

TPS202x/3x and TPS204x/5x USB Power Distribution Application Report

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Literature Number: SLVA049
October 1998



Printed on Recycled Paper

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TPS202x/3x and TPS204x/5x USB Power Distribution

ABSTRACT

The USB specification, revision 1.1, defines the power distribution requirements for the self-powered hubs (including hosts), bus-powered hubs, and functions. This application report demonstrates how Texas Instruments power management products meet or exceed voltage regulation, voltage droop, and EMI requirements in the USB power distribution system.

Introduction

The Universal Serial Bus (USB) interface is a 12-Mb/s or 1.5-Mb/s, multiplexed serial bus for low to medium bandwidth PC peripherals (e.g., keyboards, printers, scanners, and mice). The four-wire USB interface provides dynamic attach-detach (hot plug-unplug) of peripherals. 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 from its own internal power supply.

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

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

TPS202x/3x and TPS204x/5x Power Distribution Switches

Texas Instruments offers a variety of power switch devices for USB applications: the TPS202x, TPS203x, TPS204x, and the TPS205x. All devices are high-side switches with built-in overcurrent protection that includes open-drain, active-low overcurrent flag output for overcurrent reporting. The switches provide power switching and maintenance-free fault protection; they are controlled by 3.3-V and 5-V logic level compatible enables. For added flexibility in interfacing with hub controllers, the devices are available in active-low or active-high enables.

The TPS202x (active-low) and TPS203x (active-high) families of devices are 50-m Ω high-side N-channel MOSFET switches that are offered at different current limit levels. The TPS202x/3x families are ideal for ganged-port protected power distribution system topologies.

The TPS2041/2/4 and TPS2051/2/4 series of devices are 135-m Ω high-side N-channel MOSFET switches rated for a fixed continuous current of 0.5 A with typical current limit of 0.9 A. The TPS204X series differs in the number of power switches available in each packaged device: TPS2041 (Single), TPS2042 (Dual), TPS2044 (Quad). The TPS2041 series is ideal for individual port protection of one-port (TPS2041), two-port (TPS2042), or four-port (TPS2044) topologies. The TPS204X devices are enabled with an active-low 3-V or 5-V logic enable. The TPS2042 and TPS2044 devices incorporate a dual thermal trip to allow fully independent operation of the dual power distribution switches. In over-current or short-circuit conditions, the junction temperature rises. Once the die temperature rises to an internal set trip point, the thermal sense circuitry determines which switch is in an over-current condition and turns that power switch off, isolating the fault without interrupting operation of the adjacent power switch. The second thermal trip point is a higher temperature point that turns off both switches. Active-high versions are also available: TPS2051, TPS2052, and TPS2054 as single, dual, and quad power switches. Table 1 lists characteristics of the TPS20xx family of devices.

Table 1. Texas Instruments Power Distribution Switches

TI PART NUMBER	NO. OF SWITCHES	ENABLE LOGIC	ON RESISTANCE	CONTINUOUS CURRENT	CURRENT LIMIT
TPS2041	Single	Active-low	135 m Ω	0.5 A	0.9 A
TPS2051	Single	Active-high	135 m Ω	0.5 A	0.9 A
TPS2042	Dual	Active-low	135 m Ω	0.5 A	0.9 A
TPS2052	Dual	Active-high	135 m Ω	0.5 A	0.9 A
TPS2044	Quad	Active-low	135 m Ω	0.5 A	0.9 A
TPS2054	Quad	Active-high	135 m Ω	0.5 A	0.9 A
TPS2022†	Single	Active-low	50 m Ω	1.0 A	1.5 A
TPS2032†	Single	Active-high	50 m Ω	1.0 A	1.5 A
TPS2023†	Single	Active-low	50 m Ω	1.5 A	2.2 A
TPS2033†	Single	Active-high	50 m Ω	1.5 A	2.2 A
TPS2024†	Single	Active-low	50 m Ω	2.0 A	3.0 A
TPS2034†	Single	Active-high	50 m Ω	2.0 A	3.0 A

† Product Preview, release 1Q99

Definitions

Bus-powered hub – Bus-powered hubs (BPH) obtain all power from upstream ports and often contain a nonremovable function. One typical BPH application is a keyboard. The total current drawn by a BPH is the sum of the hub controller current, nonremovable function, and downstream port and is no greater than 500 mA or 5 unit loads. Each port must distribute 1 unit load.

Current limit – USB specification requires SPHs to limit current to downstream ports and report over-current conditions to the controller.

Downstream port – A port that is electrically further from the host and generates downstream data traffic from the hub.

Dynamic attach and detach – To attach or remove devices while host is in operation (hot-plug, unplug event).

High-power, bus-powered function – All power to these devices comes from the upstream port. Its current draw can be 1 unit load before configuration and up to 5 unit loads after configuration.

Host – The host computer system where the USB host controller is installed.

Inrush current – The current surge into uncharged downstream input capacitors.

Low-power, bus-powered function – All power to these devices comes from the upstream port. Its current draw is less than 1 unit load.

Power Switching – USB specification requires BPHs to power switch downstream ports to limit aggregate current draw of the controller, function, and ports to less than 100 mA before enumeration.

Self-powered function – May draw up to 1 unit load from the upstream port. The remainder of power is provided from a local power supply.

Self-powered hub – Self-powered hubs (SPH) have a local power supply that power nonremovable functions and the downstream ports. Typical self-powered hubs are PCs, monitors, printers, and stand alone hubs. The SPH is required to have current limit and report overcurrent conditions. The SPH must be able to supply 5 unit loads to all external downstream ports even when the hub is in a suspended state. A battery-powered SPH may configure for 1 unit load or 5 unit loads of output current per port.

Unit load – One unit load is 100 mA.

Upstream port – The port on a device that is electrically closer to the host and generates upstream data traffic from the hub.

USB – Universal Serial Bus

Voltage droop – The momentary drop in voltage under transient load conditions.

Voltage regulation – The difference in DC voltage levels under continuous load and no-load conditions.

USB Power Distribution

The USB power distribution requirements are designed so that 4.35 V is the minimum voltage supplied to downstream functions. The USB power distribution system is supplied power from a host or self-powered hub and distributed downstream. Resistive voltage drops are associated with each connection, PCB trace, cable, or other component on the power distribution system.

USB specification 1.1 dictates the minimum voltages on the downstream ports of the self-powered hubs, bus-powered hubs, and on a downstream function when operating in continuous load current states and transient states during hot-plug events (see Figure 1).

The minimum dc voltage on self-powered hubs at the board side of the connection is 4.75 V; it is 4.4 V on a bus-powered hub. Bus-powered hubs are allowed a 100-mV voltage drop leaving a 250-mV voltage drop for the cable. During hot-plug connections, the self-powered hub voltage is allowed to drop 330 mV to 4.42 V and 4.07 V on the bus-powered hub. Downstream functions should have a dc voltage of 4.35 V. All hubs and functions must be able to provide configuration information with a minimum voltage of 4.4 V at the connector end of the upstream cables.

The specification also dictates that all downstream devices (self-powered hubs, bus-powered hubs, bus-powered functions, and self-powered functions) can only sink (draw) current from the source voltage. All USB downstream devices must be able to enter into the suspend state to reduce current consumption. Suspend current is a function of unit load allocation. All devices initially default to low power and are limited to 500 μ A of suspend current. Devices configured for high power and enabled as a wake up source may draw 2.5 mA. Configured bus-powered hubs may consume 500 μ A of suspend current per port and 500 μ A for the hub and nonremovable function for a total of 2.5 mA. When determining the suspend current, the current through the pull-up (1.5 k Ω) and pull-down (15 k Ω) resistors on the data lines must be included. Figure 1 summarizes the voltage drops and droops in the USB power distribution system.

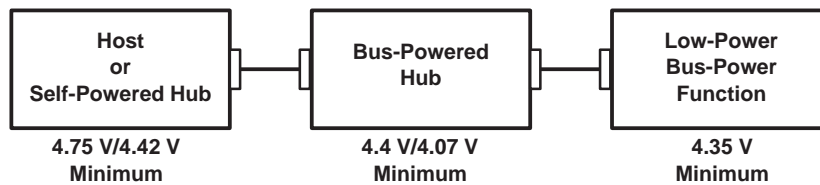


Figure 1. Maximum Voltage Drops and Droops on the USB Power Distribution System

USB Power Distribution for Self-Powered Hubs (Including Hosts)

Self-powered hubs (SPH) have a local power supply that powers nonremovable functions and the downstream ports (Figure 2). The hub must supply 5.25 V to 4.75 V on the board side of the downstream connection under full-load and no-load conditions and is required to have current limit and report overcurrent conditions to USB software. Typical SPHs are desktop PCs, monitors, printers, and stand alone hubs.

Power for the hub controller may be supplied by the local power supply or by the upstream voltage bus for loads up to 100 mA. The advantage of using the power from the upstream port is that communication to the hub controller is possible and the distinction between an unconnected and unpowered device can be made. Most hub controllers use 3.3-V supply voltage, and a low drop-out (LDO) voltage regulator is needed to regulate the 5-V bus voltage to 3.3 V.

The number of downstream ports supported by self-powered hubs is limited by the current the local power supply can support and by safety concerns. Each port must be capable of supplying 5 unit loads and must limit current when the aggregate current drawn exceeds 5.0 A. The current limit should exceed the continuous current level of 500 mA by enough to ensure that dynamic-attach events and startup currents do not trip the overcurrent protection. Figure 2 shows a typical SPH.

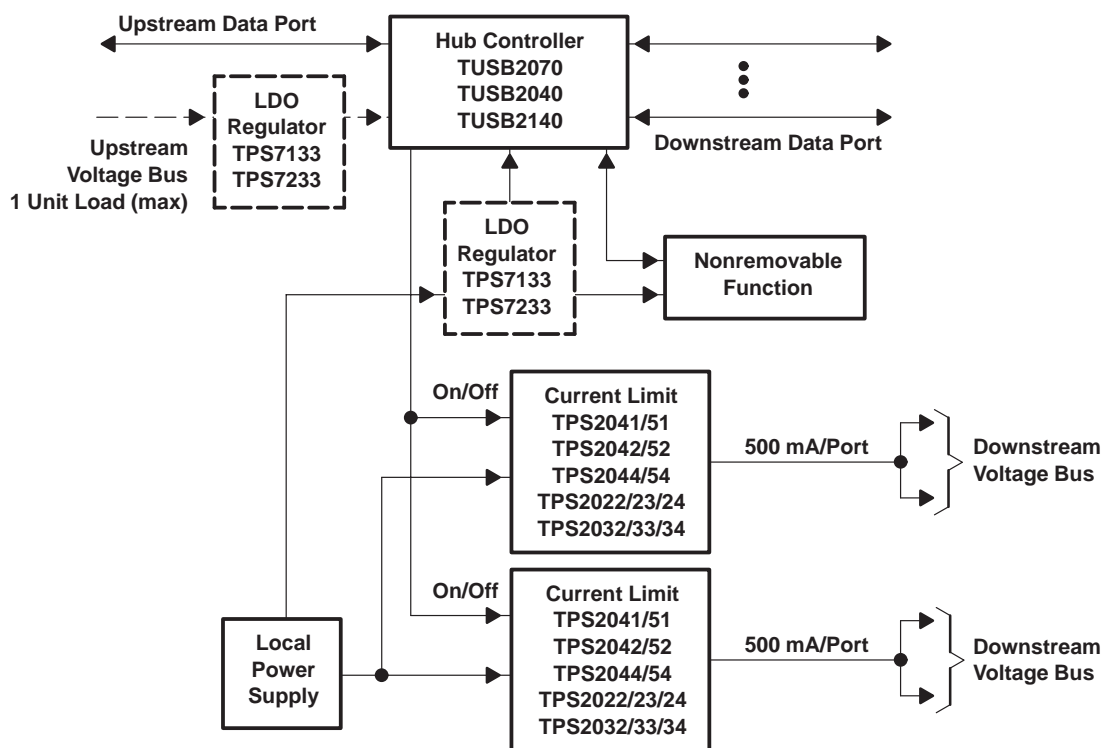


Figure 2. Self Powered Hub

Self-Powered Hub Port Protection Topologies

The self-powered hub power distribution system can be designed with two distinct topologies for port protection: individual port protection or ganged port protection. The ganged port protection is the most economical and the least flexible topology for fault isolation.

The ganged topology uses a common current limit element for two or more ports. In a ganged solution, more current flows through the current limit device. The resistance of the current limit device must be low, so as not to exceed the maximum voltage drop limit under full operating conditions. Fault isolation is another limitation of a ganged solution. To isolate the fault in a ganged solution, power will be interrupted to the adjacent port. This may not be desirable in some USB applications. An individual port protection topology provides a more robust configuration and a better end-user experience.

The individual port protection is the most flexible topology for fault isolation in the USB power distribution system. The individual port protection topology uses current limit elements for each port, making isolating faults with minimal interruption to the adjacent ports possible.

Ganged Port Protection

When designing a ganged topology a low-resistance switch is needed to minimize voltage drop in the hub, because current for all downstream ports passes through the current limit device (see Figure 3). The TPS202x power switches are low 50-m Ω devices with current limit and overcurrent response flag as required in USB self-powered hubs. The current limit level of the devices has been optimized for ganged two (TPS2022), three (TPS2023), and four (TPS2024) port protection topologies.

The TPS2022 is ideal for a two-port ganged solution; it is rated for a continuous current of 1 A and has a current limit of 1.5 A. Using ferrite beads with a resistance of 10 m Ω or less, a two-port TPS2022 ganged port solution can be designed with 5.05 V \pm 3% power supply with up to 88 m Ω of trace resistance on the higher current path. If more trace resistance is required, use the following equation to calculate the required source voltage for a tighter tolerance power supply.

$$V_{PS} = 4.75 \text{ V} + n \times 0.5 \text{ A} \times (R_{TRACE} + R_{SWITCH}) + 2 \times 0.5 \text{ A} \times R_{BEAD}$$

n = number of ports

$$R_{SWITCH} = 50 \text{ m}\Omega$$

In a manner similar to the two-port ganged protection solution, a three- or four-port ganged solution can be designed with the TPS2023 or TPS2024 devices, respectively. By using the above equation, the right power supply can be calculated for a specific number of ports, power switches, and trace resistances. V_{PS} is the minimum voltage of the power supply at full load over the temperature range and line regulation. The output voltage of the hub must be greater than 4.75 V and no greater than 5.25 V over all legal load conditions on the upstream side of the connector.

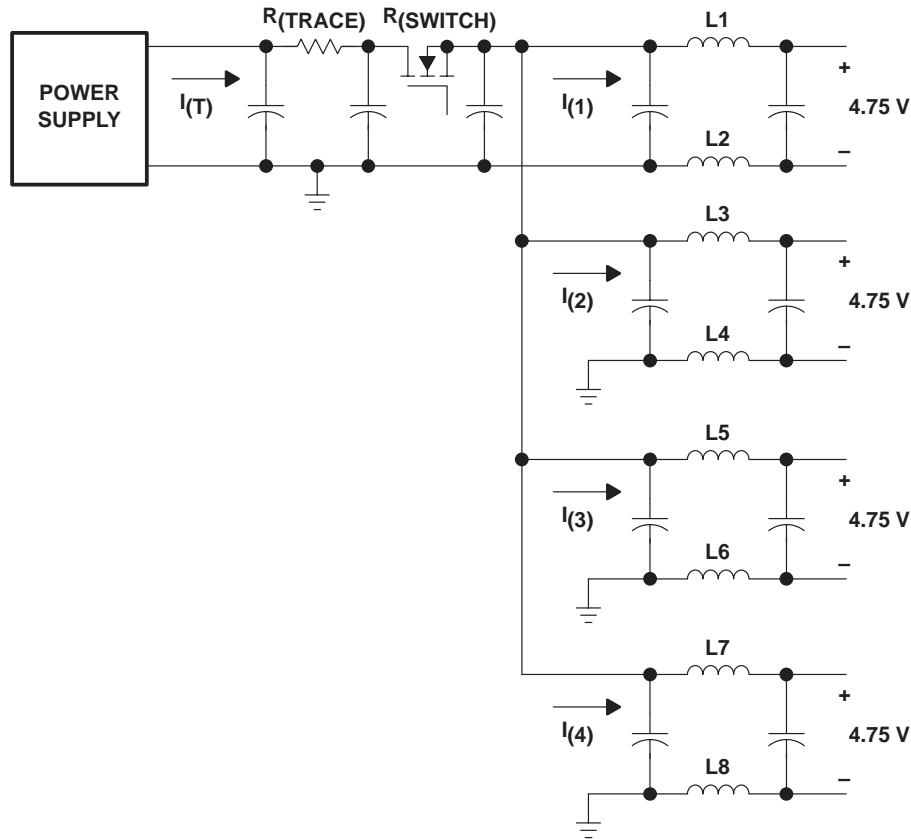


Figure 3. Simplified Ganged Port Protection Topology

The typical voltage droop on a two-, three- and four-ganged port self-powered hub was measured using different types (e.g. tantalum and aluminum) and values of output capacitors with the legal USB hot plug load of $10\ \mu\text{F}$ and $44\ \Omega$. Tantalum, aluminum electrolytic, and ceramic capacitors were used for the $10\text{-}\mu\text{F}$ load capacitors to investigate the effect on the drooping. The $10\text{-}\mu\text{F}$ ceramic capacitor resulted in the largest output voltage droop and the aluminum electrolytic gave the smallest droop. Typical USB applications use aluminum electrolytic capacitors of $10\ \mu\text{F}$ or less, and voltage droop results will be shown using a $10\text{-}\mu\text{F}$, 50-V capacitor. Voltage droop on the hub output varied with the length of cable and the equivalent series resistance of the load and output capacitors. Figure 4 shows the TPS2024 in a ganged-port protection topology, and Table 2 lists voltage droop results for a ganged topology. Figure 5 shows scope traces for a four port ganged hub using $33\text{-}\mu\text{F}$ tantalum capacitors, and Figure 6 shows the same data using $100\text{-}\mu\text{F}$ aluminum electrolytic capacitors.

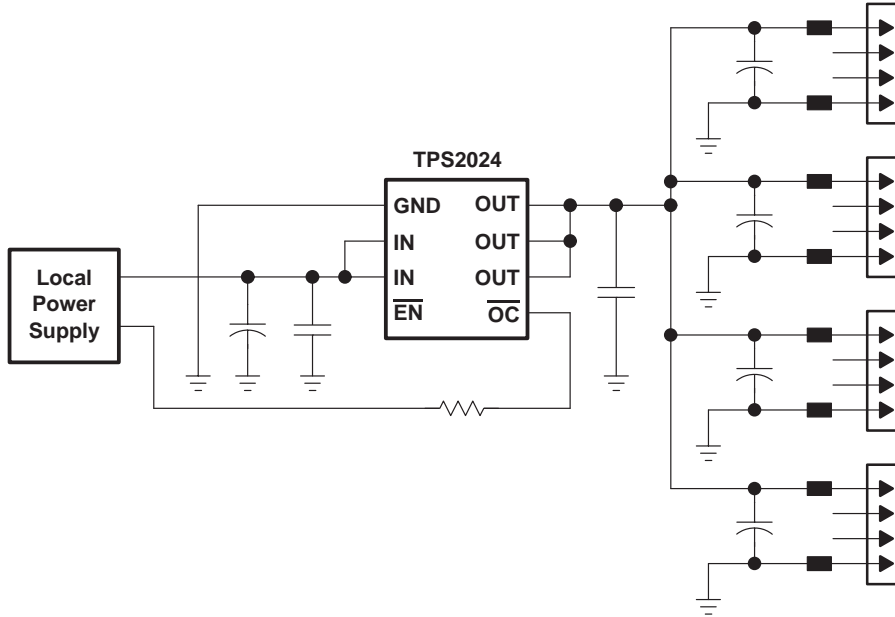


Figure 4. TPS2024 in a Ganged Port Protection Topology

Table 2. Voltage Droop Results for a Ganged Port Protected Self-Powered HubTopology

GANGED	33 μ F	47 μ F	68 μ F	100 mF ALUMINUM
2			120	230
3		120		150
4	110			100

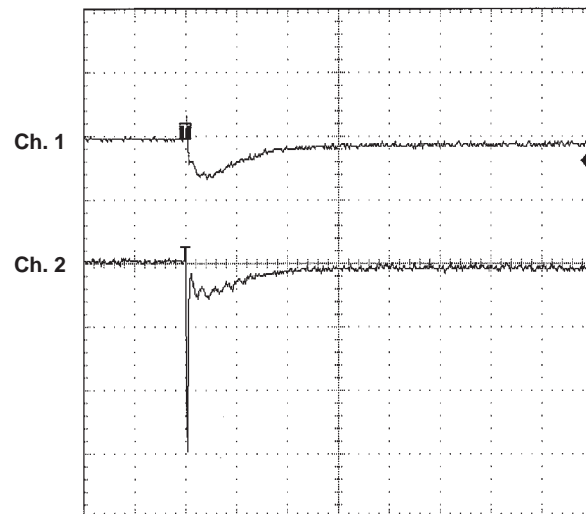


Figure 5. Four Port Ganged Hub Using 33 μ F Tantalum Capacitors

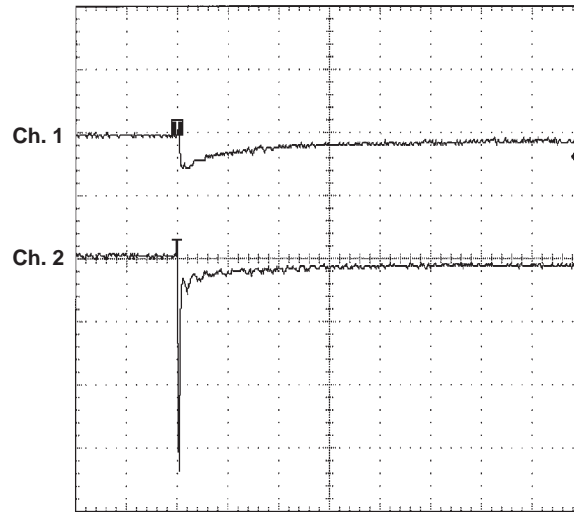


Figure 6. Four-Port Ganged Hub Using 100 μ F Aluminum Electrolytic

Individual Port Protection

Individual port protection has two advantages over ganged port protection in the USB power distribution system: individual port fault isolation, and better voltage droop performance. In a ganged-port protection system, a fault on a single port will interrupt service to an adjacent port. In an individual port protection system, a fault can be isolated without interruption to the adjacent ports. Also, individual port protection provides better voltage droop performance by the resistive isolation of the power switches between ports, reducing charge sharing and voltage droop during hot plug events.

The TPS2042 is an ideal device for a two-port hub requiring an individual port protection solution; the device is rated for a continuous current of 0.5 A per switch with a typical current limit of 0.9 A. The TPS2042 also features independent thermal protection for each switch, which disables the switch in overcurrent when an over temperature condition occurs. A two-port hub can be designed with up to 71 m Ω of trace resistance on the higher current path using a 5.05-V \pm 3% power supply and two ferrite beads on each port with a resistances of 10 m Ω or less. If more trace resistance is needed, a tighter tolerance power supply should be used.

$$V_{PS} = 4.75 \text{ V} + n \times 0.5 \text{ A} \times R_{TRACE} + 0.5 \text{ A} \times R_{SWITCH} + 2 \times 0.5 \text{ A} \times R_{BEAD}$$

$$n = \text{number of ports}$$

$$R_{SWITCH} = 135 \text{ m}\Omega$$

Using the above equation the power supply tolerance can be calculated for a three- and four-port individually protected hub using the TPS204x power switch devices. The tolerance of the power supply must be such that the voltage will not exceed 5.25 V or drop below 4.75 V over all conditions. The same 10- μ F/44- Ω USB load was used for the voltage droop test on the individually protected part. Figure 7 shows a simplified individual port protection schematic, and Figure 8 shows the TPS2044 in an individual port protection USB application.

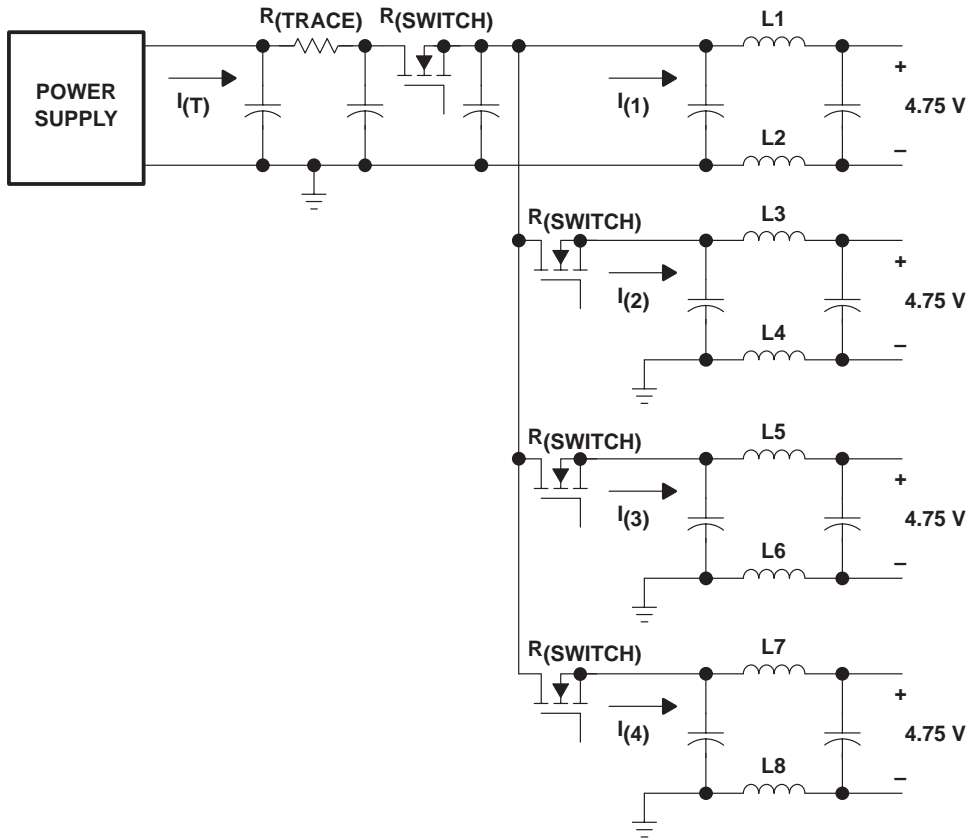


Figure 7. Simplified Individual Port Protection

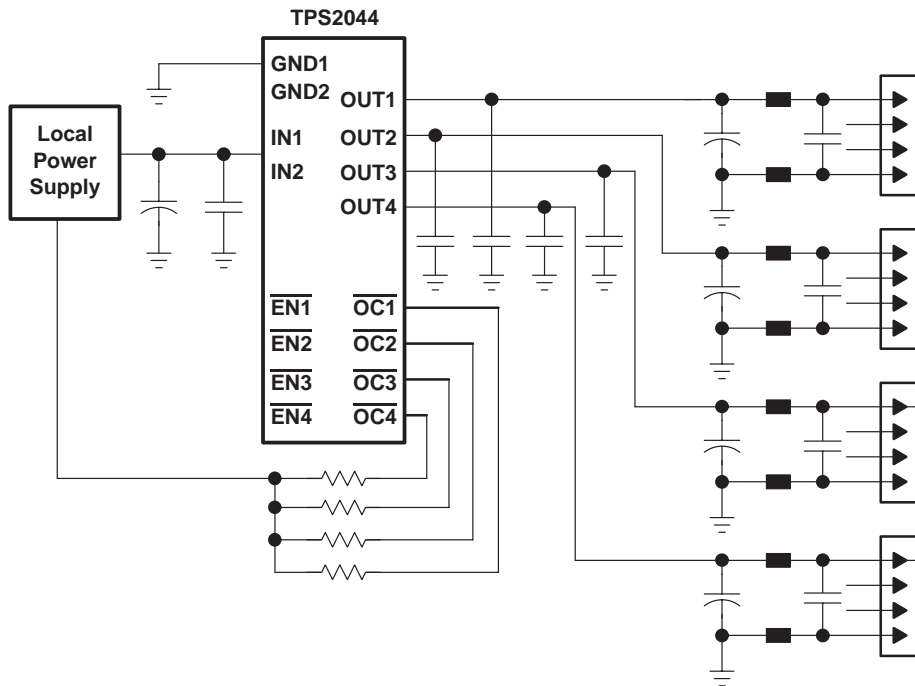


Figure 8. TPS2044 in an Individual Port Protection USB Application

Table 3 lists the voltage droop in an individual port protected SPH. Figures 9 and 10 show scope traces of the TPS2044 four-port hub using 33- μF tantalum and 100- μF aluminum electrolytic output capacitors respectively.

Table 3. Voltage Droop Results in Individual Port Protected Self-Powered Hub

VOLTAGE DROOP on a SELF-POWERED HUB				
GANGED	33 μF	47 μF	68 μF	100 mF ALUMINUM
2			110	150
3		100		140
4	100			90

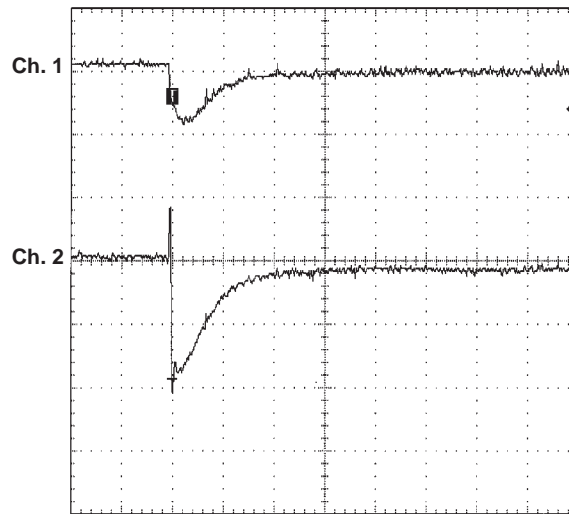


Figure 9. TPS2044 Four-Port Hub Using 33 μF Tantalum Output Capacitors

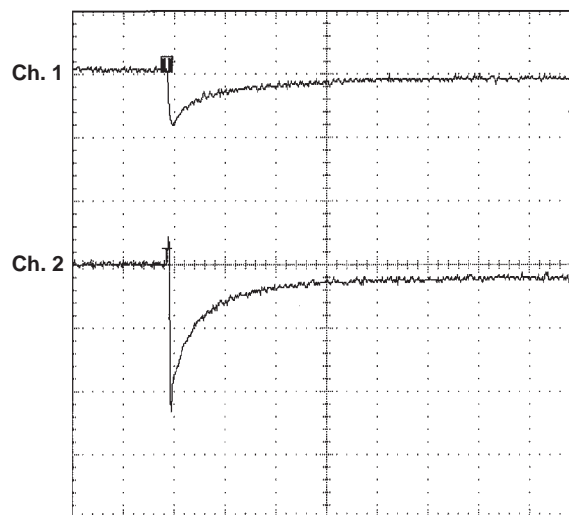


Figure 10. TPS2044 Four-Port Hub Using 100 μF Aluminum Electrolytic Output Capacitors

Output Capacitance

A minimum of 120- μ F low equivalent-series-resistance (ESR) output capacitance is required per hub (i.e., a four-port hub can use a minimum of 33 μ F per port) to bypass the Vbus power lines. The hot plug droop voltages should be considered when choosing the type of capacitor. The ESR of the output capacitor affects the V_{bus} voltage droop during hot plugging when the maximum allowable USB load of 10 μ F in parallel with 44 Ω , or a high-power bus-powered device, transitions from low-power mode to high-power mode. The cable length and load capacitor ESR determines the peak inrush current and the maximum voltage droop.

For low voltage applications, solid tantalum capacitors take up less physical space for the same capacitance and voltage rating than aluminum electrolytic capacitors, and do not suffer from electrolyte dry out, which limits the life expectancy of aluminum electrolytic capacitors. To meet the USB specification, tantalum capacitors as low as 33 μ F, 47 μ F, and 68 μ F can be used in four-, three-, and two-port hubs, respectively. If through-hole components are preferred for the output capacitors, 100- μ F aluminum electrolytic capacitors with less than 1 Ω of ESR can be used to meet the voltage droop requirement. Table 4 summarizes the data for capacitors used to test voltage droop.

Table 4. Output Capacitors Used in Testing Voltage Droop

VALUE	ESR AT 100 kHz	CAPACITOR TYPE	PART NUMBER	MANUFACTURER
33 μ F	0.90	Tantalum	293D336X0010D2T	Vishay Sprague
47 μ F	0.70	Tantalum	293D476X0010D2T	Vishay Sprague
68 μ F	0.70	Tantalum	293D686X0010D2T	Vishay Sprague
100 μ F	0.46	HFQ Radial Aluminum Electrolytic	ECA-1AFQ101	Panasonic

Ferrite Beads

Ferrite beads should be used in series with each Vbus, ground, and data line to reduce EMI and voltage droop during hot-plug events. Table 5 lists the ferrite beads used in the testing of the TPS20xx parts. The ferrite beads that were used have low dc resistance that has minimal impact on voltage regulation.

Table 5. Ferrite Beads Used in Testing Voltage Droop

IMPEDANCE (Ω) AT 100 MHz	DC RESISTANCE (m Ω)	FERRITE BEAD	PART NUMBER	MANUFACTURER
80	10	Ferrite bead surface mount	ACB-1812-5.0A	Associated Components Technology
80	0.9	Ferrite bead surface mount	SMB40	Allied Components
95	0.9	Ferrite bead surface mount	2743037447	Fair-Rite

Transient \overline{OC} Pin Response

The hot-plug connection of the legal USB load of a 10- μ F and 44- Ω load to an enabled power switch device may cause a false overcurrent response when the inrush current flows through the device, charging the down stream capacitor. An RC filter must be connected to the \overline{OC} pin shown in Figure 11 to reduce the erroneous \overline{OC} responses. Also, using low ESR, large value, electrolytic capacitors on the output of the devices reduces the pulse width or eliminates the false \overline{OC} response by minimizing the current flow through the device during the hot-plug events, thereby providing a lower impedance energy source.

The pulse width of the erroneous \overline{OC} response is typically less than 200 μs without an output capacitor on the device when hot plugging a 10- μF aluminum electrolytic capacitor. If the hot-plug load is greater than 10- μF , the \overline{OC} pulse width will be greater. Since the \overline{OC} response is dependent on the many components in the power distribution, it is recommended to test the power distribution system with only a pullup resistor to determine the necessary filter to attenuate the glitch. Once the pulse width of the glitch is known, the filter resistance and capacitance values can be calculated using the equation below. For most applications 0.5 to 1 ms is sufficient. As a precautionary note, the pullup resistance should not be so large as to cause a false overcurrent response at startup when the hub controller voltage reaches its final voltage well before the \overline{OC} pin voltage.

$$T_{\text{filter}} = R_{\text{filter}} \times C_{\text{filter}} \quad (1)$$

$$T_{\text{startup}} = (R_{\text{pullup}} + R_{\text{filter}}) \times C_{\text{filter}}$$

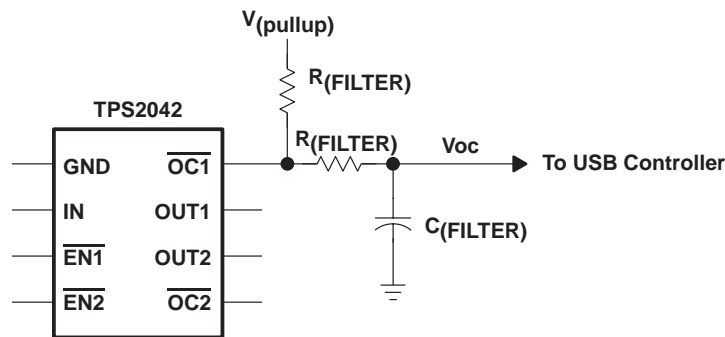


Figure 11. R-C Filter for the \overline{OC} Pin

Self/Bus Powered Hybrid Hub

Many available self-powered hubs are designed to switch to bus-powered mode when local power is not available. The TPS2041 and TPS2021 can be used in the upstream vbus power line, as shown in Figure 12, to prevent power flow upstream. A disable signal should be used to turn off the power switch when the local power supply is present.

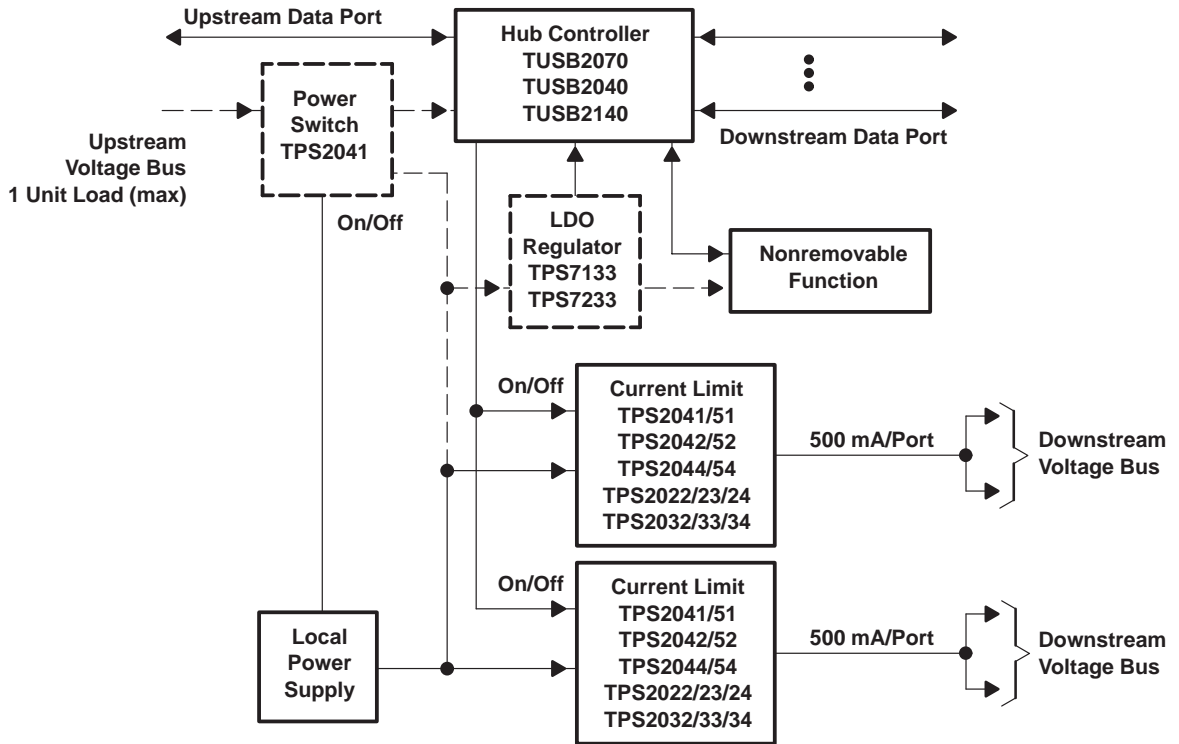


Figure 12. Self/Bus Powered Hybrid Hub

Summary

Texas Instruments power management products meet or exceed voltage regulation, voltage droop, and EMI requirements in the USB power distribution system.