Buck-boost converter enables USB Power Delivery on the road

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Four-switch buck-boost converter provides high efficiency, compact power solution to meet the USB Power Delivery challenge in cars and power banks.

Universal serial bus (USB), originally conceived for data uses, is the most commonly used power source for charging cellular phones and lower power portable devices, typically <7.5 W. USB Power Delivery (USB PD) extends this range to include higher power devices including tablets and laptops. While extremely useful for on-the-move consumers, the wider output voltage (5-20 Volts) and higher power requirements (up to 100 Watts) create special challenges for the power supplies operating from lower voltage sources. USB ports deriving power from automotive battery rails (12 V) or from portable battery banks (power banks) must be capable of creating a voltage higher or lower than the input voltage source. Additionally, the DC/DC voltage conversion stage must be able to accept commands from the PD controller to change the output voltage and power dynamically depending on the load requirement. This article presents a new approach to architect the USB PD-capable power source using a buck-boost converter. This approach meets the output voltage, power, and slew rate requirements of a 100 W USB PD capable port while achieving a small solution size and high efficiency.

Background

USB was initially created as a data interface with limited power capability. Over time the usage model has been extended to become a primary source of power for mobile devices with and without a data interface. USB is truly universal as a power source and does not change across environment – whether at home, in the car, the office, hotels, and airports. Even in different countries with differing voltages and electric plug configurations, USB is the same worldwide. As the number of mobile devices grows in the form of smartphones, tablets, e-readers, cameras and other portable electronics, people increasingly rely on USB for charging. Not surprisingly, most of the portable battery packs or power banks also have adopted USB as the charging method.

Notwithstanding the ubiquity of USB ports, the existing USB standards [1, 2, 3] are limited in terms of both voltage and power. Traditionally, USB voltage has been limited to 5 V and the power level is limited to 7.5 W in USB battery charger 1.2 (USB BC 1.2) [3]. Looking at the variety of portable devices available in the market today, such as smartphone, e-readers, tablets, netbooks, hard disk drives and portable printers to name a few, it is clear that the traditional voltage and power levels of USB leave a lot to be desired.

USB Spec	Voltage (V)	Max Current (A)	Max Power (W)
USB 1.0	5	0.1	0.5
USB 2.0	5	0.5	2.5
USB 3.1	5	0.9	4.5
USB BC 1.2	5	1.5	7.5
USB Type-C™	5	3	15
USB PD	5-20	5	100

Table 1: *Voltage, current, and power allowed by USB specifications [1, 2, 3, 4, 5].*

Table 1 summarizes the evolution of USB power capability moving up to USB PD.

USB Power Delivery

As a result of the legacy USB power limitations and the increasing need to charge larger devices faster, the USB PD specification was formulated in parallel with the USB 3.1 and USB Type-C™ specifications. The purpose of this specification is to build on the widespread acceptance of USB and extend it to negotiate higher voltages and higher power devices such as tablets, notebooks, laptops and hundreds of battery/bus-powered mobile devices. The Type-C specification alone increases the 5-V power rating to 15 W, while the USB PD specification further extends the power ratings at distinct voltage levels: 15 W at 5 V, 27 W at 9 V, 45 W at 15 V, and 100 W at 20 V level. The Type-C specification allows for backwards compatibility to all Type-A and Type-C ports and receptacles through legacy adapter cables. However, products using older connectors are still limited to USB 2.0 and USB 3.1 power capabilities.

To work with 5 V devices, the USB PD specification incorporates strict guidelines on backward compatibility. All USB PD sources are mandated to provide 5 V on V_{BUS} upon first power up. Higher source voltage is only applied when it is established that a connected device is a PD-capable sink requesting >5 V on V_{BUS}.

USB PD specification summary

In USB PD [5], ports negotiate the voltage, current or power level, and the direction of power flow. The USB PD protocol uses the channel configuration (CC) wire on the Type-C [4] cable as the communication channel for establishing the power contract. USB PD is independent of other power delivery protocols, proprietary or standard (for example, Quick Charge™, USB BC 1.2).

The USB PD protocol allows for source and sink roles to be swapped; however, this article focusses on source-only ports similar to the dedicated charging ports in USB BC1.2 [3]. In USB Type-C and USB PD terminology, this means a port with a pull-up resistor or current (Rp or Ip) asserted. This is the port that provides power to V_{BUS} for the sink to consume.

The sequence of a complete USB PD power contract, as seen from the source side:

- The source detects a sink with a pull-down resistor (Rd) on the CC wire attached.
- The source brings V_{BUS} from GND to 5 V.
- The source detects the cable capability by trying to communicate with the cable. Cables are not required to respond, and a cable that does not respond is assumed to be capable of carrying up to 3 A.

- The source advertises its source capabilities. A response to the advertisement means the sink is PD-capable. If ignored, the sink is only Type-C capable, and V_{BUS} will remain at 5 V.
- The source accepts a request from sink for one of the advertised capabilities.
- The source sends a power-supply-ready (PS_RDY) message when the source power supply is ready to source power at the agreed to voltage level.

The source can inform the sink of changes in its capabilities at any time, with other PD messages such as power role swaps or Alternate Mode may occur after the initial PD contract is established. The source continues to observe the CC wire for a detachment of the Type-C connection. The source takes the V_{BUS} down to GND again when the sink is detached or a hard-reset signal is received, suggesting an error in communication.

USB PD power sources

USB PD sources can come in the form of AC/DC wall adapters or DC-voltage sources. An example of a common PD-capable source is a USB port in a car, or a USB car charger operating from the cigarette lighter port. They both use a 12-V car battery rail as the external power supply **(Figure 1a)**. A source implementation with an internal storage is a power bank.

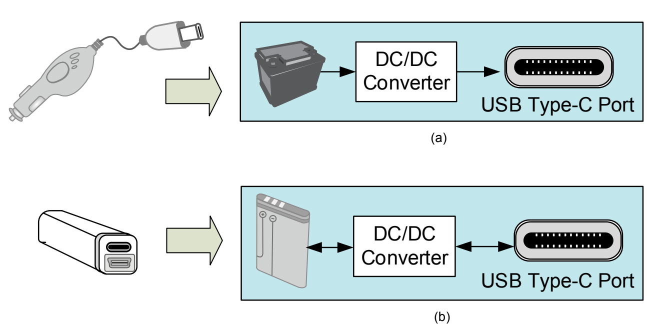


Figure 1: *USB charging devices include a USB port in a car or a portable USB car charger (a); and a portable rechargeable battery/power bank (b).*

Buck-boost in a charger

The wide output voltage (V_{BUS}) range of USB PD presents a unique challenge for the power stage design. For chargers operating from an AC wall outlet with standard voltages of 110 V and 220 V, generating a 5-V to 20-V output involves only a step-down conversion. For USB PD-capable chargers operating from a car 12-V battery **(Figure 1)** or a power bank **(Figure 2)**, however, requires generating an output voltage (V_{BUS}) higher or lower than the input – depending on the state of the battery and the negotiated power level.

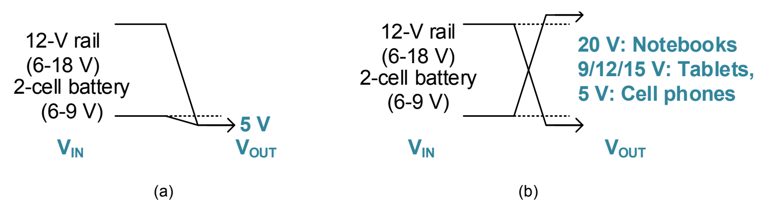
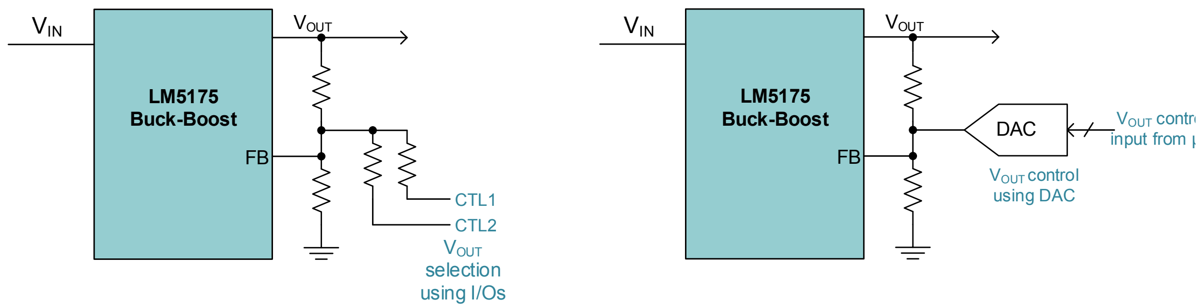


Figure 2: *Non-PD implementation only requires a step-down conversion (a); PD implementation requires step-up/down conversion in a car charger or power bank (b).*

To support higher voltages specified in USB PD in a car charger or power bank, the power supply design for a USB PD port will need to change from a simple buck **(Figure 2a)** to a buck-boost **(Figure 2b)** topology. Traditionally, buck-boost designs involve cascaded multiple stages or complex topologies including multiple windings and transformers. Single-stage, efficient buck-boost solutions that cover the wide input and output voltage range in a small form factor are preferable [6].

Building a USB PD power supply

A single-stage, four-switch buck-boost, such as the TI LM5175, provides a simple, efficient and compact power-stage solution for converting a widely varying input voltage source. An example includes a car battery rail into a well-regulated selectable or dynamically controllable output rail needed for USB PD.



(a) (b)

Figure 3: *Resistor (a) and DAC-based (b) schemes for changing the output voltage of a four-switch buck-boost converter and or power bank (b).*

Figure 3 shows two different schemes for creating a programmable output voltage using a four-switch, buck-boost converter. The first scheme (**Figure 3a**) uses active low-logic signals to switch external resistors in the lower side of the feedback resistor divider of the buck-boost converter. This simple scheme is suitable for creating a fixed small set of output voltages [7, 8].

For implementations where the output voltage needs to be tuned dynamically (as in certain proprietary fast-charge schemes implemented by some smartphone vendors) or when a large number of USB bus voltages are needed, a digital-to-analog converter (DAC)-based scheme (**Figure 3b**) is suitable as the voltage programming levels can be changed in firmware.

The LM5175 buck-boost DC/DC converter stage easily pairs with a range of USB PD controllers, including TI's TPS25740/A and TPS25741, to create a complete USB PD compatible power source using its feedback node. **Figure 4** shows a high-level diagram of a USB PD solution that works with an automotive battery input range, and supplies PD standard voltages. Type-C PD downstream port controllers [7] handle the Type-C port detection and PD contract negotiation, and enable the DC/DC power stage upon port attachment to come up with a default 5 V at V_{BUS}. If requested by a PD-capable sink, the PD controller commands the DC/DC supply to change its output voltage to the requested voltage, for example by pulling the CTL1/2 pins low.

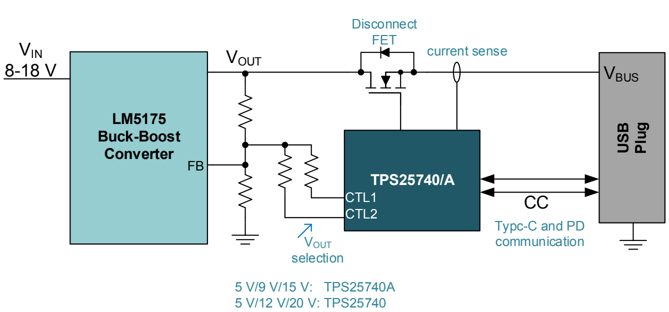


Figure 4: *An USB PD power provider/charger implementation using a four-switch buck-boost and USB PD controller [8].*

A more complex USB PD implementation with USB data is shown in **Figure 5**. This configuration uses a buck-boost power stage with a USB PD and Type-C controller [9], with USB data support. Using a DAC such as the LM10011 to interface the PD controller with the buck-boost DC/DC stage provides more flexibility in programming the USB bus voltage.

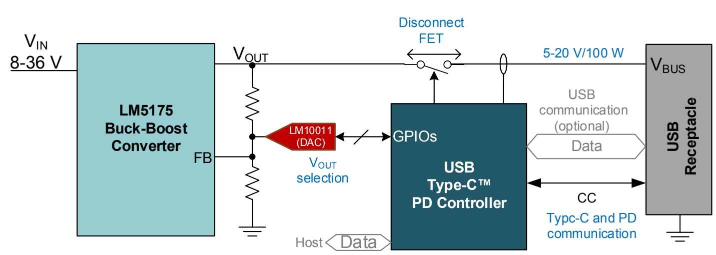


Figure 5: *USB power provider and data implementation using a four-switch buck-boost and Type-C PD controller.*

Conclusion

USB PD extends USB voltage to 20 V and the output power to 100 W. This is a leap forward from the existing 5 V/7.5 W offered by the USB battery charging specification Rev 1.2, and brings the promise of USB-based charging to tablets and full-featured laptops among other devices. However, for battery-operated USB sources such as USB ports in cars, aftermarket car chargers and power-banks, this creates a new DC/DC conversion challenge as the power stage must be able to buck as well as boost depending on the requested output voltage.

The four-switch buck-boost, such as the LM5175 from Texas Instruments, can handle the wide input and output voltage ranges required in automotive and portable battery-pack-operated USB chargers. This article demonstrates how a synchronous four-switch buck-boost DC/DC controller can be used along with a variety of PD controllers such as the TI TPS25740 or TPS25740A (DFP power only) and USB PD controller (power plus data-capable) like TPS25741 to create high-efficiency, out-of-the-box compact USB PD-compliant solutions.

References

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