Extract maximum power from the supply when charging a battery

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Introduction

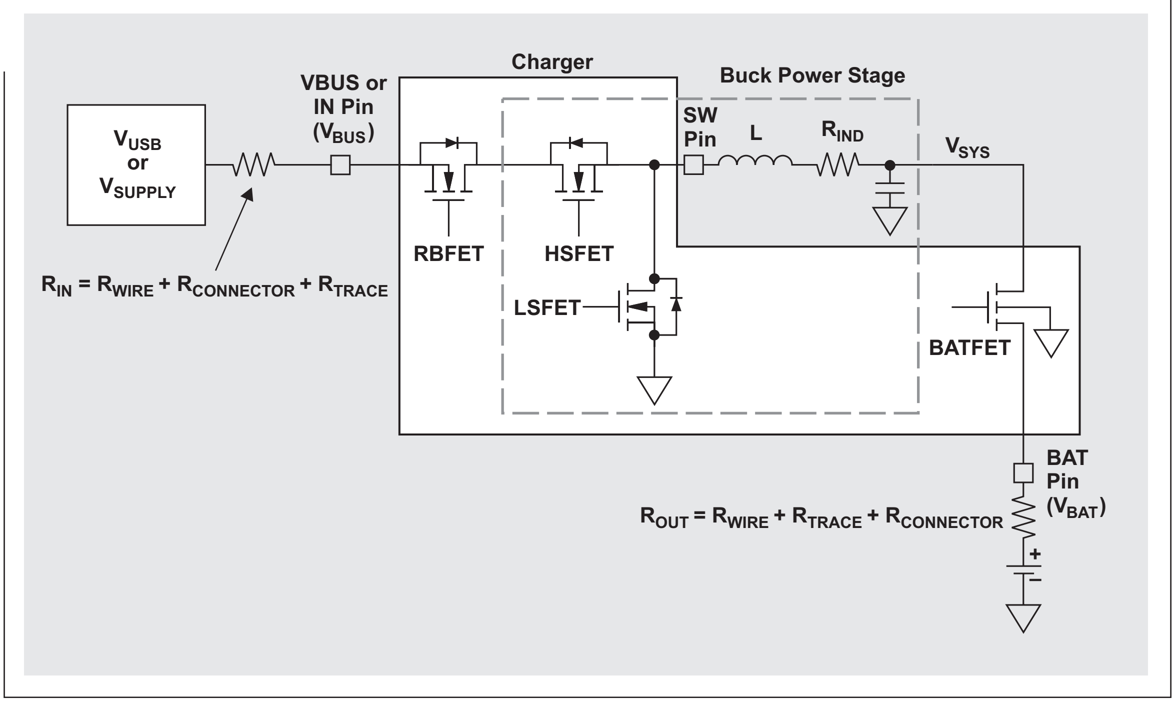
Designers of rechargeable battery-powered equipment want a charger that minimizes charge time with maximum charge current by maximizing the power taken from the supply without collapsing the supply. Resistances between the supply and the battery present a challenge. This article explains how to design the charging circuit to achieve the maximum power from the adapter despite the undesired resistances between the supply and battery.

General operation of a switch-mode charger

Figure 1 contains a circuit model of the buck converter-based charger that shows all of the non-ideal resistances, including the inductor's DC resistance (R_{IND}).

The input supply voltage to the charger IC at its VBUS or IN pin is from a typical USB port or a wall adapter. For this article, voltage at this pin is V_{BUS}. This model will be used to derive the minimum supply voltage for a given battery regulation threshold.

Figure 1. Switching charger model with resistances



Review of Li-Ion charger operation

As shown in Figure 2, the charger works in three main phases of operation, depending on the battery voltage:

1. Low battery voltage signifies a deeply discharged battery. Hence, it must be charged by a low value of current until it is brought to the threshold value, V_{PRECHG}. This is known as precharge phase.
2. Once the battery voltage increases to a certain threshold (V_{PRECHG}), the prescribed maximum charge current is allowed to flow. This current is maintained by a regulation loop known as the current-regulation/constant-current phase.
3. After the battery voltage increases to the set regulation voltage and the charge current has tapered down, the battery is fully charged. While the charge current is tapering down, the charger operates in voltage-regulation/constant-voltage phase. The typical regulation voltage is 4.2 V for Lithium-Ion (Li-Ion) cells.

For fastest charge time, the charger must provide the maximum charge current for which it has been set, until V_{BAT} = 4.2 V.

To determine the minimum value of the input voltage (V_{BUS_MIN}) permissible, the designer must consider the following:

1. Operation headroom between V_{BUS} and V_{BAT} to reach a target charge current
2. Switching regulator's maximum duty cycle

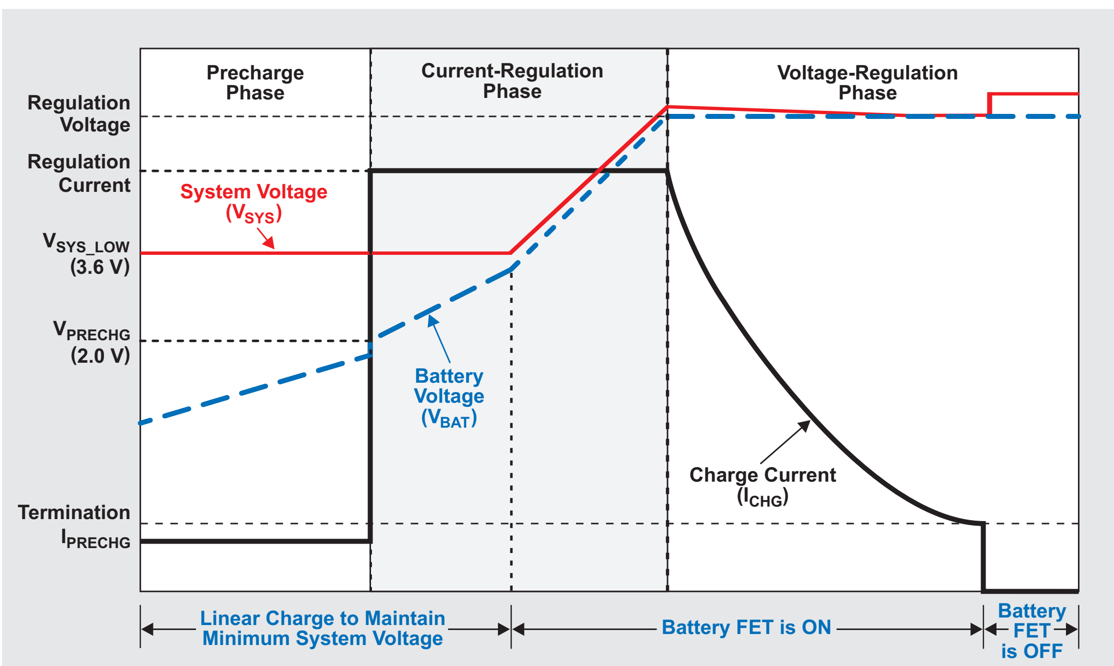
Operation headroom

The resistance in the MOSFETs and the inductor generates voltage drop as current flows. If the voltage difference between V_{BUS} and V_{BAT} is too small, the target charge current cannot be achieved. For example, if V_{BUS} is 4.3 V, V_{BAT} is 4.2 V and total resistance from BUS input to battery is 150 mW, the maximum current to the battery is 660 mA.

Switching regulator maximum duty cycle

Realistically, no high-side NMOS buck converter can reach 100% duty cycle. There is always dead time to avoid shoot-through during HSFET/LSFET turn-on/turn-off. If the duty cycle exceeds the maximum value, the switching regulator will skip some LSFET turn-on pulses to maintain average output current/voltage.

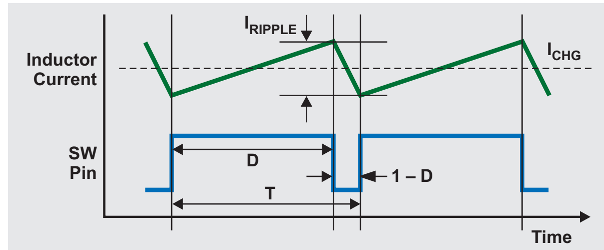
Figure 2. Charge profile for the BQ2419x/25x/26x/29x charger



Calculating V_{BUS_MIN} threshold

The V_{BUS_MIN} threshold is the minimum BUS pin voltage required to support the target maximum charge current and keep the duty cycle below the buck converter's maximum duty cycle. Figure 3 shows the inductor current and switch-node voltage of a buck converter operating in the continuous-conduction mode (CCM). V_{BUS} can be derived as follows via ripple-current calculations for the inductor.

Figure 3. Inductor current versus operation duty cycle in CCM



$$I_{RIPPLE} = \frac{\Delta V \times \Delta T}{L} \tag{1}$$

On the inductor current rising edge:

$$I_{RIPPLE} = \frac{\left[V_{BUS} - I_{CHG} \times (R_{RBFET} + R_{HSFET}) - I_{CHG} \times (R_{IND} + R_{BATFET}) - V_{BAT}\right] \times D \times T}{L}. \tag{2}$$

On the inductor current falling edge:

$$I_{RIPPLE} = \frac{\left[V_{BAT} - I_{CHG} \times (R_{IND} + R_{BATFET}) - I_{CHG} \times R_{LSFET}\right] \times (1-D) \times T}{L}. \tag{3}$$

Since the ripple current is the same, the V_{BUS} equation can be derived.

$$V_{BUS} = \frac{1}{D} V_{BAT} + I_{CHG} \times (R_{RBFET} + R_{HSFET} + R_{IND} + R_{BATFET}) - \frac{1-D}{D} \times I_{CHG} \times (R_{BATFET} + R_{IND} + R_{LSFET}) \tag{4}$$

Equation 4 can be simplified with a few assumptions:

- With L = 2.2 µH, the ripple current at 96% duty cycle is less than 300 mA. (One is considered as average current.)
- With maximum duty cycle of 96%, (1 – D) / D is only 4.2% compared to the second item in the equation. Therefore, the third item can be ignored.

The V_{BUS_MIN} threshold is the V_{BUS} voltage at maximum duty cycle.

$$V_{BUS\_MIN} = \frac{V_{BAT}}{D_{MAX}} + I_{CHG} \times (R_{RBFET} + R_{HSFET} + R_{IND} + R_{BATFET}) \tag{5}$$

If V_{BUS} falls below calculated V_{BUS_MIN} threshold, then the battery will not fully charge.

Minimum USB supply voltage

This section shows how the input voltage to the charger can fall below the permissible value when USB adapters are used due to input line resistance. The USB specification states that the output to the device from a low-power port can be as low as 4.1 V under full load, after passing through all hubs and cables.

Assume that the input supply in Figure 1 is a USB port providing V_{USB} of 5 V with zero resistance in series. R_{IN} is the lumped resistance of the cable, connector and PCB trace. The charger is modeled as an ideal buck converter that can reach 100% duty cycle.

The input voltage (V_{BUS}) at the charger must be above the battery charging regulation threshold V_{BATREG} (typically 4.2 V). Assume that the minimum to which V_{USB} falls is 4.75 V.

$$V_{BUS} = V_{USB\_MIN} - I_{USB\_MAX} \times R_{IN} > V_{BATREG} \tag{6}$$

With resistance from the USB supply to BUS pin of R_{IN} = 400 mΩ, Table 1 shows the minimum V_{BUS} voltage from USB2.0 port and USB 1.5-A adapter.

Table 1. USB Supply Comparison

	V_{USB_MIN}	I_{USB_MAX}	V_{BUS}	BELOW V_{BUS_MIN}?
USB 2.0	4.75 V	0.5 A	4.55 V	No
USB 1.5-A Adapter	4.75 V	1.5 A	4.15 V	Yes

At maximum duty cycle, V_{BUS} is close to V_{BAT}, so $I_{USB} \approx I_{CHG}$. Equation 5 can now be expanded to determine the minimum input supply voltage for a given charge current.

$$V_{SUPPLY\_MIN} = \frac{V_{BAT}}{D_{MAX}} + I_{CHG} \times (R_{IN} + R_{RBFET} + R_{HSFET} + R_{IND} + R_{BATFET}) \tag{7}$$

Equation 7 can be used to determine how low to make the cable resistance and connector (for instance, select a higher quality cable and connector), or how wide/thick to make the PCB trace to avoid excessive voltage drop at the charger's BUS pin. This maximizes the adapter's power for charging the battery.

Input voltage-based dynamic power management (V_{IN}-DPM)

If multiple adapters and/or cables and/or connectors are expected to be used, it may be difficult to design for all line-resistance scenarios. A charger with V_{IN}-DPM prevents the input voltage from crashing regardless of input line resistance.

What is V_{IN}-DPM?

V_{IN}-DPM is an analog loop included in many TI chargers. The purpose of the loop is to extract the maximum amount of current available from the supply without crashing the adapter, i.e., the input current (and therefore the resulting charge current) is limited in order to maintain supply voltage at V_{IN}-DPM. This feature can be used when a USB port is one of the input power sources.

Operation without V_{IN}-DPM

Consider using a charger without the V_{IN}-DPM protection as shown in Figure 4. As the system load current and battery charge current increase, the input current also increases. Hence, the drop across the supply resistance increases. The voltage seen at the charger's input pin is less than the rated output voltage offered by the supply. Also, the supply (voltage source) has a compliance limit on the amount of current it can produce. When a load current is drawn such that the input current required to maintain the sum of charge current and load current is beyond the capability of the supply, the input voltage starts to fall because the input capacitor discharges due to the high current demanded. When the input voltage hits the undervoltage threshold, the charger turns off. During this off time, the input voltage recovers as the input capacitor recharges. Once it rises above the UVLO, charging begins again. Once the charger turns on, the same cycle repeats, resulting in the non-ideal on/off pulsing in the charge current.

Benefits of V_{IN}-DPM

A charger with the V_{IN}-DPM feature prevents the non-ideal pulsing of charge current by limiting input current. Specifically, as the input voltage reduces and hits the set V_{IN}-DPM threshold, the V_{IN}-DPM function activates to reduce the input current to a smaller value. This prevents the input voltage from crashing to the undervoltage point.

Adapters typically supply currents between 100 mA to several amperes, and the latest USB ports can supply up to 1.5 A and higher. When using a charger with V_{IN}-DPM, portable-equipment manufacturers can optimize the charger for adapters and USB ports having a certain output power limit, such as a current limit. V_{IN}-DPM allows operation with other lower cost adapters, USB ports and/or the cables in between. For example, a smartphone with a charger having V_{IN}-DPM would be able to extract

Figure 4. Non-ideal pulse charging by charger with high input line resistance and no V_{IN}-DPM

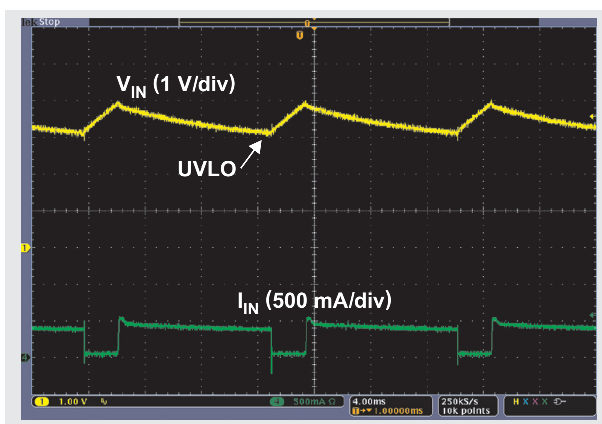
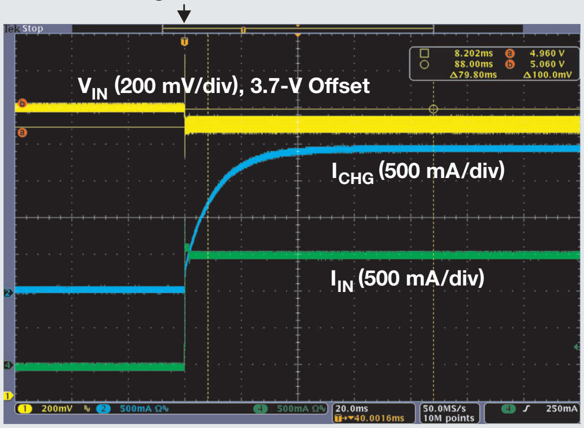
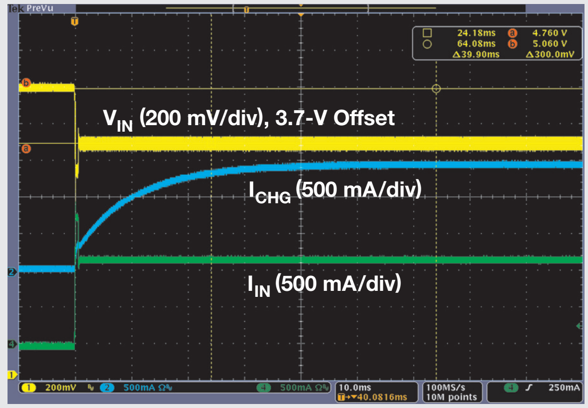


Figure 5. Example of a battery charger without and with V_{IN}-DPM engaged



(a) R_{IN} = 50 mΩ



(b) R_{IN} = 250 mΩ

maximum power from a 1.5-A USB port without collapsing the port, even if a low-cost, highly-resistive USB charging cable is used. Figure 5 shows the effects of two different input resistances from the power supply to the IC. The evaluation circuit was a battery charger like the bq24192, bq24250, bq24260 or bq24295, that was configured for 1.5-A input current limit, 2.0-A charge current and 4.76-V V_{IN}-DPM threshold.

In both cases, charging continues and the adapter does not crash. However, in Figure 5(b), the V_{IN}-DPM circuit reduces the input current limit in response to the voltage drop across the series resistance. With reduced input current, the charger will reduce first the charge current and then the system load current.

Conclusion

Resistances between the supply and charger can prevent the charger from pulling the maximum power from its supply without collapsing the supply and hitting the charger's undervoltage lockout. An equation for determining the minimum supply voltage required for a charger to provide the maximum charge current from given supply adapter was developed. Additionally, the V_{IN}-DPM feature allows the use of a variety of adapters and/or power connections without fear of collapsing the adapter voltage as it dynamically reduces the charger's input current limit.

Related Web sites

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