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Advantages of IC-Based Hot-Swap Circuit Protection

There are many approaches for protecting a system against electrostatic discharge (ESD), surge current, overcurrent, undervoltage, overvoltage, and other problems. Industry, company, or regulatory standards such as UL, USB, IEEE, CSA, or IEC often require circuit protection.

This application note discusses some important advantages offered by hot-swap ICs.

Hot-swap circuits protect equipment, personnel, or both. Some power supplies, for example, have built-in and adjustable current limiting (standard in hot-swap circuits) that prevents damage to the power supply and the circuit being powered. Typical RAID and telecom systems have hot-swap capability for exchanging circuit boards or disk drives on the fly.

At minimum, hot-swapping requires that you limit inrush current to prevent the possibility of a system-wide brownout when a large capacitive load is energized. Current limiting also helps reduce the size of the source power supply and limits electrical arcing at the connector contacts. Other hot-swap features include: low series resistance, circuit-breaker action, status indication, dual insertion-point detection, and power-good signaling.

Protection circuitry adds components and cost while increasing the time to design and test a system, but those drawbacks must be weighed against the less-tangible costs (not always uppermost in a designers mind) associated with non-protected systems: equipment damage, system down-time, injury and resulting lawsuits, replacement and repair costs, technician wages, etc.

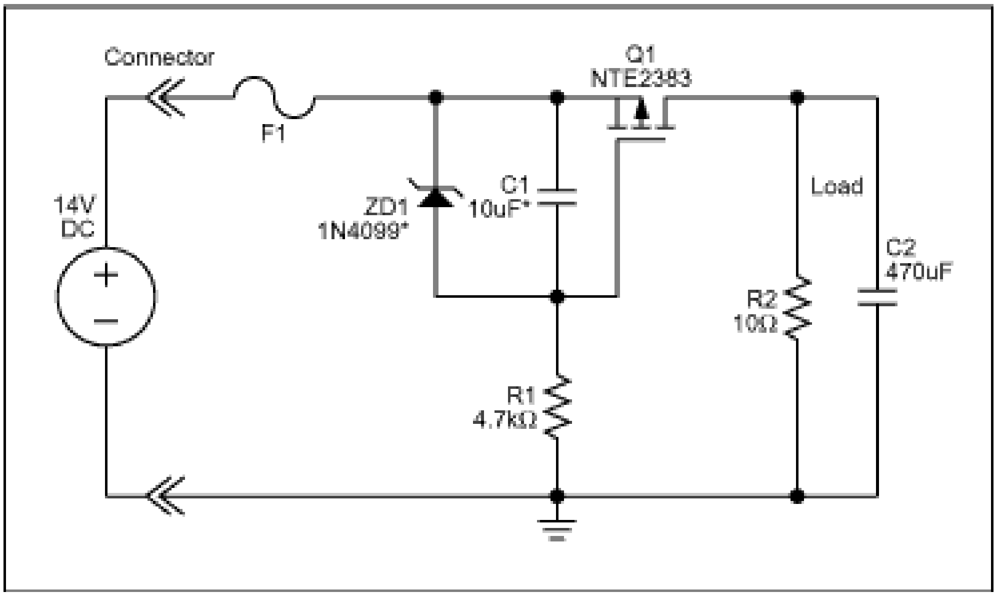
The introduction of hot-swap capability can immediately offset costs by allowing a smaller main power supply. Reducing the level of surge current that a power supply must deliver allows smaller filter capacitors and a smaller power supply. Other benefits include smaller-sized wiring and circuit traces, smaller and less expensive circuit connectors, and generally smaller components in the power path.

The simplest current-limiting component is the fuse, which can be used by itself or in combination with other protection elements. Because fuses are effective against over-current, they are either required (in circuits approved by UL, for instance) or included as a protection of last resort in the event of catastrophic failure.

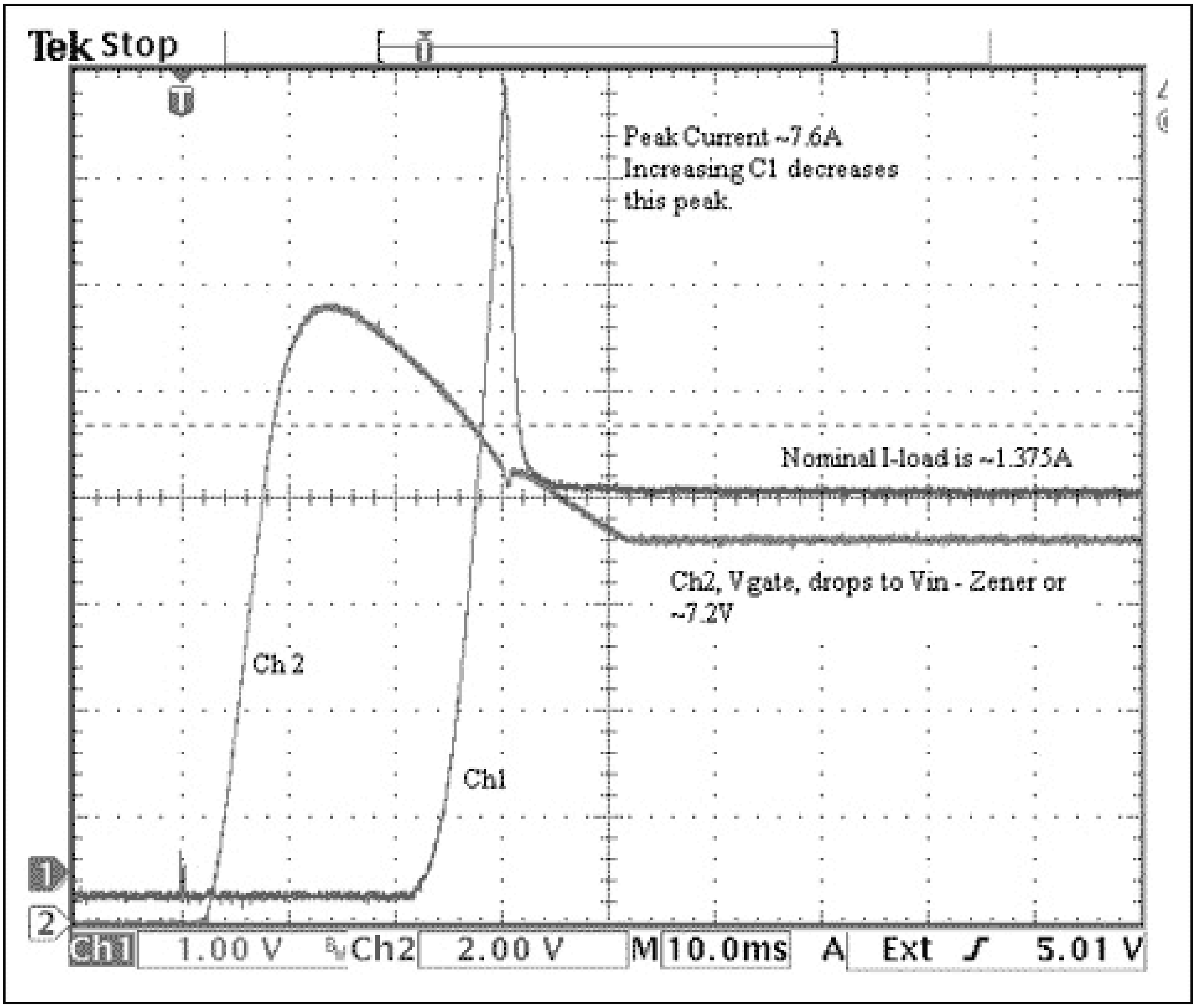
For standard fuses, the major detraction is their one-time use. An alternative is the poly-fuse, an otherwise similar device that physically expands and contracts according to the amount of heat generated by current flowing through it. The temperature-dependent poly-fuse has a limited-voltage operating range, but it can reset itself (an advantage over standard fuses).

A common circuit in hot-swap applications is the capacitor-zener-FET combination (Figure 1). It limits inrush current by charging C1 across the gate-source junction of Q1. Assuming that C1 is discharged when power is applied, the circuit keeps Q1 off by acting as a short across the gate-source junction. As C1 charges, Vgs increases and allows Q1 to turn on slowly. The size of C1 and the Vgs characteristic of Q1 determine how quickly Q1 turns on and charges the load capacitor (C2).

Figure 1. A discrete "cap-zener-FET" hot-swap circuit:



(a) controls Q1's turn-on via the charge rate of C1, as shown in the scope plot,

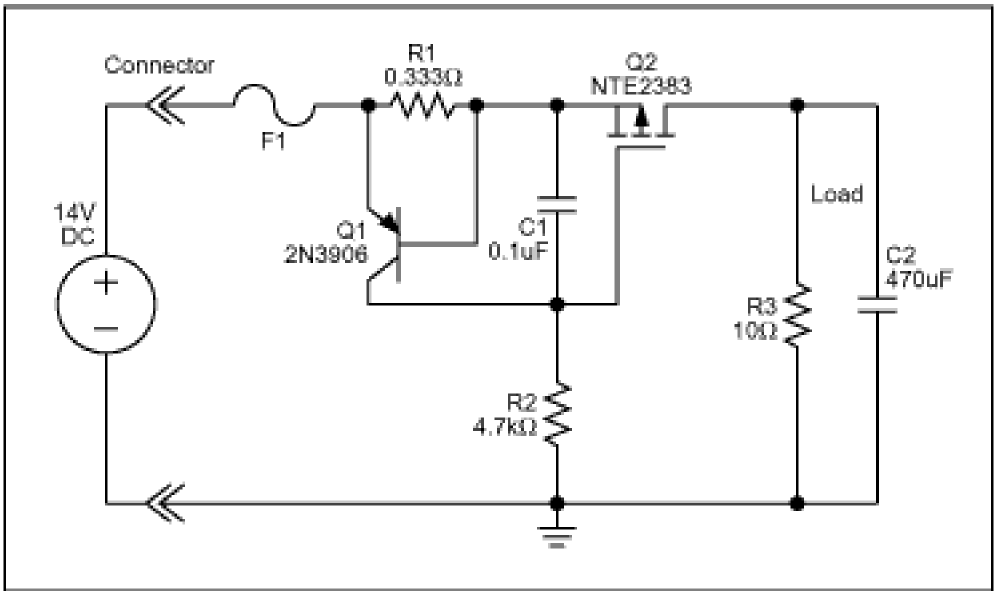


(b): CH1 = load current; CH2 = Q1 gate voltage.

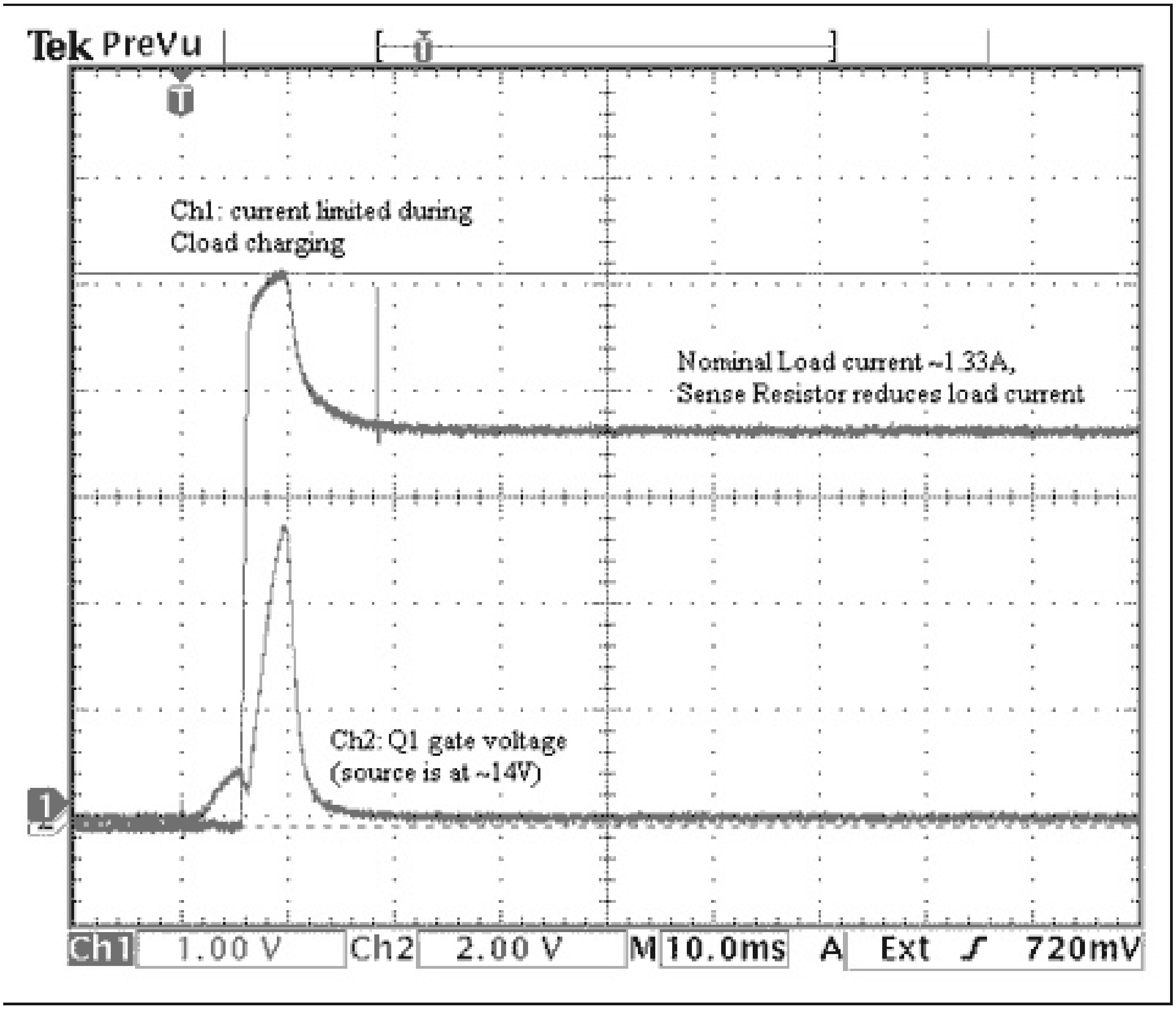
Zener diode ZD1 prevents the Q1 gate-source junction from exceeding its maximum rating. (Note that the Vgs maximum in Figure 1 (±20V) is too small to withstand 24V industrial or 48V telecom applications.) If power is cycled rapidly, the load capacitor can be discharged while C1 remains sufficiently charged to maintain Q1 ON. That condition can diminish the current-limiting feature, allowing a large current surge when power is reinstated. As another drawback of the capacitor-zener-FET topology, current limiting is active only during power-up, and only if C1 is discharged. Once energized, the circuit is incapable of protecting against over-current and short-circuit conditions. (A fuse is typically employed for that purpose.)

Another circuit for hot-swap applications (Figure 2) uses a pnp transistor (Q1) and current-sense resistor (R1) to provide continuous current sensing and limiting. As power is applied, current flows through R1 and Q2 to the load. Current through R1 creates the V_{BE} bias voltage for Q1. If the current is great enough to bias Q1 on, then Q1 limits conduction through Q2 to the load by reducing gate-source voltage of Q2. Note that a zener diode could be added across Q2's gate-source junction (as in Figure 1) to prevent over-voltage on Q2 and Vce breakdown on Q1.

Figure 2. Another hot-swap circuit:



(a) implements current sensing and 2A-limiting with a pnp transistor, as illustrated by the turn-on waveforms,

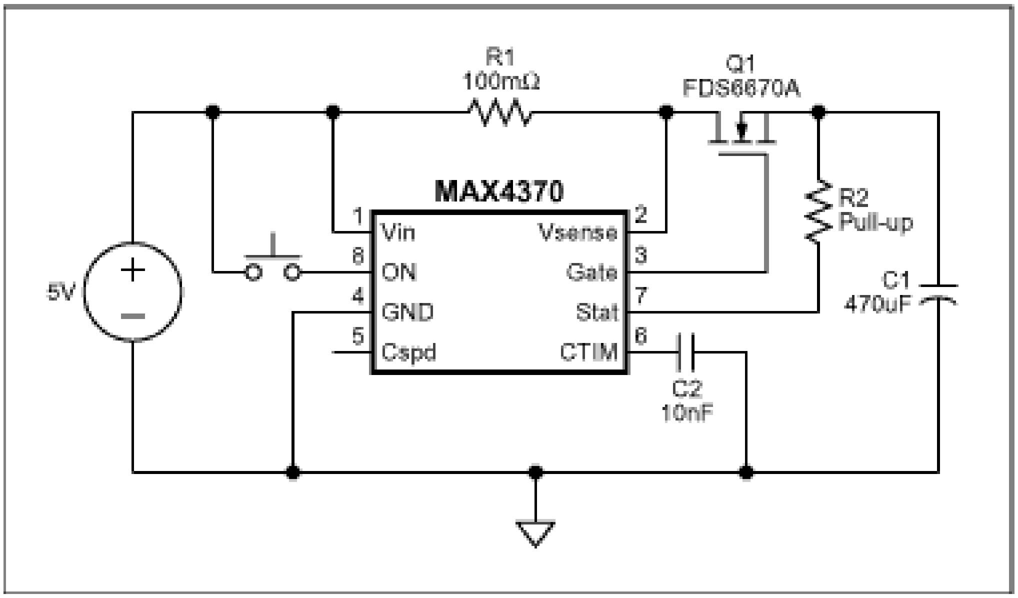


(b): Ch1 = current; Ch2 = Q2 gate voltage.

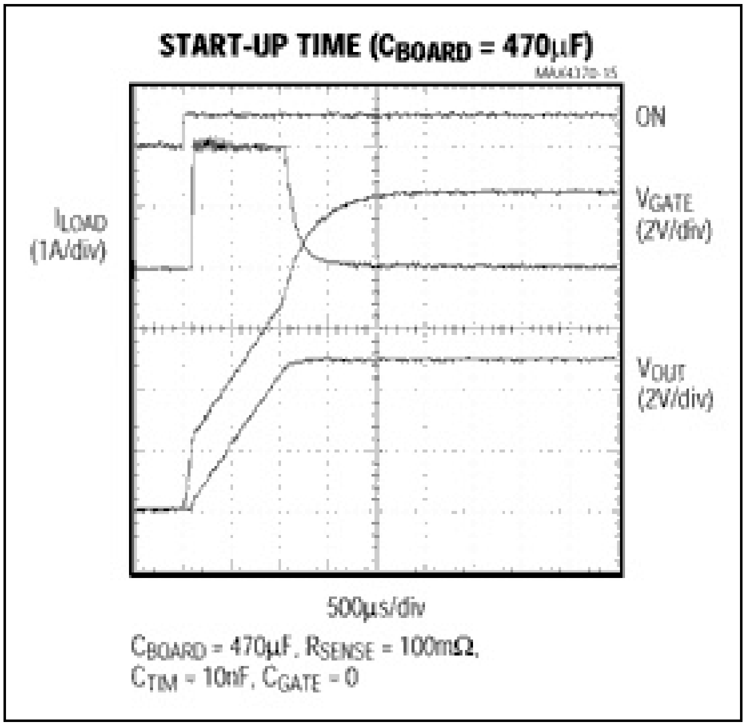
The good news for this circuit (unlike that of Figure 1) is that current limiting is always enabled. Bad news is the added power dissipation of R1 in series with the load. Also, the current limit can change as much as ±20%, as a consequence of Q1's V_{BE} variation over the temperature range -40° C to 85° C. The zener diode in Figure 1 (and in Figure 2, if added) should be small enough to protect the transistors, but large enough to allow the FET its full conduction range for Id while minimizing $Rds_{(on)}$.

IC-based hot-swap circuits offer many features in a small package, and they require few external components. Figure 3, for example, shows a low-voltage hot-swap application that requires only a current-sense resistor (R1) and series-pass element (Q1) for operation between 2.7V to 13.2V. It offers inrush-current limiting as well as dual overcurrent fault protection, which consists of a fast U1 response for high-amplitude circuit faults, and a slow U1 response for low-amplitude, non-continuous overcurrent conditions.

Figure 3. An IC-based hot-swap circuit:



(a) offers better accuracy and other improvements,



(b) Note the limiting of I_{LOAD} in a scope plot of the start-up waveforms .

The Figure 3 circuit has continuous current monitoring, as does that of Figure 2. The IC-based version, however, has better initial accuracy and better temperature performance than does the discrete version. The pnp transistor in Figure 2 has a typical V_{BE} drift of 2mV/° C, producing an approximate output change of ±120mV for temperature excursions within the range -40° C to 85° C, starting from 25° C. U1 in Figure 3, on the other hand, exhibits maximum drifts of ±6.5mV and ±20mV for the slow and fast current-limit comparators.

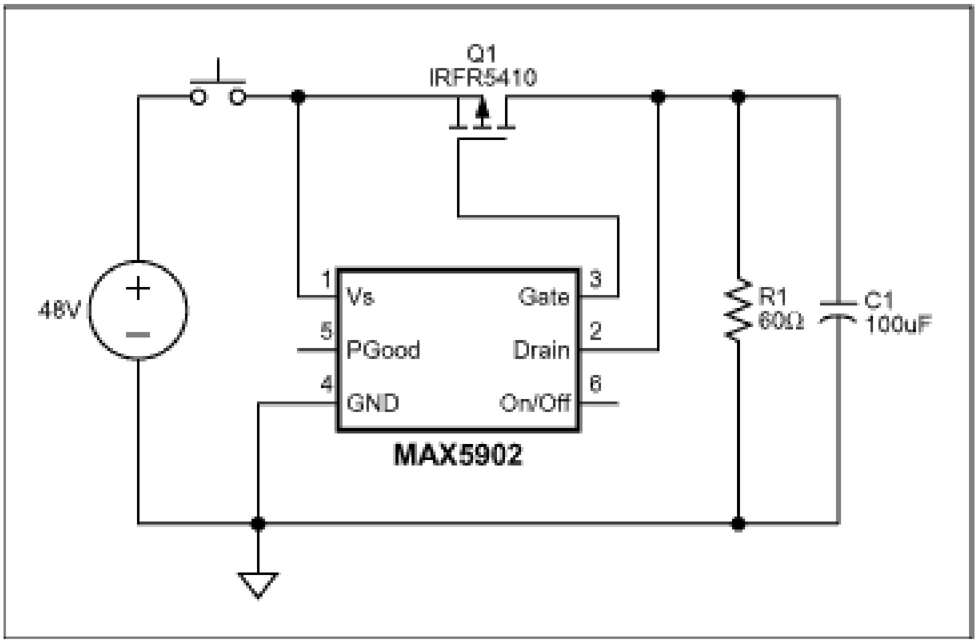
Transistors seldom specify V_{BE}, but U1 has a voltage trip point that is well defined and much lower (50mV_{TH}, which is one-twelfth that of V_{BE} at 0.6V). The result is a smaller sense resistor with less power loss. Moreover, the IC-based circuit does what the Figure 1 and 2 circuits cannot:

- utilize lower-cost n-channel MOSFETs
- provide a status output
- respond to low- and high-level fault conditions
- provide a power-control pin (ON) suitable for load control or for pin detection with dual card insertion

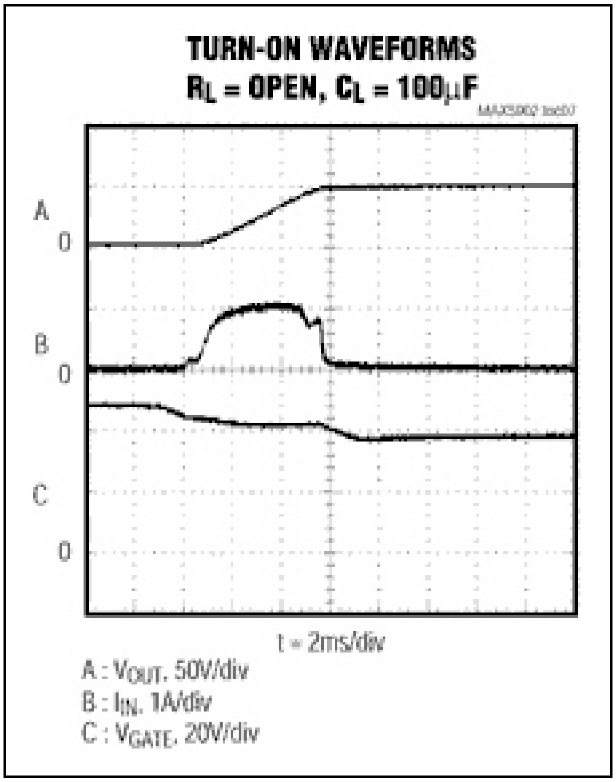
U1 in Figure 3 also acts as a circuit breaker by latching load power off when a fault is detected. If you require auto-retry or 15V inductive-kickback protection, you can substitute a MAX4272 or MAX4273 hot-swap controller for U1.

High voltage, IC-based hot-swap circuits offer many features, including the space saved by substituting a SOT23 package for a discrete circuit. A SOT23-sized controller (Figure 4) operates from 9V to 72V and requires only one external p-channel MOSFET (Q1) for basic operation. The circuit does not require a current sense resistor to limit in-rush current or detect fault conditions. Instead, it employs as a current-sense element the $Rds_{(on)}$ of a p-channel MOSFET (Q1).

Figure 4. A dedicated hot-swap IC:



(a) simplifies the application,



(b) Turn-on waveforms are illustrated at 2ms/div.

U1 keeps the MOSFET off when power is first applied, and maintains that off state indefinitely if the ON/OFF pin is held low, or if the supply voltage is below the undervoltage lockout level, or if the die temperature exceeds +125° C. If none of those conditions apply when the built-in turn-on delay expires (150mS typical), U1 gradually turns on Q1. During this turn-on phase, U1 slowly enhances Q1, allowing voltage on the load (drain of Q1) to rise at a typical rate of 9V/ms.

Inrush current to the load is therefore limited to a level proportional to the load capacitance and the constant slew rate: I_{LIMIT} (typical) = C_{LOAD}*9V/mS. After Q1 is fully enhanced and the load voltage is settled to its final value, the voltage drop across Q1 (I_{LOAD}*$Rds_{(on)}$) is monitored for faults by U1. If the voltage drop exceeds the circuit-breaker threshold, U1 turns Q1 off and immediately disconnects the load.

Unlike discrete-component circuits, that of Figure 4 features thermal-shutdown protection, undervoltage-lockout protection, shutdown via the On/Off pin, and a "Power-Good" status signal. U1 is available with or without a circuit-breaker function, and the circuit breaker is available with either an auto-retry or a latched-off option. To implement a system that accepts -9V to -100V (like -48V Telecom), you should substitute a MAX5900 or MAX5901 hot-swap controller for U1.

IC hot-swap controllers offer many advantages over their discrete counterparts. Though discrete circuits cost less, they may be more costly to the overall system in terms of robustness, down-time and repair costs. Larger primary power supplies, more robust wiring and connectors are just some of the tangible costs associated with the discrete-component approach. Discrete designs also lack a STATUS output, thermal shutdown, undervoltage lock-out, and shutdown (on/off) inputs for load control and for the detection of circuit-board insertion.

A similar version of this article appeared in the Sept. 23, 2002 issue of *Planet Analog* magazine.

More Information

MAX4272: QuickView -- Full (PDF) Data Sheet -- Free Samples
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MAX5900: QuickView -- Full (PDF) Data Sheet -- Free Samples
MAX5901: QuickView -- Full (PDF) Data Sheet -- Free Samples