

AN-9720

Power Path Implementation Tradeoffs, Featuring the FAN5400 Family of PWM Battery Chargers

Overview

Many battery-powered systems, such as smart phones, must be fully functional and their electronics up and running shortly after the user plugs a charger into the phone. The system electronics need to be functional regardless of the state of the battery, even if the battery is fully discharged or absent. The FAN5400 family charger IC allows power to be delivered to the system when the charger is plugged in, whether the battery is absent or present, and allows the system to power up and be functional quickly after the charger is plugged in. Other approaches, such as power path, add additional impedance in series with the battery.

This application note describes how the FAN5400 family of battery chargers distributes power between the system and battery to achieve similar results of power path, often without the overhead and power loss of an additional switch element.

The block diagram in Figure 1 is a typical implementation of power path using an “ideal” diode. Current flow is indicated by the arrows, which reveal that the “ideal” diode (whether internal or external) helps to steer current appropriately.

While this implementation meets the criteria for power path, an ideal diode is never truly ideal. For example, the internal ideal diode of one such IC is actually a PMOS with a typical value of 180mΩ. This means that there is a permanent 180mΩ power dissipating series element between battery and system load that creates significant additional power loss during periods of high-current drain from the battery, such as GSM pulses. A parallel diode PMOS switch can reduce this resistance; however, this increases the solution size and cost.

The implementation in Figure 1 differs from the FAN5400 approach in the block diagram in Figure 2. Although on the surface it may seem like FAN5400 does not have power path functionality; it serves almost all the same needs and, in addition, can provide the benefit of having no power dissipating series element between system load and battery.

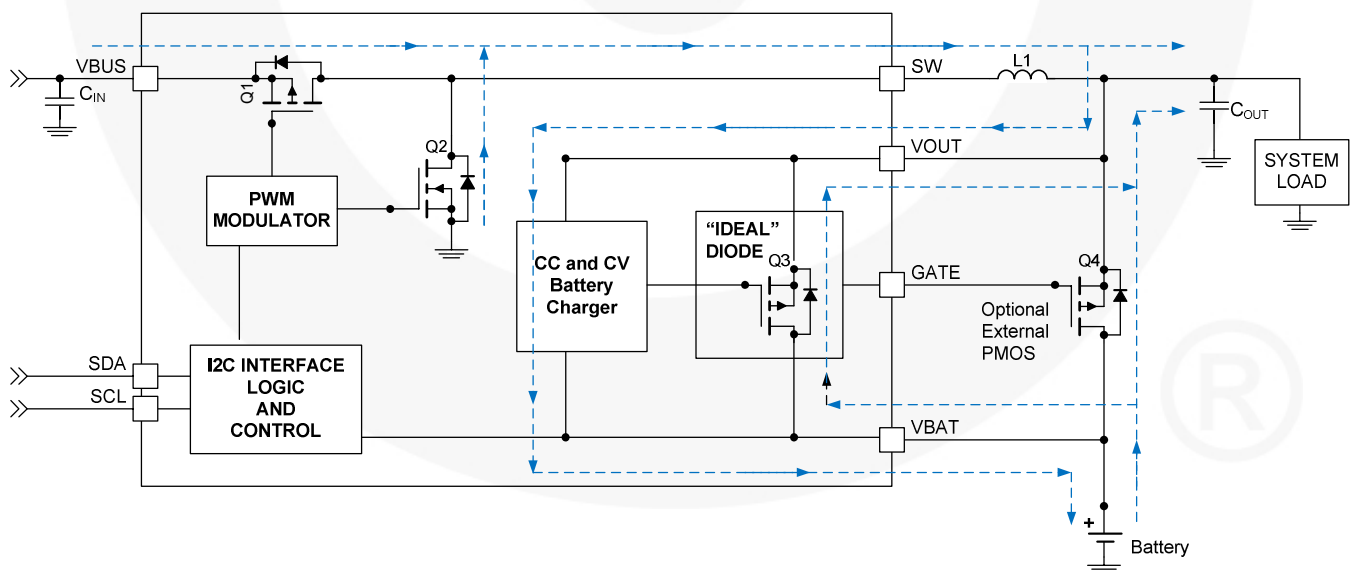


Figure 1. Typical Implementation of Power Path using an “Ideal” Diode

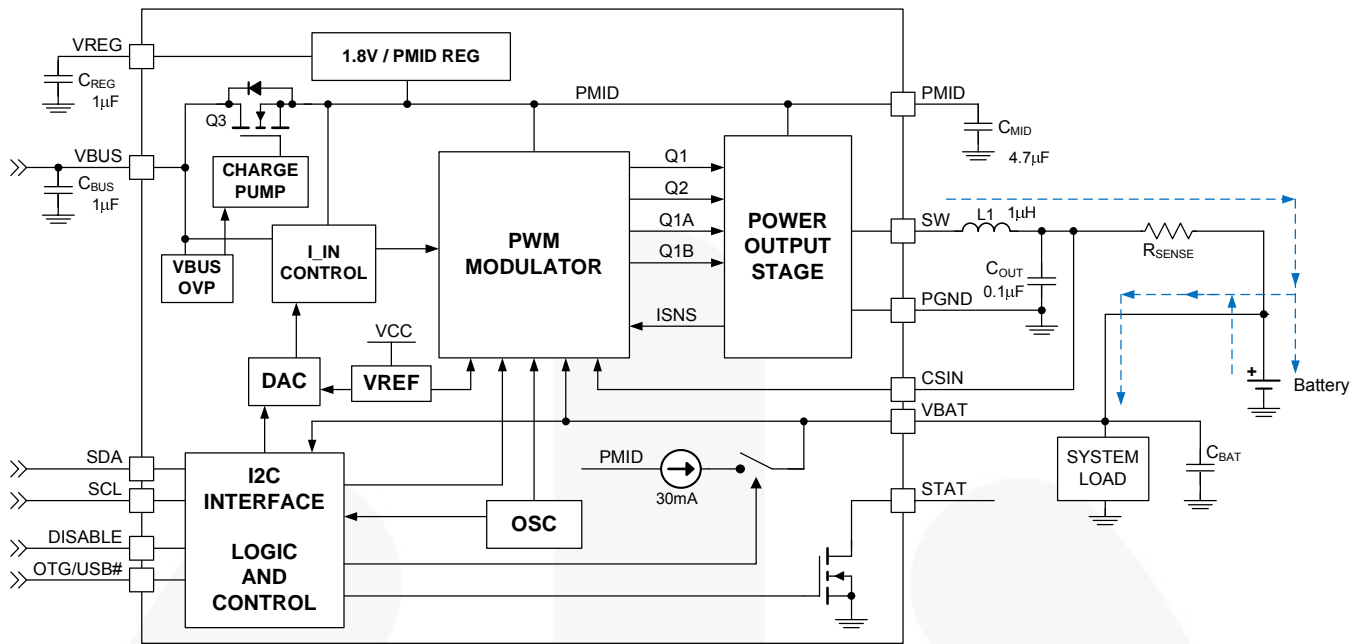


Figure 2. FAN5400 Block Diagram

System and Battery Power Sharing

Power sharing between the system and the battery means that power can be steered or prioritized to go to the system in the case that the input power is not sufficient to power both the system and charge the battery.

The typical configuration for the FAN5400, as shown in Figure 3, is one where the system is connected in parallel to the battery. The way in which this configuration can steer power similar to power path is sometimes confusing, so scenarios based on real-world battery capacity and input power numbers are provided below.

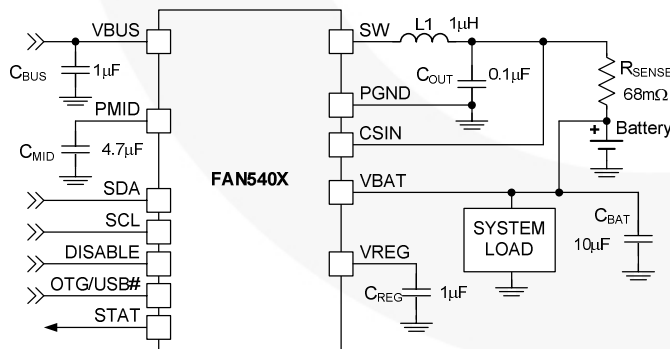


Figure 3. Typical Application Circuit, System Parallel with Battery

Example 1: 1500mAh Battery (1C Maximum Charge Current Capability of Battery is 1500mA), Input Power Source USB 2.0, 5V 500mA

Scenario A) Partially charged battery at 3.6V and system load turns on at 400mA

Before the system load turns on, the charger is already in CC mode. Because the input power source is 5V 500mA and the battery is at 3.6V, there is ~632mA of current available to charge the battery. This is computed by accounting for the charger conversion efficiency and also the output current multiplication factor achieved when bucking down a voltage:

$$I_{OUTMAX} = V_{IN} / V_{OUT} * I_{IN} * Efficiency \quad (1)$$

Using the values in this example reveals that $5V/3.6V \cdot 500mA \cdot 91\% = 632mA$. The 91% efficiency data point can be found in Figure 4.

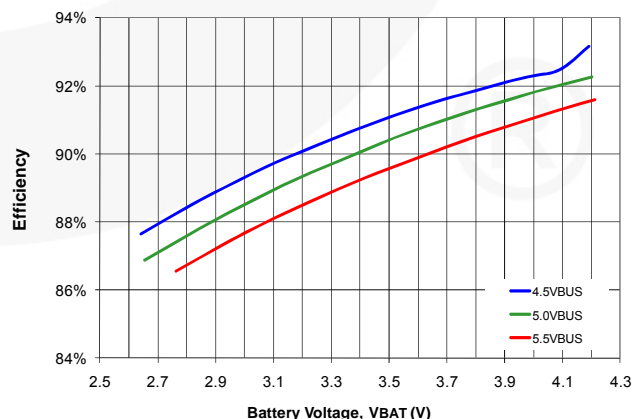


Figure 4. FAN5400 Conversion Efficiency vs. Battery Voltage vs. VBUS Voltage

Once the system load turns on, 400mA is diverted to the system and only 232mA is left to charge the battery. This is the equivalent of power steering; the charger is prioritizing the system over the battery. Once the system load turns off, the full 632mA once again flows to the battery. The benefit of FAN5400, as configured in Figure 3, is that there is no power-dissipating series element between the system and load.

Scenario B) Partially charged battery at 3.6V and system load turns on at 2000mA

Before the system load turns on, the charger is already in CC mode and using all input power to charge the battery at 632mA, similar to Scenario A. When the system load turns on, 632mA is diverted to the system and the remaining system load of 1368mA comes from the battery.

This is the equivalent of power steering; the charger is prioritizing the system over the battery. Once the system load turns off, the full 632mA once again flows to the battery. Again, the circuit in Figure 3 has an advantage of no dissipating element between the system and load.

Scenario C) Battery is fully charged at 4.2V and system load turns on at 400mA

Before the system load turns on, the charger is off. When the load turns on, all the system power first comes from the battery. As soon as $V_{BAT} < V_{OREG} - V_{RCH}$, the charger turns on. V_{RCH} is the recharge threshold and has a value of 120mV. Because the input power source is 5V 500mA, the maximum available current the charger can provide is computed as $5V/4V \cdot 500mA \cdot 92\% = 575mA$ (battery is assumed to have to 4V for the sake of this exercise). The charger turns on, attempting to charge the battery at 575mA. However, because the system load is still present, only $575mA - 400mA = 175mA$ is flowing into the battery.

This is the equivalent of power steering; the charger is prioritizing the system over the battery. Once the system load turns off, the full 575mA flows to the battery until the battery enters CV Mode; at which point, the charge current decreases. Again, the circuit in Figure 3 has an advantage of no dissipating element between system and load.

Scenario D) Battery is fully charged at 4.2V and system load turns on at 2000mA

Before the system load turns on, the charger is off. When the system load turns on, the power first comes from the battery and almost immediately the battery charger turns on and goes into CC Mode. This is because Li-Ion batteries typically have an output impedance of 150mΩ, which almost instantly forces $V_{BAT} < V_{OREG} - V_{RCH}$. Similar to Scenario C, the charger attempts to charge the battery at 575mA. (Actually slightly higher than 575mA because battery voltage is lower in this case, as compared to Scenario C, and the multiplication factor is slightly higher. For the sake of this exercise, it is inconsequential.) The charger attempts to charge; however, because the system load is 2000mA, the 575mA flows to the load and the remaining system load of 1425mA comes from the battery.

This is the equivalent of power steering; the charger is prioritizing the system over the battery. Once the system load turns off, the full 575mA flows to the battery until the battery enters CV Mode, at which point, the charge current decreases. Again, the circuit in Figure 3 has an advantage of no dissipating element between system and load.

Example 2: Assume a 700mAh Battery (1C Maximum Charge Current Capability of Battery 700mA), Input Power Source AC/DC Adaptor 5V 900mA or USB 3.0, 5V, 900mA

Scenario A) Partially charged battery at 3.6V and system load turns on at 400mA

Before the system load turns on, the charger is in CC Mode. Because the battery is at 3.6V, there is $5V/3.6V \cdot 900mA \cdot 91\% = 1138mA$ of current available to charge the battery. However, the battery is limited to a maximum 1C charge current of 700mA and, therefore, the charger is set to charge at 700mA. What is unique in Example 2, in comparison to Example 1, is that the input power supply can supply more power than the battery is able to accept in 1C scenario. When the system load turns on, 400mA is diverted to the system and only 300mA is left to charge the battery.

Some designers might object because the input power supply is not being used to the full extent that the combination of the battery and system load can accept. One solution is to connect the system load to CSIN, as shown in Figure 5.

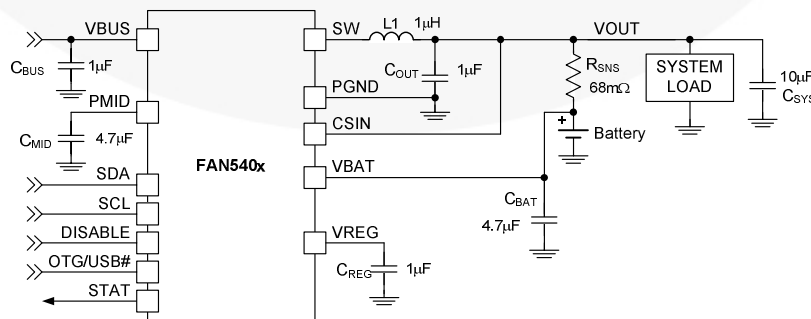


Figure 5. Application Circuit with System Load Connected to CSIN

Connecting the system load to CSIN allows the AC/DC adaptor or USB source to supply current up to maximum power level even if that is higher than the battery's 1C level. In this configuration, before the load turns on, the battery is charging at its 1C maximum charge capability of 700mA. When the 400mA system load turns on, the entire 400mA system load is supplied by the charger and the battery continues to charge at 700mA.

One drawback to this configuration is that there is a power dissipating $68\text{m}\Omega$ series element always in the path between the battery and the system load. This constant power dissipating element between battery and system load is similar to the one found in the power path implementation in Figure 1. However, the $68\text{m}\Omega$ in FAN5400 is substantially less than the $180\text{m}\Omega$ found in some products with power path.

Scenario B) Partially charged battery at 3.6V and system load turns on at 2000mA

Before the system load turns on, the charger is in CC Mode and charging the battery at 700mA, similar to Scenario A. When the system load turns on, if the configuration from Figure 3 is used, 700mA is supplied to the system load from the charger and the remaining 1300mA by the battery.

If the configuration from Figure 5 is used instead, 1138mA is supplied to the system load from the charger and the remaining 862mA is supplied by the battery.

Both configurations are the equivalent of power steering; but in the configuration of Figure 5, all the input power is being used. The tradeoff is the $68\text{m}\Omega$ -series element between battery and system load. Once the system load turns off, 700mA flows to the battery in both configurations.

Scenario C) Battery is fully charged at 4.2V and system load turns on at 400mA

Before the system load turns on, the charger is off. When the load turns on, the system power first comes from the battery. AS SOON AS $V_{\text{BAT}} < V_{\text{OREG}} - V_{\text{RCH}}$, the charger turns on. V_{RCH} is the recharge threshold and has a value of 120mV. Because the input power source is 5V 900mA, the maximum available current the charger can provide is $5\text{V}/4\text{V} \cdot 900\text{mA} \cdot 92\% = 1035\text{mA}$ (assume the battery has dropped to 4V for the sake of this exercise). The charger turns on, attempting to charge the battery at 700mA. However, because the system load is still present, if the configuration in Figure 3 is used; only 300mA is left to charge the battery.

If the configuration in Figure 5 is used; when the load turns on, 635mA flows to the battery and 400mA is supplied from the charger to the system load. This makes sense because there is a total of 1035mA charger output current. Once the system load turns off, the full 700mA flows to the battery until the battery enters CV Mode; at which point, the charge current decreases. The tradeoff is the $68\text{m}\Omega$ -series element between the battery and system load.

Scenario D) Battery is fully charged at 4.2V and system load turns on at 2000mA

Before the system load turns on, the charger is off. When the system load turns on; if the configuration from Figure 3 is used, the power comes first from the battery and almost immediately the battery charger turns on and goes into CC Mode. This is because Li-Ion batteries typically have an output impedance of $150\text{m}\Omega$, which almost instantly forces $V_{\text{BAT}} < V_{\text{OREG}} - V_{\text{RCH}}$. Similar to Scenario C, the charger attempts to charge the battery at 700mA. However, because the system load is 2000mA, the 700mA flows from the charger to the system load and the remaining system load of 1300mA comes from the battery.

If the configuration in Figure 5 is used; when the load turns on, 1035mA flows from the charger to the load and the remaining 965mA is supplied by the battery. Once the system load turns off, 700mA flows to the battery until the battery enters CV Mode; at which point, the charge current begins to decrease. Again, the tradeoff is the 68Ω -series element between the battery and system load.

Charge Termination when System Load is Connected to CSIN

When the system load is connected to CSIN as it is in Figure 5; if the system load is larger than the power that can be supplied from the USB port with the I_{BUS} limit (e.g. 500mA), the battery current is reduced below the termination threshold. Normally, when the battery current is reduced below the termination threshold, charge is terminated. However, if the charger input is in current limit, the FAN540X does not allow charge termination. Charge termination occurs only if I_{BAT} is less than I_{TERM} and the charger input is not in current limit for at least 32ms. This prevents false termination from system loading.

After charge termination occurs, the charger stops running and system power is drawn from the battery. Charge termination can be disabled by disabling the TE bit through I²C. Charge termination may, however, be desired if the phone or data card is in a low-power mode and a drain on the USB port is not desired. In that case, recharge occurs automatically when the battery voltage drops V_{RCH} (120mV) below V_{OREG} or if it is desired to turn on before 120mV, the system can manually turn on the charger as soon as a drop in V_{BAT} is sensed.

Powering the System with No Battery

The FAN5402 and FAN5405 continues charging after VBUS POR with the default parameters, regulating the V_{BAT} line to 3.54V until the host processor issues commands or the 15-minute timer expires. In this way, the FAN5402/05 can start the system without a battery.

The FAN5400 family's soft-start function can interfere with the system supply with battery absent. The soft-start activates

whenever V_{OREG} , I_{INLIM} , or $I_{OCHARGE}$ are set from a lower to higher value. During soft-start, the I_{IN} limit drops to 100mA for about 1ms, unless I_{INLIM} is set to 11 (“no limit”). This could cause the system processor to fail to start. To avoid this behavior, use the following sequence.

1. Set the OTG pin HIGH. When VBUS is plugged in, I_{INLIM} is set to 500mA until the system processor powers up and can set parameters through I²C.
2. Program the Safety Register
3. Set I_{INLIM} to 11 (no limit).
4. Set OREG to the desired value (typically 4.18)
5. Reset IOLEVEL bit, then set IOCHARGE.
6. Set I_{INLIM} to 500mA if a USB source is connected or any other level that is preferred.

During the initial system startup, while the charger IC is being programmed, the system current is limited to 340mA for 1ms during steps 4 and 5. This is the value of the soft-start I_{CHARGE} current used when I_{INLIM} is set to no limit.

If the system powers up without a battery present, the CV bit should be set. When a battery is inserted, the CV bit clears.

Powering a System when the Battery is Deeply Discharged

When the battery voltage is lower than the voltage required to power the system load, the power routing implementation (**Error! Reference source not found.** and Figure 5) cannot bring up the system.

In contrast, power path, as implemented in Figure 1, can still power the system even if the battery voltage is substantially lower than the system load needs to operate. This is the primary advantage of the circuit in Figure 1 as compared to FAN5400. However, it is important to realize that the slope of the curve during this phase of the charge cycle is incredibly steep, which means that the battery voltage is brought up to the minimum system load requirement within a matter of seconds.

To understand how quickly the battery voltage rises, it is necessary to examine the internal operation of the battery pack. Inside every battery pack is a protection IC, as shown in Figure 6, that features two back-to-back MOSFETs and an analog control circuit to prevent over-charging and over-discharging by monitoring the cell voltage and discharge current. The protection circuit is also referred to as “secondary protection” since the charging system must also ensure that the battery is not over-charged. The protection circuit provides a back-up safety circuit where overcharging is concerned.

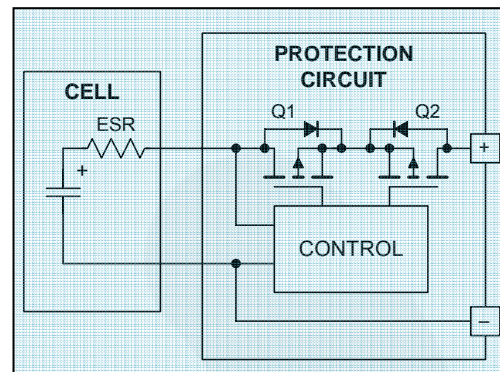


Figure 6. Li-Ion Battery Pack

Q2 in the protection circuit opens if the cell is deeply discharged ($V_{CELL} < 2.7V$). Charging is therefore still possible by driving current into the pack through Q2’s body diode. Refer to Figure 7 for the different states.

Table 1. Internal Batter Protections Scheme

Condition	Detection	Response	Reset
Over-Charge	$V_{CELL} > 4.25$	Open Q1	$V_{CELL} > 4.10$
Over-Discharge	$V_{CELL} < 2.7$	Open Q2	$V_{CELL} > 2.95$
Over $I_{DISCHARGE}$	$V_{CELL} - V_{BAT} > X$	Open Q2	$V_{CELL} \approx V_{BAT}$

In the extreme case that the battery is deeply discharged, the discharge protection switch (Q2) is open. When the charger is plugged in the USB port; if OTG = 0, the trickle charge of 30mA charges the system capacitor to 2V in 20ms time (*refer*

to Table 2). The charger continues to run in “auto” mode until the applications processor wakes up at 3.4V in about 15-seconds time. The applications processor then enumerates with USB and sets $I_{BUS} = 500mA$ and $I_{CHARGE} = 700mA$.

Table 2. Bringing Battery Out of Deep Discharge

Condition	V_{BAT}	I_{BAT}	Comment
Linear Charge (20ms)	0 to 2.0	30mA	$V_{BAT} = EMF + 0.7$ Charger is charging system cap.
t_{15MIN} (default) PWM Charge with I_{BUS} set by OTG Pin (15s)	2.0 to 3.4	100mA	$V_{BAT} = (EMF + 0.7 + 1 \cdot ESR)$ Some charge going to VCELL Apps processor wakes up at $V_{BAT} \approx 3.4V$
High-Current PWM Charge 1s to Q2 Close	3.5+	700mA	Higher charge current set by processor. This causes V_{CELL} to rise, which causes Q2 to close at point A in Figure 7. V_{BAT} drops to about 2.9 and charging continues from there.

The charge cycle behavior is shown graphically in Figure 7. The time it takes to charge a typical battery to a stable 3.4V is 40 seconds. This process is explained below.

A
Processor wakes up when $V_{BAT} > 3.4V$, which occurs about 15s after V_{BUS} is plugged in.

B
Q2 closes about 1s after the processor programs the IC for higher charge current. This causes V_{BAT} to drop (no more diode in series with V_{BAT}).

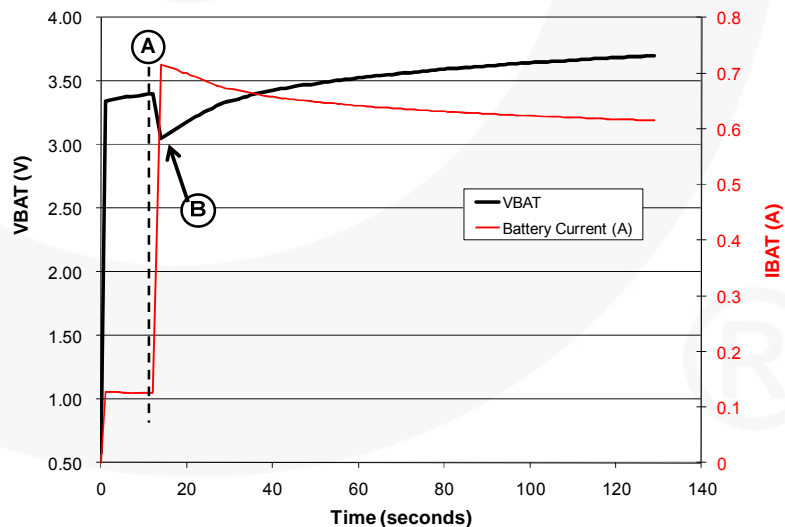


Figure 7. Charge Characteristics for Deeply Discharged and Dead Batteries

Conclusion

Although there are situations where the FAN540X partial power path in Figure 2 cannot immediately power the system load when the battery is very low or deeply discharged, this timeframe for a typical cell phone battery is only 40 seconds. It is important to weigh this against the benefits offered by the FAN540X. This benefit was discussed in detail, showing that

the FAN5400, configured as in Figure 3, does not have a power-dissipating series element between battery and system load and provides the two more critical aspects of dynamic power routing... power sharing between the system and the battery and powering the system with no battery.

Related Resources

[FAN5400 Family — USB-Compliant Single-Cell Li-Ion Switching Charger with USB-OTG Boost Regulator](#)

[AN-1721 — Li-Ion Battery Charging Basics, Featuring the FAN5400 / FAN5420 Family of PWM Battery Chargers](#)

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