Introduction

The transient voltage suppressor (TVS) is an avalanche diode specially designed to clamp overvoltage and dissipate high transient power. TVS must be selected in two ways:

1. Check that the circuit operating conditions do not exceed the specified limit of the component.
   - For non-repetitive surge operation
   - For repetitive surge operation
   - For normal operation

2. Check that the maximum value of the clamped voltage under the worst conditions corresponds to the specification of the circuit to protect.
1 Review of TVS characteristics

1.1 Stand-off voltage

$V_{RM}$ is the maximum voltage that TVS can withstand in normal operation. Normal operating voltage must be lower than $V_{RM}$.

1.2 The breakdown voltage or knee voltage

$V_{BR}$ is the voltage value above which the current in TVS increases very fast for a slight increase in voltage. The breakdown voltage $V_{BR}$ is specified at 25 °C and its temperature coefficient is positive.

1.3 The clamping voltage

$V_{CL}$ as specified in the datasheets is the maximum value for a “standard” current pulse with a peak value of $I_{PP}$ (Figure 2), specified for any type of TVS. If TVS is subjected to a different exponential pulse duration, the value of $V_{CL}$ can be calculated using the application note AN575 or getting the dynamical resistance with the curve given in ST TVS family datasheets “Dynamic resistance versus pulse duration”.

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**Figure 1. Electrical characteristics - parameter definitions**

- $V_{RM}$: Maximum stand-off voltage
- $I_{RM}$: Maximum leakage current @ $V_{RM}$
- $V_R$: Stand-off voltage
- $I_R$: Leakage current @ $V_R$
- $V_{BR}$: Breakdown voltage @ $I_{BR}$
- $I_{BR}$: Breakdown current
- $V_{CL}$: Clamping voltage @ $I_{PP}$
- $I_{PP}$: Peak pulse current
- $R_D$: Dynamic resistance
- $V_F$: Forward voltage drop @ $I_F$
- $I_F$: Forward current
- $\alpha_T$: Voltage temperature coefficient

**Figure 2. Pulse definition for electrical characteristics**

- $V_R$
- $V_{BR}$
- $V_{CL}$
- $I_{PP}$
- $I_{BR}$
- $I_F$
- $V_F$
- $R_D$
- $I_{PP}$
- $I_F$
- $V_F$
- $R_D$
- $I_{PP}$
- $I_F$
- $V_F$
- $R_D$
- $I_{PP}$
- $I_F$
- $V_F$
- $R_D$
TVS peak power dissipation

TVS goal is to protect equipment against transient disturbances. The duration of these transients is linked to the application where the TVS operates. For example, electrostatic discharge (ESD) durations are in the range of tens of nanoseconds while other surges durations can vary from tens of microseconds for industrial application, to hundreds of microseconds for telecom and even tens of milliseconds for automotive standards.

TVS performances are given in the datasheet for both 8/20 µs and 10/1000 µs waveforms ($V_{CL}$, $I_{PP}$). Additionally, the peak pulse power versus pulse duration curve (see Figure 3) allows the designer to select the right TVS for the specific pulse duration of her/his application.

**Figure 3. Maximum peak pulse power versus exponential pulse duration for SMB15F series**

- Peak pulse power calculation versus exponential pulse duration

\[ P_{PP} = V_{CL} \times I_{PP} \]  

(1)

If the initial temperature exceeds 25 °C, a power derating is applied in accordance with the curve of Figure 4, which is available for all TVS datasheets.

**Figure 4. Maximum peak power dissipation versus initial junction temperature for SMB15F series**

Peak power capability at 175 °C remains at high level: $P_{PP} = 1080$ W (72% of peak power at 25 °C).

If the current through the TVS is not exponential, the diagrams of Figure 5 gives the multiplication factor to calculate the equivalent exponential pulse duration.

For example, to get equivalent exponential pulse duration of a rectangular surge, the square duration needs to be divided by 1.4.
Figure 5. Pulse duration equivalence factors for same power dissipation

- **Exponential**
  - $L = 1$
  - $t = 0.5$

- **Rectangular**
  - $L = 1.4L$

- **Sawtooth**
  - $L_{si} = 1.4L$

- **Sinusoidal**
  - $L_s = 2.2L$
3 TVS average power dissipation

In repetitive operation, the specification to be considered is average power ($P_{AV}$). It is calculated (Eq. (2)) from the surge frequency ($f$) and the energy dissipated during each pulse ($W$).

$$P_{AV} = f \times W$$  \hspace{1cm} (2)

The junction temperature ($T_j$) calculated from this average power should never exceed the specified maximum junction temperature. This temperature is calculated (Eq. (3)) from the thermal resistance ($R_{th(j-a)}$), ambient temperature ($T_{amb}$) and average power ($P_{AV}$), exactly like for a rectifier diode.

$$T_j = T_{amb} + R_{th(j-a)} \times P_{AV}$$  \hspace{1cm} (3)
4 How to size a TVS

4.1 Non-repetitive surges

Let's take an example: a source (V1) with a rated voltage of 28 V supplies equipment E, which has to be protected against overvoltages. This source is subjected to random non-repetitive exponential overvoltage with an amplitude of 200 V and a duration of 8 ms (td) at 10% of peak voltage (standard wave - see Figure 6). The equivalent internal impedance Z of the surge source is 13 Ω.

The maximum ambient temperature is 125 °C. In no circumstance, equipment E must be subjected to a voltage higher than 55 V.

![Figure 6. Protected equipment and surge](image)

4.1.1 TVS selection

We assume that supply voltage V1 = 28 V varies by ±15%, i.e. between around 23.8 V and 32.2 V. The protection voltage $V_{RM}$ of the TVS should then be greater than or equal to 32.2 V.
4.1.2 Predetermination of the peak power $P_{PP}$ and $t_p$ value

Equipment $E$ cannot withstand a voltage above 55 V so $V_{CL} \leq 55$ V.

Assuming that there is a TVS that meets this criterion, an initial calculation of the TVS power can be made:

$$P_{PP} = V_{CL} \times I_P$$

$$P_{PP} = \frac{V_P - V_{CL}}{Z} = \frac{200 \text{V} - 55 \text{V}}{13 \Omega} \approx 11 \text{A}$$

$$P_{PP} = 55 \text{V} \times 11 \text{A} = 605 \text{W}$$

(4)

This power corresponds to an operating temperature of 125 °C. The datasheets indicate the power at 25 °C, so we have to correct the power according to the curves of admissible power versus initial temperature (Figure 4):

- at 125 °C, power capability is around 1280 W, so ratio is
  $$\frac{1280 \text{W}}{1500 \text{W}} = 0.85$$

To estimate the $t_p$ value (definition in Figure 2), we need to define by calculations the current through TVS during the pulse. These calculations have been developed in Section Appendix A. We obtain $t_p = 2$ ms.

From calculated $P_{PP}$ (Eq. (4)) and $t_p$ values (Section Appendix A) and with “Maximum peak pulse power versus exponential pulse duration” curve given in each TVS family, we can check the suitable TVS family with the calculated peak power.

From Figure 3 and $t_p = 2$ ms, SMB15F maximum power capability is 950 W at 25 °C. Applying the derating for the temperature gives $P_{PP} = 950 \text{W} \times 0.85 = 808 \text{W}$ at 125 °C.

SMB15F is suitable for this application example, as dissipated peak power at 125 °C is equal to 605 W.

Note: The SMB6F power capability is lower than 400 W for $t_p = 2$ ms and $T_j = 125$ °C, therefore it is not suitable in this example.

4.1.3 Selection of the TVS

We can now establish an initial specification of the TVS to use.

- $V_{RM} \geq 32.2$ V
- $V_{CL} \leq 55$ V for $I_p = 11$ A
- $P_{PP}$ (125 °C) = 605 W for $t_p = 2$ ms, corresponding to:
  $$P_{PP} (25 °C) = \frac{605 \text{W}}{0.85} = 712 \text{W}$$

(5)

The ST TVS type corresponding to these characteristics is the SMB15F33A.

Below its characteristics:

- Power capability: 1500 W at 10/1000 µs exponential current waveform
- $V_{RM} = 33$ V
- $V_{BR}$ min. = 36.7 V
- $V_{BR}$ typ. = 38.6 V
- $V_{BR}$ max. = 40.5 V
- $V_{CL}$ max. = 53.3 V for $I_{pp} = 29$ A at 10/1000 µs exponential current waveform
- $R_D$ max. = 0.441 Ω at 10/1000 µs exponential current waveform
- $\alpha_T = 10.10^{-4} °C$
4.1.4 Determination of the clamping voltage $V_{CL}$

To determine $V_{CL}$ at $I_P = 11$ A, we use the equation:

$$V_{CL} = V_{BR} + R_D \cdot I_P$$

$R_D$ can be estimated using the Figure 7. Dynamic resistance versus pulse duration curves.

![Figure 7. Dynamic resistance versus pulse duration](image)

For SMB15F33A, typical $R_D$ value for $t_P = 2$ ms is $0.3 \, \Omega$.

$$V_{CL\, \text{typ.}} = V_{BR\, \text{typ.}} + R_D\, \text{typ.} \atop {\text{at} \ t_P = 2 \, \text{ms}} \times I_P = 38.6 \, V + 0.3 \, \Omega \times 11 \, A = 41.9 \, V \quad (6)$$

We can calculate the maximum clamping voltage with:

- Maximum $R_D$ value: twice the typical value (as shown with 10/1000 µs typical and maximal $R_D$ value given in datasheet)
- Maximum $V_{BR}$ given in datasheet

$$V_{CL\, \text{max.}} = V_{BR\, \text{max.}} + R_D\, \text{max.} \atop {\text{at} \ t_P = 2 \, \text{ms}} \times I_P = 40.5 \, V + 2 \times 0.3 \, \Omega \times 11 \, A = 47.1 \, V \quad (7)$$

4.1.5 Temperature correction

The maximum clamping voltage at maximum ambient temperature 125 °C is:

$$V_{CL\, T_j} = V_{CL\, 25^\circ C} \times \left(1 + aT \times (T_j - 25^\circ C)\right)$$

Maximum $V_{CL\, (125^\circ C)} = 47.1 \times (1 + 10.10^{-4} \times (125-25)) = 51.8 \, V$, below the 55 V limit.

SMB15F33A is suitable in terms of power capability and, during surges, the clamping voltage is lower than the maximum voltage admissible by the circuit to protect, even with the worst case TVS parameters.
4.2 Repetitive surges

In other application, electronic circuits need to be protected against repetitive surges. Let’s take the following example, where we have to protect the transistor shown in Figure 8 with a TVS having clamping voltage $V_{CL}$ that does not exceed 90 V.

![Figure 8. Transistor protection](image)

For this usual topology, each time the transistor turns off, a spike (called later $V_{spike}$) is generated due to the inductive effect. This spike reaches very high voltage value and would damage the transistor if no protection is implemented.

4.2.1 Calculation method

We consider $V_{CL} \approx V_{BR}$ due to low current through TVS in comparison with TVS capability current value. Experience shows that this hypothesis is confirmed in most of the cases with a TVS protecting a switch. Therefore, the TVS should be initially selected according to its thermal characteristics.

$P_{AV}$ is the average power dissipated through the TVS.

An approximated value can be obtained by supposing that the TVS absorbs the whole energy contained in the inductance. This hypothesis is realistic when the ratio $\frac{V_{spike}}{V_{BR}}$ is significant.

Average power is calculated with Eq. (9) for the maximum supply voltage (nominal voltage value + 20% = 12 V + 2.4 V)

$$P_{AV} = \frac{1}{2} \times L \times I^2 \times f = \frac{1}{2} \times 0.3 \times \left( \frac{12V + 2.4V}{45 \Omega} \right)^2 \times 50 Hz = 0.77 W$$  \hspace{1cm} (9)

Let’s try with ST product type SMA6F70A.
4.2.2 First attempt
Below its characteristics:

- Power capability: 600 W at 10/1000 µs exponential current waveform
- $V_{RM} = 70$ V
- $V_{BR \text{ min.}} = 77.9$ V
- $V_{BR \text{ typ.}} = 82$ V
- $V_{BR \text{ max.}} = 86.1$ V
- $V_{CL \text{ max.}} = 113$ V for $I_{PP} = 5.5$ A at 10/1000 µs exponential current waveform
- $R_{D \text{ max.}} = 4.91$ Ω at 10/1000 µs exponential current waveform
- $\alpha T = 10 \times 10^{-4}$/°C
- $R_{th(j-a)} = 150$ °C/W (see Figure 9 below)

Maximum junction temperature $T_j = 175$ °C

Figure 9. Thermal resistance junction to ambient versus copper area under each lead

4.2.2.1 $T_j$ calculation

$$T_j = T_{amb} + P_{AV} \times R_{th(j-a)} = 50 \text{ °C} + 0.77 \text{ W} \times 150 \text{ °C/W} = 165.5 \text{ °C}$$  (10)

This value is compatible with the TVS characteristics as 165.5 °C calculated is lower than 175 °C, maximum junction temperature given in SMA6F datasheet.
4.2.2.2 Determination of the $V_{CL}$

For such a low current level through TVS ($(12 \text{ V} + 2.4 \text{ V}) / 45 \Omega = 0.32 \text{ A}$), clamping voltage is very close to $V_{BR}$ value as shown on Figure 10.

**Figure 10. Maximum clamping voltage versus peak pulse current**

4.2.2.3 Temperature correction

We consider SMA6F70A with $V_{CL} = V_{BR} \text{ max} = 86.1 \text{ V}$.

$$V_{CL}(T_j) = V_{CL}(25^\circ \text{C}) \times (1 + aT \times (T_j - 25^\circ \text{C}))$$  \hspace{1cm} (11)

$V_{CL}(165.5 \ ^\circ \text{C}) = 86.1 \text{ V} \times (1 + 10.5 \times 10^{-4} \times (165.5 \ ^\circ \text{C} - 25 \ ^\circ \text{C})) = 98.8 \text{ V}$

This value $V_{CL}$ is too high. Let's try another TVS.

4.3 Second attempt

To reduce clamping voltage, we need to choose a TVS with a lower $V_{BR}$, while keeping the $V_{RM} \geq 14.4 \text{ V} (12 \text{ V} + 2.4 \text{ V})$.

Let's select then SMA6F58A with below characteristics:

- $V_{RM} = 58 \text{ V}$
- $V_{BR} \text{ max} = 71.4 \text{ V}$
- $aT = 10.4 \times 10^{-4}/\text{^\circ} \text{C}$

$$V_{CL}(T_j) = V_{CL}(25^\circ \text{C}) \times (1 + aT \times (T_j - 25^\circ \text{C}))$$  \hspace{1cm} (12)

$V_{CL}(165.5 \ ^\circ \text{C}) = 71.4 \text{ V} \times (1 + 10.4 \times 10^{-4} \times (165.5 \ ^\circ \text{C} - 25 \ ^\circ \text{C})) = 81.8 \text{ V}$

The SMA6F58A TVS is suitable for this application.
Conclusion

TVS protect ICs against over-voltage and other stresses. From the constraints of the application environment (type of surge, maximum ambient temperature, maximum voltage admissible by circuit to protect,…), this application note shows, through examples, how to size the TVS power capability, to calculate the maximum clamping voltage for both single pulse and repetitive pulses. This allows to choose the correct TVS power family and stand-off voltage.

After, this first step, measurements in the real application conditions are mandatory to confirm that the selected TVS is suitable.
Appendix A  $t_p$ calculation

Pulse duration time is defined with Figure 2. This type of pulse corresponds to most of the standards used for the protection device. This duration time is defined at 50% of exponential peak current through TVS when surge is applied.

From surge voltage definition given in Figure 6 (i.e. $t_d$ defined at 10% of peak), and to simplify, we take into account the exponential decreasing voltage only, given with Eq. (13).

$$v(t) = V_p \times e^{-t/\tau}$$  \hspace{1cm} (13)

We can calculate the constant time Tau ($\tau$) with Eq. (14) and Eq. (15).

$$v(t_d) = 10\% \times V_p = V_p \times e^{-t_d/\tau}$$  \hspace{1cm} (14)

$$\tau = -\frac{t_d}{\ln 0.1} = 8 \text{ ms} \approx 3.47 \text{ ms}$$  \hspace{1cm} (15)

When the surge is applied on the TVS, the current flows through it only when $v(t)$ is higher than $V_{BR}$. Current formula is given by Eq. (16).

$$i(t) = \frac{v(t) - V_{BR}}{Z} = \frac{V_p \times e^{-t/\tau} - V_{BR}}{Z}$$  \hspace{1cm} (16)

where $V_{BR}$ is the breakdown voltage of TVS used and $Z$ is the impedance of surge source. Then, we can calculate the $t_p$ value with Eq. (17) and Eq. (18). For $t_p$ value, $i(t_p) = I_p / 2$

$$i(t_p) = \frac{I_p}{2} = \frac{V_p \times e^{-t_p/\tau} - V_{BR}}{Z}$$  \hspace{1cm} (17)

$$t_p = -\tau \times \ln \left( \frac{Z \times \frac{I_p}{2} + V_{BR}}{V_p} \right) = -3.47 \text{ ms} \times \ln \left( \frac{13 \Omega \times \frac{11}{2} A + 40 \text{ V}}{200 \text{ V}} \right) \approx 2 \text{ ms}$$  \hspace{1cm} (18)

Where $I_p$ is the peak current already calculated (11 A) in Section 4.1.2 and as defined in Section 4.1.1, $V_{BR} = 40 \text{ V}$ (to get $V_{RM} \geq 32 \text{ V}$).
## Revision history

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<td>Previous version</td>
</tr>
<tr>
<td>29-Jul-2014</td>
<td>4</td>
<td>Updated for new products.</td>
</tr>
<tr>
<td>03-May-2021</td>
<td>5</td>
<td>Updated Figure 1, Figure 2, Figure 3, Figure 4 and Section 4. Inserted Section Appendix A. Minor text changes.</td>
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