Quick Guide on Automotive Load Dump Protection (ISO 16750-2) – Part 1

Understanding ISO 16750-2 Load Dump Pulses and TVS Diode Calculation for Automotive Protection

1. INTRODUCTION

Electric and non-electric vehicles have increasingly incorporated electronic features to enhance both performance and comfort. With recent technological advances, these devices, modules, and components have continued to shrink in size—a desirable characteristic that, however, can also make them more vulnerable to unexpected electrical surge events.

ISO 16750-2 describes in detail several types of electrical transients that can occur in automotive systems. Among the various defined pulses, this document focuses on the load dump event, designated as Test A and Test B (ISO 7637-2 names this pulse 5a and 5b, however these pulses were removed from the document to refer to ISO 16750-2 pulse definitions; it's worth noting that is still a common practice in the industry to name load dump pulse as "Pulse 5"). Load dump is characterized as a discontinuity in supply voltage condition caused by the unexpected disconnection of the battery from the supply circuit while the system is energized.

Among the available solutions for mitigating surge events, the transient voltage suppressor (TVS) diode is almost always present. Whether used as the primary protection element or as part of a multistage protection scheme, TVS diodes are considered essential in circuits operating at higher voltages. They provide an initial clamping action or supplementary protection in conjunction with other devices, limiting overvoltage stress on low voltage modules and secondary circuits.

In this application note, a practical methodology for automotive load dump protection is presented, focusing on the selection of a suitable TVS diode capable of withstanding ISO 16750-2 load dump transients. The guide explains the key parameters required for TVS diode selection, including reverse working voltage, clamping voltage, peak pulse current, and peak pulse power, and demonstrates how to evaluate compliance with ISO 16750-2 Test A and Test B conditions. By applying these design principles, engineers can improve the robustness, reliability, and surge immunity of automotive electronics, including ECUs, DC-DC converters, power distribution modules, and other vehicle electronic systems exposed to high-energy load dump events.

2. WHAT IS AUTOMOTIVE LOAD DUMP AND HOW DOES A LOAD DUMP EVENT DAMAGE ELECTRONICS?

Load dump is a type of transient event that occurs in automotive electrical systems when the alternator is supplying current to charge the battery and the latter is abruptly disconnected, either by accidental disconnection, corroded terminals, poor connection or degraded cables. This sudden abrupt loss of connection results in a rapid overvoltage transient that can damage multiple loads and electronic modules that remain connected to and powered by the alternator, as illustrated in Figure 1.

The key parameters required to characterize and protect systems against load dump events are the ***Surge Voltage (V_p) and the Pulse Duration (t_d)***. The pulse amplitude depends primarily on the alternator speed and the level of field excitation when the battery is disconnected. The pulse duration further contributes to the severity of the event, as it subjects electronic components to sustained overvoltage stress. Depending on the system voltage, the load dump pulse duration can range from approximately 350ms in 24V systems to up to 400ms in 12V systems, significantly challenging the power handling capability of protection devices during this transient.

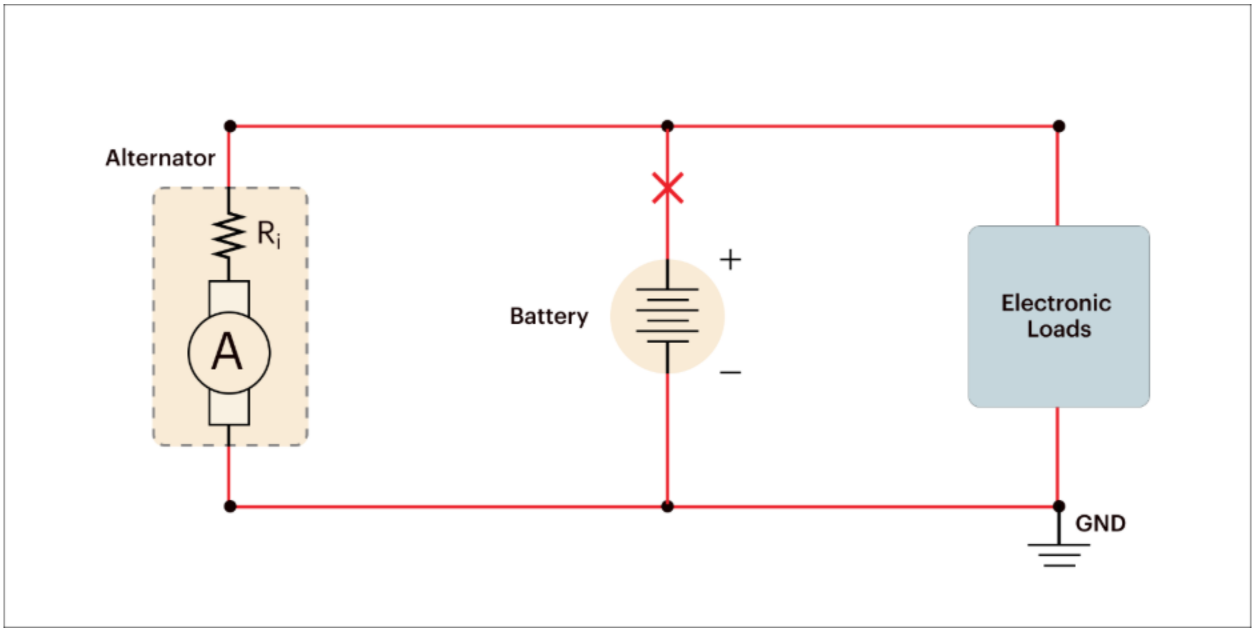
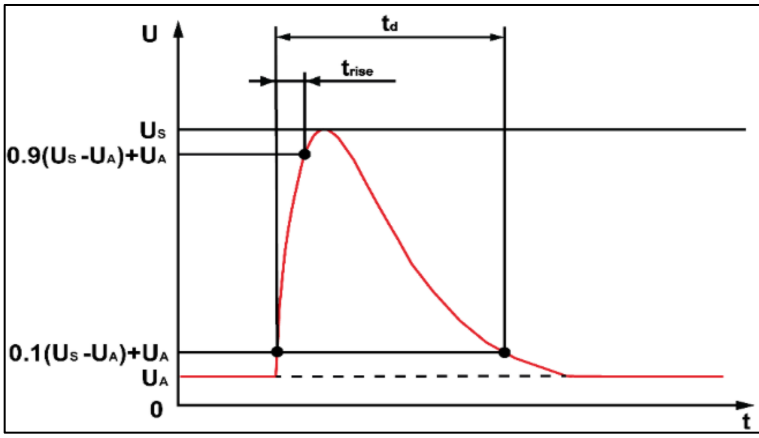


Figure 1: Load Dump transient caused by battery disconnection

3. ISO 16750-2 TEST A AND TEST B EXPLAINED: WAVEFORMS AND TEST CONDITIONS

Automotive applications demand high reliability and safe operation. To address this, standards such as ISO 16750-2 define robust test conditions intended to simulate undesirable electrical transients that the circuit must be able to withstand through additional protection. Compared with ISO 7637-2 which established lower voltage amplitudes and individual (non-repetitive) pulse test, ISO 16750-2 has more stringent conditions; emphasizing the need for careful and robust protection strategies to prevent damage and ensure long term system reliability.



Key

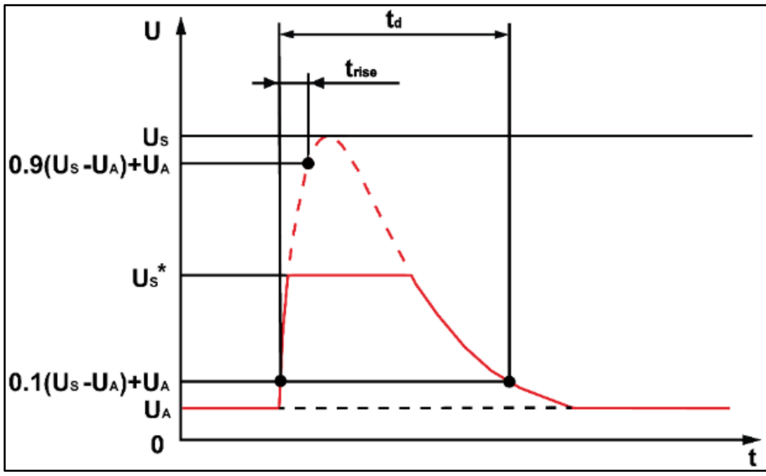
- t time, in seconds
- U test voltage, in volts
- t_d duration of pulse, in seconds
- t_{rise} rising slope, in seconds
- U_A supply voltage for alternator in operation, in volts (see ISO 16750-1)
- U_s supply voltage, in volts

Parameter	Type of system		Minimum test requirements
	UN = 12V	UN = 24V	
U_s [a] [V]	$79 \le U_s \le 101$	$151 \le U_s \le 202$	10 pulses at 1 min intervals
R_i [a] [Ω]	$0.5 \le R_i \le 4$	$1 \le R_i \le 8$	
t_d [ms]	$40 \le t_d \le 400$	$100 \le t_d \le 350$	
t_{rise} [ms]	10 (+0/-5)		

a If not otherwise agreed, use the upper voltage level with the upper value for internal resistance or use the lower voltage level with the lower value for internal resistance.

Figure 2: Test conditions for Test A under ISO 16750-2

Test A in ISO 16750-2 specifies the parameters for the transient without centralized suppression with a minimum of 10 pulses at the specified interval. Amplitude can reach peak values of up to 101V for 12V systems and 202V for 24V systems.



Key

- t time, in seconds
- U test voltage, in volts
- t_d duration of pulse, in seconds
- t_{rise} rising slope, in seconds
- U_A supply voltage for alternator in operation, in volts (see ISO 16750-1)
- U_s supply voltage, in volts
- U_s^* supply voltage with load dump suppression, in volts

Parameter	Type of system		Minimum test requirements
	UN = 12V	UN = 24V	
U_s [a] [V]	$79 \le US \le$	$151 \le US \le 202$	5 pulses at 1 min intervals
U_s^* [V]	Severity 1: 27 Severity 2: 30 Severity 3: 32 Severity 4: 35	As specified by customer (typical value 58 V)	
R_i [a] [Ω]	$0.5 \le R_i \le 4$	$1 \le R_i \le 8$	
t_d [ms]	$40 \le t_d \le 400$	$100 \le t_d \le 350$	
t_{rise} [ms]	10 (+0/-5)		

a If not otherwise agreed, use the upper voltage level with the upper value for internal resistance or use the lower voltage level with the lower value for internal resistance.

Figure 3: Test conditions for Test B under ISO 16750-2

For Test B, the pulse shape and parameters are given according to an alternator with centralized load dump suppression, where for 12V systems the maximum surge voltage is described as Severity 4, (US = 35V), however, the exact value depends on the alternator technology, vehicle architecture, and any customer-specified severity levels. The minimum requirement for Test B is five pulses at a one-minute interval.

4. KEY TVS SELECTION PARAMETERS FOR AUTOMOTIVE LOAD DUMP PROTECTION

The first step in selecting a suitable protection device is to define the minimum requirements the TVS diode must meet to withstand load dump transients. The following section summarizes the key TVS parameters.

Reverse Standoff Voltage or Reverse Working Maximum Voltage (V_{RWM})

The reverse working maximum voltage or reverse working maximum voltage is defined as the highest voltage the TVS diode can withstand in reverse bias without entering breakdown. This value must exceed the normal operating voltage of the system. According to ISO 16750-2, the maximum supply voltage (U_{Smax}) reaches 16V for 12V systems and 32V for 24V systems. These values must therefore be considered as the minimum required VRWM accounting for normal supply voltage variations.

Breakdown Voltage (V_{BR})

This is the voltage at which the TVS begins to conduct significantly, allowing it to clamp the surge and protect downstream circuitry. It lies between the *reverse working maximum voltage (V_{RWM})* and the *clamping voltage (V_C)* and should be chosen above the maximum expected supply variations to avoid false triggering while ensuring fast response in this kind of transient.

Clamping Voltage (V_C)

This parameter represents the voltage level seen by the protected circuit during a surge event; therefore, it must remain below the maximum allowable limit of the circuit to prevent system failure or the need for more robust and typically more costly components. Typical tolerance limits are approximately 37V–40V for linear regulators and 40V–60 V for DC-DC converters.

Peak Pulse Current (I_{PP})

The maximum current that the TVS diode can safely conduct for a specified surge waveform before thermal overload or failure occurs is called the *peak pulse current* (I_{PP}). This is a critical selection parameter as TVS devices typically fail due to excessive current rather than excessive voltage.

Peak Pulse Power (P_{PP})

Finally, the surge absorbing capability of the selected device must be verified by ensuring that its rated power and pulse duration are matched to the surge conditions. This ensures the device can reliably withstand the event; where applicable, power derating should be applied.

AEC-Q101 Qualification

AEC-Q101 is the automotive qualification standard for discrete semiconductors. TVS diodes qualified to AEC-Q101 have been validated for thermal, mechanical, and electrical reliability, making them suitable for automotive applications such as load dump protection, ECU protection, and power distribution systems.

These conditions allow for an initial screening of multiple part numbers and serve as guidance for the proper selection of the protection device. With these criteria established, the following TVS calculation can be performed, conducted to ensure compliance with ISO 16750-2, specifically for load dump pulses Test A and B.

Figure 4 illustrates the characteristic curve of a unidirectional TVS diode and shows the relationship between the key selection parameters discussed in this section, *including Reverse Working Maximum Voltage (V_{RWM}), Breakdown Voltage (V_{BR})*, and *Clamping Voltage (V_C).* Understanding how these parameters interact is essential when selecting a TVS diode for automotive load dump protection, as they directly influence the device's ability to remain inactive during normal operation while providing effective surge suppression during transient events.

The following overview is intended to support the load dump selection process presented in this application note. Readers seeking a more detailed explanation of TVS diode operation, characteristic curves, protection mechanisms, and parameter definitions are encouraged to refer to MCC's article, "Understanding TVS Diodes: A Comprehensive Guide."

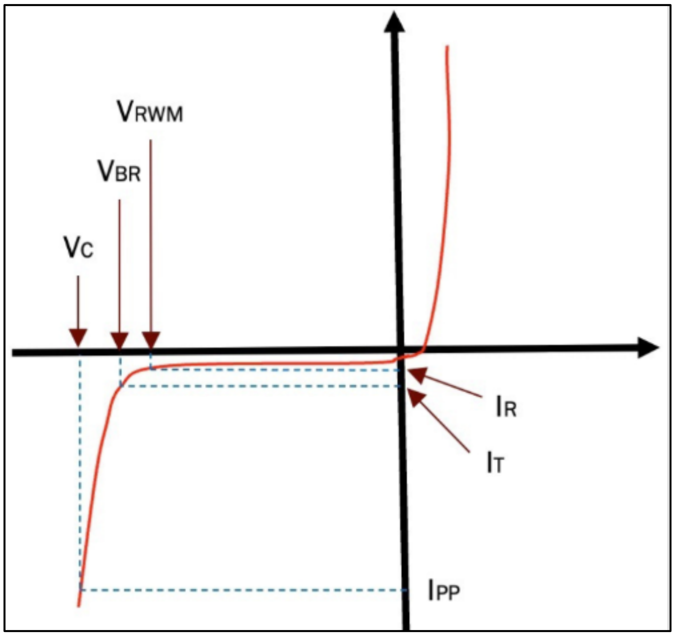


Figure 4: Unidirectional TVS – Characteristic curve

5. STEP-BY-STEP TVS SELECTION EXAMPLE FOR ISO 16750-2 PULSE 5A (12V SYSTEM)

Test conditions

This calculation uses the upper voltage level and the maximum internal resistance as defined in ISO 16750-2 for the Load Dump pulse. For a nominal 12 V system (U_N), the parameters considered are a surge voltage of 101V (V_S), pulse duration of 400ms (t_d), and the upper internal resistance value of 4Ω (R_i).

System (U_N)	Supply Voltage (Vs)	Alternator resistance (Ri)	Duration of pulse (td)
12 V	101 V	4 Ω	400 ms

The maximum ambient temperature for this application is 105°C. For the maximum value of clamped voltage, we will consider 35V (V_C), which is a typical high input voltage for voltage regulators and DC-DC converters in automotive design.

1. Minimum V_{RWM}

The *reverse working maximum voltage* must account for battery voltage fluctuations. According to ISO 16750-1, a 12V system can experience variations up to 16V; therefore, this value is used as the minimum required V_{RWM}

2. Calculate I_{PP}

To calculate the *peak pulse current* due to the surge across the TVS we will use $Eq.$ (1):

$$I_{PP} = \frac{V_P - V_C}{R_i} = \frac{101V - 35V}{4\Omega} \rightarrow I_{PP} = 16.5\,A \tag{1}$$

Where V_P is the *load dump surge voltage*, V_C is the *maximum clamping voltage* and R_i is the *internal resistance* from the alternator.

3. Obtain P_{PP}

The *peak pulse power* across the protection device will be estimated considering the maximum V_C established and the calculated I_{PP} from the previous step:

$$P_{PP} = V_C * I_{PP} = 35V * 16.5A \rightarrow P_{PP} = 577.5\,W \tag{2}$$

4. Calculate pulse duration (t_p)

Most protection-device datasheets define a pulse with (t_d), measured from 10% of the peak value and up to the point where decays to 50% of the *peak pulse current* (I_{PP}) as shown in Figure 5. This is the pulse shape used to measure peak-power pulse for all pulse widths shown in Figure 6.

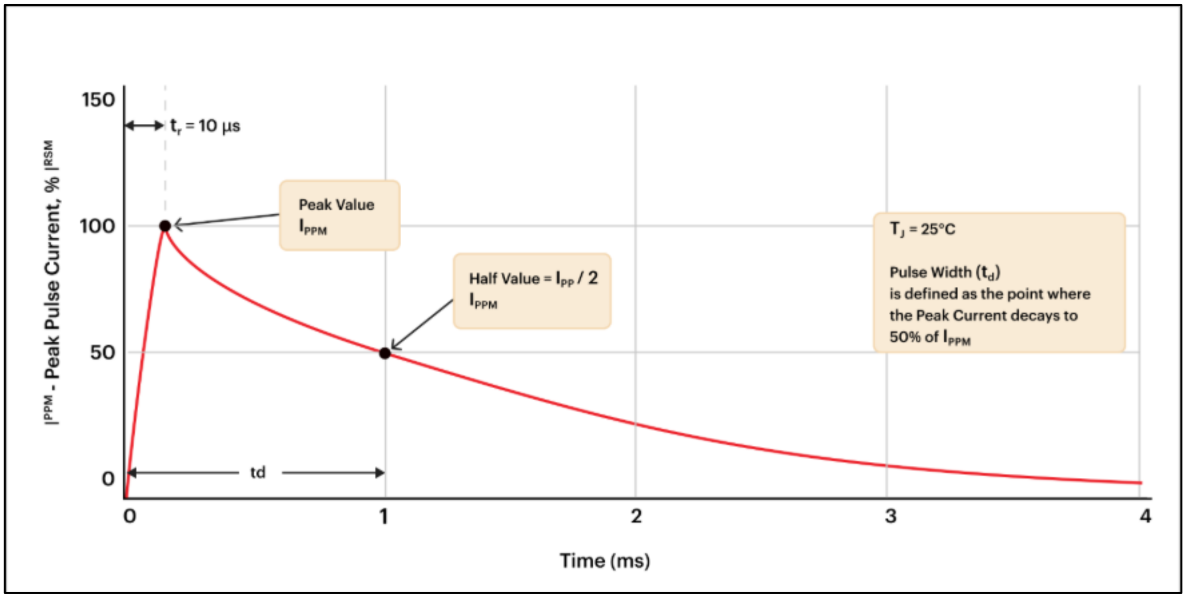


Figure 5: Pulse Waveform – Peak Pulse Current

To align with the pulse-width definition shown in Figure 5, we need to find the load dump pulse duration at 50% of the *peak pulse current* (***I_{PP}***). This adjusted pulse duration is then used for power matching in the TVS selection process. For the calculation of this duration, we will use the equation of exponential decreasing voltage *Eq.* (3) similar to the discharge stage of a capacitor.

$$v(t) = V_0 * e^{-\frac{t}{RC}} \quad (3)$$

Where $v(t)$ is the *decreasing voltage across the TVS diode*, ***V_0*** represents the *surge voltage* and ***RC*** the *constant of the equivalent circuit to discharge*. Fixing to fit the TVS parameters, we get:

$$v(t) = V_P * e^{-\frac{t}{\tau}} \quad (4)$$

By replacing ***t*** with the pulse duration ***t_d***, the resulting equation becomes:

$$v(t_d) = V_P * 10\ \% = V_P * e^{-\frac{t_d}{\tau}} \quad (5)$$

Where 10% is the voltage percentage from which we measure the transient duration.

$$V_P * 10\,\% = V_P * e^{-\frac{t_d}{\tau}} \quad (6)$$

Dividing by V_P on both sides of the equation, we obtain:

$$10\% = e^{-\frac{t_d}{\tau}} \quad (7)$$

This expression is then solved to determine the time constant τ. Here we use t_d = 390ms, considering 10ms of rise time for the load dump pulse (as *Eq*. (3) only considers the decaying portion of the pulse)

$$\tau = -\frac{t_d}{\ln(0.1)} = -\frac{390ms}{\ln(0.1)} \rightarrow \tau = 169ms \quad (8)$$

Subsequently, to describe the decrease in current, we apply *Eq.(9)*.

$$i(t) = \frac{V_0 * e^{-\frac{t_p}{\tau}}}{R} \quad (9)$$

It is important to note that the protection device will start dissipating the excessive voltage once the surge exceeds the breakdown value of the TVS, therefore the subtraction of this value is added to the previous equation, with the corresponding adaptation of current parameters, as shown below:

$$i(t) = \frac{V_0 * e^{-\frac{t}{\tau}} - V_{BR}}{R} \rightarrow i(t_p) = \frac{V_P * e^{-\frac{t_p}{\tau}} - V_{BR}}{R_i} \quad (10)$$

From Eq.(10), the pulse duration t_p is solved as below:

$$i\,(t_p) * R_i = V_P * e^{-\frac{t_p}{\tau}} - V_{BR} \rightarrow i(t_p) * R_i + V_{BR} = V_P * e^{-\frac{t_p}{\tau}}$$

$$\frac{R_i * i(t_p) + V_{BR}}{V_P} = e^{-\frac{t_p}{\tau}}$$

$$\ln\left(\frac{R_i * i(t_p) + V_{BR}}{V_P}\right) = \ln\left(e^{-\frac{t_p}{\tau}}\right)$$

$$\ln\left(\frac{R_i * i(t_p) + V_{BR}}{V_P}\right) = -\frac{t_p}{\tau}$$

$$t_p = -\tau * ln\left(\frac{R_i * i(t_p) + V_{BR}}{V_P}\right) \rightarrow t_p = -\tau * ln\left(\frac{R_i * \frac{I_{PP}}{2} + V_{BR}}{V_P}\right) \quad (11)$$

Lastly, in Eq.(11), ***i(t_p)*** is set equal to corresponding to the 50% peak pulse current used in the pulse width definition, as previously shown in Figure 5. Using Eq.(11) with the known values of τ=169ms, R_i=4Ω, I_{PP}=16.5A, V_P=101V, and using $V_{BR} \approx \frac{V_C}{1.3} = \frac{35V}{1.3} = 26.9$ to estimate the breakdown voltage, the following result is obtained:

$$t_p = -169ms * \ln\left(\frac{4\Omega * \frac{16.5A}{2} + 26.9V}{101V}\right) \rightarrow t_p = 88ms \quad (12)$$

5. TVS power capability

At this stage, the Peak Pulse Power Rating Curve provided for each TVS family is used to select a device suitable for the calculated operating conditions. MCC offers the following Load-Dump-specific TVS series in the DO-218AB package:

- SM5S series (3.6kW): SM5S10AHE3-SM5S43CAHE3(DO-218AB).pdf
- SM6S series (4.6kW): SM6S10(C)AHE3_SM6S43(C)AHE3HE3(DO-218AB).pdf
- SM8S series (6.6kW): SM8S10(C)AHE3_SM8S85(C)AHE3(DO-218AB).pdf
- SM8Z series (8kW): SM8Z10(C)AHE3_SM8Z43(C)AHE3(DO-218AB).pdf

From the MCC catalog, a TVS diode that is AEC-Q101 compliant and qualified for load dump testing is selected. For this analysis, the SM8SXX(C)AHE3 family was chosen. From the corresponding Peak Pulse Power Rating Curve, the suitability of individual part numbers for the application can be evaluated. Then we determine the power capability of the device at the pulse width calculated through *Eq.*(12) obtaining a peak pulse power capability of 2000W at 88ms.

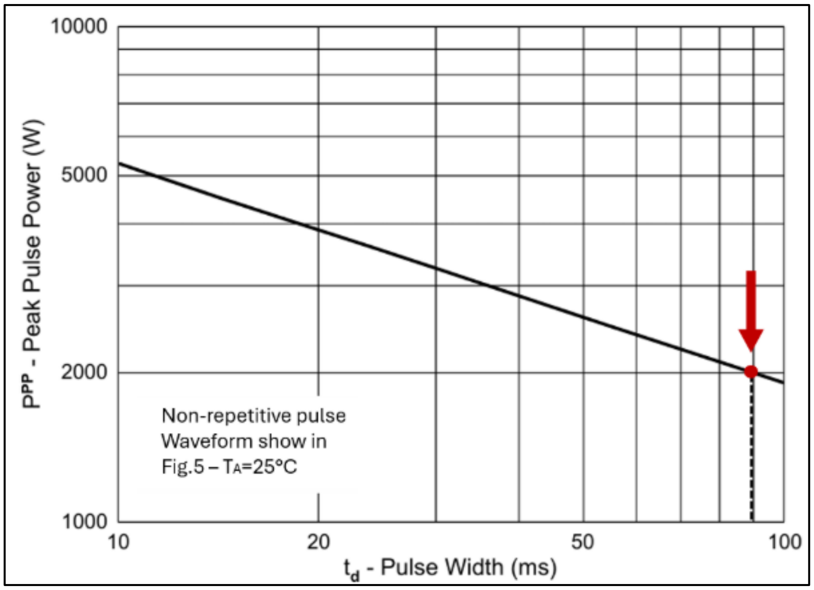


Figure 6: Peak Pulse Power Rating Curve – SM8S10(C)AHE3 THRU SM8S85(C)AHE3

6. Power derating

Increments in temperature impact the power capability of protection devices, thus a power derating must be applied to ensure a more reliable performance of the device. As previously noted, an ambient temperature of 105°C is used for this evaluation.

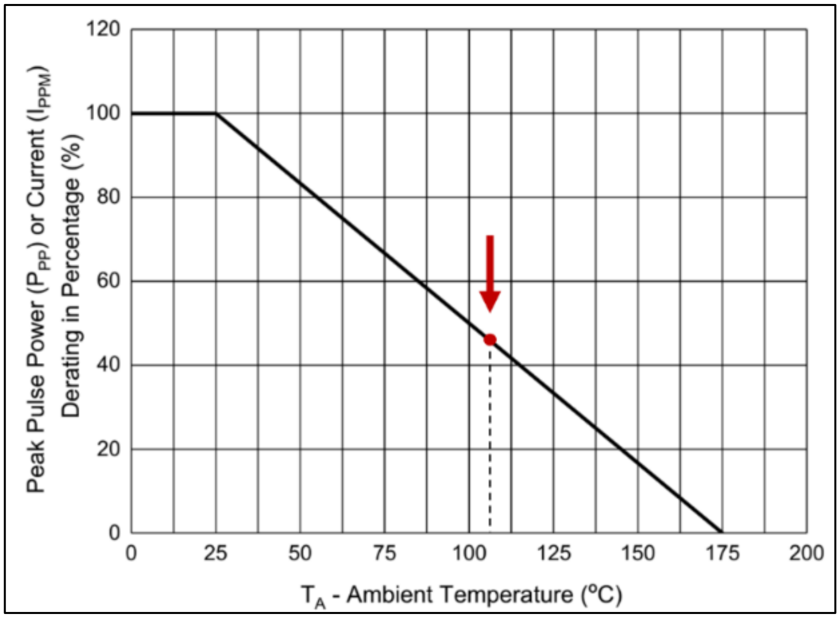


Figure 7: Peak Pulse Derating Curve for Temperature – SM8S10(C)AHE3 THRU SM8S85(C)AHE3

The derating factor is approximately 45**%**; this value is applied to the previously determined peak pulse power to obtain the power capability at the application temperature:

$$P_{PP}\,@105°C = P_{PP}\,@25°C * 45\% = 2000W * 45\% \rightarrow P_{PP}\,@105°C = 900W \quad (12)$$

After applying power derating, the resulting $\boldsymbol{P_{PP}}$ @105°C remains higher than the peak pulse power calculated from Eq. (2) (577.5W) which represents the power dissipated across the TVS during the transient event. Based on this result, the calculation could be considered complete, as the protection device operates within a safe operating area even after temperature derating. Nevertheless, an additional step is included to further enhance robustness and provide an extra margin of protection.

7. Component reliability on application

As discussed in one of the application notes, "Enhancing Data Center Uptime with TVS Diodes in Hot-Swap Controllers" a successful protection strategy requires the TVS device to support a 50% safety margin over the peak pulse power (calculated in *Eq.* (2). Accordingly,

$$P_{PP}\,@105°C > 1.5\,P_P \quad (14)$$

Substituting values in *Eq.* (14) we get:

$$900\ W > (1.5 * 577.5\ W) \rightarrow 900\ W > 866.3\ W \quad (15)$$

At this stage, it can be observed that the TVS family selected to protect against transient events in automotive applications, specifically the load dump, fulfills the power requirements to operate safely not only with the energy during the event but also with an additional margin as recommended for ensuring long-term reliability on our devices.

6. CONCLUSION

Load dump is one of the most severe transient events encountered in automotive electrical systems, with surge amplitudes that can exceed 100V and durations lasting hundreds of milliseconds. As demonstrated throughout this application note, proper TVS diode selection requires more than simply choosing a device with a suitable voltage rating. Parameters such as *Reverse Working Maximum Voltage* (V_{RWM}), *Breakdown Voltage* (V_{BR}), *Clamping Voltage* (V_C), *Peak Pulse Current* (I_{PP}), *Peak Pulse Power* (P_{PP}), and AEC-Q101 qualification must all be considered to ensure reliable protection against ISO 16750-2 Test A and Test B load dump conditions.

Using the step-by-step calculation presented for a 12V automotive system, the selected SM8S22CAHE3 TVS diode was shown to satisfy the voltage, current, power, temperature derating, and reliability margin requirements associated with the load dump transient. This methodology provides a practical approach for engineers designing automotive ECUs, DC-DC converters, power distribution modules, and other electronic systems exposed to high-energy surge events.

However, analytical calculations alone do not fully describe the dynamic behavior of a TVS diode during a real load dump event. In Part 2 of this series, we will validate the calculation results using SPICE simulation and experimental test data. The simulation will illustrate the transient voltage, clamping behavior, peak pulse current, and power dissipation of the selected TVS diode under ISO 16750-2 load dump conditions, allowing a direct comparison between theoretical calculations and real-world device performance.

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