the right has no protection.

APPLICATION NOTE

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CONCLUSION

Fast charging is just one of the latest smartphone developments. However, this new capability comes with additional safety and battery life concerns. Fast charging has the potential to strain lithium-ion cells and can result in excessive heating. In addition, faults in the high-power delivery of new USB Type-C™ cables can cause damage from overheating.

The broad line of Bourns® Mini-Breaker TCO products have provided precision overtemperature protection in more than 3 billion circuits. To safely realize the speed and convenience benefits of smartphone fast charging, lithium-ion cell and USB Type-C™ cable manufacturers can rely on the combination of high performance and market-leading quality Bourns has designed into its miniature TCO devices, offering the proven capability of controlling abnormal, excessive current virtually instantaneously up to rated limits.

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