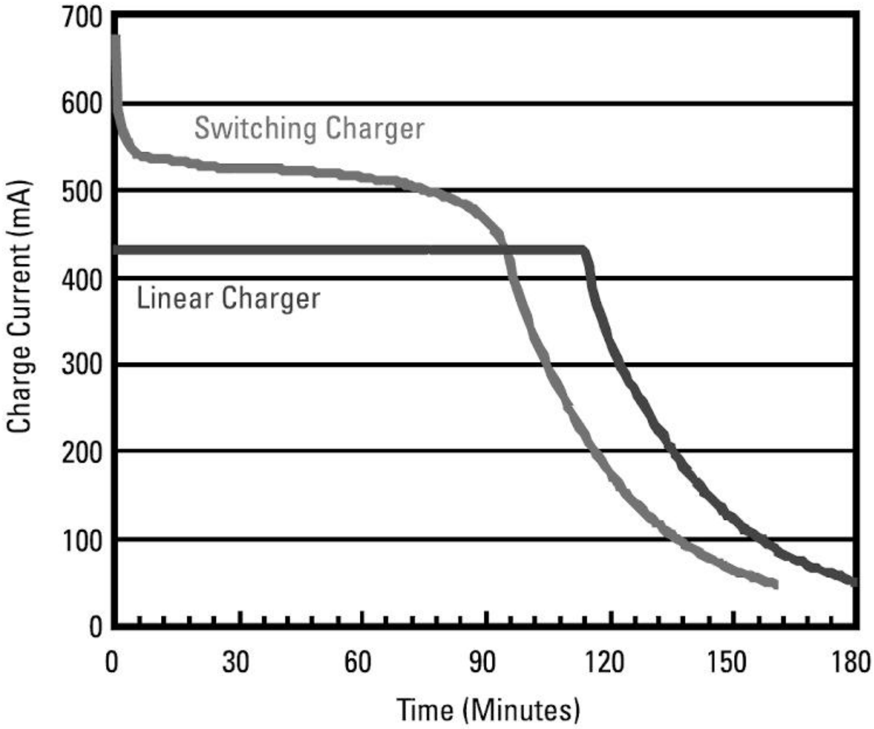

Figure 2.18 The battery charging time of a linear charger and switch-mode charger.

2.3.6 USB Battery Charging

USB ports have become very popular for providing power to portable devices. Recently the power from not only the adapter but also from the USB port has been used to charge the battery. It is extremely convenient and handy for consumers to just carry a USB cable for charging portable devices while traveling.

The most useful benefit of a USB's power capabilities is the ability to charge batteries in portable devices. A practical USB battery charger optimizes battery charging performance, safety, and the user experience. The USB specification spans several generations of power management. The initial USB 1.0 and 2.0 specifications described two types of power sources: 5V at 500 mA and 5V at 100 mA for powering connected devices. These specifications were not written with battery charging in mind; they were intended only to power small peripherals like mice and keyboards. This did not prevent designers from finding a USB battery charging solution. The recent development of a supplementary USB specification [*Battery Charging Specification*, Revision 1.1, April 15, 2009 (BC1.1)], acknowledges that charging ability and describes power sources that can supply up to 1.5A. All USB power ports, when active, were classified as either "low power" (100 mA) or "high power" (500 mA). Any port could also operate in a suspended mode, which limits supply to 2.5 mA. Ports on PCs and laptops are "high power," whereas ports on hubs that receive no power other than what is supplied by the upstream USB host are considered "low power." Once plugged in, a device is initially allowed to draw up to 100 mA while enumerating and negotiating its current budget with the host. Subsequently it could raise 500 mA, or it might be held at 100 mA.

Standard downstream port (SDP): This is the same port defined by the USB 2.0 specification and is the typical form found in desktop and laptop computers. The maximum load current is 2.5 mA when suspended, 100 mA when connected and not suspended, and 500 mA when configured for that current. A device can recognize a SDP with hardware by detecting that the USB data lines, D+ and D–, are separately grounded through 15 kΩ. It needs to enumerate to be USB compliant, although much of the present-day hardware does not enumerate.

Charging downstream port (CDP): This defines the higher current USB port typically used with PCs, laptops, and other hardware. The CDP can supply up to 1.5A. A device plugged into a CDP can recognize it as such by means of a hardware handshake implemented by manipulating and monitoring the D+ and D– lines.

Dedicated charging port (DCP): This describes power sources like wall adapters that do not enumerate so that charging can occur without communication at all. DCPs can supply up to 1.5A and are identified by a short between D+ to D–. This allows the creation of DCP "wall warts," which feature a USB mini- or micro-receptacle instead of a permanently attached wire with a barrel or customized connector. Such adapters allow any USB cable to be used for charging.

The main task for a device connecting to a USB port is to know how much power can be drawn from the USB port. Overdrawing power from a current-limited USB port could result in a USB crash. The USB often will not restart until the device is unplugged and reconnected. A portable design has choices about how to manage port detection. It can be compliant with BC1.2, compliant only with USB 2.0, or noncompliant. If fully compliant with BC1.2, it must be able to sense and limit input current for all USB source types, including legacy USB 1.0 and 2.0 ports. If compliant with 2.0, it will charge from SDPs after enumeration, but may not recognize CDPs and DCPs. If it cannot recognize a CDP, it can still charge and remain compliant but only after enumeration, in the same way that it would with an SDP. Other partially compliant and noncompliant charging schemes are discussed later.

A device can implement port detection using its own software, or it can use a charger or interface IC that detects by interacting with the USB D+ and D– data lines without relying on system resources. The design's partitioning of these roles depends on the system architecture. For example, a device that uses a microcontroller, or a dedicated IC, to manage power may prefer to use that

IC for port detection. Since the device already can communicate with the host over the USB connection, it can make charging choices based on the results of enumeration and configuration. A different device might not be designed to communicate with a USB or might not want to devote system software to manage USB charging. It just wants to use available USB ports as a power source. This approach can be used to avoid complexity or in response to worries that software bugs might cause incorrect charging.

2.3.7 Port Detecting and Self-Enumerating Charger

The MAX8895 from Maxim Integrated Circuits determines how effectively to use available input power without relying on the system to determine the power source output power capability. The charger automatically determines the adapter type and can distinguish between:

- *DCP:* 500 mA to 1.5A.
- *CDP (host or hub):* to 900 mA for high speed; to 1.5A for low and fast speed.
- *Low-power SDP (host or hub):* 100 mA.
- *High-power SDP (host or hub):* 500 mA.

The available current can be used by the battery or the system, or it can be split between them. A built-in suspend timer automatically triggers a suspension when no bus traffic is detected for 10 ms. In addition to automatically optimizing current from USB and adapter sources, it also deftly handles switchover from adapter and USB power to battery power. It also allows the system to use all available input power when necessary. This enables immediate operation with a dead or missing battery when power is applied. All power-steering MOSFETs are integrated, and no external diodes are needed. Die temperature is kept low by a thermal regulation loop that reduces charge current during temperature extremes.

2.4 Battery Charger and System Interactions

Figure 2.19 shows the most commonly used battery charging and system power architecture, where the system is directly connected to the battery. The output of the charger is first to charge the battery. In addition, the battery charge output provides power to the system, which makes this architecture simple and low cost. Many linear chargers such as the LTC4059 from Linear Technologies, ADP3820 from Analog Devices, ISL6293 from Intersil Corporation, and

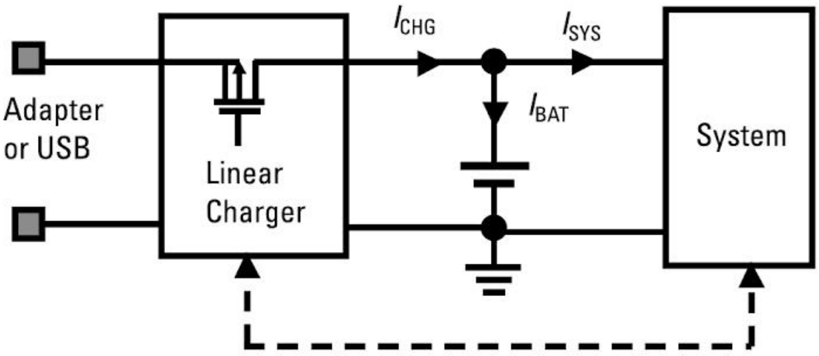

Figure 2.19 Battery charging and system power architecture block diagram.

bq24010 from Texas Instruments are available. However, connecting a system load to the battery can cause various issues such as longer battery charge times, charge termination, and false safety timer warnings. In this configuration, the charger output current I_{CHG} is not dedicated to charging the battery, but is instead shared between the system and the battery. Current I_{CHG} is the current that the charger can control. The battery charger makes charging decisions based on this current, and is not aware that the system steals some of the charge current. Therefore, the charger is not able to directly monitor and control the effective battery charge current I_{BAT} into the battery.

During the precharge phase, the precharge current is typically 10% of the fast-charging current for a deeply discharged battery (less than 3.0V). The system load I_{SYS} steals away some portion of this current and the effective charge current becomes even smaller. For example, the precharge current of the charger output is 100 mA while the system draws 60 mA. As a result, the effective precharge current into the battery is only 40 mA. This not only increases the battery precharge time, but also may cause a precharge timer false expiration if the battery voltage does not rise to 3V within the precharge timer period. This may provide a false precharge safety timer warning because of not enough precharge current, but not because of a defective battery. It is even possible for the system current to be larger than the precharge current, in which case the battery would be discharged instead of being charged even with the connected power source. The discharge protection MOSFET could be turned off in the battery pack when the battery cell reaches the undervoltage protection threshold and the system will be permanently locked off. To solve this issue, the system has to be either in shutdown mode or low-power standby mode so that the precharge current is dedicated to charging the battery to above 3.0V within the precharge safety timer period. This is the main reason why you may not be able to turn on a cell phone or even make a phone call when the adapter is connected to a deeply discharged battery. Similarly, once the battery enters the fast-charge phase, the system load still steals some charge current from the charge output, which increases the battery charge time and may result in fast safety time false expiration.

Another possible issue is charge termination. The charger will monitor the battery charge current so it can terminate the charging process when its output current falls below the charge current termination threshold. As we discussed, the charger does not detect the effective charge current; instead, it monitors the total current of the system and battery. If the system has a constant DC current higher than the charge termination current threshold, then the charger will never be able to detect the charge termination, which results in the false safety timer expiration. How can we solve these application-related issues and improve system performance? Various dynamic power path management techniques that monitor the real effective battery charge current are discussed next to solve these problems.

2.5 Dynamic Power Management Battery Charger

The issues mentioned in the preceding section are caused by the interaction between the charger and the system. The charger cannot detect the real effective charge current for making the right charge decisions. To operate the system while charging a deeply discharged battery, a power path management technique should be used to eliminate the system and charger interaction. Powering the system and charging the battery should have independent power paths.

2.5.1 System Bus Voltage-Based Dynamic Power Path Management (DPPM) Charger

Figure 2.20 shows a simplified linear battery charger block diagram with a power path management. MOSFET Q1 is used to preregulate the system bus voltage V_{OUT} in LDO mode or fully turned on for obtaining the maximum input power. This establishes a direct power path from the input to the system for

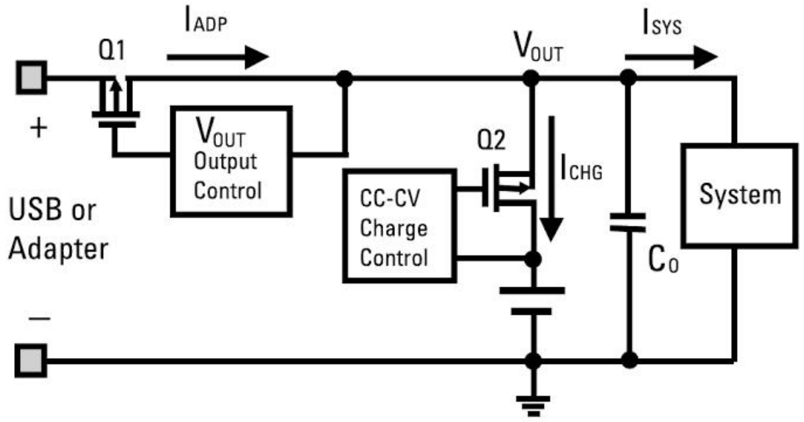

Figure 2.20 Power path management battery charger block diagram.

providing power to the system. MOSFET Q2 is dedicated to fully controlling the battery charging in a linear charger fashion. The battery charger controller and MOSFET Q2 are composed of a linear battery charger, and the system bus voltage is used as the input voltage of a linear battery charger, which should be always higher than the battery voltage and also should be high enough to power the system. Because there are two independent power paths for powering the system and charging the battery, battery and system interference no longer exists. This power architecture establishes two separate paths for system and battery charging, called power path management (PPM). The dedicated battery charging path is able to not only power the system even without a battery or a deeply discharged battery, but also can completely eliminate the false safety timer expiration and charge termination issues as well. It allows the system to operate while charging a deeply discharged battery since the system bus voltage is regulated to a set value such as 4.4V, for example, or adapter voltage through MOSFET Q1 with or without a battery.

Figure 2.21 shows the waveforms for the DPPM operating principle. Since the system current is usually pulsating, its peak system current could be higher than the input peak current limit. The capacitor C_o connected in the system bus starts to discharge and system bus voltage drops at t_1 when the current required from the system and battery charger is higher than the amount

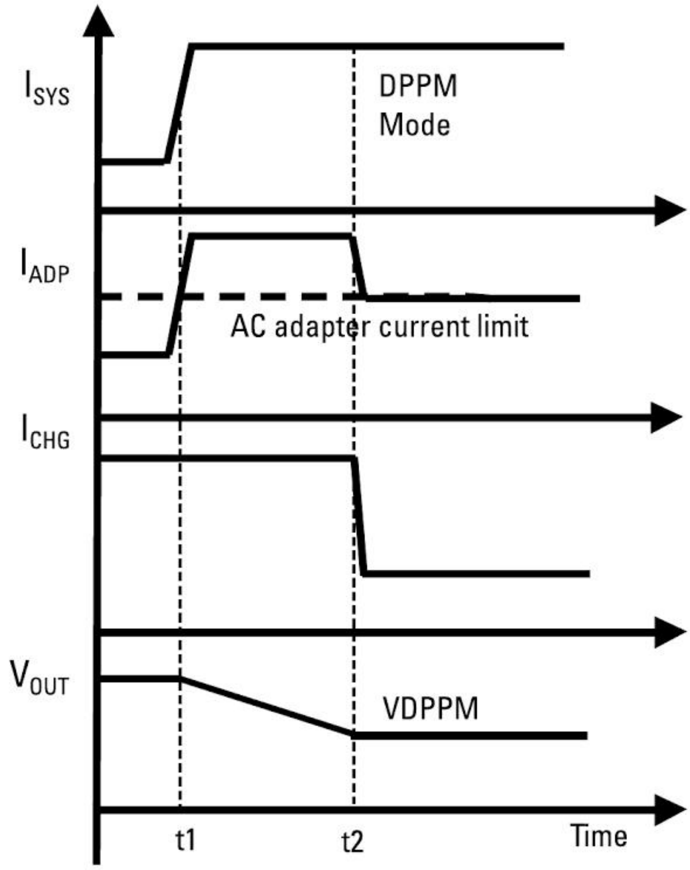

Figure 2.21 DPPM charger waveforms.

of input current available from the AC adapter or USB. Once the system bus voltage falls to keep the preset DPPM threshold at t_2, the battery charge control regulation loop is going to regulate the system bus voltage by reducing the battery charging current so that the total current demand from the system and battery charger is equal to the maximum current available from the adapter to prevent the system bus voltage from dropping further. The DPPM control loop tries to reach a steady-state condition where the system gets its needed current and the battery is charged with the remaining current. This maximizes the use of the power available from the adapter or USB. Most system loads are very dynamic with a high pulsating current. The adapter will be overdesigned if its power rating is based on the maximum peak power from the system and battery charger since the average power from the system is much smaller than its peak maximum power.

The DPPM control technique allows the system to use a smaller power rating and cheaper AC adapter while supplying system power and charging the battery simultaneously. The system bus voltage could be fluctuated between its maximum input voltage or preregulated voltage and DPPM threshold voltage. Such fluctuated voltage may cause audible noise if the frequency is below the audible frequency of 20 kHz.

Figure 2.22 shows a DPPM Li-ion battery charger example with the following design specifications: 800-mA fast-charge current and a 5-hr safety timer. Whenever the charge current is reduced due to either active thermal regulation or active DPPM operation mode, the safety timer is automatically

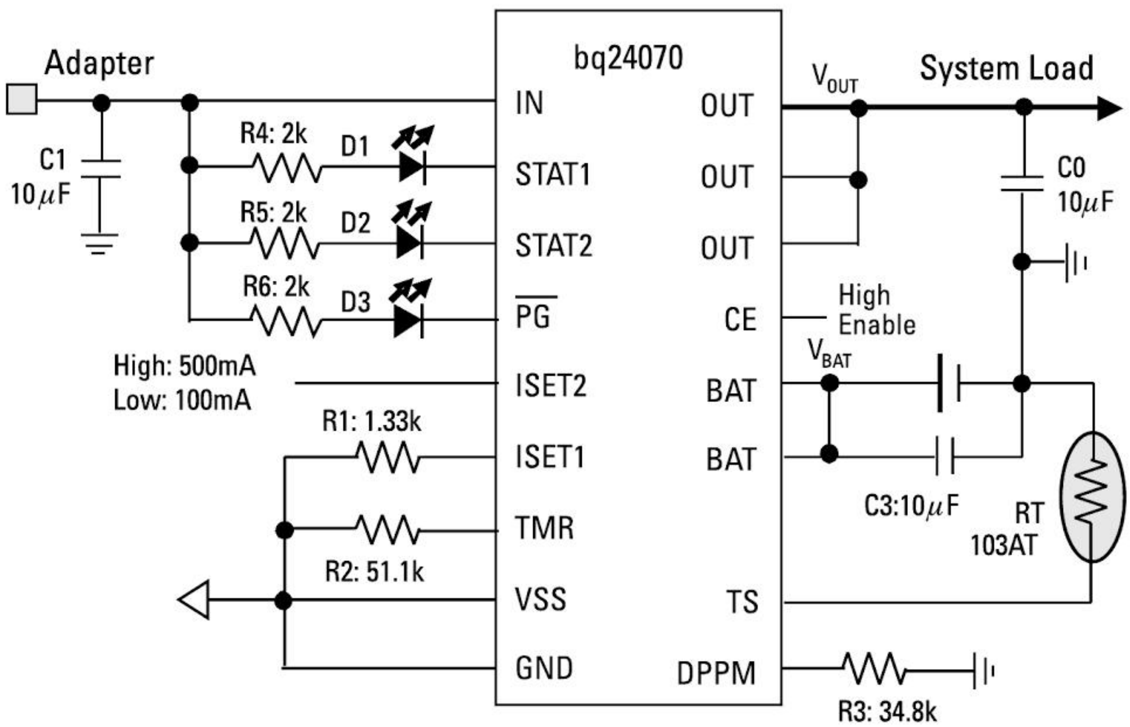

Figure 2.22 Dynamic power path management battery charger.

adjusted to increase the timer value, which avoids unexpected false safety timer expiration. In addition, the charge termination is also disabled to prevent false charge termination when either the DPPM or thermal regulation loop is active.

2.5.2 Input Current-Based Dynamic Power Management (DPM) Linear Charger

The input power source (e.g., an adapter) has an output current limit. Its output voltage may be crashed when the current drawn by the system exceeds the adapter current limit. Two options are available for avoiding an adapter voltage crash. One is to increase the adapter power rating to match the peak system power and maximum charge power demand. This will, however, increase the adapter size and cost. The second option is for the charger control system to monitor the input current and automatically regulate the battery charging system so that the total current required by the charging system is below the input power source current limit. In other words, the charger system gives higher priority to powering the system and the remaining power will be used to charge the battery. Figure 2.23 shows a block diagram for an input current-based DPM linear charger. MOSFET Q2 is dedicated to regulating the battery charge voltage and current in a linear fashion, while MOSFET Q1 is used to regulate the system bus voltage. Figure 2.24 shows its operating waveforms. When the system current increases at t_1, the input current I_{IN} immediately exceeds the input current limit. The input current is fed into the error amplifier A2, compares the input current limit threshold, and then regulates the on-resistance of MOSFET Q2 for reducing the charge current. The input current reaches it reference input current I_{REF} at t_2 when the charge current drops to I_{CHG2} at t_2. When the peak system current is removed at t_3, the input current is below the input current

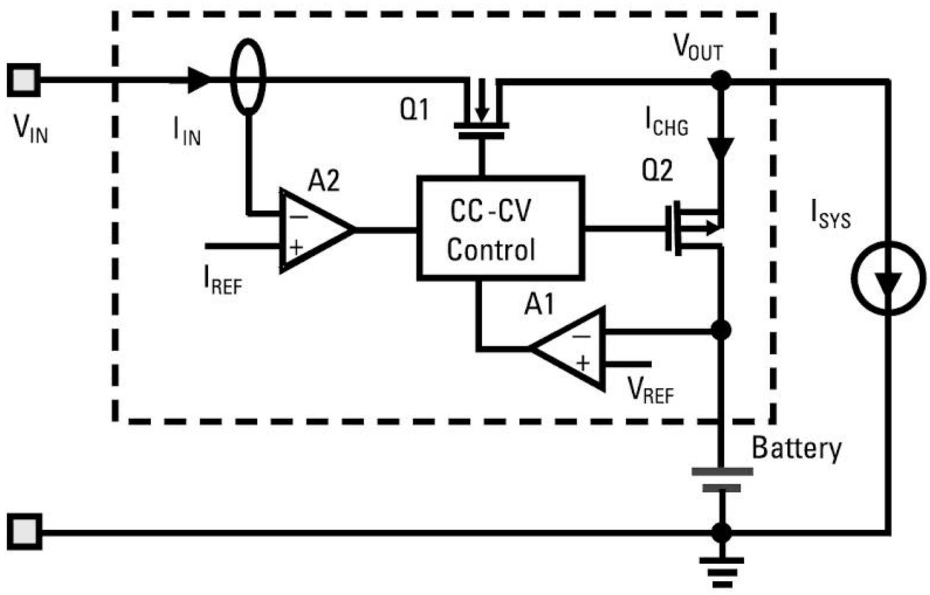

Figure 2.23 Input current–based DPM linear charger block diagram.

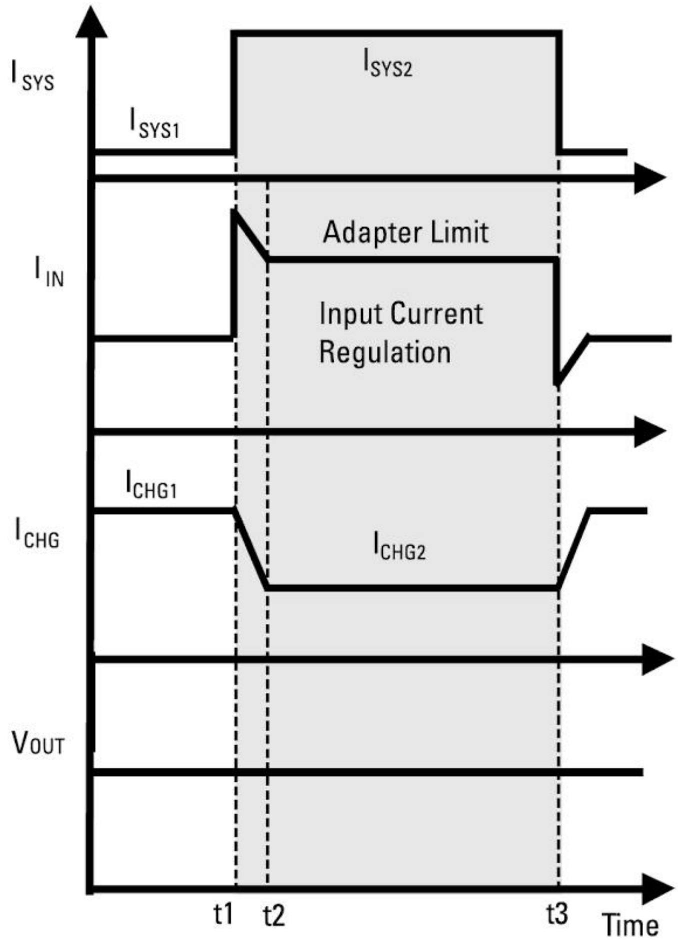

Figure 2.24 Operating waveforms of the input current-based DPM linear charger.

limit and the battery charge current is regulated at its fast-charge current for maximizing the charging speed. The main advantage is that the system bus voltage is DC constant without audible noise.

Figure 2.25 shows a typical application circuit that uses the input current-based DPM linear charger LTC4066 from Linear Technologies. It fully supports USB 100 mA/500 mA charging, and has the charge current output for both charging and discharging, which can be used as an ADC input for fuel gauging. An ideal diode function between the system output and battery provides power from the battery when output/load current exceeds the input current limit or when input power is removed. Powering the load through the ideal diode instead of connecting the load directly to the battery allows a fully charged battery to remain fully charged until external power is removed. Once external power is removed, the output drops until the ideal diode is forward biased. The forward-biased ideal diode will then provide the output power to the load from the battery. Furthermore, powering switching regulator loads from the OUT pin rather than directly from the battery results in shorter battery charging times. This is due to the fact that switching regulators typically require constant input power. When this power is drawn from the OUT pin voltage,