The architecture of a switched-capacitor charger with fast charging and high efficiency

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Introduction

Consumers are constantly demanding their smartphones last longer between charging times and charge more quickly. Because of this, smartphone batteries are increasing in both size and charging rates. A 3,000-mAh battery may be capable of charging at 6 A, but charger efficiency and the power dissipation in the phone has been a limiting factor to charging at this high rate.

Table 1 offers a brief history of faster charging from Texas Instruments.

Table 1. Improvements of charging topologies

Charging topology	Charging rate	1-W power-loss charging current	Supporting standard
Standard buck charger	2 to 3 A	2 A	USB 2.0, Battery Charging Specification (BCS) 1.2
Dual buck charger	3 to 4 A	2.5 A	USB 3.1, BCS 1.2 with High Voltage Direct Charge Protocol
Flash charge	4 to 5 A	4.5 A	USB Power Delivery (PD) 3.0 with programmable power supply (PPS)
Switched-capacitor current doubler	4 to 8 A	6.5 A	

With the introduction of USB PD and PPS, the safe and quick charging of large-capacity smartphone batteries is possible with a new switched-capacitor charging system. There are several challenges to overcome in order to deliver high current to a large-capacity battery and the switched-capacitor architecture addresses all of them.

Figure 1 shows the key losses in a typical large-capacity smartphone.

Reducing the current across the cable minimizes I^2R losses in R_{ConA}, R_{Cable}, R_{ConD} and $R_{Control}$. The converter efficiency (η) must be very high to keep power loss and thermals under control. It is important to minimize the battery-connector resistance, R_{ConB}, as the current will be twice that of the USB cable current.

Protections ensure that the charger can monitor all key system aspects for overvoltage, overcurrent and temperature. All USB Type-C™ cables must support a minimum of 3 A at 20 V, but high-power and more-expensive versions can support up to 5 A at 20 V.

The switched-capacitor architecture enables the delivery of high current to the battery while keeping USB cable current and voltage drops low. It's possible to accomplish 6-A battery charging with standard 3-A-capable USB Type-C cables, or up to 10 A with 5-A-capable cables when using switched-capacitor devices in parallel.

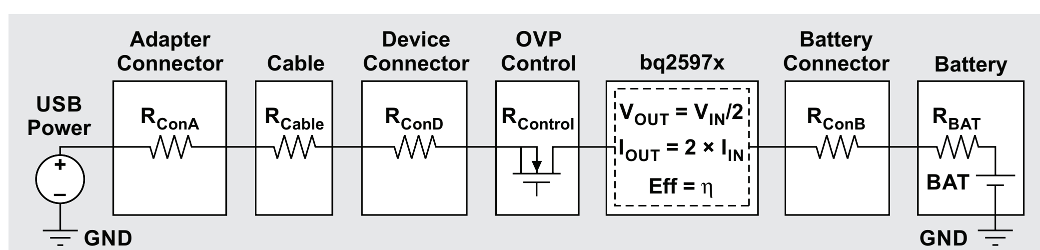
Architecture of a switched-capacitor charger

A typical buck-converter charger can achieve greater than 90% efficiency at 6 A, but that means a dissipation of over 2 W in the phone. A typical thermal budget for a smartphone allows less than 1 W of dissipation. A direct charge solution such as the bq25870 has lower losses in the phone, but the cable current and the charge current are the same.

The switched-capacitor charger can achieve up to 97% efficiency at 6 A delivered to the battery with only 3 A required on the USB Type-C cable. This which means less than 800 mW of dissipation in the phone, while requiring less than 3 A on a standard USB Type-C cable.

The switched-capacitor charger relies on a smart wall adapter to regulate the voltage and current at the input to the charger. The USB PD PPS protocol allows a sink-directed source output. In this case, the sink is the phone

Figure 1. Typical losses in a high-capacity smartphone charging system



and the source is the wall adapter. When the wall adapter is not in current foldback, the phone directs the voltage output in 20-mV steps, acting as a current-limited voltage source. When the wall adapter is in current foldback, the wall adapter maintains the voltage, and the phone directs the output current in 50-mA steps. The performance of the switched-capacitor solution will depend on the type of source.

The switched-capacitor charger uses four switches to alternately charge and discharge C_{FLY} capacitors. Figure 2 shows the simplified circuit, along with the equations for voltage and current during charging and discharging of C_{FLY} capacitors.

In the charging phase (t_1), Q1 and Q3 turn on and Q2 and Q4 turn off. This enables C_{FLY} to be in series with the battery, where C_{FLY} charges while delivering current to the battery. During the discharge phase (t_2), Q1 and Q3 turn off and Q2 and Q4 turn on. During this time, the C_{FLY} capacitor is parallel to the battery and provides charging current to it. The duty cycle is 50%, the battery current is half of the input voltage and the current delivered to the battery is twice the input current.

Figure 3 shows the waveforms of the battery current and voltage. This figure models the equivalent series resistance of the fly capacitor, as well as the resistances of the switches.

Figure 2. Simplified switched-capacitor circuit and equations

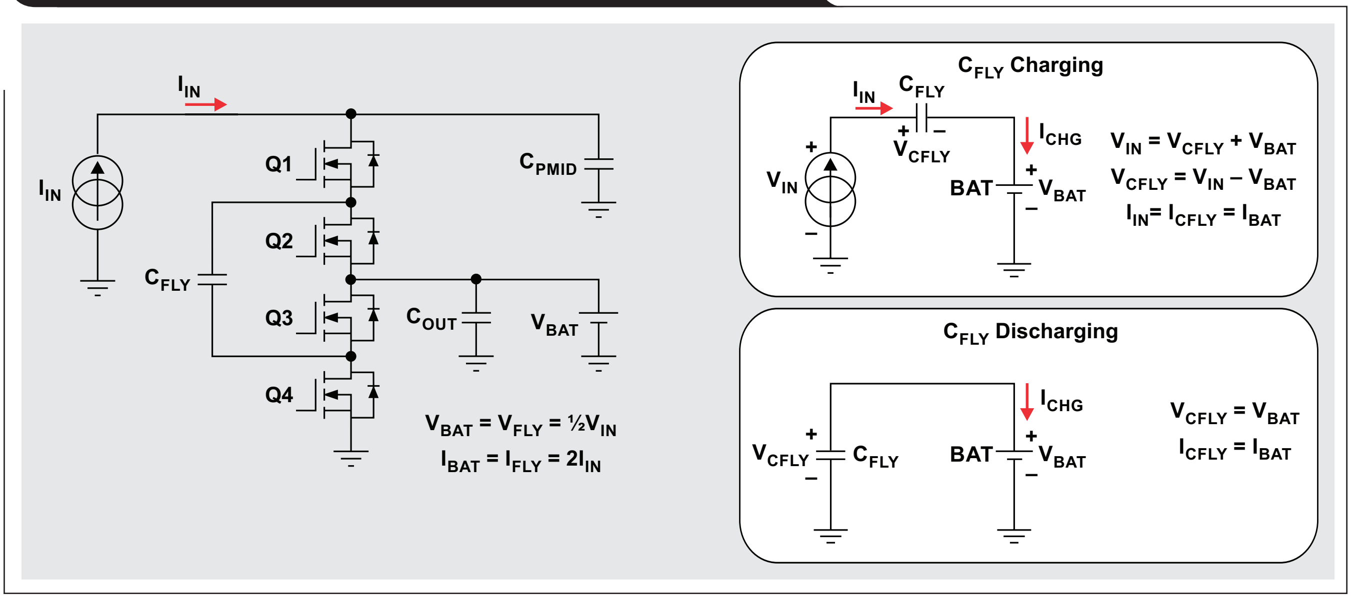


Figure 3. Switched-capacitor voltage and current waveforms for a constant current source

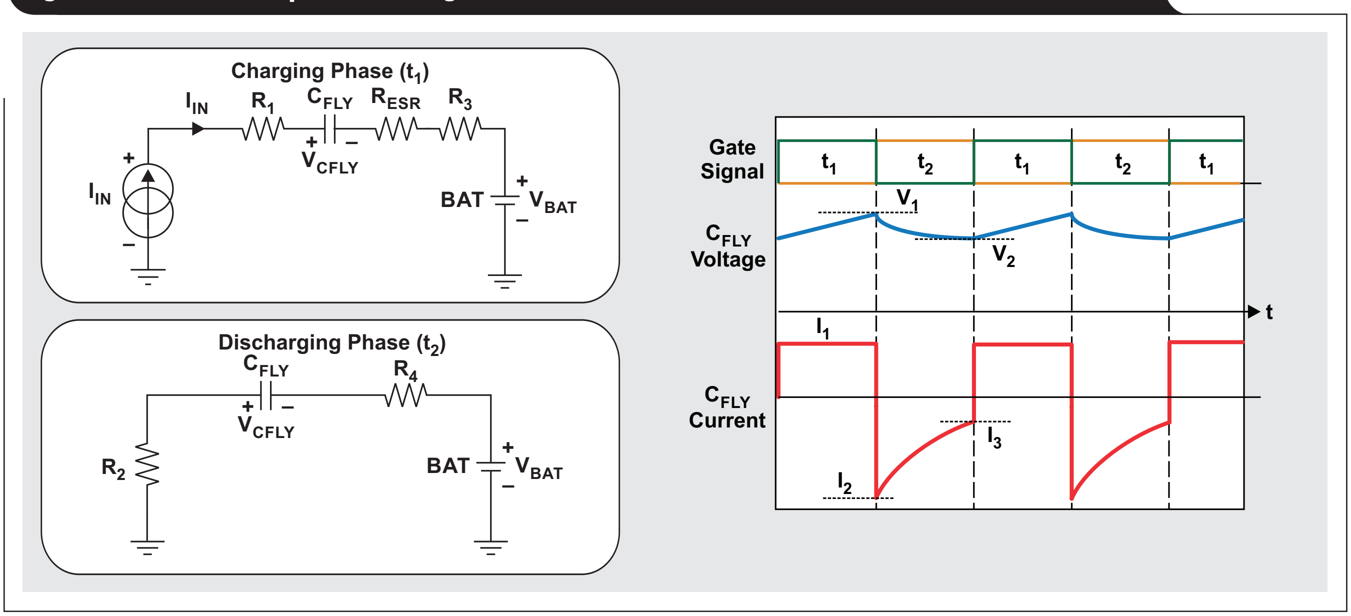
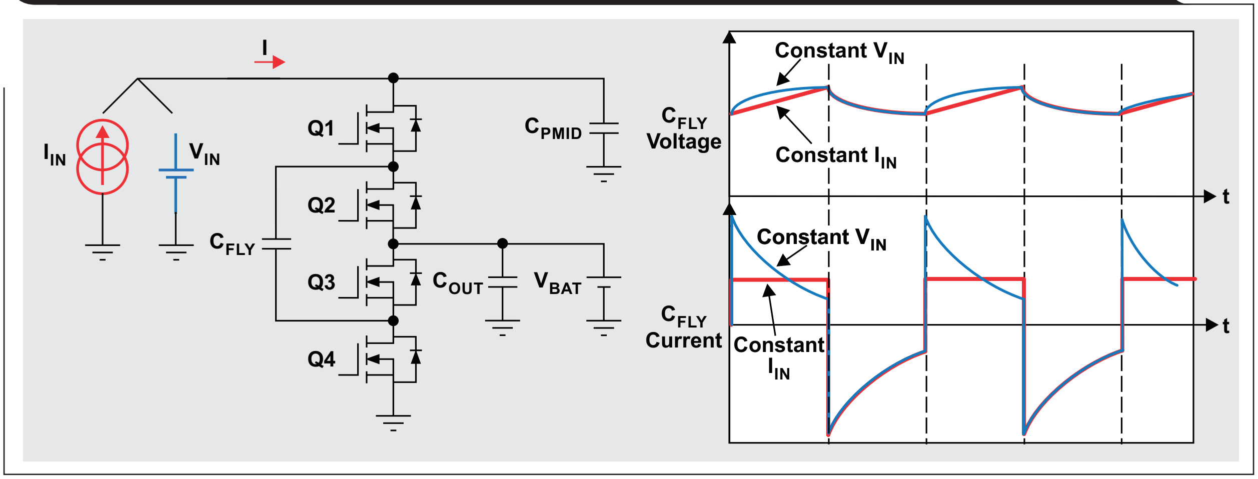


Figure 4. Switched-capacitor voltage and current waveforms for a constant-current source



When using a constant-current source, the C_{FLY} current is constant while C_{FLY} charges. If using a constant-voltage source, the C_{FLY} current follows the resistor-capacitor (RC) constant curve as shown in Figure 4. Although not significant, the effect of using a voltage source instead of a current source is increased ripple current, increased root-mean-square (RMS) current, and reduced efficiency due to higher conduction losses.

Performance

The most important decision for a switched-capacitor charger is selection of the C_{FLY} capacitor. A minimum of two C_{FLY} capacitors are required per phase, with four being optimal. Additional C_{FLY} capacitors can be used, but returns are diminished by added cost and board space.

Using fewer than four C_{FLY} capacitors results in higher voltage and current ripple, and increased stress on each capacitor. The total effective capacitance should be 24 µF or greater for optimal efficiency. Using four 22-µF capacitors with a 10-V rating will achieve a 24-µF capacitance, taking into account the bias-voltage derating of the ceramic capacitors. A slower switching frequency can increase efficiency, but this also comes at the expense of high current ripple and increased stress on each capacitor.

Figures 5 and 6 show the efficiency for the bq25970 switched-capacitor battery charger. The effects of the number of capacitors and switching frequency are clearly evident.

Smart control

To use the switched-capacitor architecture as a battery charger, a PPS wall adapter must control and monitor the battery voltage and current. The USB PD specification has incorporated support for direct-charge adapters with PPS. The PPS protocol enables switched capacitor chargers, while also supporting legacy USB 2.0, USB 3.1, USB Type-C current or BCS 1.2 voltage and currents.

The wall adapter (source) must protect itself and not rely on the battery charger (sink) for protection. Similarly, the sink must protect itself and not rely on the source for

Figure 5. Efficiency with four C_{FLY} capacitors per phase

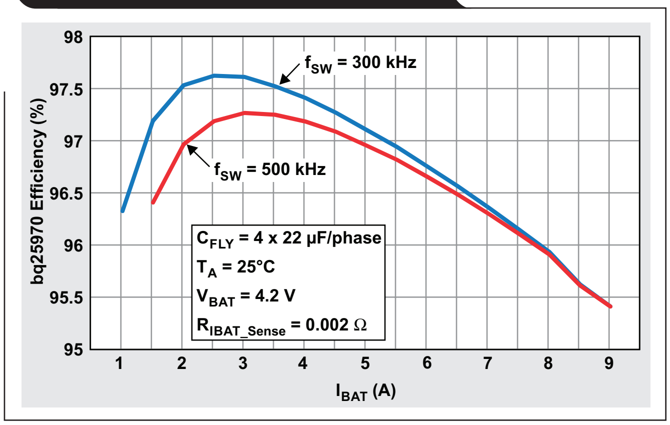


Figure 6. Efficiency with three C_{FLY} capacitors per phase

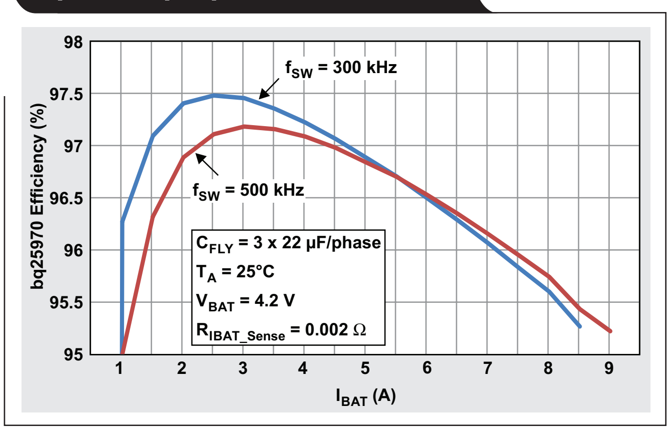
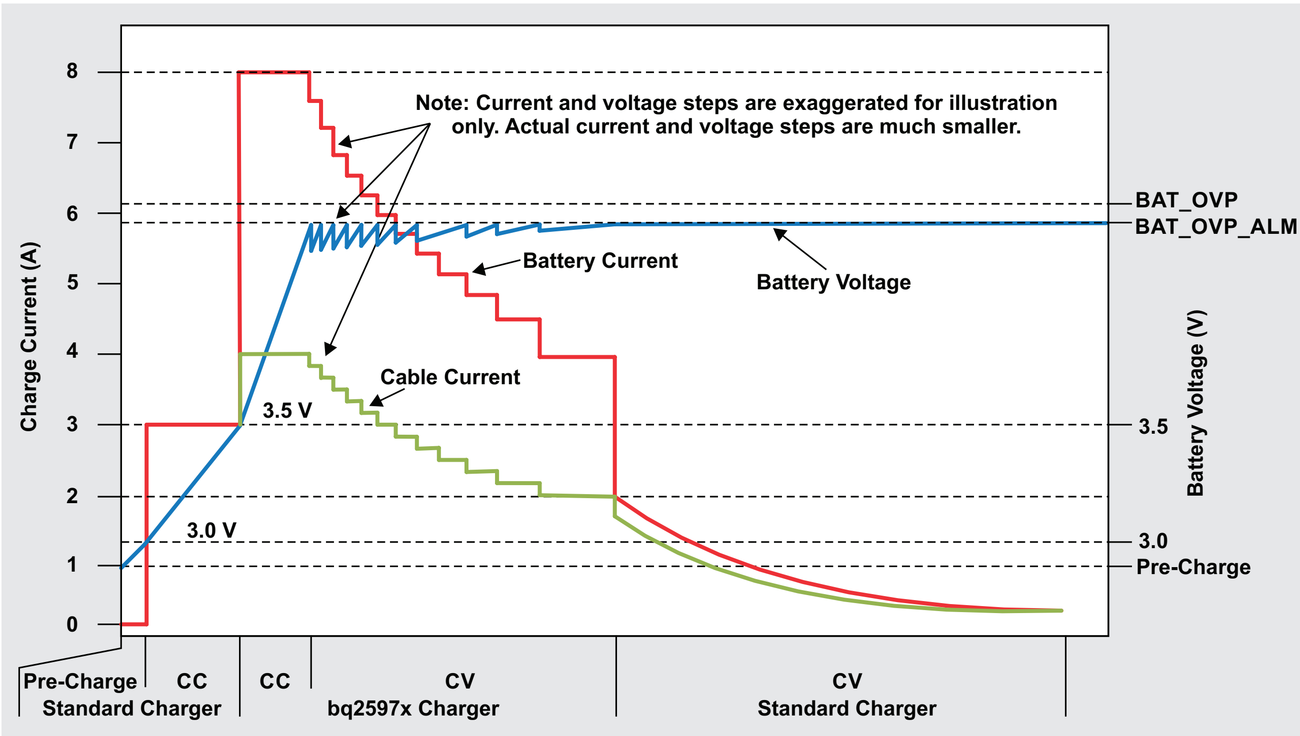


Figure 7. Battery-charging profile for a switched-capacitor solution



protection. The source must also implement overcurrent protection, and for the switched-capacitor architecture, it needs to be adjustable based on the sink requirements. The source may adjust the output voltage in 20-mV increments and the current in 10-mA increments.

The switched-capacitor solution is designed for use with a standard charger for pre-charge and final termination. The combination of a PPS wall adapter source and a standard charger enables the system to accomplish the battery-charge profile shown in Figure 7.

If the battery being charged is below a predetermined voltage, such as 3.5 V, the standard charger is used during pre-charge and constant-current charging until reaching that voltage. At that time, the phone notifies the PPS source over the communication channels of the Type-C cable to increase the voltage/current to meet the charging requirements.

Once the battery voltage reaches a voltage near the final charging voltage, the PPS reduces the voltage/current in small increments to prevent a battery overvoltage condition.

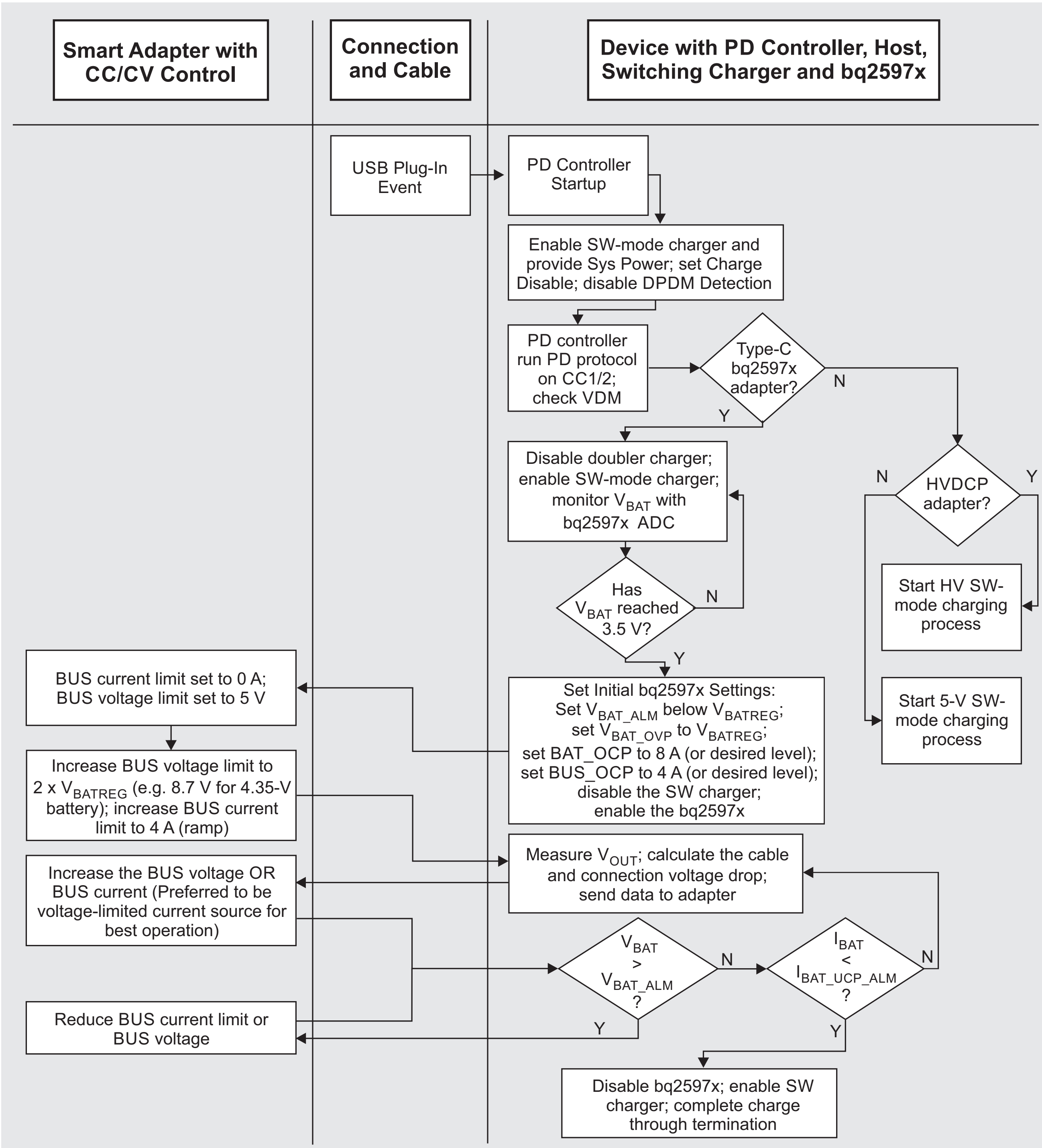
Once the PPS reduces the voltage/current so that the charging current is below the undercurrent threshold for the switched-capacitor device, charging stops and the standard charger resumes charging for current tapering and final termination.

Example of a total system solution

On the following page, Figure 8 shows a flowchart of the charging profile. Initially, only 5 V is present on the USB cable, which is then negotiated depending on the capabilities and state of the sink. A single wall adapter (source) can charge many different types of phones (sinks).

A test system was constructed to implement this flow. The wall adapter used the UCC28740 flyback controller, the UCC24636 synchronous rectifier, the INA199 current shunt monitor, a USB PD controller and an MSP430™ microcontroller to execute the code. The phone side used the bq25970 switched-capacitor charger, the bq25890 switching charger, the TUSB422 USB PD USB Type-C port controller interface (TCPCi) and an MSP430 microcontroller to execute the code.

Figure 8. Simplified flow diagram for a smartphone that is switched-capacitor capable



Figures 9 and 10 show the charge-cycle data and total charge-time data for the test system.

Conclusion

Much faster charging times with lower power dissipation and lower temperatures can be achieved when using USB PD PPS and a switched-capacitor charger for smartphones. The protection and alarm levels should be carefully selected to make sure that they meet the battery and system thermal constraints.

Related Web sites

www.usb.org/developers/powerdelivery/

Product information:
bq25970
bq25890
TUSB422
TS3USB221
UCC28740
UCC24636
INA199

Figure 9. System charge time with 3,200-mAh battery charged at 6 A

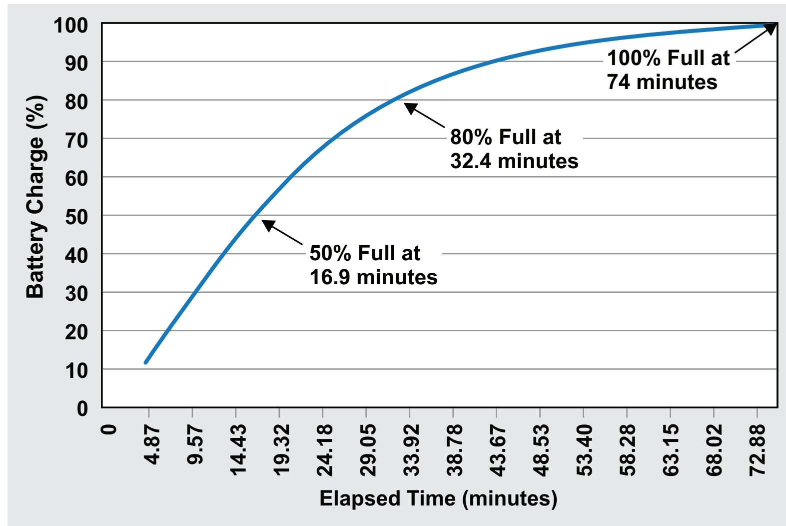
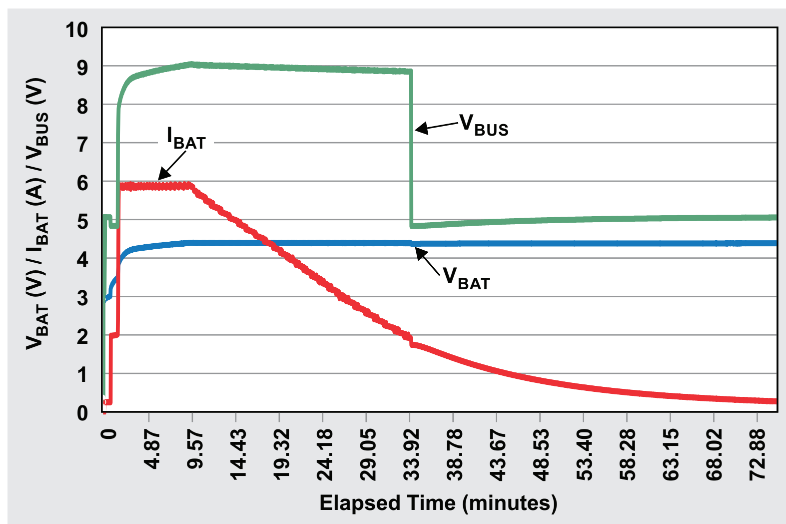


Figure 10. System charge cycle with 3,200-mAh battery charged at 6 A



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