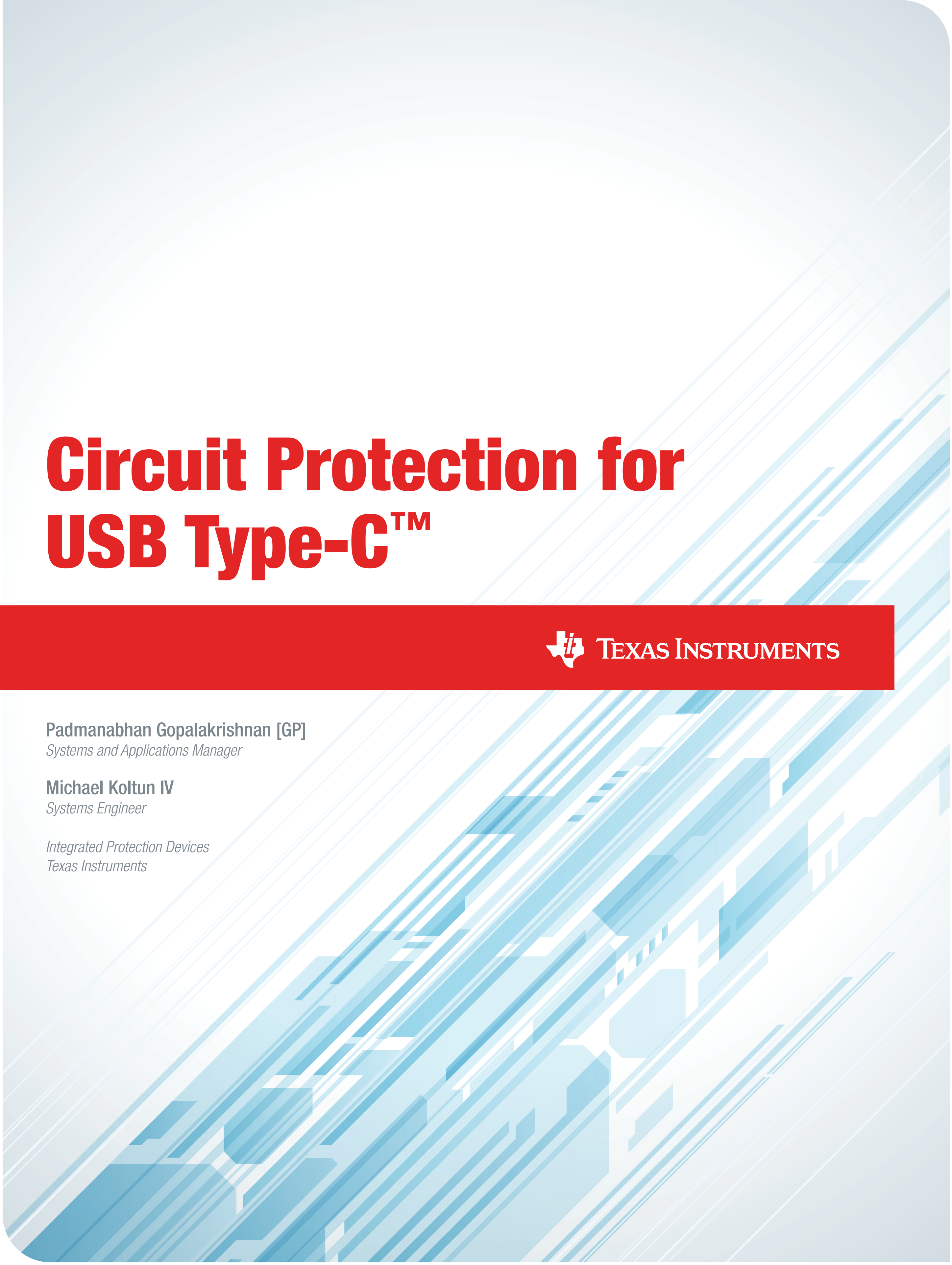

Circuit Protection for USB Type-C™

TEXAS INSTRUMENTS

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Why adding proper circuit protection to your USB Type-C™ design reduces the risk of system damage and field failures.

USB Type-C™ is the latest universal serial bus (USB) standard that combines support for data, video and power delivery into a single, flexible interface. USB Type-C defines a new receptacle, plug and cable standard compatible with all existing USB interfaces. The simplicity and convenience of the end consumer experience is expected to drive rapid adoption of the new connector, but introduces new challenges to system designers as they make the migration. This paper will discuss how the new features and capabilities of the USB Type-C connector can also introduce risk for system damage and field failures, if proper circuit protection is not a key component of the system design. Such a failure can occur independently of the end-equipment, whether it be for personal electronics, industrial or automotive applications.

Although the USB interface has long been the work horse of interfaces for high-speed data and up to 7.5 W of power delivery (through USB BC1.2), the system use cases demanded by the market, the evolution of technology, and competitive proprietary interfaces have accelerated the need for a more flexible, capable and powerful interface. Adoption of USB Type-C started in 2015. Early adopters were first to see the benefits, as well as the new potential failure mechanisms the new connector may introduce. [1]

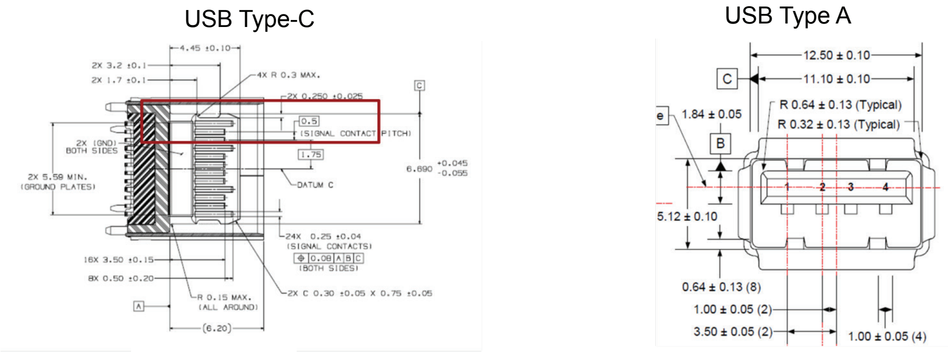
Benefits of USB Type-C

Reversible in a small form factor connector

The symmetrical definition of the Type-C connector enables reversible plug orientation in a small form factor connector. The Type-C connector supports either host or device mode, and in time will replace various Type-B and Type-A connectors and cables in the market. The 24-pin, double-sided connector is similar in size to the USB Micro-B connector, with a Type-C port measuring 8.4 millimeters (0.33 inches) by 2.6 millimeters (0.10 in).

Increased USB power delivery

The USB Type-C connector supports the USB Power Delivery (USB PD) standard, which enables higher power transfers than previous USB protocols. On the higher end, power capabilities with the Type-C standard are now extended up to 100 W. This standard is based on new provisions allowing the


USB Type-C

USB Type A

- 0.5 mm pitch between pins

- 2.5 mm pitch between pins 1,2; 3,4
- 2 mm pitch between pins 2,3

Figure 1. *Mechanical layout of a USB Type-C versus a USB Type-A connector. (Source: Images courtesy of USB Type-C and USB Type A standards.)*

source to dynamically manage current from 0.5 A to 5.0 A. In this case, the nominal voltage on the V_{BUS} can be up to 20 V. This enables end products from laptops to mobile phones and power tools to charge faster.

Small pin-to-pin pitch

To support the smaller and symmetrical form factor, the Type-C connector has 0.5-mm pin-to-pin pitch as shown in **Figure 1**. This small pitch is 20 percent of the pin-to-pin distance of the Type-A connector pins, and the proximity of the pins increases the risk for a pin-to-pin short.

For example, a short could occur with a twist of the connector, or if the cable is pulled out of the receptacle at an angle. This type of pin-to-pin short failure is easy to replicate in the lab with simple experiments (**Figure 2**).

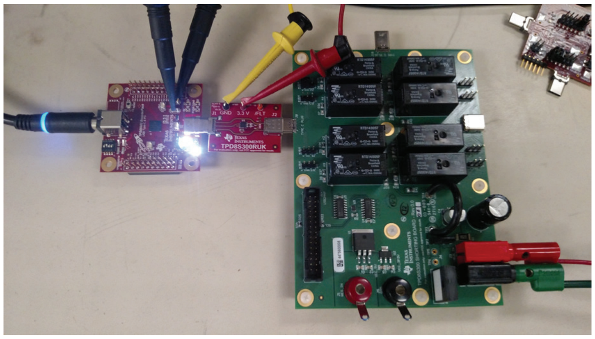


Figure 2. *An evaluation module (EVM) with an interposer board shows evidence of a pin-to-pin short.*

In addition to risk for a pin-to-pin short from mechanically twisting the connector, a build up of small debris due to connector aging can cause a short with V_{BUS}. **Figure 3** shows an example of debris leading to a pin-to-pin short due to a small pitch in the connector.

Cable reversibility

The 24-pin connector provides four power/ground pairs, two differential pairs (D+/D–) for USB2.0 data (even though only one pair is populated in a Type-C cable), four pairs for SuperSpeed data bus (TX/RX), two side-band use (SBU) pins, and two configuration channel pins (CC) for detecting cable orientation, a dedicated biphase mark code (BMC) configuration data channel, and V_{CONN} +5-V power for active cables.

Connecting an older device to a host with a Type-C receptacle requires a cable or adapter with a Type-A or Type-B plug, or a receptacle on one end with a Type-C plug on the other end. Legacy adapters with a Type-C receptacle are not defined or allowed by the specification because they can create many invalid and potentially unsafe cable combinations.

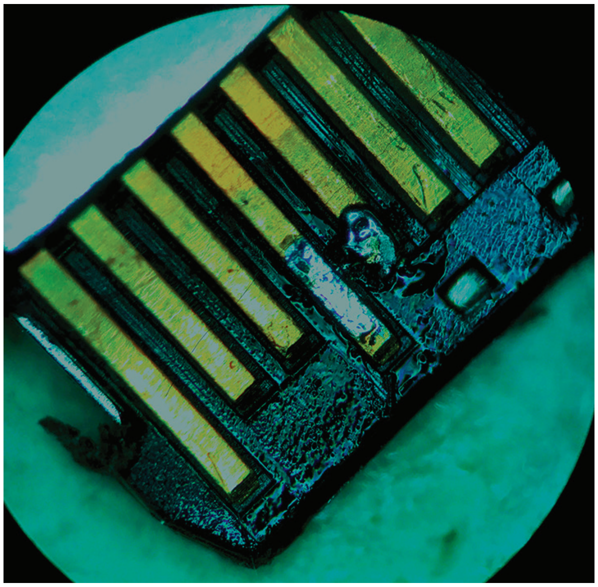


Figure 3. *Illustration of debris in a small pitch aiding easy shorts.*

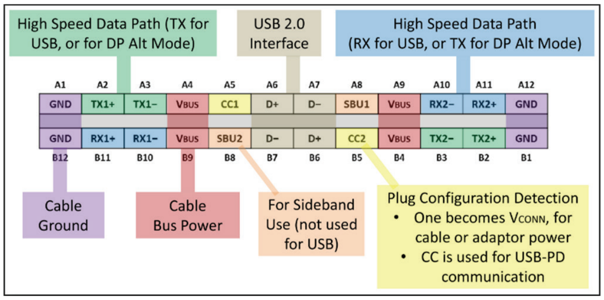


Figure 4. *Illustration of a full-featured Type-C plug-in pin out.*

Since the introduction of Type-C, over 2000 manufacturing companies have introduced Type-C cables to the market worldwide. Texas Instruments developed the industry's first integrated Type-C and a USB Power Delivery (PD) controller. As an early adopter of this new standard, TI has seen the issues encountered by early adopters and in the field due to non-compliant cables.

Protecting against non-compliant cables

Amazon conducted a survey of Type-C cables and found that a large amount of cables surveyed were non-compliant with the USB-IF specification, making the risk of an end user purchasing a non-compliant Type-C cable real [2]. The system design must include circuit protection to ensure that a faulty or non-compliant cable does not damage the system.

In addition to non-compliant cables, there are many power adaptors that are also non-compliant with the Type-C standard. These adaptors could deliver up to 20 V of power to V_{BUS} before the PD negotiation begins to support this high voltage. This high voltage can damage Type-C ports that are designed to support only 5 V on V_{BUS}.

Additionally, if the CC pin is pulled up to the V_{BUS} rail in these faulty adaptors, the system will see a short-to-V_{BUS} failure. If R_P is pulled up to V_{BUS} in these adaptors, greater than 5.5 V can be exposed to the CC pin. If a standard 3A R_{PULLUP} cable is used (**Figure 5**), 7.43 V can be exposed on the CC pin.

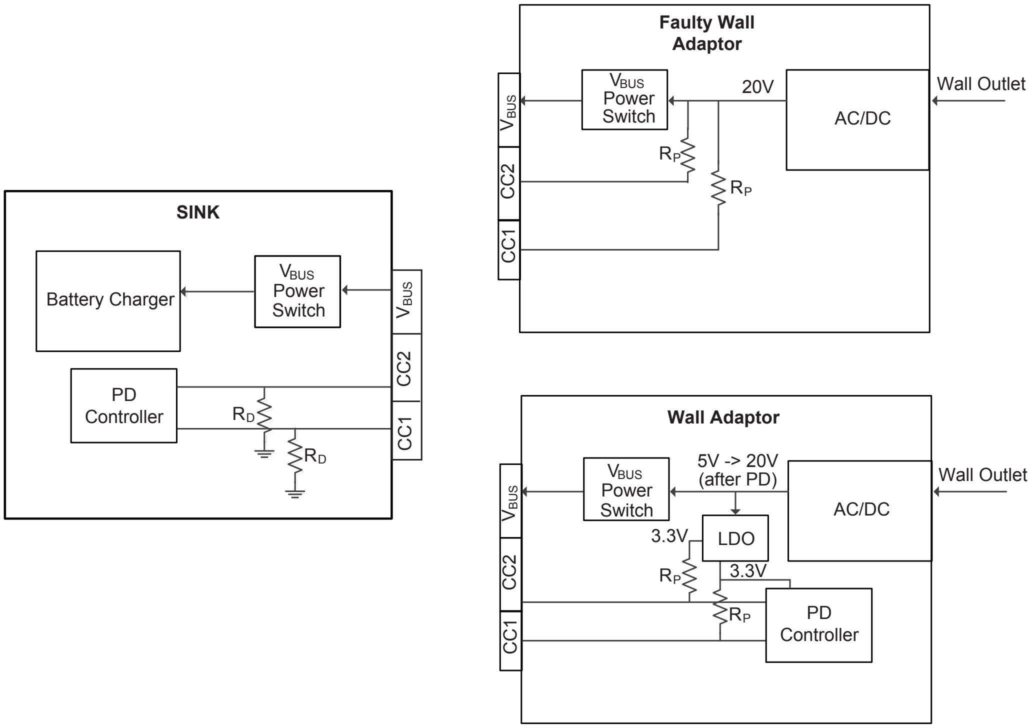


Figure 5. *CC pin exposure for regular and faulty wall adaptors.*

With the aim to develop low-cost accessories to support the fast-growing market for Type-C, cable manufacturers may introduce problems that impact the end application. If the cable is mis-wired or improperly soldered, the small pin-to-pin pitch increases the probability that a short can occur. As also mentioned, even if a cable is compliant to the USB-C standard, mechanical twists during usage and removal of the Type-C cable can still cause these shorts; so whether a cable is compliant or not, shorts to V_{BUS} on adjacent pins can occur. Therefore, the end-equipment manufacturers need circuit protection to avoid this risk. In addition to the potential for these cables to expose the system to an over-voltage condition, the cable could also carry up to 5 A of current. If this should occur, any small damage caused by the cable could be detrimental to the end product.

Now we will review the different types of configurations and the potential circuit protection considerations for each.

Challenges

Circuit protection

While the advantages we just mentioned are a benefit of this standard, they also pose a challenge to system designers who need to ensure that the downstream circuitry can withstand 20 V. Currently, all USB PD controllers in the market are only 5-V tolerant or less on the CC, SBU, and transceiver/receiver (TX/RX) pins. The CC and SBU pins are directly adjacent to the V_{BUS} pins, so a short to these pins can expose 20 V to the downstream circuitry and be destructive to the system.

Combining IEC and short-to-V_{BUS}

Any external connector will require system-level IEC 61000-4-2 ESD protection. Some end products require ±8-kV contact. When we need to combine OVP and IEC ESD protection, it is critical to have a clamping voltage low enough to protect the system. Note that the type of diode required when using Type-C is not a conventional transient-voltage suppression (TVS) diode, but a high-voltage, DC-tolerant TVS diode. Many options available in the market today clamp at voltages too high to protect the downstream controllers in the event of an IEC ESD strike. An integrated protection solution for OVP and IEC ESD combined ensures robust protection for the end system.

Short-to-V_{BUS} events

We have identified various causes of the short-to-V_{BUS} event; however, how does a system designer protect from such short-to-V_{BUS} faults? Next we will discuss the unique characteristics of the short-to-V_{BUS} fault, which makes implementing a proper protection solution from this fault event complex.

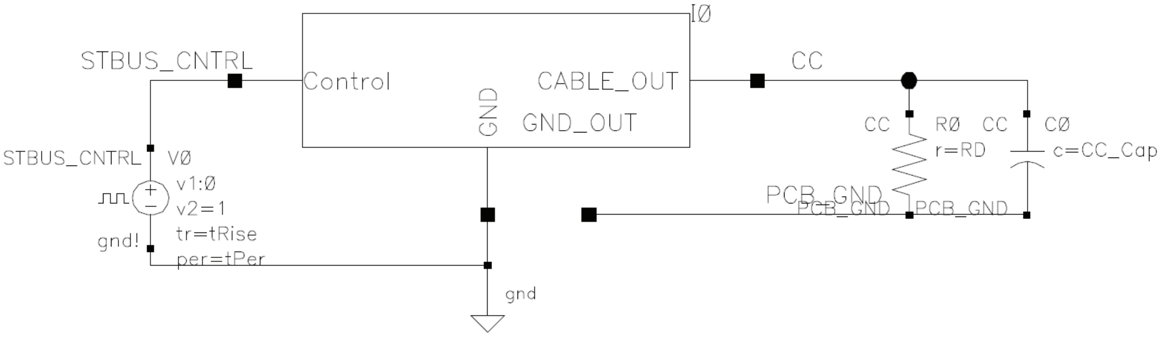


Figure 6. *Short-to-V_{BUS} system set up without a protection device.*

Short-to-V_{BUS} model

Figure 6 shows a system configuration as it is performing a short-to-V_{BUS} to a CC line without a protection device.

There are two high-level use cases of the short-to-V_{BUS} event: short-to-V_{BUS} through a cable and short-to-V_{BUS} without a cable. If a Type-C cable is present and a short in a Type-C connector happens on the connector where V_{BUS} power is sinking, then a cable exists between the voltage source and shorted CC or SBU line. If a Type-C Cable is present, but a short happens on the connector where V_{BUS} is sourcing power, then even though a Type-C cable is present, the voltage source is applied directly to the CC and SBU pins, bypassing the cable. Both the cable and non-cable use case for short-to-V_{BUS} present their own challenges and both use cases need to be accounted for to ensure robust protection for the system.

Short-to-V_{BUS} through a cable

The short-to-V_{BUS} generator shown **Figure 7** is capable of generating a short both with and without a cable. The waveform was generated assuming a one-meter USB-C cable.

$$RD = 5.1\ k\Omega,\ and\ CC\_Cap = 200\ pF \tag{1}$$

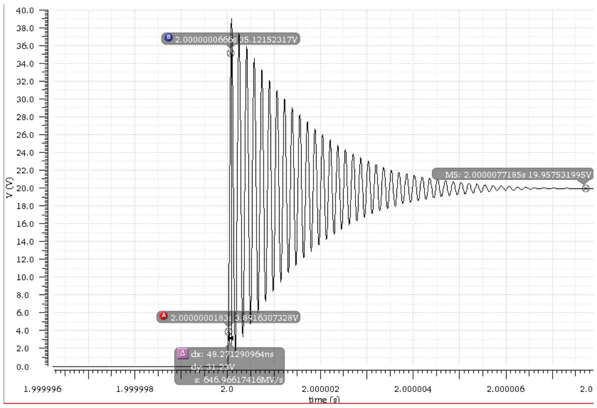
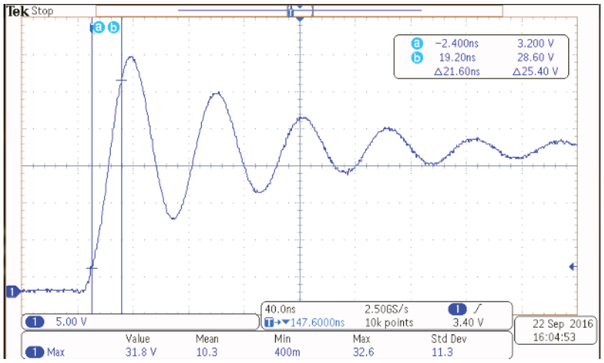


Figure 7. Simulated short-to-V_{BUS} waveform through a one-meter USB-C cable.

Figure 8 shows the capture of a short-to-V_{BUS} event with a one-meter Type-C cable in the lab.

$$RD = 5.1\ k\Omega,\ CC\_CAP = 220\ pF \tag{2}$$



	Value	Mean	Min	Max	Std Dev
1 Max	31.8 V	10.3	400m	32.6	11.3

Figure 8. Lab-performed short-to-V_{BUS} waveform through a one-meter USB-C cable.

As the waveform shows, when a cable is present during a short-to-V_{BUS} event, enough inductance exists in the resistor-inductor-capacitor (RLC) circuit relative to the resistance and capacitance to generate a peak voltage during the ringing that is nearly double the value of the settling or final voltage. If the CC line capacitors de-rate greatly over their voltage range, then the peak voltage that is present during the ringing can be more than double the setting or final voltage. This means for a 22-V short, up to 44 V can be seen on the CC or SBU lines during a short-to-V_{BUS} event. What was initially thought to require only 22-V protection ends up needing to be 44 V.

Short-to-V_{BUS} without a cable

The short-to-V_{BUS} waveform shown in **Figure 9** is configured to simulate the short-to-V_{BUS} tester when a cable is not used.

$$RD = 5.1\ k\Omega,\ CC\_CAP = 200\ pF \tag{3}$$

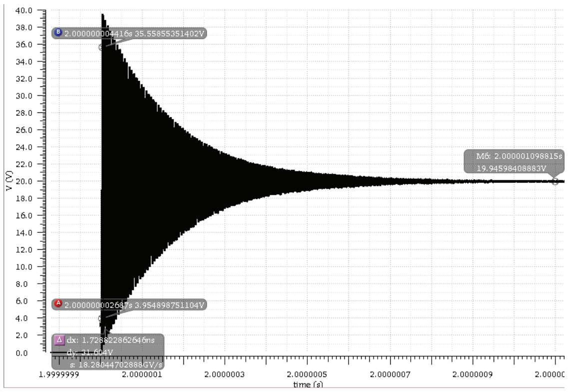


Figure 9. Simulated short-to-V_{BUS} waveform without using a USB-C cable.

Figure 10 is a capture of a short-to-V_{BUS} event in the lab without a cable.

$$RD = 5.1\ k\Omega,\ CC\_CAP = 220\ pF \qquad (4)$$

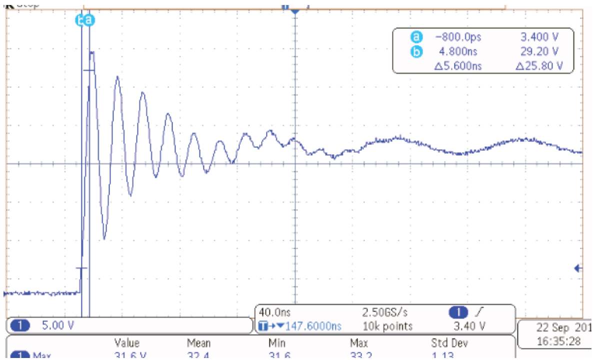


Figure 10. Lab-performed short-to-V_{BUS} waveform without using a USB-C cable.

When not using a cable, a short-to-V_{BUS} event is especially challenging to protect from. Because the inductance is so low without a cable, the rise time of the short event can be less than 10 ns from 10 percent to 90 percent of the rising edge. This is extremely fast. This rise time is so fast it makes using only a discrete field-effect transistor (FET) to protect the line useless. Also, in this use case, the total resistance of the path is so low, the amount of current that can be introduced on the CC and SBU lines increases substantially, when compared to using a cable.

Other system requirements

ESD protection

A consumer-interfacing product needs to have some level of the International Electrotechnical Commission (IEC) 61000-4-2 standard for electrostatic discharge (ESD) protection. This standard more accurately approximates the types of ESD events that end-products may encounter when a user operates them. However, with the possibility of the CC and SBU lines being exposed to 22 V of direct current (VDC) from the connector side, the IEC solution becomes more challenging. Solutions exist on the market today with breakdown voltages greater than 22 V. However, the issue is that the majority of these devices that also have low-clamping performance to minimize voltage to the downstream PD Controller have deep snapback technology. **Figure 11** shows a transmission-line pulse (TLP) curve from this type of device that is currently on the market.

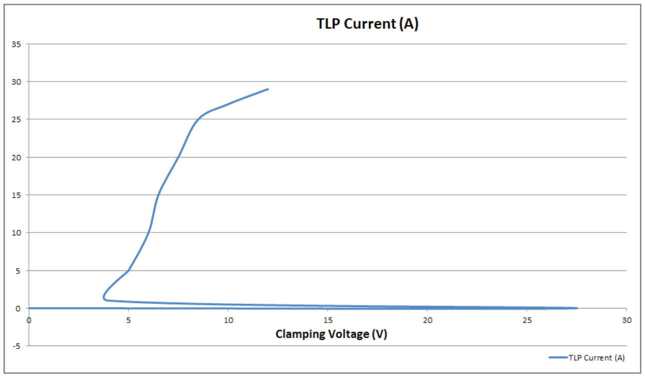


Figure 11. TLP curve of a deep snapback ESD protection diode.

This device's TLP curve shows that the trigger voltage is well above 22 V, so it would seem that this diode should be able to withstand a 22-VDC short. For IEC ESD strikes, the deep snapback technology makes the clamping voltage very low, allowing for a much lower voltage tolerance for the system and/or total protection circuit. The key issue is that this does not provide protection when a short-to-V_{BUS} event occurs. If a short-to-V_{BUS} occurs, the voltage can ring much greater than 22 V, even up to 44 V as previously discussed.

Therefore the trigger voltage of this ESD cell can be surpassed. Once the diode is triggered, it begins conducting in its high-current region. Since we are applying a 22-VDC source to this line, this diode can conduct in its high-current region indefinitely. This leads to over heating and causes permanent damage to the diode, and also introduces an over-voltage condition to the downstream system circuitry.

Since deep snapback technology clearly has issues in the short-to-V_{BUS} system, non-snapback diodes must be investigated. Therefore, we tested a non-snapback diode and collected its TLP curve, shown in **Figure 12**.

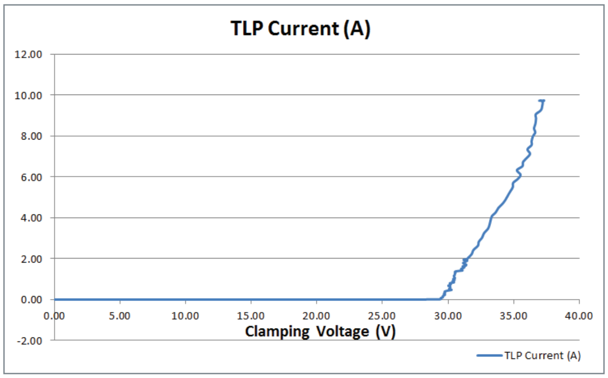


Figure 12. *TLP curve of a non-snapback ESD protection diode.*

As **Figure 12** shows, its trigger voltage is near 30 V. Since it does not have deep snapback technology, even if a short-to-V_{BUS} 22-VDC event happens, the diode will turn off after ringing and settle in the off state and will not be damaged. However, as **Figure 12** also shows, the 16-A TLP clamping voltage (which approximates 8-kV contact IEC ESD clamping voltage), will be well above 40 V. Using an OVP FET greater than 40 V may be fine, but this can be a very large and expensive solution.

There are not many good market solutions today that are tolerant to high-voltage DC on the connector-side, while still providing robust IEC system protection.

V_{CONN} support

If Type-C is used for any SuperSpeed communication, V_{CONN} needs to be supported on the CC lines per the Type-C specification to power active cables. For an OVP protection solution to function on the CC lines, it also must support passing a 5.5-VDC power rail. If your design supports a standard 1-W V_{CONN}, then you need to provide 200 mA of current. This power level leads to a total system budget for CC line resistance of 1.25 Ω, assuming a maximum of 250-mV drop on the 5-V power rail. If a USB-PD alternate mode is used, greater than 1 W can be provided. V_{CONN} current up to 1.25 A can be provided in an alternate mode according to the USB-C standard. Let's take an example of 300 mA being provided; this allows a maximum system resistance of 833.33 mΩ, assuming a 250-mV drop on the 5-V power rail.

The designer must take these maximum resistance requirements into account when designing an OVP protection solution for short-to-V_{BUS} events. Many Type-C PD controller's with a V_{CONN} current-limit switch integrated have a maximum R_{ON} greater than or equal to 500 mΩ. In this configuration, very low resistance is required for an OVP protection solution on the CC lines.

Dead battery support

Over-voltage protection solutions when a device is in dead-battery state inherently isolate the Type-C connector's CC pins from its USB PD controller. Protection of 22 VDC needs to be maintained in a dead-battery condition. This means that the OVP FET must be off in a dead-battery condition, and that any dead-battery resistors in a USB PD controller will no longer be exposed on the Type-C connector. System solutions must include high-voltage-tolerant dead-battery resistors in the OVP solution, if dead-battery support is needed.

A discrete protection solution

Looking at the short-to-V_{BUS} event and other system requirements for the CC line that we discussed earlier, a discrete protection solution must support the following conditions:

- Handles ringing up to 44 V
- Supports <10-ns rise times on the short-to-V_{BUS} event
- Supports IEC 61000-4-2 system-level ESD protection
- Supports at least a 5-V, 1-W power rail for Type-C ports with active cable support
- Supports dead-battery conditions for mobile devices relying on Type-C as their power source

This combination of conditions makes developing a discrete OVP solution for Type-C protection challenging. Consider simply using a single discrete OVP FET. **Figure 13** shows the parasitic capacitances in an n-channel MOSFET.

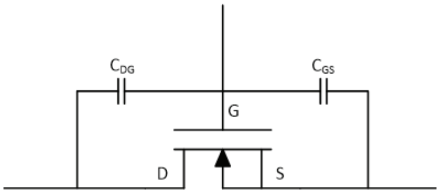


Figure 13. N-channel MOSFET with parasitic capacitances included.

If only using a discrete FET, a few issues arise. This discrete FET must be at least 44-V tolerant, and have around 500 mΩ or less resistance. This makes for a very large FET. However, a discrete FET alone will not work because it will not protect from a short-to-V_{BUS} event that occurs without traveling through a cable. With less than 10-ns rise times, the parasitic capacitors present on the discrete FET will effectively create a short between the drain and the source, putting a great portion of the initial 22-V transient directly on the downstream USB PD controller. This has the potential to destroy any 5-V tolerant USB PD controller unless you use additional voltage clamping circuity in conjunction with the discrete OVP FET. Therefore, clamping circuitry should be added after the OVP FET and before the USB PD controller to mitigate stress from this fast rise time.

Additionally, since IEC ESD protection is required, an ESD protection diode needs to be placed on the connector-side of the discrete FET in order to protect both the system and the OVP FET from being damaged. Since the majority of market solutions for IEC ESD clamp above 40 V, you will still need to use a large 40-V FET, even though additional clamping circuitry is being placed on the connector-side of the discrete FET.

Another challenge is that 5 VDC must pass through this discrete OVP FET. If using an n-channel FET, at least a 6.5-V to 8-V gate voltage will most likely be required to properly keep this FET in the low-resistance triode region to support at least 200 mA of current passing. You will need to add a charge pump to the system, plus gate driver circuity with OVP to properly turn off the OVP FET during an OVP event. If using a p-channel FET instead, this configuration can help to eliminate the need for a charge pump. However, the gate drive circuitry with OVP will still be required to properly bias the gate for normal operating and OVP conditions.

Moreover, if your design requires dead-battery support, you need to add high-voltage tolerant dead-battery resistors to the OVP solution, plus additional control circuitry to remove these resistors once you add power back to the system.

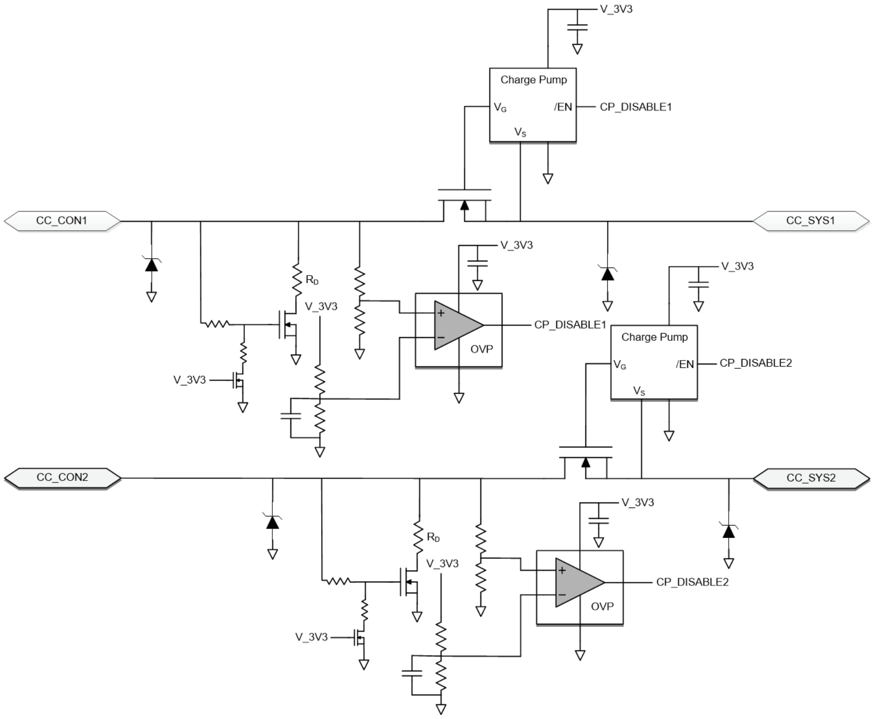


Figure 14. *Discrete OVP protection solution for the CC lines*

For a CC line on a USB Type-C port, a large amount of circuitry is required to properly protect from a short-to-V_{BUS} event. The circuitry in our example that we discussed in this section about discrete protection is used for one CC line only; but another CC line plus two SBU lines also need to be protected.

Figure 14 shows an example of a discrete solution that can be used to protect two CC lines.

While the solution in **Figure 14** requires 37 discrete parts, it still does not have SBU protection.

Due to the vast complexity and solution size of protecting a system from both the short-to-V_{BUS} event and IEC system-level ESD event while maintaining normal Type-C system operations, TI has developed a small, monolithic solution that provides complete protection for the Type-C port, the TPD8S300. The entire protection system is on a single chip, vastly simplifying the design and implementation of the Type-C port. Instead of having to design a huge discrete solution, a system designer can simply add one TPD8S300 to their system to meet their entire short-to-V_{BUS} and IEC 61000-4-2 ESD protection requirements (**Figure 15**).

As can be seen from the diagram in **Figure 15**, 4-channels of OVP short-to-V_{BUS} protection (for the CC and SBU pins), 8-channels of IEC ESD protection (for the CC, SBU, and USB2.0 pins), and the dead battery resistors are all included in a small 3-mm by 3-mm QFN solution.

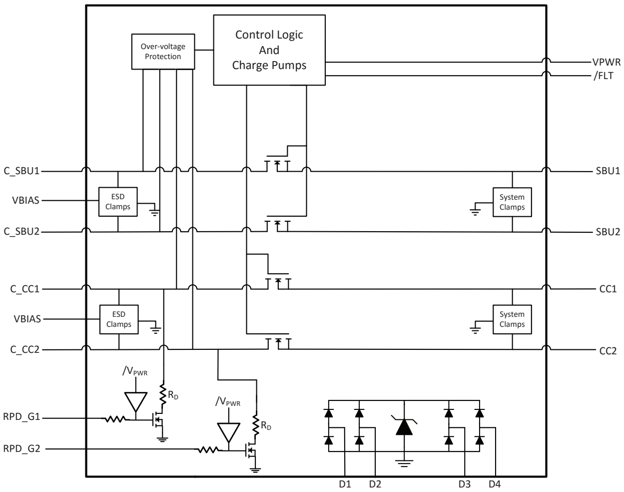


Figure 15. *Functional block diagram of a small, monolithic solution that provides complete protection for the Type-C port.*

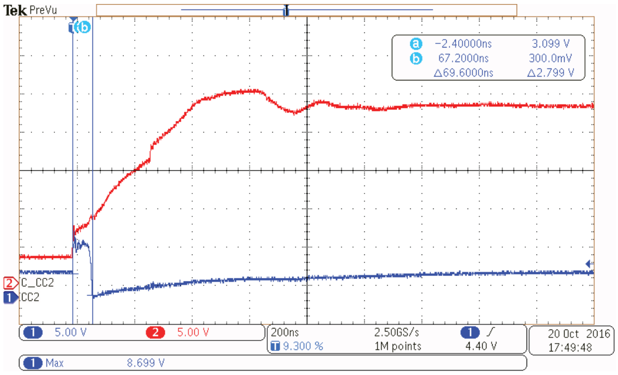


Figure 16. *Clamping waveform of the TPD8S300 during a short-to-V_{BUS} event.*

The waveform in **Figure 16** shows the clamping performance of the TPD8S300 during a short-to-V_{BUS} event while protecting the TPS65982. The level of complexity for protecting a Type-C port demands a monolithic solution, such as the TPD8S300.

Conclusion

Adopting emerging technologies can be very beneficial, but early adaptors can also face new, unexpected challenges. Adopting USB-C has proven to be very beneficial, but it has brought its own unique protection requirements. Texas Instruments has developed robust protection solutions to meet these new protection requirements and to ensure USB Type-C adopters get the full range of benefits this new connector provides.

As more companies adopt the Type-C standard, it is almost impossible to control where the end-users will end up purchasing their product accessories. Ensuring that the system is robust enough to support any available cables, adaptors, and any potential mechanical events in the field reduces the risk for hard-field failures and increases end-product reliability and brand credibility. Adopting a solution that can detect and protect the end-system is small price to pay for such a large return.

References

1. Agam Shah. 6 things to know about the USB-C port in the new MacBook. PCWorld, March 10, 2015.
2. Katie Collins. Amazon threatens to banish anyone selling dodgy USB-C cables. CNET, March 30, 2016.
3. Liam Tung. Amazon to shoddy USB-C cable sellers: 'You're banned.' ZDNet, March 30, 2016.

Additional Resources

- USB Type-C and Power Delivery Overview
- TPD8S300 Product Folder
- TPS65982 Product Folder

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Only those TI components which TI has specifically designated as military grade or “enhanced plastic” are designed and intended for use in military/aerospace applications or environments. Buyer acknowledges and agrees that any military or aerospace use of TI components which have ***not*** been so designated is solely at the Buyer's risk, and that Buyer is solely responsible for compliance with all legal and regulatory requirements in connection with such use.

TI has specifically designated certain components as meeting ISO/TS16949 requirements, mainly for automotive use. In any case of use of non-designated products, TI will not be responsible for any failure to meet ISO/TS16949.

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