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TVS Clamping in Hot-Swap Circuits

To guarantee reliability, the server system designer must consider hot-swap circuit parasitics and the associated transient behavior. The designer should use a TVS (transient voltage suppressor) diode clamp at the line card input. Experimental measurements of a typical system provide a basis to examine the key parameters and the major steps in selecting system protection components, such as a TVS diode.

Power systems dedicated to next-generation high-performance blade servers, datacenters, storage and communication infrastructure systems are a group that "feels the need--the need for speed!" Specifically, a secular trend of continually increasing processor clock rates and data throughput is evident. Barring a correction in the voracious global appetite for high bandwidth data, this trend is likely to continue.

Unfortunately, the power consumed by these systems is leveraged dramatically higher in the face of rapidly escalating costs to cool these systems. The emphasis is thus on energy monitoring and savings at the system and facility levels. Also, it becomes imperative to understand the electrical stresses in the system backplane, the connector to the line card, and the line card itself to ensure maximum reliability and maintain continuous uptime in these systems.

To this end, hot-swap controllers[1,2] have become a preferred method to provide highly desirable system protection and electrical management in distributed power systems, particularly to meet the stringent requirements of the server market[3]. The hallmarks of hot-swap controllers in such applications generally include safe control of live board insertions (inrush current control) and removals, fault monitoring diagnostic and protection, and high accuracy electrical (voltage, current, power) and environmental (temperature) parameter measurement to provide real-time system telemetry in analog or digital domains. In particular, if a fault occurs in one line card in a server rack, that fault should remain isolated to that particular line card and impact neither the system backplane nor the other line cards powered from that live backplane. Typically, the hot-swap controller is interfaced to a:

- Pass MOSFET in series with the power path, thus enabling ON/OFF functionality
- Low ohmic shunt for current sensing

Fig. 1 represents the schematic of a line card interface and hot-swap circuit in a typical server system and represents the template for the subsequent discussion. Detailed description of the edge card to backplane connector and the components downstream of the hot-swap circuit is superfluous to this discussion. The hot-swap controller[1] embodied in *Fig. 1* is optimized specifically for power delivery in server and datacenter applications.

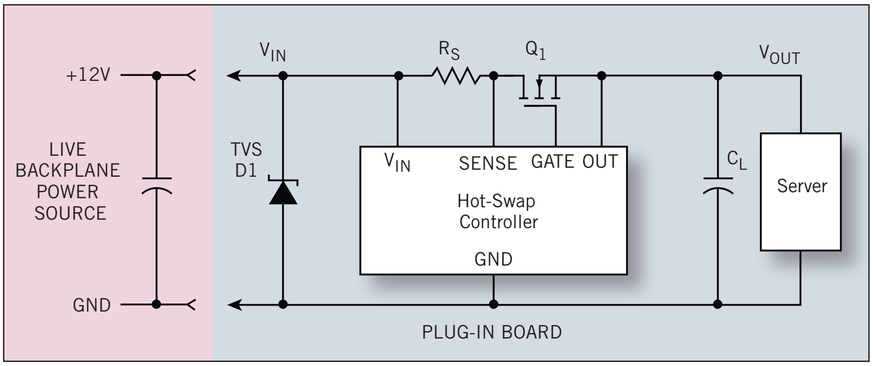


Fig. 1. Typical hot-swap circuit configuration

HOT-SWAP CIRCUIT-BREAKER EVENT

Essentially, the pass MOSFET, Q_1, in *Fig. 1* is rapidly turned off by the hot-swap controller when a fault is detected and current slew rates during current interruption may reach 100A/µs or greater. However, the supply rail bus structure in the input power path inevitably has parasitic inductance (related to the length and inherent loop area of the supply busbars). The energy stored in this inductance will transfer to other elements in the circuit to produce an over-voltage dynamic behavior. The dynamic is most accurately characterized by a resonant transfer of energy from the parasitic inductance to the effective circuit capacitance with damping provided by the resistances (parasitic or otherwise) inherent in the circuit. This is the classic inductive load voltage overshoot governed by Faraday's Law – a potentially destructive voltage transient is created that is often overlooked, yet can systematically compromise the reliability of the hot-swap MOSFET, the hot-swap controller, and downstream circuits.

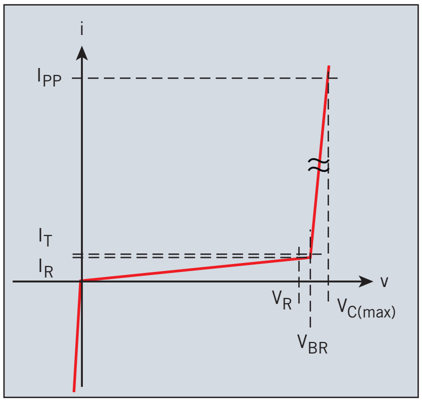


Fig 2. . TVS linearized I–V characteristic curve (unidirectional TVS, cathode terminal defined as positive)

Because it permits the highest possible current to build up before the fault is detected, a zero impedance short-circuit asserted directly across the output of the circuit in *Fig. 1* is especially troublesome. After the short-circuit fault response time, the pass MOSFET is finally commanded off by the hot-swap controller in a "circuit-breaker" event and the forward current is rapidly interrupted.

A voltage clamp is invariably required to limit the over-voltage amplitude. The parasitic energy must be dumped into the clamp when the MOSFET turns off. The unclamped over-voltage peak can be approximated by *Equation 1:*

$$\text{Vin\_peak} = V_{IN} + I_P Z_O \qquad (1)$$

Where:

I_P = Input current before circuit interruption

Z_O = Characteristic impedance of the equivalent LC circuit

It can be argued that while a local input bypass capacitance C_{in} is helpful as it reduces Z_O, it is seldom practical as the pulse of current to charge C_{in} upon card insertion/hot-plug is generally detrimental to the capacitor's reliability. Given the capacitor's location before the hot-swap circuit, it thus represents a system-level reliability concern and is typically not installed.

TVS DIODES IN HOT-SWAP SYSTEMS

To prevent damage to vulnerable downstream components under these conditions, a fast response, unidirectional TVS (Transient Voltage Suppression) silicon diode[4] is connected from V_{IN} to GND in shunt protective configuration as shown in *Fig. 1*. A TVS diode is similar to a zener diode but with optimized die element area and bonding to cater for the large surge current and peak power dissipation that exists during avalanche breakdown (ABD). Electrical testing and screening of the devices also differ given their dissimilar target applications.

In hot-swap applications, the TVS serves primarily as a shunt path to ground for the differential mode current that needs to be interrupted.

The boundaries restricting a TVS in such hot-swap applications are driven by the following parameters:

(1)Electrical

- Stand-off voltage V_R (equal to or greater than the DC or continuous peak operating voltage level);
- Peak pulse power P_{PP} (related to the active p-n junction area);
- Clamping voltage $V_{C(max)}$ at the subjected peak pulse current IP (circuit-breaker event);
- Sharpness of the I–V curve impacting the required voltage overhead;

Table 1: SPECIFICATION AND DETAILS OF A HOT-SWAP CIRCUIT TVS COMPONENT (Littelfuse 5.0SMDJ15A)

RELEVANT TVS PARAMETER	SYMBOL	VALUE	RELATED TVS PARAMETER	SYMBOL	VALUE
Reverse stand-off voltage	V_R, V_{SO} or V_{WM}	15V	Max reverse leakage current / standby current at VR	I_R	5 µA
Breakdown voltage *	V_{BR}	16.7V – 18.5V	Test current at V_{BR}	I_T	1 mA
Max clamping voltage **	$V_{C(max)}$	24.4V	Max peak pulse current at $V_{C(max)}$ using 10/1000µs waveform	I_{PP}	205A
Peak pulse power ***	P_{PP}	5 kW (= $V_{C(max)}$ x I_{PP})	Pulse duration	t_d	
Junction capacitance	C_j	500 pF @ 15V			
Temperature coefficient	α_{VBR} or $\Delta V_{BR}/\Delta T$	0.1% V_{BR} @ 25°C per °C			
Thermal resistance junction-to-lead	$R_{\theta JL}$	15°C/W	Component package		DO-214AB (SMC J-bend)

* V_R = 90% $V_{BR(min)}$. $V_{BR(min)}$ ≃90% $V_{BR(max)}$.

** $V_{C(max)}$ is typically 145% $V_{BR(min)}$ [5].

*** P_{PP} rating is specified at T_A = 25°C and derates linearly from 25°C to 150°C with the 10/1000 µs reference waveform at 0.01% duty cycle repetition rate.

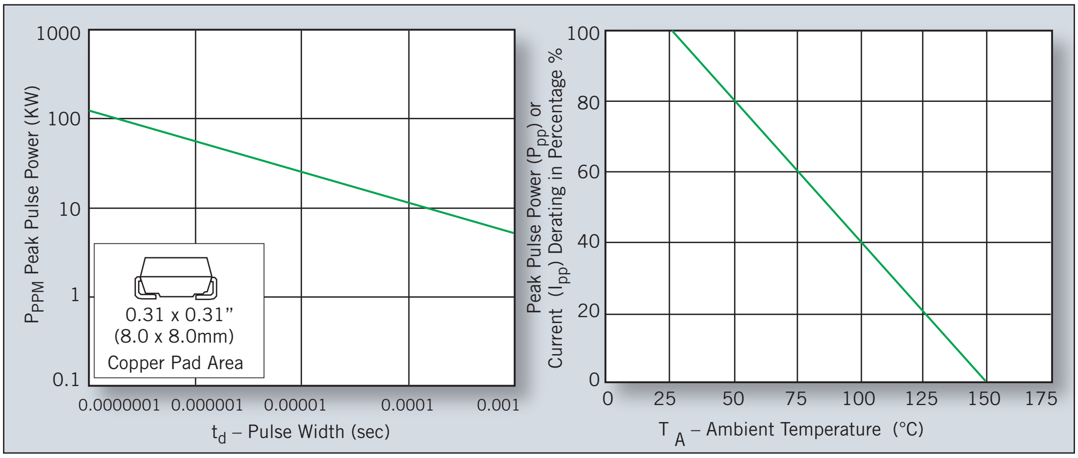


Fig. 3. Littelfuse 5.0SMDJ15A TVS (a) peak pulse power vs. pulse duration, (b) thermal derating characteristic

(2)Mechanical

- Finite available PC board area
- Component form factor (footprint and profile) specification
- Thermal and heatsinking properties

(3)Cost

The relevant parameters of a TVS manufactured by Littelfuse and suitable for protecting the circuit exemplified in *Fig. 1* are presented in *Table 1*. The piecewise linear-approximated I-V characteristic curve of this TVS is depicted in *Fig. 2*. The reverse breakdown voltage, V_{BR}, and standoff voltage, V_R, determine the levels at which the TVS device turns on and turn off (conducting state and high impedance), respectively. The product of the clamping voltage, $V_{C(max)}$, and the rated peak pulse current, I_{PP}, equates to the nominal TVS power rating. The actual clamping voltage for a circuit pulse current of amplitude I_P is given by *Equation (2)*.

$$V_C = I_P\left(\frac{V_{C(max)} - V_{BR}}{I_{PP}}\right) + V_{BR} \qquad (2)$$

The quantity in brackets in this equation is the TVS dynamic impedance, R_d, during ABD. Note that a TVS with higher power rating will provide higher I_{PP} for a given $V_{C(max)}$ and will thus have lower dynamic impedance. So, if a sharper knee is required, it can be advantageous to select a larger TVS than that ordinarily required based solely on peak power specifications. Particularly relevant TVS figure-of-merits (FOM) are the clamping factor, $C_F = V_{C(max)}/V_{BR}$, and the voltage clamping ratio, $V_{C(max)}/V_R$.

The typical double exponential 10/1000ms test waveform (10 µs being the front time and 1000 µs being the fall time to one-half peak value) with which TVS P_{PP} ratings are typically specified is based on a late 1960s Bell labs specification. The pulse is a non-repetitive one-shot event or, at worst, repetitive with very low duty cycle (e.g. 0.01%) such that the die's thermal equilibrium time constant enables the die to cool back to the ambient temperature before the next pulse arrives. The specification with pulse durations other than the 10/1000µs reference can be derived using the P_{PP} vs td curve, an example of which is shown in *Fig. 3a*[4]. This is recognized as the characteristic Wunsch-Bell log-log plot[5] where, for pulse durations up to approximately 1 ms, P_{PP} and t_d are related as specified by *Equation (3)*. As expected, the TVS can sustain higher peak power levels for shorter pulse widths.

$$P_{PP} = \frac{CK}{\sqrt{t_d}} \qquad (3)$$

Where:

C = Constant of proportionality related to the size of the TVS

P_{PP} and I_{PP} ratings during ABD are generally proportional to TVS junction die size so devices with differing P_{PP} ratings will normally scale vertically along the power axis while retaining the same negative slope as in *Fig. 3a*. The factor K is dictated by the current waveform shape and is based on the energy, e-- see *Equation (4)*-- or the area under the current waveform over the pulse duration. Triangular, double exponential, and half-sine wave pulses have K fac-

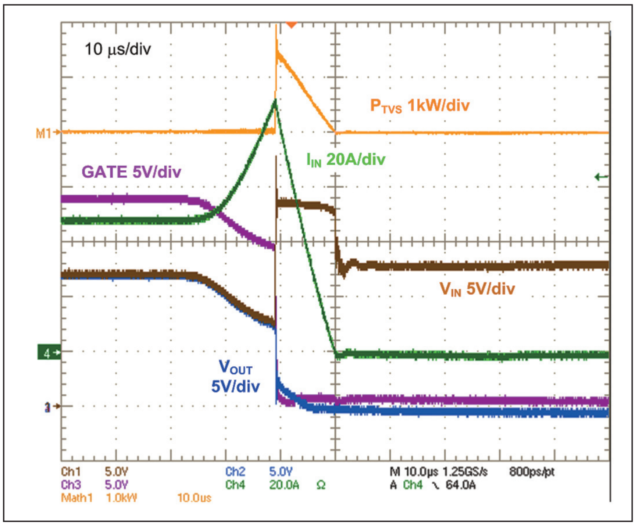


Fig. 4. Scope waveforms of a hot-swap circuit-breaker event induced by an output short-circuit

tors of 2, 1.5, and 1.33 times that of a square wave pulse, respectively[5]. Thus, a TVS with triangular wave current has a P_{PP} vs t_d curve scaled 1.33 times higher than the datasheet curve referenced with a 10/1000 µs waveform.

$$e = V_C \int_0^{t_d} i_{TVS}(t)\,dt \qquad (4)$$

The time for the current in the TVS to fall to zero, tp, in a hot-swap circuit implementation is governed by the circuit parasitic inductance, L, as specified by *Equation (5)*. As the current decay is linear, the current waveform is triangular and given by *Equation (6)*.

$$t_p = \frac{LI_P}{V_C - V_{IN}} \qquad (5)$$

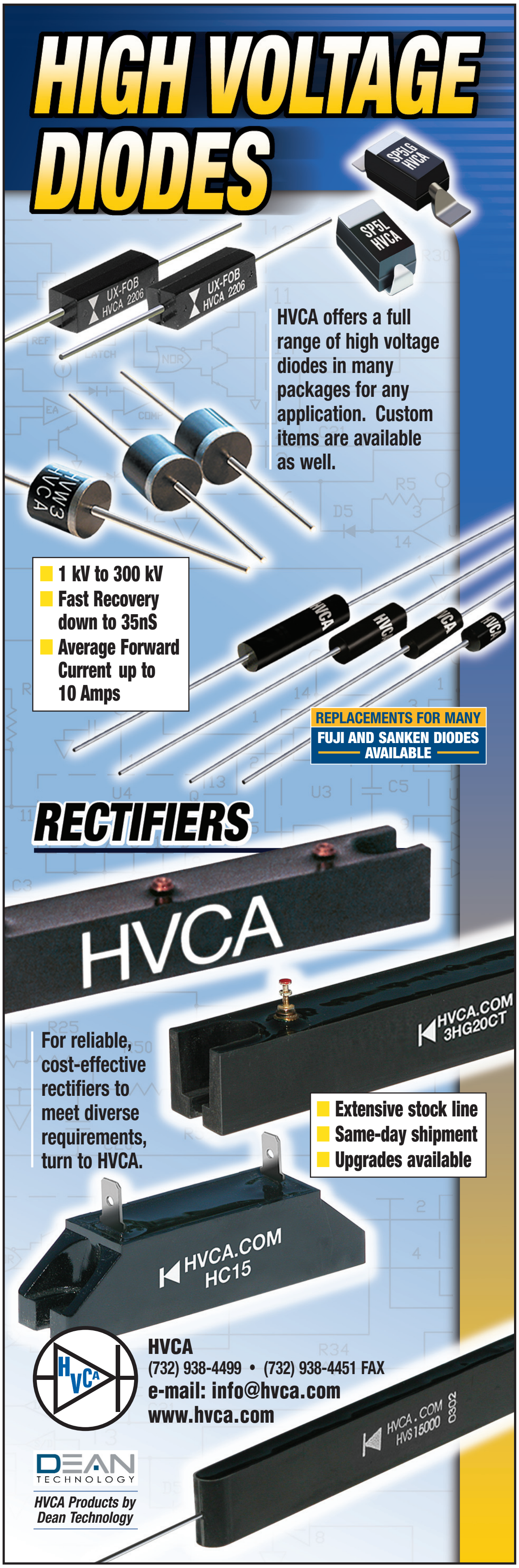
$$i_{TVS}(t) = -\frac{I_P}{t_p}t + I_P, \quad 0 \le t \le t_p \qquad (6)$$

Shown in *Fig. 3b* is the P_{PP} thermal derating with increasing ambient temperature. It is important to bear in mind that the PCB to which the (surface-mount) TVS is soldered acts as a primary method of heatsinking. As such, the TVS can leverage the copper polygons, planes and thermal vias that are already available in the motherboard PCB layer stack-up to improve its thermal characteristics.

TVS SELECTION PROCEDURE

A judiciously chosen TVS for a hot-swap circuit application is obtained (iteratively) as follows:

1. Select a unidirectional TVS with standoff voltage, V_R, equal to or greater than the DC or continuous peak operating bus voltage level. A 14V or 15V TVS is appropriate for a low impedance 12VDC ±10% server system input bus.
2. Determine the peak pulse current level, I_P, based on the hot-swap controller circuit breaker threshold voltage, its response time, and the chosen shunt resistor.
3. Using Equation (2), calculate the circuit clamp voltage, V_C, given the I_P level derived from step 2 and the relevant datasheet parameters. Is V_C low enough? If not, the alternative is to use a larger TVS to obtain a sharper knee.
4. Find the product of V_C and I_P to get the actual peak power level sustained by the TVS.
5. Using Equation (5) and knowing the input parasitic inductance, determine the pulse duration, t_d, of the triangular pulse waveform (i.e. time to decay to zero).
6. Derate P_{PP} for the pulse duration in step 5 using a plot akin to *Fig. 3a*. As mentioned previously, the triangular pulse current waveshape enables 33% higher pulse power relative to the double exponential reference waveform curve.
7. Derate P_{PP} for ambient temperature using a plot akin to *Fig. 3b*. The mutual heating effect from adjacent components should also be considered.
8. Does the net derated P_{PP} from step 7 provide adequate design margin (at least 50%) over the actual TVS



peak power calculated from step 4? If not, choose a larger TVS and repeat steps 1-8.

EXPERIMENTAL RESULTS

Let's consider a practical implementation based on the LM25066 hot-swap controller evaluation board[1] with an input voltage range of 12V±10%. From the previous discussion, it is recognized that high current slew rates coupled with parasitic inductances in series with the input path could cause potentially destructive transients to appear at the V_{IN} and SENSE pins of the LM25066 following a turn-off command to the pass MOSFET. A 15V Littelfuse TVS, 5.0SMDJ15A, is connected across the input as close to the IC as possible. With a 0.5 mΩ shunt, the LM25066 provides an active current limit at 50A (25 mV current limit threshold voltage) with a fast-acting circuit breaker function at 90A (45 mV circuit breaker threshold voltage). The relevant current and voltage waveforms during a short circuit are illustrated in the scope waveforms of *Fig. 3*.

As the input current increases from its initial steady-state level of 45A during the short-circuit event, the supply rail impedance causes the input voltage to sag. When the input current reaches 90A, the pass MOSFET turns off (green current trace). The input voltage has an initial spike due to parasitic trace inductance but quickly gets clamped by the TVS at approximately 18V. Given the TVS dynamic impedance, the clamp voltage reduces slightly as the TVS current decreases towards zero. The time for the TVS current to ramp to zero, 11 ms, is the pulse duration, td, for TVS selection. From *Equation (5)*, the current slew rate and the clamping voltage of 18V indicate that the series parasitic inductance is 1.1 μH and its peak stored energy at 90A is hence 8.9 mJ. This energy also corresponds to the area under the TVS instantaneous power waveform in *Fig. 4*.

A TVS should be considered an essential circuit component in high current systems, enabling increased robustness and reliability during transient circuit events.

REFERENCES

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