Hot-swapping POWER

HOT-SWAP POWER CONTROLLERS CAN MAKE THE DIFFERENCE BETWEEN A PRODUCT THAT LASTS LONG ENOUGH TO BE A CLASSIC AND ONE THAT'S JUST A BUS CRASH WAITING TO HAPPEN.

Illustration by Mike O'Leary

By Joshua Israelsohn, Technical Editor

AT A GLANCE

▷ Hot-swap controllers don't just protect systems and modules from damage. They allow modules to gracefully engage and disengage a bus without interrupting ongoing data transactions.

▷ Controllers require differing numbers of support components. Some manufacturers accommodate a larger range of real-world hazards in their reference designs than do others. Scrutinize these issues carefully before you scrimp on Rs and Cs.

▷ Controllers can offer fault detection and aid in system diagnostics but only if the system-interface design anticipates these functions.

FOUR TRENDS HAVE CHANGED THE WAY designers approach in-system power management. Traditional 5V-logic supplies have long since given way to 1.8 to 3.3V, making architectures with higher distribution voltages and local power conversion more appealing. Core and I/O circuits commonly operate on different supply voltages, requiring coordination and sequencing of multiple supplies. Load currents, particularly the dynamic components, can reach many tens of amperes for a small circuit area, which increases the requirements for local energy storage and good pc-board layout. End users' demands for flexible-system configurations and high uptime ratios increase as does the impact of power cycling and initialization sequences.

This last trend, reflected in the increasing number of bus standards incorporating hot-swap criteria for inrush-current and signal-contact sequencing, has pushed hot-swap power controllers out of the limited domain of high-ticket equipment and into broader, more cost-sensitive applications. Meanwhile, the first three trends define the context in which engineers design modern hot-swappable subsystems.

WHICH SIDE DRIVE?

A hot-swap power controller's most fundamental role is to limit inrush current when a module or peripheral first makes contact with the host's power-supply rails. In extremis, this function protects the module and the system from damage, primarily to bypass capacitors and connectors due to overcurrent and arcing, respectively. In less severe cases, the limit on inrush current set by a hot-swap power controller protects the system supply from a loss of regulation and a consequential system reset (**Reference 1**).

Second, you can use a hot-swap power controller to control interface logic and bus switches (**Reference 2**). Ensuring the proper engagement of the system bus without undue loading or glitching is as critical as preventing disturbances on the system power supply. Compare the status signals' timing (fault, reset, and power-good) with respect to the supply ramp and your interface logic's power-cycling requirements. Remember that most timing elements in hot-swap applications have loose tolerances that vary independently, such as timing-capacitor values and their charging or discharging current sources, which can stack up against you if you don't design conservatively.

Finally, a circuit-breaker function, less often invoked but no less important, isolates the system from a rogue module or faulty field wiring for modules that connect to external devices. As with inrush current, fault detection and isolation protect the system from excessive load currents that might otherwise result in a loss of regulation or, in severe cases, physical damage. In both cases, power controllers can report faults to the system, simplifying diagnostics particularly in large distributed systems. Protection and isolation work both ways: The power controller can disengage a module from a system supply that fails to meet a specified minimum voltage or, with some controllers, exceeds a prescribed maximum.

The controller may reside on either side of the connector. If a commercial bus specification or an application convention does not prescribe the choice, you need to decide how you want to partition the power-distribution system. Backplane-side controllers have the advantage of protecting the system from modules of arbitrary design. In this arrangement, the system limits its load current at the cost of backplane complexity and less configuration flexibility.

One advantage of module-side hot-swap controllers is that they keep design issues related to turn-on and fault currents local to the module. With the power controller on board, the module designer can offer a meaningful maximum supply-current specification under all conditions. The ability of the power controller to isolate not only faults and transients but also levels of abstraction in the design hierarchy enhances the value of these devices for designers at both the system and module level.

Some hot-swap controllers differentiate themselves with application or bus features and parametrics. Other controllers offer the flexibility that a designer needs to optimize the part's behavior for a custom subsystem interface. Low voltage parts typically operate with supplies of less than 20V (**Table 1**). Controllers for telecomm and related applications operate on 48V nominal supplies, usually with wide tolerances. Devices further differentiate themselves by the range of features they support balanced against package size and price.

GETTING IN GEAR

Designing most controllers into your application requires specifying a few passive components to set the start-up dynamics, establish the current-limit threshold, and fix the supply-monitor threshold for devices that support the function. Additionally, many but not all controllers require an external MOSFET that operates as a pass element.

The MIC2583 from Micrel is typical of low-voltage general-purpose hot-swap controllers (**Figure 1**). Operation begins when the voltage at the On pin rises through its threshold—nominally 1.23V. A current source connected through the Gate pin charges the timing capacitor, C_G, causing the MOSFET gate to ramp and the output to slew (**Figure 2**). If you use a large-geometry power MOSFET, the pass element's gate-source capacitance, C_{GS}, can significantly contribute to or even dominate the turn-on timing. For slew-dominated start-up configurations, the gate capacitor required for a given slew rate is

$$C_G = \frac{I_{GATE}}{dV_{OUT}/dt} - C_{GS}.$$

On the other hand, the controller's total load capacitance, C_L, can be sufficiently large so that it cannot be charged at the programmed slew rate without exceeding the inrush-current limit set by the combination of the sense resistor, R_S, and the controller's internal threshold. In this case, the inrush-current limit and the load capacitance combine to fix the output slew rate to

$$\frac{dV_{OUT}}{dt} = \frac{I_{LIM}}{C_{LOAD}}.$$

Hot-swap controllers integrate a circuit-breaker function to guard against fault currents once the load capacitance charges. Manufacturers of controllers often describe the parts as featuring "dual-fault-level detection" or similar wording. Simply put, momentary overcurrent conditions cause the device to current-limit, whereas conditions that persist trip the circuit-breaker function. In the case of the MIC2683, tripping the circuit breaker causes the part to assert the $\overline{\text{fault}}$ signal, which you can use to drive an indicator or to signal the host system if the interface provides an appropriate status line. The circuit-breaker function guards against shorts or module failures that result in excessive supply current. The time limit set by the capacitor C_{FILTER} prevents the circuit-breaker function from tripping on a short current impulse. If the controller starts in its current-limited mode, C_{FILTER} must set a time interval long enough to allow the load capacitance to charge at I_{LIM}. To ensure a slew-limited start-up, set

$$C_G \geq \frac{I_{GATE}}{I_{LIM}} C_L - C_{GS}.$$

However, be aware that sufficiently large values of C_{FILTER} can cause the controller to ignore faults for an appreciable time, forcing the system power supply to contend with the resulting currents—the very condition that the controller is supposed to guard against.

Other parts disentangle the start-up interval from the transient filter by arm-

ACRONYMS

ACPI: Advanced Configuration and Power Interface
FET: field-effect transistor
IDE: integrated drive electronics
MOSFET: metal-oxide semiconductor field-effect transistor
OVLO: overvoltage lockout
PCI: Peripheral Component Interconnect
UVLO: undervoltage lockout
SCSI: Small-Computer-System Interface
TVS: transient voltage suppressor

TABLE 1—REPRESENTATIVE HOT-SWAP POWER CONTROLLERS

		Supply										Status signals
		Voltage			Current		Breaker threshold nominal (mV)	On-chip features				
Manufacturer	Model	Minimum (|V|)	Maximum (|V|)	Absolute max (|V|)	Typ (mA)	Maximum (mA)		Automatic retry	Output UVLO detect	Output OVLO detect	Load discharge	Fault
Intersil	HIP1011E (octal)	10.8	13.2	14	5.3	8	ADJ					√
	ISL6118 (dual)	2.7	5.5	6	0.12	0.2	NA					√
	ISL6121	2.5	5.5	6	0.12	0.2	NA					√
Linear Technology	LTC4211CMS	2.5	16.5	17	1.0	1.5	50		√			√
	LTC4211CMS8	2.5	16.5	17	1.0	1.5	50		√			
Maxim	MAX4271	2.7	13.2	15	0.6	1	50			√		√
	MAX4272	2.7	13.2	15	0.6	1	50	√		√		√
	MAX4273	2.7	13.2	15	0.6	1	50	√		√	√	√
Micrel	MIC2582	2.3	13	20	1.6	2.5	43		√			
	MIC2583	2.3	13	20	1.6	2.5	43		√		√	√
	MIC2583R	2.3	13	20	1.6	2.5	43	√	√		√	√
Summit	SMH4812	20	ZL	ZL	3	10	50	√	√	√		√
Supertex	HV300	10	90	100	0.8	1	50		√	√		
Texas Instruments	TPS2306 (dual)	2.75	13.6	15	2	4	ADJ		√			√

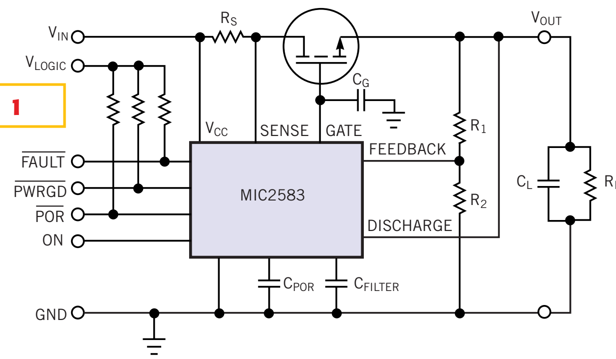
Notes:
ADJ: adjustable by user-selectable resistor; NA: not applicable (on-chip current sense); ZL: zener limited (designed for 48V nominal supplies).

ing the breaker function only after charging the load capacitance. These ICs usually have two thresholds. The upper threshold, often three or four times that of the low one, is not filtered and represents a hard peak-current limit in all operating modes.

Also, common among competing parts, the MIC-2683 implements a number of other useful signaling features that you can use to control the start-up behavior of your module. A power-good signal deasserts when the controller senses a minimum voltage on its output, which is determined by the voltage divider, R_1 and R_2, and an internal threshold voltage. The capacitor C_{POR} determines the further delay from the power-good edge until the power-on-reset pin also deasserts to ensure that the module has properly powered and initialized the onboard logic. Subsequent failures of the system supply to maintain the minimum voltage set by the R_1/R_2 divider cause the controller to reassert the power-good and power-on-reset signals.

The MIC2682, a version of the 2683 stripped down to fit in an eight-pin package, forgoes the fault and power-good status outputs. It also dispenses with the timing capacitor, C_{FILTER}, and instead uses a fixed 5-μsec delay time. Lastly, the MIC2682 does not have the 2683's provision for discharging its load when it shuts off.

Figure 1



Beyond basic protection, hot-swap controllers such as Micrel's MIC2583 provide a range of status signals and monitoring capabilities.

STANDING ON THE BRAKES

The presence of the gate timing capacitor, C_G, has a number of important consequences beyond setting the turn-on slew rate. When a module is first connected to a hot backplane, the large dV/dt appearing on the supply line can couple onto the pass element's gate. A capacitive divider comprises the two MOSFET parasitic capacitances, C_{GD} and C_{GS}; the external gate capacitor, C_G; and the load capacitance, C_L (**Figure 3a**). Assuming that the MOS device's body stray is small enough to ignore and the load capacitance is very large compared with C_{GS}, the model reduces further (**Figure 3b**). The plug-in transient can turn on the pass element by coupling a threshold voltage, V_{TH}, onto the gate if

$$V_{TH} \le V_{CC}\frac{C_{GD}}{C_{GD}+C_{GS}+C_G}.$$

The external gate timing capacitor mitigates against this outcome but does so at a price. When the controller senses a fault condition and tries to disconnect the power supply from its load, it has to discharge C_G as well as C_{GS} to turn off the pass transistor.

The LTC4211 from Linear Technology doesn't use a capacitor on the gate node to establish its timing. It includes a 200-μA current sink to anchor the gate at start-up and prevent the plug-in transient from turning on the MOSFET. With a lower node capacitance to discharge, the controller reduces its shutdown time, preventing fault currents from loading the system power supply.

The 4211 uses one capacitor to define two timing cycles in its start-up sequence. The first cycle allows the chip to initialize itself, discharge the timing and filter capacitors, check critical nodes, and arm the high-speed high-current circuit-breaker comparator. The second cycle allows the controller to soft-start its output, arm the low-speed low-current circuit-breaker comparator, and deassert the reset signal.

The filter capacitor controls the dynamics of the low-speed low-current comparator, allowing it to ignore brief overcurrent conditions. The high-current threshold, set to three times the low-current limit, has a fixed response time and trips the breaker within 300 nsec. Like similar hot-swap controllers, the circuit-breaker function latches and requires the On-control input to cycle low then high to initiate a restart. You can implement a simple automatic circuit-breaker reset and retry circuit using the fault signal (**Figure 4**).

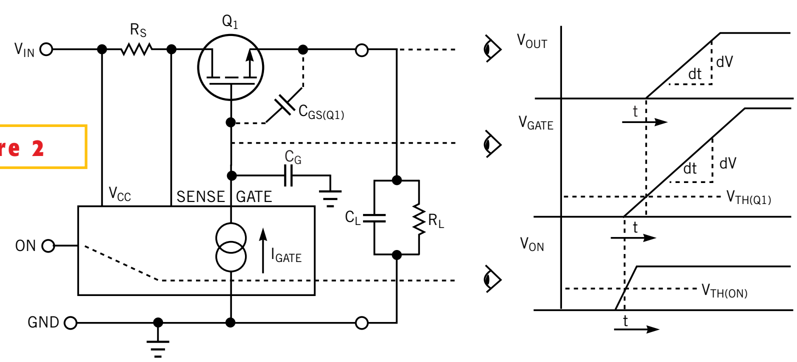
Like the MIC2683, the LTC4211 comes in two forms—a full-function device in a 10-pin package and an eight-pin abbreviated version. The eight-pin device loses the C_{FILTER} connection and instead uses a fixed 20-μsec response time. It also foregoes the fault status signal.

The MAX4272, one of a trio of hot-swap controllers from Maxim, fits a self-contained auto-retry breaker function in an eight-pin package. The chip uses its start-up timing capacitor to control the retry interval as well. Maxim also offers a version with a latching breaker, the MAX4271, and, like other vendors, a more complete signal compliment in a larger package with the MAX4273. These parts suspend their circuit breakers during start-up and instead use the high-current threshold to control the MOSFET gate signal; as long as the inrush current is below the threshold, the gate voltage ramps up from a 100-μA current source. If the current exceeds the threshold, the gate signal switches to a 70-μA current sink, resulting in a current limited start-up cycle.

Like many controllers offered in small pin-count packages, the MAX4271 and 4272 have only one status signal as well

Status signals			
Power good	Reset	Package	Price
		SSOP-28	$4.78 (10,000)
		SOIC-8	$1.25 (10,000)
		SOIC-8	$1 (10,000)
√	√	MSOP-10	$1.95 (1000)
	√	MSOP-8	$1.95 (1000)
		SOIC-8	$1.95 (1000)
		SOIC-8	$2.05 (1000)
	√	QSOP-16	$2.24 (1000)
	√	SOIC-8	$1.95 (1000)
√	√	QSOP-16	$2.28 (1000)
√	√	QSOP-16	$2.28 (1000)
√		SSOP-16	$4.33 (1000)
√		SOIC-8	$1.50 (10,000)
		SOIC-16	$3.50 (1000)

Figure 2



Looking at the On control pin, the MOSFET's gate, and the output reveals the basic turn-on timing relationships.

as simple timing relationships. If your application requires a minimum reset interval after the power supply has ramped through a minimum operating voltage, you need to consider how to derive the reset signal. You can calculate the start-up behavior and adjust the timing-capacitor value to ensure that sufficient time elapses between reaching your minimum supply-voltage requirement and the end of the start-up cycle. The timing of the start-up interval depends on the load, gate, and timing capacitances; their charging currents; and the load-current-limit threshold. Of these terms, even those that carry minimum and maximum specifications tend to have broad tolerances. You should set the timing capacitor conservatively and recheck your calculation any time you change the load capacitance during the design's lifetime. Alternatives include choosing a controller with an explicit reset signal, which usually requires a larger package size and an additional capacitor, or adding a reset generator that you can gate with the Stat signal.

TWICE PIPES

Many hot-swap applications require multiple coordinated supply voltages. You can manage the power-up and power-down sequence through independent hot-swap power controllers, but one of the available multichannel controllers simplifies the task. The TPS2306 from Texas Instruments is a two-channel controller with independent ramp-up and ramp-down controls for each channel. The four-ramp control signals, coupled with resistive dividers sampling the two outputs, allow you to select either supply to ramp-up first. The part's design also allows you to choose either first-up first-down or first-up last-down power-supply sequences.

One typical application coordinates core and I/O supplies, with the low-voltage core ramping up first. A divider on the 3.3V output determines the ramp delay for the 5V-I/O supply. When ramping down, the circuit waits for the 5V output to fall through a threshold before signaling the 3.3V supply to shut down.

Unlike most hot-swap power controllers, the TPS2306 allows you to set the current sense thresholds for each channel. This feature gives you an additional degree of freedom in the trade-off between the set current limit and the device's insertion loss. This issue is potentially important for supplies delivering high currents because sense resistors have practical lower limits. The extra flexibility costs an additional RC per channel. The 2306 also distinguishes itself because it is one of the few hot-swap controllers with an operating temperature of −40 to +150°C.

Bus-specific parts, such as the HIP-1011E from Intersil, focus on well-defined operating environments and thereby save space and external components. The 1011E octal hot-swap power controller for the PCI bus is the latest in the HIP1011 line. It provides independent control of two PCI slots with two channels each for 12, −12, 5 and 3.3V supplies. The ±12V supplies use on-chip current-sensing and pass devices; the low-voltage supplies use external resistors and MOSFETs. External capacitors set the ramp rates on the ±12V lines.

The HIP1011E scales the overcurrent threshold for all eight channels with one resistor driven by a 100-μA current source. The master threshold directly sets the trip point for the ±12V channels. You scale the 5 and 3.3V trip currents further by selecting an appropriate value of sense resistor, as you would with the

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Summit Microelectronics
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Supertex
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1-800-336-5236
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For more information about transient-voltage suppressors, refer to the following vendors' Web sites:

General Semiconductor
1-631-847-3000
www.gensemi.com
Enter No. 345

Microsemi
1-949-221-7100
www.microsemi.com
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Protek
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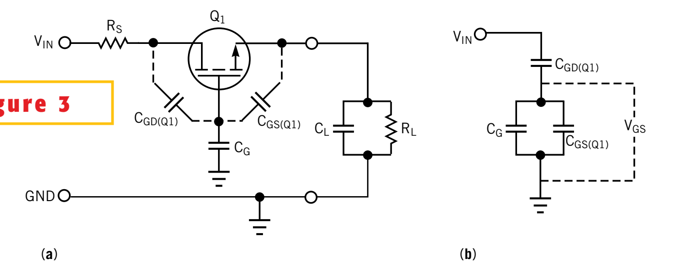
TPS2306 described earlier.

Intersil also offers the ISL6118, a dual-channel hot-swap controller intended for use on the 3.3V AUX power line in ACPI applications. It includes on-chip MOSFET pass transistors, current monitors, and all necessary timing circuits. The controller requires a pair of pullup resistors on the two fault lines as its only external components. The ISL6121 is a single-channel version with performance geared toward Fibre Channel, IDE, and SCSI disk drives in high-availability storage applications.

Figure 3



Compare the magnitudes of both explicit and stray capacitances (a) to derive a simplified model (b) when assessing the danger of false start-ups.

INSURANCE

Ironically, although hot-swap power controllers protect systems and modules, depending on the supplies and the electrical nature of the system, you may need to protect the protector. Abruptly plugging a module (and there is no *gradual* way to do it) can excite resonances formed by system wiring, the backplane, and circuit-board traces working into the shunt capacitances, most notably that of the MOSFET. Depending on the size of the parasitics and the edge speeds you produce, the peak overshoot can reach 2.5 times the supply nominal voltage (**Reference 3**). Unplugging a module, no more graceful an act, engenders an inductive kickback—a fundamental response of inductors to an interruption in their steady-state current:

$$V_L = L\frac{dI_L}{dt}.$$

Compare your supply nominal with the absolute maximum voltage that a candidate hot-swap power controller can tolerate; in many cases, anticipatable transients can threaten the device.

Beyond applying good mechanical design to minimize the inductive terms associated with wire runs and board traces, you can use two other methods of limiting supply-line excursions to safe amplitudes. Zener diodes or transient voltage suppressors clip the waveform, and snubbers damp the resonances (**Figure 5**). You should mount these components as close to the hot-swap controller as you can and connect them with short leads to minimize their own stray inductance.

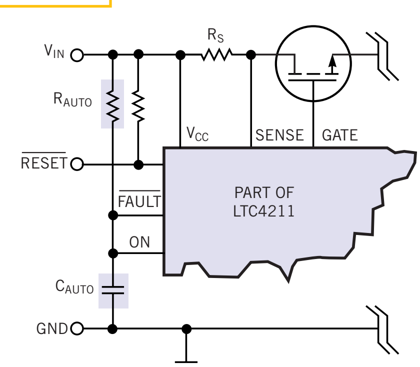
Sense resistors also require careful layout. An easy way to help ensure predictable controller performance is to preserve the accuracy of the current-sensing circuit. Kelvin connections to the sense resistor allow you to sense the voltage drop across the resistor exclusive of the drops across the connecting copper traces (**Figure 6**). A typical hot-swap power controller has a low-current circuit-breaker trip threshold in the neighborhood of 50 mV; you scale the trip current by selecting an appropriate sense resistor. The sheet resistivity of a 1-oz copper circuit-board trace is about 540 μΩ/sq (**Reference 4**), which may seem like an insignificant number until you recast it in proportion to the threshold: 1%/A/sq. It doesn't take many squares working into several tens of amperes before sensing errors account for an appreciable fraction of the controller's current range.

HITTING THE POLE

Although the goals for hot-swap power controllers are roughly the same, the details change somewhat when you get tangled up in the telephone wires or anywhere you find power distributed on −48V lines. This type of hot-swap controller usually manages a local dc/dc converter that provides the lower regulated voltages that the module requires. The controller itself, however, must make do with a power supply with a comparatively loose tolerance, commonly +50%/−25%.

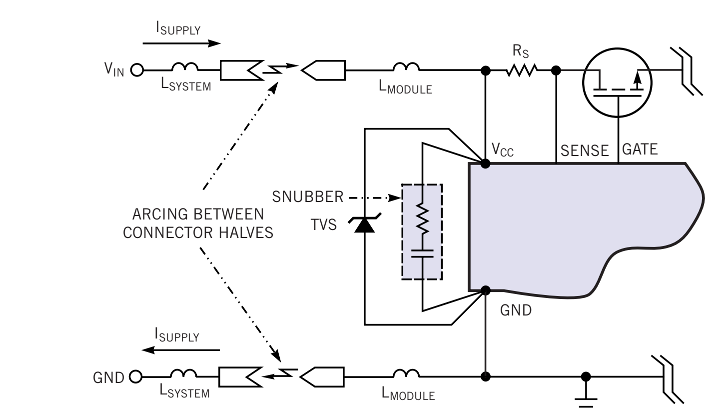
You don't need a hundred-volt process to safely manage communications supplies and the additional inductive kickback generated when you unplug a module. A shunt-regulated controller can hang from a series current-limiting resistor and strike its internal circuits with a fraction of the total available supply voltage. Be sure to specify a conservatively rated series resistor for this application. The film resistors available today have much less overload capability than did their carbon-composition counterparts of yesteryear.

Figure 4



You can use a status signal to implement an auto-restart.

Figure 5



A snubber network and a zener or TVS can quench energy released by inductive kickback when you unplug a hot module. Contact bounce during plug-in can cause the same problem, which can otherwise result in arcing between the connector halves.

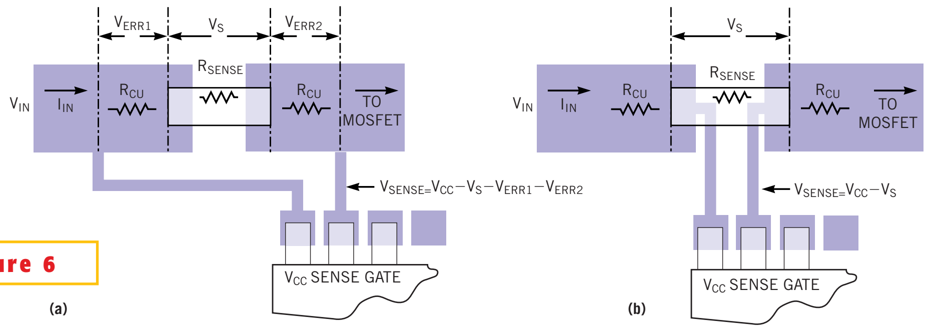


Figure 6

Non-Kelvin sense-resistor connections can result in significant current-sensing errors—about 3% per ampere for the layout (a). Proper Kelvin sensing only requires care in the pc-board layout but pays back handsomely with improved sensing accuracy (b).

The SMH4812 from Summit Microelectronics is a shunt-regulated hot-swap controller for communications and other relatively high-voltage services. An internal zener diode establishes a 12V rail with a tolerance of ±1V. Depending on the pass FET you select, the 4812 can control dc supplies of ±20 to ±500V.

A string of three external resistors between the input-supply rails allows you to set undervoltage and overvoltage lockout limits. When first powered, the 4812 tests that the supply lies between those two limits. Two pin-detect inputs allow the chip to check that the card is properly seated in its connector. Following the lockout and pin-detect tests, the controller starts ramping the MOSFET gate. Once the gate voltage rises to within a gate threshold of the 12V rail and the controller confirms that the output is within 2.5V of the input supply, the chip deasserts the power-good open-drain status output, which you can use to control the dc/dc converter.

Current sources driven from the 12V rail power 5.0V ±5% and 2.5V ±1% reference outputs, which can power ancilliary loads before the controller starts the local dc/dc converter. The reference outputs can drive 1 mA maximum each.

When the 4812's circuit-breaker function trips, it automatically resets after 2.5 sec, so you can use the part in areas that have no supervisory logic to poll and reset tripped controllers. If you think that devices that draw on large power supplies shouldn't reset their breakers without due inspection, you can get this IC with an optional nonvolatile fault latch that does not reset either by itself or after power cycling. The fault latch remains active until the manufacturer reprograms it.

Unlike many of its competitors, Supertex exploits a high-voltage process for its HV300, which is designed to operate to −90V. Internally, the devices operate on a 10V rail supplied by an integrated regulator. Immediately following plug-in, while the internal regulator is settling, all circuits remain in reset. The HV300 also holds the gate drive for the external n-channel MOSFET low to prevent coupled charge from turning on the pass transistor. This feature can be even more important for communications supplies than in low-voltage applications. No correlation exists between contact make-or-break speed and supply voltage nor are the capacitive terms strictly proportional, so expect the gate-charge-coupling term to be worse in a 48V application.

Once the IC's internal supply requirements are met, the HV300 checks its UVLO and OVLO comparators to ensure that the input supply meets the application requirements. Once the controller is satisfied with the conditions, it starts ramping the MOSFET. A current source driving an external capacitor controls the ramp. The gate drive is buffered from this control signal, which keeps the gate-node capacitance as low as possible. Under fault conditions, the hot-swap controller only needs to discharge the MOSFET gate capacitance, not the ramp-control capacitor. The HV300 includes a 100-mA current sink for this purpose.

COMPARING STICKERS

Be careful when comparing claims and specifications for hot-swap controllers. The number and type of support components vary significantly from part to part and from manufacturer to manufacturer. The spec tables often but do not always provide test conditions. Operating conditions vary; for example, some manufacturers specify maximum operating current at 25°C, whereas others offer specs over the part's full operating-temperature range.□

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Author's biography

Never one to power down, Joshua Israelsohn practices safe hot swapping wearing his trusty and fashionable wrist strap. He does, however, wait for the #502 to stop before jumping on or off the bus.