

Designing a USB Power Distribution System Using the TPS2014 and TPS2015 Power Distribution Switches

PMP Systems Power

ABSTRACT

The USB specification (version 1.0) defines the power distribution requirements for self-powered hubs (including hosts) and bus-powered hubs. This application report explains how the TPS2014 and TPS2015 power distribution switches provide the power switching and overcurrent protection needed to meet the USB requirements and how they are superior to other devices commonly used to accomplish the same functions.

Overcurrent protection devices such as fuses and PTC resistors (also called polyfuses or polyswitches) have slow trip times, high on-resistance, and lack the necessary circuitry for USB-required fault reporting. The faster trip times of the TPS2014 and TPS2015 power distribution allow designers to design hubs that can operate through faults. The TPS2014 and TPS2015 have low on-resistance and internal fault-reporting circuitry that help the designer to meet voltage regulation and fault notification requirements. Because the TPS2014 and TPS2015 are also power switches, the designer of self-powered hubs has the flexibility to turn off power to output ports. Unlike a normal MOSFET, the TPS2014 and TPS2015 have controlled rise and fall times to provide the needed inrush current limiting required for the bus-powered hub power switch.

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1 Introduction

The universal serial bus (USB) interface is a 12-Mb/s, multiplexed serial bus designed for low to medium speed PC peripherals (for example, keyboards, printers, scanners). The four-line USB interface is conceived for dynamic attach-detach (hot-plug-unplug) of peripheral devices. Two lines are provided for differential data and two lines are provided for 5-V power distribution.

USB data is a 3.3-V level signal, but power is distributed at 5 V to allow for voltage drops in cases where power is distributed through more than one hub. Each function must provide its own regulated 3.3 V from the 5-V input or its own internal power supply.

The USB specification defines the following five classes of devices, each differentiated by power sourcing and sinking requirements:

- Bus-powered hubs
- Self-powered hubs
- Low power, bus-powered functions
- High power, bus-powered functions

Self-powered and bus-powered hubs distribute data and power to downstream functions. This application report describes power distribution solutions for both types of hubs.

2 TPS2014 and TPS2015 Power Distribution Switches

The Texas Instruments TPS2014 and TPS2015 are high-side, 95-mΩ, n-channel MOSFET switches with built-in overcurrent protection. The switches provide both power switching and maintenance-free fault protection in either of the following single 8-pin packages:

- Small-outline integrated circuit (SOIC)
- Plastic dual inline package (PDIP)

The TPS2014 and TPS2015 switches differ only in recommended continuous current and short-circuit current limits (see Table 1).

Table 1. TPS2014 and TPS2015 Current Limits

T _j	RECOMMENDED MAXIMUM	TYPICAL SHORT-CIRCUIT	PACKAGED DEVICES	
	CONTINUOUS LOAD CURRENT (A)	CURRENT LIMIT AT 25°C (A)	SOIC (D)*	PDIP (P)
0°C to 125°C	0.6	1.2	TPS2014D	TPS2014P
0°C to 125°C	1	2	TPS2015D	TPS2015P

* The D package is available taped and reeled. Add an R suffix to device type (e.g. TPS2014DR).

Both devices are controlled by a logic level enable that is compatible with both 3.3-V and 5-V logic. Gate drive is provided by an internal charge pump controls the power switch rise and fall times to minimize currents during switching. The charge pump requires no external components and operates from supply voltages as low as 4 V. The undervoltage lockout ensures that the switch is in the off state at start up.

The TPS2014 and TPS2015 provide overcurrent protection by switching to a constant current source whenever the trip threshold current is exceeded. The controller is notified of a fault condition when the overcurrent logic output is set to a low. The switch remains in this constant current state until either the fault is removed or the switch is disabled.

Continuous overloads and short circuits increase the power dissipation in the switch and cause the junction temperature to rise. To prevent overheating, a thermal protection circuit shuts the switch off when the junction temperature exceeds its thermal limit.

3 USB Power Distribution

The USB power distribution requirements are designed to make 4 V the minimum voltage seen by any downstream function. Power is supplied to the 5-V bus from either the host or a self-powered hub and then distributed to downstream functions. A resistive voltage drop is associated with each connection, wire, and component where power is distributed.

The USB specification includes power distribution requirements that must be met for each component. The TPS2014 and TPS2015 power distribution switches meets the USB requirements for voltage drops, continuous current, overcurrent protection, and fault notification.

3.1 Self-Powered Hub (Including Host)

Self-powered hubs (including host) contain an internal power supply that powers the hub's internal functions and output ports. A self-powered hub can include as many output ports as the power supply can deliver. Typical designs have one, two, four, or seven output ports. Each output port in a self-powered hub must be able to supply a continuous 500 mA within the required voltage regulation.

Because power is supplied from an internal power supply, overcurrent protection is required on the output ports for safety reasons. UL limits require ports to deliver no more than 5 A. This requirement includes short circuit currents.

Power distribution for a self-powered hub can be designed either with one overcurrent protection device per output port or by ganging multiple ports to one overcurrent protection device. Although ganging multiple output ports to one overcurrent protection device appears to be a more economical solution, the on-resistance required may not make it feasible (see subsection 3.1.2).

3.1.1 Overcurrent Protection Device

The following devices commonly provide overcurrent protection for the self-powered hub:

- Power distribution switches (such as the TPS2014 and TPS2015)
- Positive temperature coefficient (PTC) resistors (commonly known as polyfuses or polyswitches)
- Fuses

The TPS2014 and TPS2015 offer several advantages over fuses and PTC resistors, including:

- Extremely fast trip time

- Fault reporting
- Low on-resistance

The TPS2014 and TPS2015 have an extremely fast trip time of approximately 10 μ s (see Appendix A). By comparison, fuses have trip times in the 100s of microseconds and PTC resistors have trip times in the 100s of milliseconds. The faster trip time of the TPS2014 and TPS2015 greatly increases a system's ability to operate continuously through a fault.

The USB specification requires that the host be informed of any overcurrent event. The TPS2014 and TPS2015 provide fault reporting through the overcurrent logic output. A system using a fuse or PTC resistor requires additional external circuitry to provide the fault reporting information.

The TPS2014 and TPS2015 have a low on-resistance, typically 85 m Ω . Fast-acting fuses have a typical resistance of 170 m Ω for a 1-A fuse and 40 m Ω for a 2.5-A fuse. PTC resistors have a resistance of 240 m Ω for a 1-A rating and 65 m Ω for 2.5-A rating. As discussed in section 3.1.2, the higher resistance of fuses and PTC resistors make it difficult, if not impossible, to meet the stringent USB voltage regulation requirements.

Unlike fuses and PTC resistors, the TPS2014 and TPS2015 are controlled switches, which allow the system to turn off ports that have failed or to support low-power states for portable products.

3.1.2 DC Voltage Regulation

All resistive voltage drops must be accounted for to ensure that the required voltage regulation is met (see Figure 1). The minimum output voltage (V_{Omin}) at the output connector is equal to the power supply voltage (V_{PS}) minus its regulation (V_{reg}) and the resistive voltage drops in the PCB traces (V_{PCB}) and overcurrent protection device (V_{OCP}). The following equation shows the relationship:

$$V_{Omin} = V_{PS} - V_{reg} - V_{OCP} - V_{PCB}$$

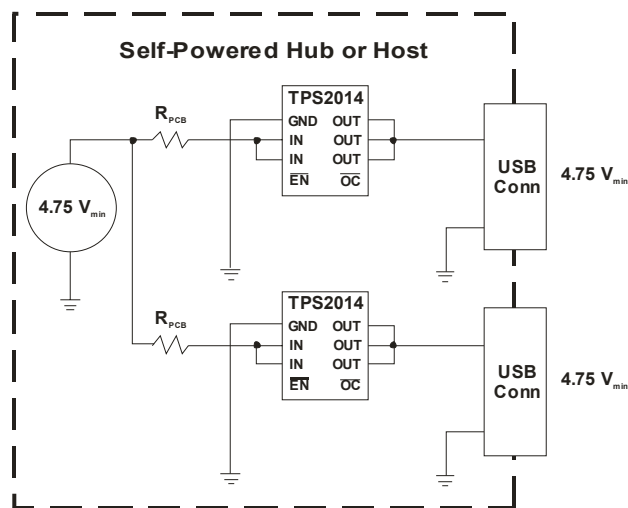


Figure 1. USB Self-Powered Hub Voltage Drops

The USB specification defines the maximum voltage drop across the overcurrent protection device and the PCB traces to be 100 mV. This leaves 250 mV (or 5 %) for the power supply regulation (V_{reg}). The voltage drop across the overcurrent protection device is a function of its output current and the on-resistance of the device. The output current is 500 mA times the number of ports ganged together on its output. The maximum on-resistance of the overcurrent protection device is defined by:

$$r_{OCP} = \frac{100mV - V_{PCB}}{0.5A \times n_{ports}}$$

This equation shows that for a 10-mV voltage drop for the PCB trace, the switch must have a resistance of 180 mΩ to support one port and 90 mΩ for two ports. With the resistance of the TPS2015, two ports is the maximum that can feasibly be ganged with one overcurrent protection device.

3.1.3 Transient Regulation

During normal operation, only moderate transients occur. The maximum and peak current that a function may draw is 500 mA. Appendix B contains the transient testing results for both normal transients and hot-insertion transients. The results show that 500-mA load transients cause almost no transient voltage droop. The required 120-μF output port capacitance is more than sufficient to meet the 330-mV droop requirement.

The real concern is the effect on other output ports of the hub during hot insertion of a function. The USB specification requires that hot insertion operations not interrupt the operation of existing connections. The USB specification limits the maximum load that can be hot inserted to 44 Ω paralleled by 10 μF. The specification also limits the maximum voltage droop this insertion causes on other ports to 330 mV.

In the non-ganged architecture of the single port per overcurrent protection device, the minimum required output capacitance of 120 μF is sufficient to meet the maximum voltage droop (see Figure 2).

The testing described in Appendix B shows that the hot insertion transient produced a voltage droop of 280 mV. The impedance of the two TPS2014 switches between the output port capacitors provided sufficient filtering to limit the voltage droop. The voltage droop can be improved with the addition of bulk capacitance on the 5-V input to the ports. The bulk capacitance also helps prevent the transients from being reflected back to the system.

In the ganged architecture, where multiple output ports are connected in parallel to one overcurrent protection device, there is no impedance between the output port capacitors (see Figure 3). Testing shows that the hot insertion produced a 1-V transient on the adjacent port, even with the required 120 μF output capacitance per port (see Appendix B). Even with the addition of 1000 μF of bulk capacitance to the 5-V input, the 330-mV droop could not be met. Impedance must be added between the ports to filter transients between ports.

Ferrite beads inserted in series with 5-V and GND lines before the output port capacitors provide lossless transient filtering. Testing shows that with the addition of the ferrite beads, the hot insertion transient produced a 300-mV voltage droop on the other port (see Appendix B). The voltage droop can be reduced even more with the addition of bulk capacitance to the 5-V input.

3.1.4 Self-Powered Hub Reference Designs

Figure 2 shows the schematic of the non-ganged reference design, which uses the TPS2014 as the overcurrent protection device. The following assumptions apply:

- Power supply regulation: 5 V (± 5 percent)
- Total PCB voltage drop: 10 mV

Using these assumptions, the required resistance of the overcurrent protection device must be less than 180 m Ω to meet USB voltage regulation requirements (see section 3.1.2). The TPS2014 has a typical on-resistance of 85 m Ω with an over-temperature maximum of 120 m Ω .

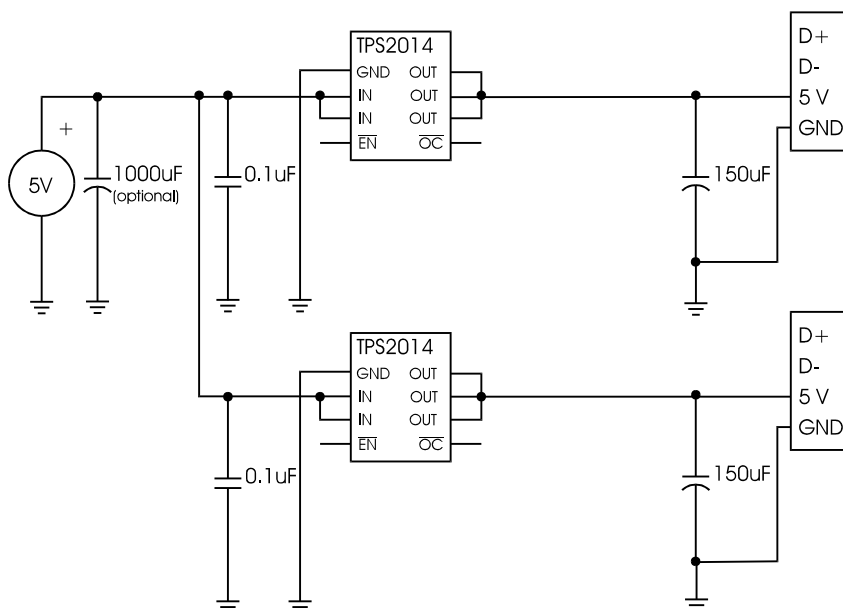


Figure 2. Self-Powered Hub Non-Ganged Reference Design

A 150- μ F tantalum capacitor is chosen for the output port capacitor because it is the closest standard value that meets the minimum 120- μ F specification requirement. The 0.1- μ F input capacitor is a bypass capacitor for the TPS2014. It is recommended that some bulk capacitance be on the 5-V input to the USB overcurrent protection devices. Bulk capacitance provides the following two functions:

- Improves the voltage droop for hot-insertion transients
- Helps keep transients on the output ports from affecting other hub functions using the 5-V power

Figure 3 shows the schematic of the ganged reference design, which uses the TPS2015 for overcurrent protection. Applying the same assumptions applied in the non-ganged reference design, the required on-resistance of the TPS2015 is 90 m Ω . Although the TPS2015 has a nominal on-resistance of 85 m Ω , the on-resistance at high temperature is 120 m Ω . Therefore, for this design to be valid, the power supply must have a 4-% regulation to allow for the additional voltage drop.

This limitation makes it very difficult to use a PTC resistor as the overcurrent protection device in a ganged configuration. The higher resistance of this device makes it impossible to meet the DC voltage regulation.

The input, output, and bulk capacitors are selected for the same reasons as those selected for the non-ganged design. The main difference is that the ferrite beads in this design are required to meet the hot-insertion voltage droop requirement, as discussed in section 3.1.3.

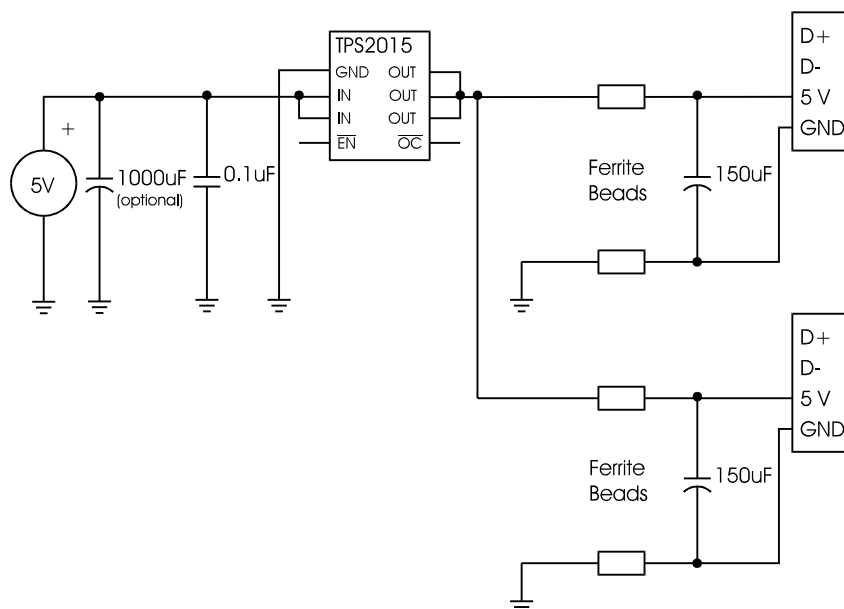


Figure 3. Self-Powered Hub Ganged Reference Design

PCB layout is also very important. Consider the following recommendations:

- Place a ground plane under all circuitry to lower both resistance and inductance and improve DC and transient performance.
- Place cuts in the ground plane between ports to help reduce the coupling of transients between ports.
- Locate the output tantalum capacitor as close as possible to the USB connector to lower impedance (mainly inductance) between the port and the capacitor and improve transient load performance.
- Locate the TPS2014/15 as close as possible to the output port to limit switching noise.
- Locate the ceramic bypass capacitors as close as possible to the IN pins of the TPS2014/15.

3.2 Bus-Powered Hub

The bus-powered hub draws power for internal functions and output ports from its input port. It distributes data and/or power to:

- Low power, bus-powered functions
- Self-powered functions
- Self-powered hubs

The bus-powered hub is allowed to consume a maximum of 500 mA for its internal functions and output ports. Each output port must be able to supply a continuous 100 mA to downstream loads. Therefore, the number of output ports a bus-powered hub can support depends on the maximum amount of current consumed for its internal functions. A bus-powered hub can support a maximum of four output ports.

Since a bus-powered hub does not know if it is being plugged into a port that can support a high-power function, its total current consumption on power up must be less than 100 mA. A power distribution switch is required to keep the output ports off during power up. Once configured, the hub can confirm that it is plugged into a high-power port, and then turn on power for its downstream ports.

Because of the high output capacitance (120 μ F minimum) on each output port, inrush current limiting is required to prevent drooping of the 5-V power supply from inrush currents.

Overcurrent protection is not required for a bus-powered hub because it is protected by the upstream port (either a self-powered hub or host). As with the self-powered hub, the output ports can be ganged together and powered from a single switch, or each port can have an individual switch.

3.2.1 Power Switch

The TPS2014/15 offers several advantages over a normal MOSFET for the bus-powered hub power switch. The 3.3-V- or 5-V-compatible logic input allows easy interface with the hub controller. The on-resistance of the TPS2014/15 is low enough to meet USB voltage regulation requirements even when the maximum of four outputs are ganged together. The controlled rise time provides the required inrush current limiting without the need for external circuitry. The TPS2014/15 undervoltage lockout guarantees that the switch is off during power up.

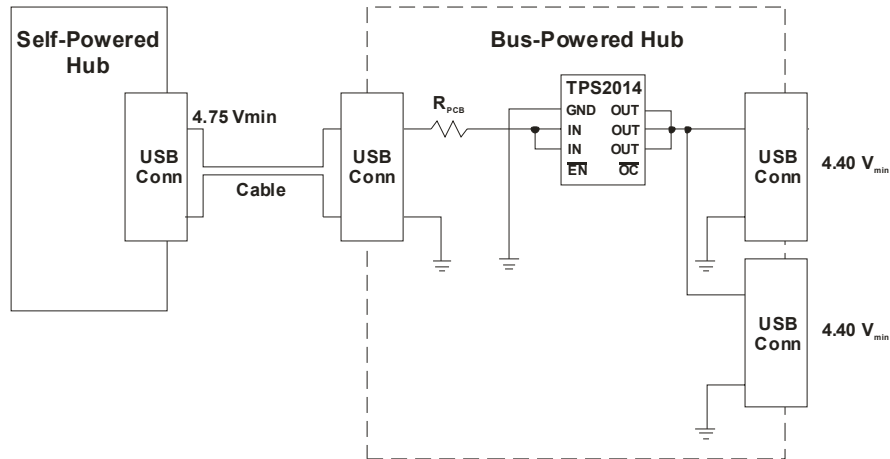


Figure 4. USB Bus-Powered Hub Voltage Drops

3.2.2 DC Voltage Regulation

The minimum input voltage at the upstream port connector is 4.75 V. The USB specification requires a minimum voltage of 4.4 V at the output port (V_{Omin}) of the bus-powered hub. As with the self-powered hub, all resistive voltage drops for the bus-powered hub must be accounted for to guarantee voltage regulation (see Figure 4).

The following calculation determines V_{Omin} for multiple ports (n_{ports}) ganged together through one switch (if using one switch per port, n_{ports} is equal to 1):

$$V_{Omin} = 4.65 - I_I \times (4 \cdot r_{conn} + 2 \cdot r_{cable}) - 0.1A \times n_{ports} \times r_{switch} - V_{PCB}$$

where

r_{conn} = resistance of connector contacts (two contacts per connector)

r_{cable} = resistance of upstream cable wires (one 5 V and one GND)

r_{switch} = resistance of power switch

V_{PCB} = PCB voltage drop

The USB specification defines the maximum resistance per contact (r_{conn}) of the USB connector to be 30 mΩ and the drop across the PCB and switch to be 100 mV. This basically leaves two variables in the equation: the resistance of the switch and the resistance of the cable. By defining the voltage drop across the PCB (V_{pcb}) to be 10 mV, the equation can be rearranged to define the resistance of the cable as:

$$r_{cable} = \frac{1}{2} \cdot \left(\frac{0.150mV}{I_I} - 0.120m\Omega \right)$$

If the hub consumes the maximum current (I_I) of 500 mA, the maximum resistance of the cable is 90 mΩ. This defines the cable length allowed for various wire gauges.

The resistance of the switch is defined as follows:

$$r_{switch} = \frac{100mV - V_{PCB}}{0.1A \times n_{ports}}$$

If the voltage drop across the PCB is limited to 10 mV, the maximum resistance for the switch is 225 mΩ for four ports ganged together. The TPS2014/15, with its maximum 120 mΩ on-resistance over temperature, easily meets this requirement.

3.2.3 Transient Regulation

A bus-powered hub has the same hot-insertion transients and minimum 120-μF output capacitance requirement as a self-powered hub. Its maximum normal load transient of 100 mA is less than the 500-mA load transient for a self-powered hub. The discussions in section 3.1.3 for ganged and non-ganged self-powered hubs thus also apply to bus-powered hubs.

3.2.4 Bus-Powered Hub Reference Designs

Although a bus-powered hub can be designed with one switch per output port, the most cost-effective solution is to gang all of the output ports together. The reference designs for ganged and non-ganged bus-powered hubs are essentially the same as those for self-powered hubs except for the bulk input capacitance (see section 3.1.4 for self-powered hubs reference designs). Because a bus-powered hub is a hot-insertable device, the USB requirement for the maximum input capacitance is 10 μF. In this case, a 4.7-μF input capacitor is recommended in place of the 1000-μF bulk capacitor.

The TPS2014 has a 120-mΩ maximum on-resistance over temperature. With a four-port load of 400 mA, it has a maximum voltage drop of 48 mV instead of the 90 mV allotted in section 3.1.2. The TPS2014/15 allows this difference in voltage drop to be allotted to the cable, thus making it easier to meet the USB voltage regulation requirements.

4 ESD

Because USB is a hot insertion and removal system, USB components (especially the connector pins) are subject to electrostatic discharge (ESD) and should be qualified to IEC801.2. The TPS2014 and TPS2015 are designed to withstand a 6-kV human body model, as defined in MIL-STD-883C. The requirements in IEC801.2 are much more stringent and require additional capacitors for the TPS2014 and TPS2015 to withstand the higher ESD energy.

Low ESR 1-μF ceramic bypass capacitors and output tantalum capacitors should be placed as closely as possible to the IN and OUT pins to increase the ESD immunity. The TPS2014 and TPS2015 pass the level-4 15-kV air discharge and level-4 8-kV contact discharge tests when these capacitors are added.

5 Summary

Three basic types of devices provide overcurrent protection. A fuse provides overcurrent protection but is not maintenance free. A fault blows its element to isolate the fault. The fuse must then be replaced before the port is operational. In addition, a fuse does not provide fault indication. Additional circuitry must be implemented to provide the host with fault information.

A PTC resistor (also known as polyfuse and polyswitch) provides maintenance-free overcurrent protection but tends to have a high resistance. To meet the USB voltage regulation requirements, a device in the 2.5 A or higher range must be chosen. Unfortunately, a device in this current range may not meet the 5-A current limit required by UL. A PTC resistor also tends to have long trip times and may not provide adequate protection to the hub or host. As with fuses, PTC resistors do not provide fault indication and thus require additional circuitry.

The TPS2014 and TPS2015 power distribution switches are designed to integrate all of the functions required for USB power distribution into a single, cost-effective package. The fast fault-clearing time provides robust and maintenance-free overcurrent protection. The overcurrent logic output provides the hub or host with the required fault notification.

Unlike fuses or polyfuses, the TPS2014 and TPS2015 switches offer controlled rise and fall times. They provide the self-powered hub or host with the option of turning off a port in the event of a fault or low-power modes. The TPS2014 and TPS2015 switches also provide a bus-powered hub with the inrush current limiting needed to meet the USB maximum hot-insertion load requirement.

6 References

1. Universal Serial Bus Specification, Version 1.0, Universal Serial Bus-Implementers Forum (USB-IF), January 19, 1996.
2. USB Voltage Drop and Droop Measurement, Intel Corporation, November 29, 1996.

Appendix A. Fault Testing

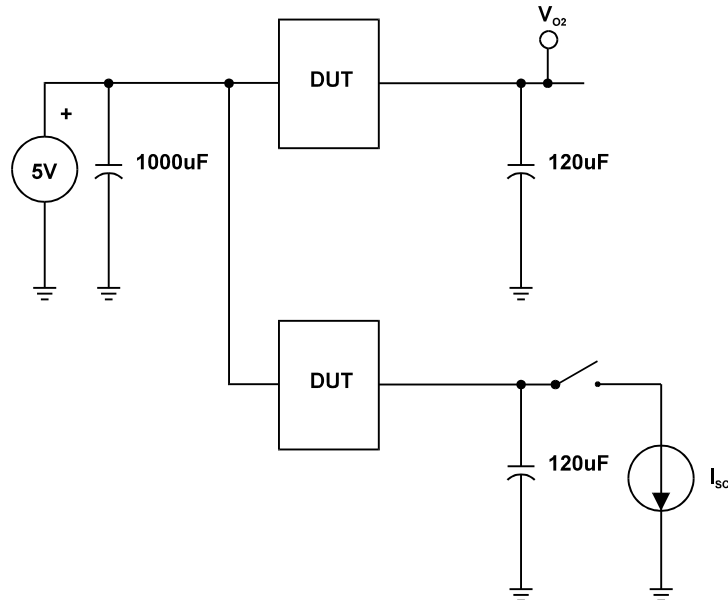
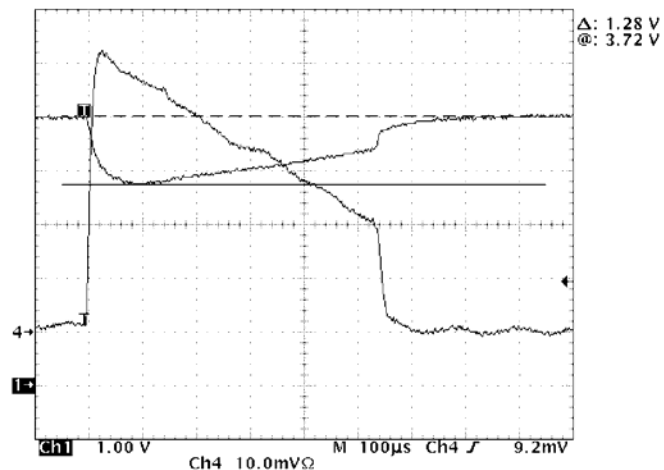


Figure 5. Non-Ganged Transient Load Test Circuit

Figure 5 shows the circuit used to test the short-circuit response of the fuse, PTC resistor, and TPS2014. A 5-V, 22-A power supply was used for the source. The short-circuit current was measured to determine the fault current and fault clearing time. The voltage on an adjacent port was measured to determine the short-circuit effect.



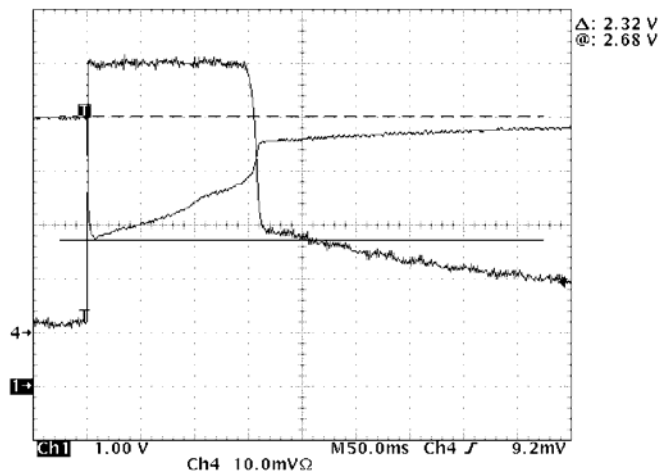
Notes:

1. Channel 1: Adjacent Port Output Voltage 1 V/div
2. Channel 2: Short-circuit Output Current 5 A/div
3. Time Scale: 50 ms/div

Figure 6. 2.5-A Fuse Short-Circuit Test

Figure 6 shows that it took approximately 550 μs for the 2.5-A fuse to clear the fault. The fault caused the system voltage to droop below 4 V for about 100 μs .

By comparison, the PTC resistor took approximately 150 ms to clear a fault and the system voltage drooped below 4 V for 150 ms (see Figure 7). The power supply was in current limit for this time, which would most likely interrupt system operation.

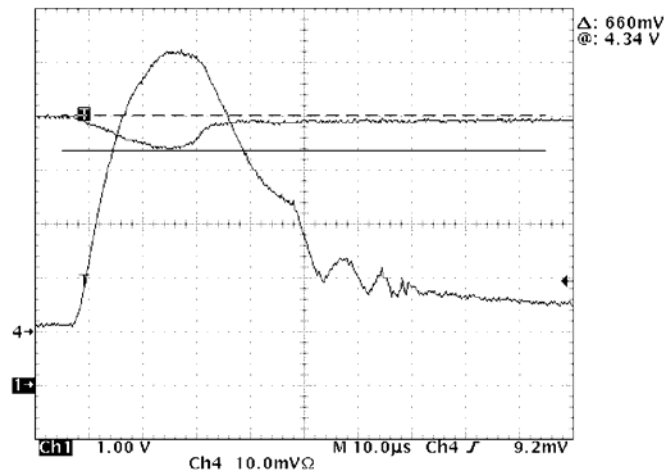


Notes:

1. Channel 1: Adjacent Port Output Voltage 1 V/div
2. Channel 2: Short-circuit Output Current 5 A/div
3. Time Scale: 50 ms/div

Figure 7. 2.5-A PTC Resistor Short-Circuit Test

The TPS2014 cleared the fault in approximately 45 μs and the system voltage never drooped below 4 V (see Figure 8). The TPS2014 provides the most robust power system protection and the best chance for a system to operate through a fault.



Notes:

1. Channel 1: Adjacent Port Output Voltage 1 V/div
2. Channel 2: Short-circuit Output Current 5 A/div
3. Time Scale: 10 µs/div

Figure 8. TPS2014 Short-Circuit Test

Appendix B. Transient Load Testing

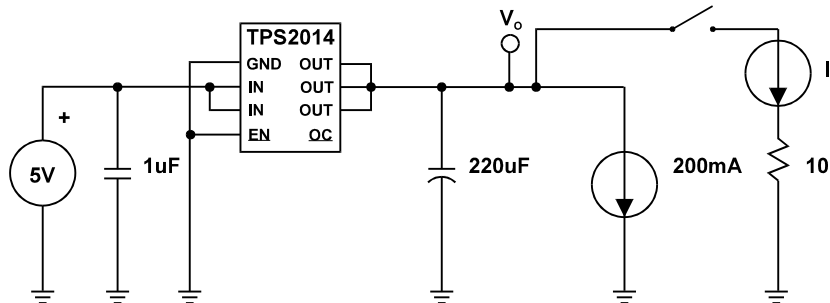
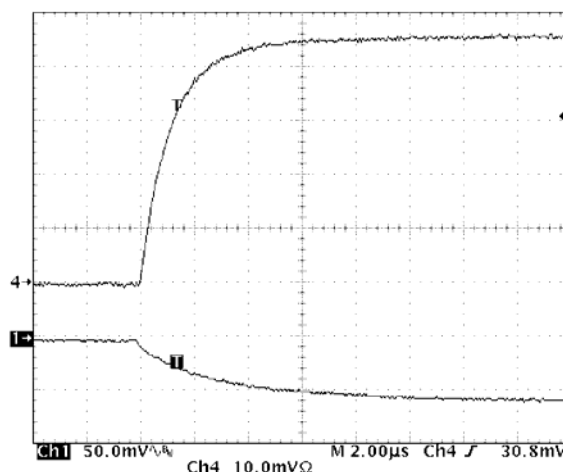


Figure 9. 500-mA Transient Load Test Circuit



Notes:

1. Channel 1: Output Voltage 50 mV/div
2. Channel 2: Output Current 100 mA/div
3. Time Scale: 2 µs/div

Figure 10. 500-mA Transient

As stated in section 3.1.3, the maximum transient load is 500 mA during normal operation. Figure 9 shows the test circuit used to determine the voltage droop during a 500-mA transient. The transient caused only a 50-mV output voltage droop. The droop is mainly due to the increased resistive losses (connectors, PCB, TPS2014) from the increased output current and not to the load transient.

The following three tests were implemented to produce the most severe transient and the highest voltage droop:

- Hot-insertion transient test for the non-ganged configuration
- Hot-insertion transient test for the ganged configuration
- Hot-insertion transient test for the ganged configuration with ferrite beads

Each test was configured as follows:

- The power supply was connected with 1-meter leads and adjusted for a test board output of 4.75 V.
- The test circuits had no bulk capacitance added. Only the required 120- μ F per port output capacitors were implemented.
- Each test was implemented with only two output ports. The collective sum of capacitance is increased by 120 μ F for each output port. The more ports a hub has, the higher the total capacitance and the lower the droop voltage.

The 10- μ F and 44- Ω transient load was placed as close as possible to the output in order to minimize interconnect resistance and inductance (see Figure 11). This causes the highest possible transient current and the most voltage droop.

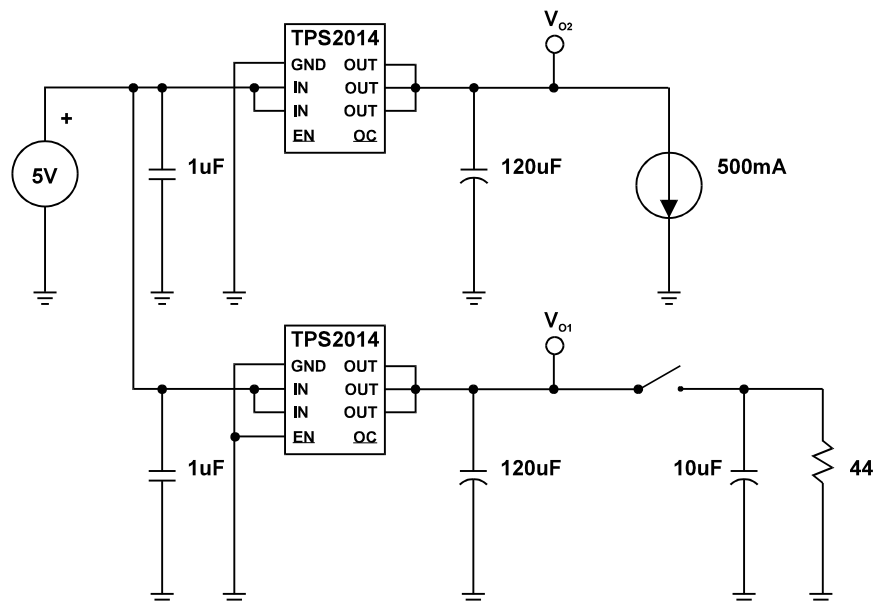
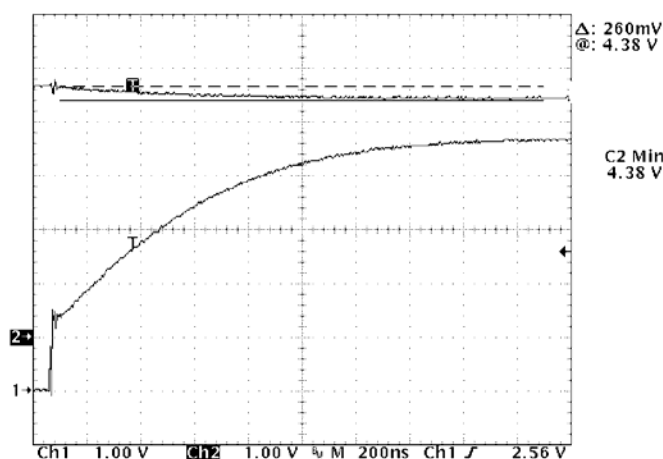


Figure 11. Non-Ganged Transient Load Test Circuit



Notes:

1. Channel 1: Switched Port Output Voltage 1 V/div
2. Channel 2: Adjacent Output Port Voltage 1 V/div
3. Time Scale: 200 ns/div

Figure 12. Non-Ganged Hot-Insertion Transient

Figure 12 shows the circuit used in the hot-insertion transient test for the non-ganged configuration. Testing shows that this circuit has a droop voltage of 280 mV, which is better than the 330-mV requirement.

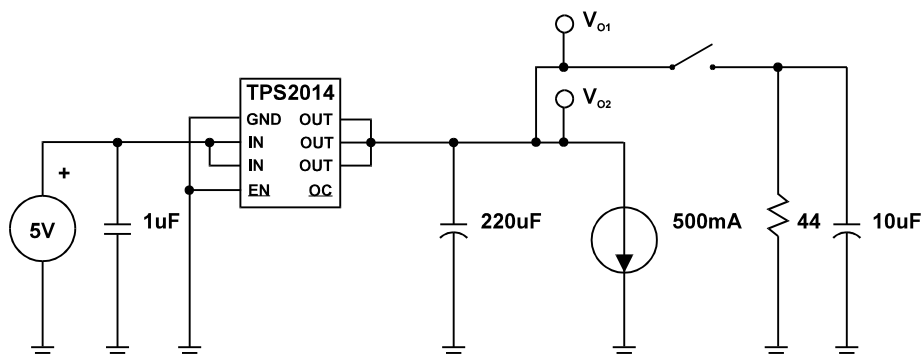
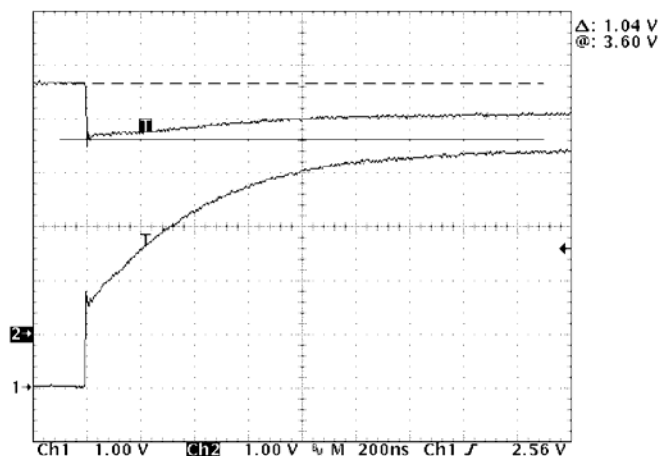


Figure 13. Ganged Transient Load Test Circuit

In the ganged configuration (see Figure 13 and Figure 14), the voltage droop for a hot-insertion was approximately 1 V. This is unacceptable. Even with an additional 1000 μF added to the output, the droop was still more than double the 330-mV limit. Since there is no impedance between the ports, there is no filtering between them. Some impedance must be added between the ports to meet the drop requirement.



Notes:

1. Channel 1: Switched Port Output Voltage 1 V/div
2. Channel 2: Adjacent Output Port Voltage 1 V/div
3. Time Scale: 200 ns/div

Figure 14. Ganged Hot-Insertion Transient

In the ganged configuration of Figure 15, ferrite beads were added between the output of the TPS2014 and filter capacitors for each port. The ferrite beads provide lossless transient impedance between the output ports. As seen in Figure 16, the voltage droop has been greatly reduced and now is only 300 mV, which meets the USB requirement. The droop voltage can also be made lower by increasing the output capacitance or having some bulk capacitance on the 5 V input.

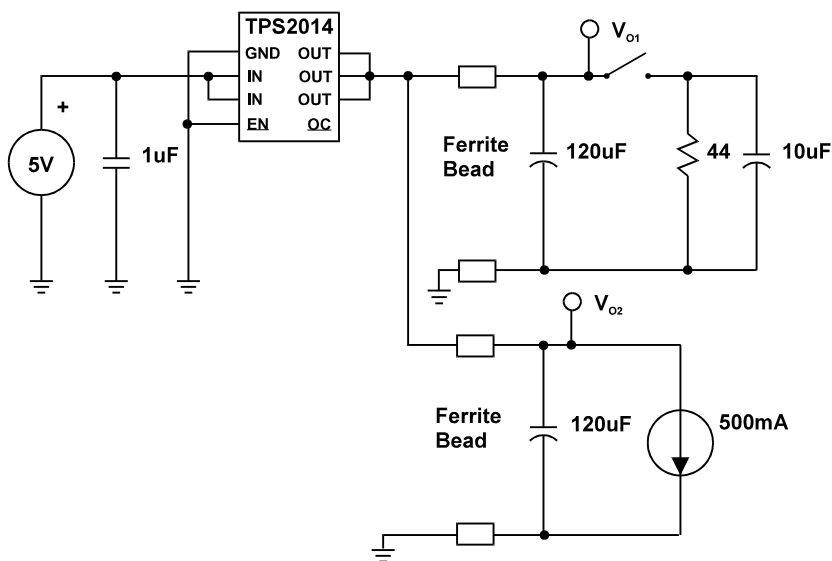
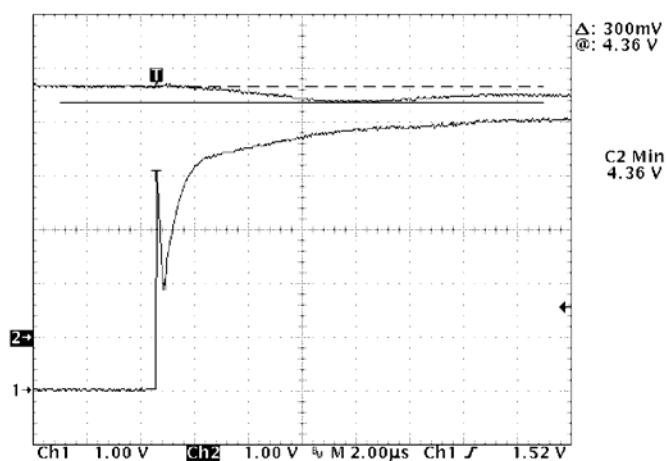


Figure 15. Ganged Test Circuit With Ferrite Beads



Notes:

1. Channel 1: Switched Port Output Voltage 1 V/div
2. Channel 2: Adjacent Output Port Voltage 1 V/div
3. Time Scale: 2 $\mu\text{s}/\text{div}$

Figure 16. Ganged With Ferrite Beads Hot-Insertion Transient

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