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".

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

$I_{PP}$: Peak pulse current
$V_{RM}$, $V_{BR}$: Breakdown voltages
$V_{CL}$: Clamping voltage
$V_F$: Forward voltage
$I_F$: Forward current
$R_D$: Dynamic resistance
$t_r$, $t_p$: Rise time, Pulse duration time
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 SM15T series

Peak pulse power calculation versus exponential pulse duration

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

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 SM15T series

Peak power capability at 150 °C remains at high level: $P_{PP} = 1250$ W (83% 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**: \( L = 1 \), \( L_R = 1.4 \) L
- **Rectangular**: \( L = 1 \), \( L_R = 1.4 \) L
- **Sawtooth**: \( L_{\text{max}} = 1.4 \) L
- **Sinusoidal**: \( L_{\text{max}} = 2.2 \) L
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 ($W$).

$$P_{AV} = f \times W$$  (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.

$$T_j = T_{amb} + R_{th(j-a)} \times P_{AV}$$  (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 over voltages. 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 60 V.

Figure 6. Protected equipment and surge

| V1 = 28 V |
| Tamb = 125 °C |
| Rs surge = 13 Ω |
| Equipment max. voltage = 60 V |
| Vp = 200 V |
| 10% Vp = 20 V |
| td = 8 ms |

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 VRM 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 60 V so $V_{CL} \leq 60$ V.

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

$$P_{PP} = V_{CL} \times I_p \text{ where } I_p = \frac{V_P - V_{CL}}{Z}$$

$$P_{PP} = 55 \text{ V} \times 10.8 \text{ A} = 648 \text{ W}$$

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 1440 W, so ratio is
  $$\frac{1440 \text{ W}}{1500 \text{ W}} = 0.96$$

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 the 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, SM15T maximum power capability is 1000 W at 25°C. Applying the derating for the temperature gives $P_{PP} = 1000 \text{ W} \times 0.96 = 960 \text{ W}$ at 125°C.

SM15T is suitable for this application example, as dissipated peak power at 125°C is equal to 648 W.

Note: The SM6T 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
- $V_{CL} \leq 60$ V for $I_p = 10.8$ A
- $P_{PP}$ (125 °C) = 648 W for $t_p = 2$ ms, corresponding to:
  $$P_{PP} (25°C) = \frac{648}{0.96} = 675 \text{ W}$$

The ST TVS type corresponding to these characteristics is the SM15T39A.

Below its characteristics:

- Power capability: 1500 W at 10/1000 μs exponential current waveform
- $V_{RM} = 33.3$ V
- $V_{BR}$ min. = 37.1 V
- $V_{BR}$ typ. = 39 V
- $V_{BR}$ max. = 41 V
- $V_{CL}$ max. = 53.9 V for $I_{pp} = 28$ A at 10/1000 μs exponential current waveform
- $R_D$ max. = 0.461 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 $I_P = 10.8$ 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)

SM15T39A is not plotted on Figure 7. However, we will use the SM15T30A, showing a ratio $= 2$ between $R_D$ at 1 ms and $R_D$ at 2 ms.

Maximum $R_D$ of SM15T39A at 1 ms = 0.461 $\Omega$, so maximum $R_D$ at 2 ms calculation gives 0.922 $\Omega$.

$$V_{CL\;typ.} = V_{BR\;typ.} + R_D\;typ.\;\text{at } t_P = 2\;\text{ms} \times I_P = 41\;V + 0.922\;\Omega \times 10.8\;A = 51\;V \quad (6)$$

4.1.5 Temperature correction

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

$$V_{CL}\left(T_j\right) = V_{CL}(25^\circ\text{C}) \times \left(1 + a_T \times \left(T_j - 25^\circ\text{C}\right)\right) \quad (7)$$

Maximum $V_{CL}(125^\circ\text{C}) = 51 \times (1 + 10.10^{-4} \times (125-25)) = 56.1$ V, below the 60 V limit.

SM15T39A 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.

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. (8) for the maximum supply voltage (nominal voltage value + 20% = 12 V + 2.4 V)

$$P_{AV} = \frac{1}{2} L \times I^2 \times f = \frac{1}{2} \times 0.2 \times \left( \frac{12 V + 2.4 V}{45 \Omega} \right)^2 \times 50 Hz = 0.512 \, W$$

(8)

Let’s try with ST product type SMA6J70A.
4.2.2 First attempt

Below its characteristics:

- Power capability: 600 W at 10/1000 µs exponential current waveform
- $V_{RM} = 70$ V
- $V_{BR}$ min. = 77.8 V
- $V_{BR}$ typ. = 81.9 V
- $V_{BR}$ max. = 86 V
- $V_{CL}$ max. = 110 V for $I_{PP} = 5.5$ A at 10/1000 µs exponential current waveform
- $R_D$ max. = 4.38 Ω at 10/1000 µs exponential current waveform
- $\alpha T = 10.5 \times 10^{-4}$/°C
- $R_{\theta j-a) = 150}$ °C/W (see Figure 9 below)

Maximum junction temperature $T_j = 150$ °C

![Figure 9. Thermal resistance junction to ambient versus copper area under each lead](image)

4.2.2.1 $T_j$ calculation

$$T_j = T_{amb} + P_{AV} \times R_{\theta j-a) = 50}$ °C + 0.512 W x 150°C/W = 126.8°C (9)

This value is compatible with the TVS characteristics as 126.8 °C calculated is lower than 150 °C, maximum junction temperature given in SMA6J datasheet.
4.2.2.2 Determination of the $V_{CL}$

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

![Figure 10. Maximum clamping voltage versus peak pulse current](image)

4.2.2.3 Temperature correction

We consider SMA6J70A with $V_{CL} = V_{BR\ max} = 86\ V$.

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

(10)

$V_{CL}(126.8^\circ C) = 86\ V \times (1 + 10.5 \times 10^{-4} \times (126.8^\circ C - 25^\circ C)) = 95.2\ V$

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 $V_{RM} \geq 14.4\ V$ ($12\ V + 2.4\ V$).

Let’s select then SMA6J58A with below characteristics:

- $V_{RM} = 58\ V$
- $V_{BR\ max} = 71.2\ V$
- $aT = 10.4 \times 10^{-4}/^\circ C$

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

(11)

$V_{CL}(126.8^\circ C) = 71.2\ V \times (1 + 10.4 \times 10^{-4} \times (126.8^\circ C - 25^\circ C)) = 78.8\ V$

The SMA6J58A TVS is suitable for this application.
5 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. (12).

\[
v(t) = V_p \times e^{-t/\tau}
\]

We can calculate the constant time \( \tau \) with Eq. (13) and Eq. (14).

\[
v(t_d) = 10\% \times V_p = V_p \times e^{-t_d/\tau}
\]

\[
\tau = -\ln(0.1) = 3.47 \text{ ms}
\]

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. (15).

\[
i(t) = \frac{v(t) - V_{BR}}{Z} = \frac{V_p \times e^{-t/\tau} - V_{BR}}{Z}
\]

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. (16) and Eq. (17). For \( t_p \) value, \( i(t_p) = I_p / 2 \)

\[
i(t_p) = \frac{I_p}{2} = \frac{V_p \times e^{-t_p/\tau} - V_{BR}}{Z}
\]

\[
t_p = -\tau \times \ln\left(\frac{Z \times \frac{I_p}{2} + V_{BR}}{V_p}\right) = -3.47 \text{ ms} \times \ln\left(\frac{13 \Omega \times \frac{10.8 A}{2} + 40 \text{ V}}{200 \text{ V}}\right) \approx 2 \text{ ms}
\]

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

Table 1. Document revision history

<table>
<thead>
<tr>
<th>Date</th>
<th>Version</th>
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<tbody>
<tr>
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<td>Updated Figure 3, Figure 4, Figure 7, Figure 9. Thermal resistance</td>
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<td>junction to ambient versus copper area under each lead and Figure 10.</td>
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<td>Maximum clamping voltage versus peak pulse current. Minor text changes.</td>
</tr>
</tbody>
</table>
Contents

1 Review of TVS characteristics ................................................................. 2
  1.1 Stand-off voltage .............................................................................. 2
  1.2 The breakdown voltage or knee voltage ............................................ 2
  1.3 The clamping voltage ....................................................................... 2
2 TVS peak power dissipation .................................................................... 3
3 TVS average power dissipation ................................................................. 5
4 How to size a TVS ................................................................................... 6
  4.1 Non-repetitive surges ........................................................................ 6
    4.1.1 TVS selection ............................................................................ 6
    4.1.2 Predetermination of the peak power $P_{PP}$ and $t_{P}$ value ............ 7
    4.1.3 Selection of the TVS .................................................................. 7
    4.1.4 Determination of the clamping voltage $V_{CL}$ ............................. 8
    4.1.5 Temperature correction ......................................................... 8
  4.2 Repetitive surges ............................................................................... 9
    4.2.1 Calculation method ................................................................... 9
    4.2.2 First attempt ............................................................................ 10
  4.3 Second attempt .................................................................................. 11
5 Conclusion ............................................................................................... 12

Appendix A $t_p$ calculation ......................................................................... 13

Revision history ........................................................................................ 14

Contents ....................................................................................................... 15

List of figures .............................................................................................. 16
List of figures

Figure 1. Electrical characteristics - parameter definitions .................................................. 2
Figure 2. Pulse definition for electrical characteristics ........................................................... 2
Figure 3. Maximum peak pulse power versus exponential pulse duration for SM15T series ............ 3
Figure 4. Maximum peak power dissipation versus initial junction temperature for SM15T series .......... 3
Figure 5. Pulse duration equivalence factors for same power dissipation .................................... 4
Figure 6. Protected equipment and surge ............................................................................. 6
Figure 7. Dynamic resistance versus pulse duration ................................................................. 8
Figure 8. Transistor protection ............................................................................................... 9
Figure 9. Thermal resistance junction to ambient versus copper area under each lead ................... 10
Figure 10. Maximum clamping voltage versus peak pulse current ............................................ 11