Current sensing in high-power USB Type-C® applications

By Ben Damkroger
Product Marketing Engineer, Sensing-CSPS

Introduction

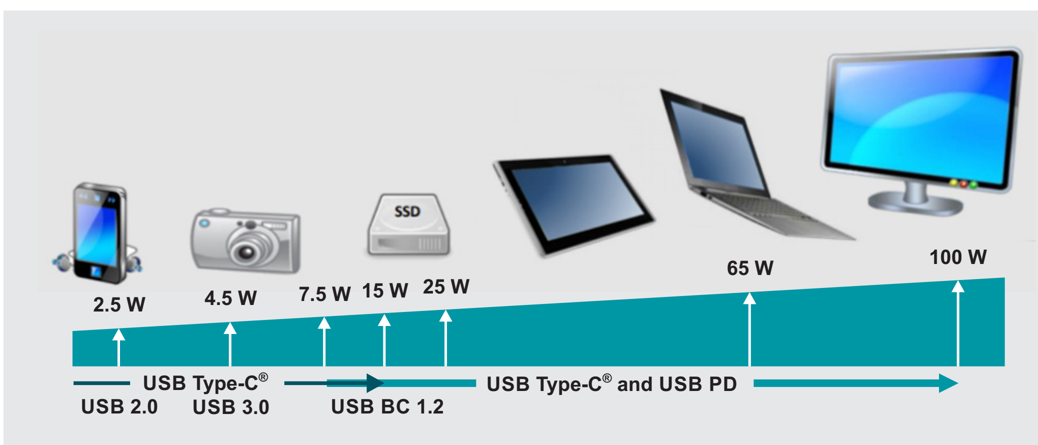
The introduction of USB Type-C,® also designated USB-C,® connectors eliminated the frustration of flipping USB cables three and four times before finding the correct orientation to plug in a device. A smaller, reversible cable is not the only thing new with the evolution of USB technology, however; the standard also enables the replacement of various electrical connectors including USB-B and USB-A, HDMI, DisplayPort, and 3.5-mm audio cables. Sadly, USB-C alone still has a power limit of only 15 W. However, USB Power Delivery (USB PD) increased that power limit to 100 W through the introduction of configurable voltage levels of 5 V, 9 V, 15 V or 20 V. This 100-W limit means that higher-power devices such as laptops, tablets and monitors can all charge and operate using a single USB PD cable.

This increased power has more design considerations than previous standards, however. USB-C cables have 24 pins, including four Vbus wires and four ground wires, more than USB 3.0. These Vbus lines require overvoltage, overcurrent and reverse-current protection. Protections should be implemented that detect transient spikes caused by faults in the Vbus line or faults internal to a load device. These protections should be added in both source and sink (load) devices to guarantee safe operation. For sink devices, due to lower manufacturing costs of power adapters and corners cut during construction as a result, there is no guarantee that consumers will use power adapters with sufficient protection. Sometimes faulty power adapters may provide the 20 V before USB negotiation, which might overload sink devices. For source devices, cheap USB cables and USB-C PD devices may have faulty wiring, causing a short on the load side of a charger and ultimately requiring some protection.

When designing devices that act as power sources, such as docking stations or chargers, shield devices are required downstream, especially when running near the 100-W limit of USB PD. Integrated current sensing in USB PD controllers is usually only ±10% to ±15% accurate. These accuracy levels may be sufficient for some, but a more accurate solution for overcurrent protection maximizes the amount of current that the USB port can provide while staying below a fixed power level.

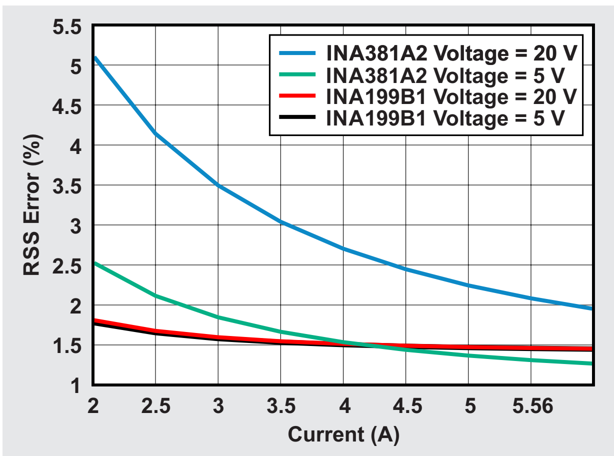
For example, to account for current tolerance in a 20-V/5-A (100-W) system, the maximum current limit should be set 10% away from 5 A at 4.545 A (5 A × 1 ÷ 1.1). With a maximum current of 4.545 A, the maximum possible power delivered to a load device is 90.9 W. Additionally, when the current is 10% below the maximum current at 4.090 A, a system would only deliver 81.8 W of power.

Figure 1. USB PD power range



To set a higher current threshold, a discrete current-sense amplifier like the INA199, with its 150-µV voltage offset and 1% gain error, can easily provide 1.5% accuracy when the current is greater than 1 A in a 100-W application. This device enables the current limit to be set at 4.926 A (5 A × 1 ÷ 1.015), which in turn means that the USB port could deliver 98.52 W to the load. Figure 2 shows the root-sum-square (RSS) error curves for the INA199 and INA381.

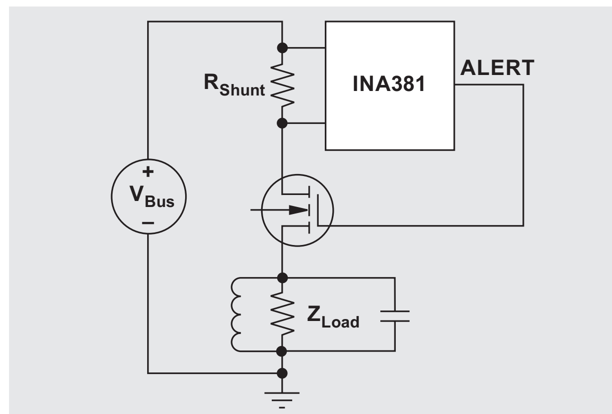
Figure 2. INA199 and INA381 total measurement error



For devices that sink power over a USB PD supply, it is strongly suggested to include current sensing to protect from internal faults. It is impossible to know whether consumers will power peripheral devices with USB PD controllers that have adequate overcurrent protection. One easy solution is to design internal overcurrent protection in the device's Vbus input by wiring a discrete current-sense amplifier, a comparator and a field-effect transistor (FET) as an e-fuse. With an e-fuse, the current-sense amplifier detects whether the current is too high and the comparator controls the FET triggers that turn off the FET and interrupts the current.

In the most straightforward implementation, the analog output of the comparator could be used to trip the FET. Or digital logic could be used with an analog-to-digital converter (ADC) and microcontroller (MCU) to decide when to switch the FET off. These overcurrent protection schemes provide a response time that is much faster than a thermal fuse and can be reset and reused without replacement. The INA381 current-sense amplifier, with its fast integrated comparator, shrinks the bill of materials by eliminating the need for a comparator and makes the design process more straightforward. Figure 3 is a simplified circuit using this device.

Figure 3. Simplified e-fuse circuit using the INA381



Selecting the correct current sensor is essential, especially given their variety. Digital power monitors, for example, provide an integrated ADC that frees up space on a system's MCU analog inputs, while also giving access to extra features like power calculation and accumulation (energy). Analog current-sense amplifiers, on the other hand, are more popular because of their low cost and versatility. The integrated gain resistors and input stages of analog current-sense amplifiers enable their inputs to detect common-mode voltages beyond their supply, thus making these devices better for current sensing than standard operational amplifiers. Current-sense amplifiers can also come integrated with comparators for faster response times and alert signals for overcurrent protection; the latter is especially important for protecting USB-C PD devices.

$$\text{Total Error} = \sqrt{V_{os}^2 + \text{CMRR}^2 + \text{PSRR}^2 + \text{Gain Error}^2 + \text{Shunt Tolerance}^2 + \text{Bias Current}^2} \quad (1)$$

As previously mentioned, current-sense amplifiers are more accurate than the integrated current sensing of most USB-C PD controllers. To understand why, first consider the various error sources found on current-sensing data sheets and use these sources to calculate errors using the root-sum-square (RSS) method. The different error sources present in current-sensing amplifiers are shown by Equation 1 above.

The input offset voltage (V_{OS}) is the dominant source of error when measuring small currents because it is larger in relation to the relatively small shunt voltage—it diminishes as the shunt voltage increases at higher currents. This offset error is inherent to all amplifiers and is a result of resistor and transistor mismatching. Gain error dominates the error at larger currents, as it remains present even at high currents, and does not diminish as the shunt voltage increases. These error sources can be manually calculated using Equation 1. For additional information, consult the References and Related Web sites on this page.

Conclusion

With the advent of USB PD, the number of high-power USB devices continues to grow. This article presented the options available to implement current protections and power monitoring, and also compensate for tolerance errors that are typically encountered with integrated current sensing in USB PD controllers. The need to maximize power to a load in a power-source device or protect a power-sink device is also highlighted. Current-sensing amplifiers provide an easy solution to many of these design challenges, with higher accuracy and greater design flexibility.

References

1. TI Precision Labs – Current Sense Amplifiers, Texas Instruments training and videos
2. Maximize your system with current sense amplifiers, Overview, Texas Instruments products and reference designs

Related Web sites

Product information:
INA199
INA381
INA381 Design tools and simulation

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