

An Introduction to Transient Voltage Suppression Devices

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APPLICATION NOTE

INTRODUCTION

Transient Voltage Suppression (TVS) protection devices such as shielded cables, crowbars, filters and clamping devices have been widely used for a number of years to solve EMI problems. These TVS devices can be used to achieve higher EMI higher immunity levels without significantly adding to the cost and complexity of the circuit. The attributes of traditional TVS devices will be compared to the features of a relatively new option, the avalanche diode TVS EMI filter. Recent advancements in IC manufacturing technology provide the TVS diode with several technical and cost advantages compared to traditional EMI devices.

Background

Transient surge voltages are a major cause of poor reliability. Surge voltages can also cause erratic behavior in control circuits and effect the normal operation of electronics. Transient surge voltages can usually be attributed to:

- Sudden load changes in adjacent circuits
- Power source fluctuations
- Coupled electronic disturbances via cables

- Opening or closing of switch contacts
- Lightning
- ESD

The power supply and data cables are common entry points for conducted and coupled transient surge voltages. In many systems, a common power supply is shared by a number of electronic modules. The modules are also connected to each other through communication buses that are often located in the same wire bundle as the power lines. The parasitic cable capacitances and inductances provide a path for the power line surge voltages to be coupled into the data lines.

TVS Protection Options

TVS devices can be categorized as a cable, crowbar, clamping or filter device. Figure 1 provides a schematic representation of the TVS devices. Each TVS option has unique advantages and disadvantages that are summarized in Table 1. Many systems use a combination of TVS devices to create a protection circuit that combines the advantages of the different TVS options.

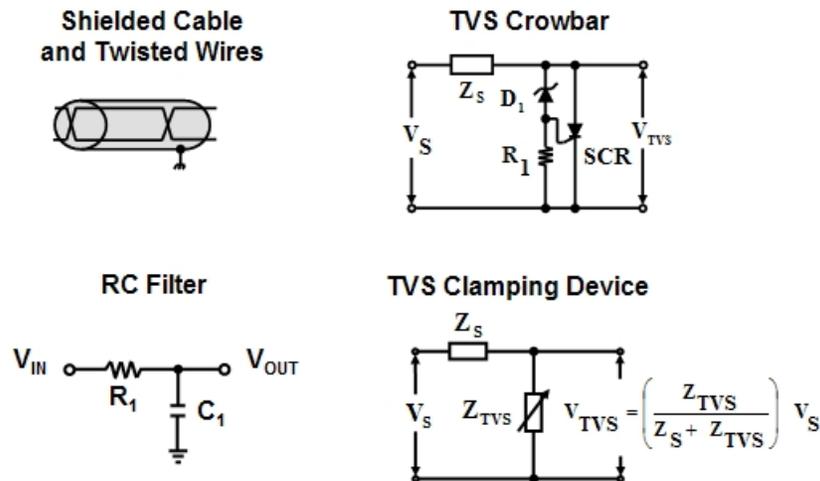


Figure 1. TVS Protection Devices

Table 1. Attributes of TVS Protection Devices

Device	Advantages	Disadvantages
Shielded Cable and Twisted Wires	<ul style="list-style-type: none"> • Increase RF Immunity • Decrease Emissions 	<ul style="list-style-type: none"> • Cost • Capacitance Increases
Crowbars	<ul style="list-style-type: none"> • High Power Rating • Shunt Surge Current to GND 	<ul style="list-style-type: none"> • Do Not Absorb Energy • Difficult to Turn "Off"
Filters	<ul style="list-style-type: none"> • Continuous Noise Filtering • Attenuate Surge Voltage 	<ul style="list-style-type: none"> • Do Not Clamp Surges • May Distort Data Line Signal
TVS Clamping Devices	<ul style="list-style-type: none"> • Clamp Surge Voltage • Fast Turn-On Time (< 1.0 ns) 	<ul style="list-style-type: none"> • Limited Power Rating • Power Rating \propto Capacitance

Shielded Cable and Twisted Wire Pairs

Figure 2 provides an example of a communication system that uses a shielded cable with a twisted wire pair. A shield is an effective tool to prevent EMI problems that arise when the wires connecting multiple electronic modules are exposed to a high noise environment. Shielded cables prevent radiated RF interference from introducing a noise voltage on the signal wires. A shield also reduces the RF

noise that a cable emits. The disadvantage of shielded wire is that the capacitance and cost of the cable increases.

In general, the cable should be connected to ground at only one end for low frequency noise and at both ends for high frequency noise. In addition, the shield should be connected to chassis ground rather than signal ground to minimize the noise induced on the PCB. Reference [5] provides further details on shielded cables.

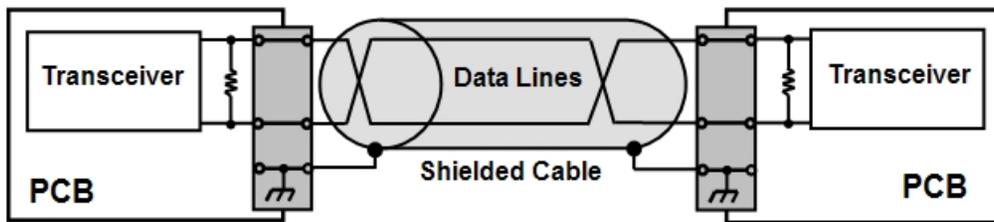


Figure 2. Shielded Cable with Twisted Wire Pairs

Additional noise immunity can be provided by using a twisted wire pair cable, as shown in Figure 3. Twisted wire pairs are an effective noise reduction tool for both differential and common mode noise. Differential mode noise occurs when the signals induced on the wires travel in opposite directions. Twisted wires reduce the loop area and enable the cancellation of the magnetic fields produced by

the current flow. Common mode noise occurs when the noise currents travel in the same direction and return to ground via the parasitic capacitance (C_p) on each data line. Twisting the wires together balances the amount of noise that is induced on each line, which enhances the common mode rejection ratio (CMRR) of the transceiver.

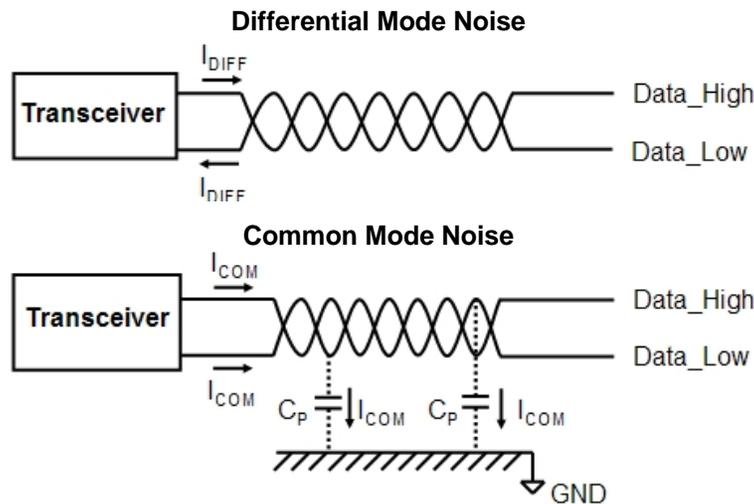


Figure 3. Differential Mode versus Common Mode Noise

Crowbar TVS Devices

Spark gaps, gas discharge tubes (GDTs), thyristors and thyristor surge protective devices (TSPDs) are TVS devices that are capable of attenuating very large surge currents. When these devices are switched “ON”, the protected circuit is connected to ground through a very low impedance switch. The energy of the transient event must be absorbed

by either the source or line impedance and the circuit will not be functional while the TVS device is “ON”. Crowbars are difficult to turn “OFF” and often require an additional commutation circuit, especially in a DC system. Figure 4 shows a schematic representation of the crowbar devices. Table 2 provides a summary of the features of several common crowbar devices.

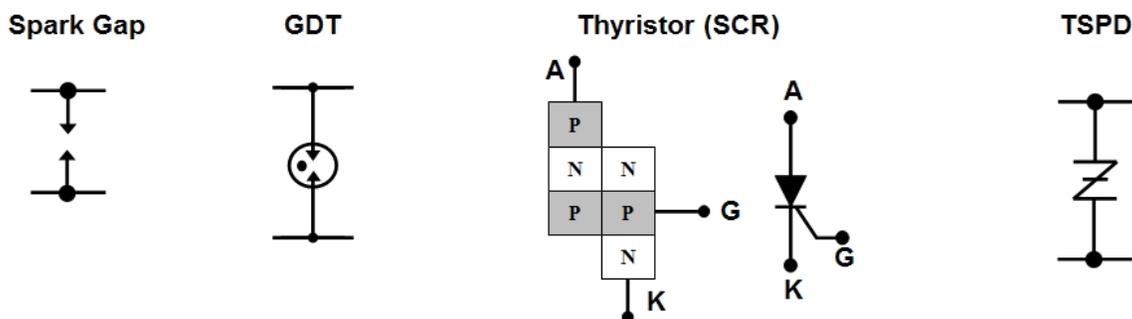


Figure 4. Examples of TVS Crowbar Devices

Spark gaps are constructed from two carbon block electrodes that are connected to the signal line and ground. The electrodes typically are separated by an air gap of 3 to 4 mils. The surge voltage causes an arc to form that shunts the transient voltage to ground. GDT devices are similar to spark gaps; however, they are constructed with a glass or ceramic tube that contains an inert gas which ionizes and conducts during a transient event. If a voltage across the device reaches the breakdown or sparkover voltage, the gas ionizes and the device “fires”. At this point, the GDT provides low impedance and remains in the “ON” state until the voltage falls below the holdover voltage.

Thyristors are constructed with four layers of P- and N-type semiconductor material. A thyristor surge protection device can be created by combining a SCR and a Zener diode, where the Zener is used to control the gate terminal’s turn-on voltage. TSPD devices are another popular thyristor option for surge protection. TSPDs are a two terminal bidirectional device that has a junction capable of handling very high surge currents. Thyristors have a current and voltage curve that has “snap back”, where the break over or trigger voltage is relatively high, while the clamping voltage is relatively low after the device turns-on. Thyristors remain in the “ON” state until the surge current falls below the holding current value.

Table 2. Attributes of Crowbar TVS Protection Devices

Device	Advantages	Disadvantages	Applications
Spark Gaps	<ul style="list-style-type: none"> • Low Cost • High Surge Current 	<ul style="list-style-type: none"> • Variable V_{br} • Short Service Life 	<ul style="list-style-type: none"> • Power Line Meters • Telecommunications
Gas Discharge Tubes (GDTs)	<ul style="list-style-type: none"> • High Surge Current • High “OFF” State Impedance 	<ul style="list-style-type: none"> • High Cost • Slow Turn-On Time • High V_{br} 	<ul style="list-style-type: none"> • Telecommunications • Lightning Protection
Thyristors	<ul style="list-style-type: none"> • Solid-State Reliability • No Life Limit 	<ul style="list-style-type: none"> • Difficult to Turn “OFF” • Medium Turn-On Time 	<ul style="list-style-type: none"> • Telecommunications • Lightning Protection
Thyristor Surge Protective Devices (TSPDs)	<ul style="list-style-type: none"> • Solid-State Reliability • 2-Terminal Device 	<ul style="list-style-type: none"> • Lower Surge Current Rating than GDT or Spark Gap • Moderate Capacitance 	<ul style="list-style-type: none"> • Telecommunications • Lightning Protection • Power Line Crossover Protection

Filter TVS Circuits

EMI filter TVS devices are available in a number of options. The most popular configuration is a low pass filter. A low pass filter attenuates the magnitude of a surge pulse by limiting the slew rate of the signal. Filters do not clamp the voltage; thus, it typically is necessary to add a clamping device such as an avalanche TVS diode to ensure that the

maximum voltage rating of the protected circuit is not exceeded. The main advantage of filters is that they reduce noise signals during the normal operation of the system. In contrast, crowbar and clamping devices are activated only during the transient event. Table 3 provides a summary of the features of several common TVS filter devices.

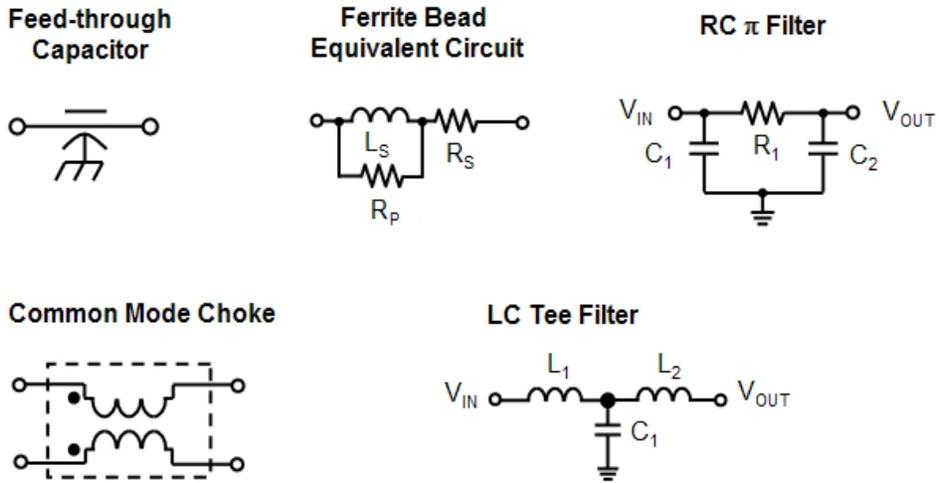


Figure 5. Examples of EMI Filter Devices

Figure 5 provides examples of several common TVS filter device options. The filter device options include feed-through capacitors, filter connectors, ferrite beads, resistor-capacitor (RC) filters, inductor-capacitor (LC) filters and common mode chokes. EMI filters are available in different circuit options, including π and tee filter configurations that offer the advantage of attenuating a noise signal that is both entering and exiting the filter network. For example, in the RC filter shown in Figure 5, R_1 and C_2 form a filter that attenuates the high frequency signals entering the network via the cable, while R_1 and C_1 attenuates the high frequency noise that is exiting the network. In other words, R_1 and C_2 reduce the susceptibility to RF and conducted noise entering the PCB, while R_1 and C_1 reduce the emissions leaving the PCB.

Feed-through capacitors and filter connectors are typically mounted on the case of the module and shunt a high frequency noise signal to chassis ground. These devices filter the noise signal before the signal reaches the PCB.

Filter connectors are available in a number of circuit configurations and the most popular type is a tee filter made with a feed-through capacitor and two ferrite beads. A ferrite bead is a series filter device that provides high frequency attenuation with a small resistive power loss at DC. At low frequencies, ferrites provide a resistance of 50 to 200 Ω , while at high frequencies they function as an inductor whose impedance increases with frequency.

A common mode choke is an effective device for filtering high-speed differential data lines. The common mode choke, shown in Figure 6, attenuates the noise that is common to both of the data lines. Chokes function by providing high impedance for common mode signals and low impedance for differential signals. A choke filter increases the CMRR of the transceiver and provides filtering without adding a large amount of distortion on high-speed data lines. A TVS device can be added to a choke to provide clamping protection for differential surges, such as an ESD event that occurs on only one of the two data lines.



Figure 6. Common Mode Chokes

Table 3. Attributes of TVS Filter Devices

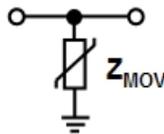
Device	Advantages	Disadvantages	Applications
Feed-Through Capacitors	<ul style="list-style-type: none"> Filters before PCB Low Ground Impedance 	<ul style="list-style-type: none"> High Cost and Large Size Requires Metal Chassis 	<ul style="list-style-type: none"> Engine Controls Modules with a Metallic Enclosure
Filter Connectors	<ul style="list-style-type: none"> Filters before PCB Low Ground Impedance 	<ul style="list-style-type: none"> High Cost and Large Size Requires Metal Chassis 	<ul style="list-style-type: none"> PCs Engine Controls
Ferrite Beads	<ul style="list-style-type: none"> Low Cost Removes Ringing 	<ul style="list-style-type: none"> Low Current Rating Can Oscillate 	<ul style="list-style-type: none"> High-Speed Data Lines USB
RC / LC Filters	<ul style="list-style-type: none"> Low Cost Provides Series Resistance 	<ul style="list-style-type: none"> Does Not Clamp Surges Can Oscillate 	<ul style="list-style-type: none"> Data Lines Power Lines
Common Mode Chokes	<ul style="list-style-type: none"> High Common Mode Attenuation Low Distortion 	<ul style="list-style-type: none"> High Cost Relatively Large Size 	<ul style="list-style-type: none"> USB FireWire (IEEE 1394)

Voltage Clamping TVS Devices

Metal oxide varistors (MOVs), polymers, Zener diodes and TVS avalanche diodes are popular voltage clamping TVS devices. Clamping devices dynamically adjust their impedance in order to maintain a constant voltage. At low voltages below their breakdown voltage, they can be modeled

as a very large resistance in parallel with a capacitance. If the surge voltage exceeds the breakdown voltage, the resistance of the device decreases in order to maintain a constant clamping voltage. Figure 7 shows a schematic representation of the voltage clamping TVS device.

Polymer and MOV



Zener Diode



TVS Avalanche Diode

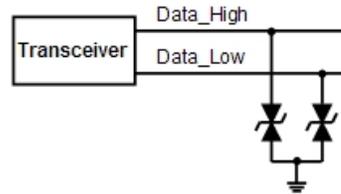
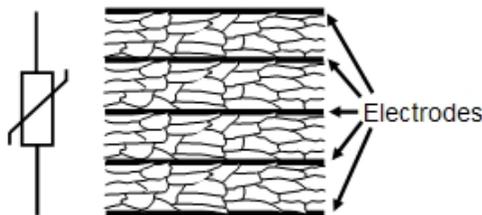


Figure 7. Examples of a Voltage Clamping TVS Device

All of the TVS clamping devices have similar electrical characteristics; however, there are distant differences in their material content. Figure 8 provides a cross-sectional diagram of a MOV and TVS diode. MOVs are constructed by forming a matrix of conductive zinc oxide grains

separated by boundaries, which exhibit similar characteristics to a P-N semiconductor junction. The array of serial and parallel connected grain boundaries function as multiple junctions and the current is distributed through the bulk of the material when a surge event occurs.

MOV



TVS Avalanche Diode

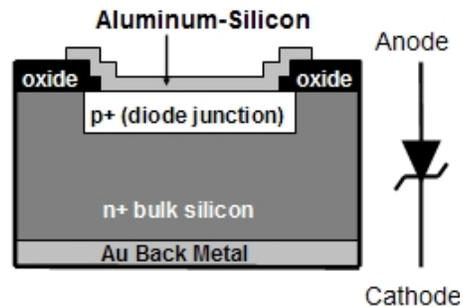


Figure 8. Cross-Sectional View of an MOV and Avalanche TVS Diode

Polymers varistors are a popular device for ESD protection. Their polycrystalline material creates a TVS device with very low capacitance; thus, polymers are effective devices for very high speed data line signals. A polymer’s electrical characteristics are similar to a thyristor and the devices exhibit “snap-back” in their current versus voltage curve. The trigger voltage of a polymer can be as high as 1.0 kV, while the clamping voltage is usually 20 to 50 V. Polymers have a limited service life and their electrical characteristics are typically guaranteed for only one to five thousand surge events.

Zener and TVS avalanche diodes have similar electrical characteristics and both devices dissipate energy in the relatively narrow junction depletion area. A Zener is designed to regulate a relatively stable voltage, while a TVS diode is designed to clamp a transient surge pulse. TVS diodes typically have a larger junction area than a standard Zener, which provides the ability to absorb high peak energy. Below the breakdown voltage (V_{br}), TVS diodes have high impedance and function as a capacitor. At voltages above V_{br} , the device functions as a variable resistor that is dynamically controlled to maintain a constant clamping voltage (V_C).

Table 4. Attributes of TVS Voltage Clamping Devices

Device	Advantages	Disadvantages	Applications
MOVs	<ul style="list-style-type: none"> • Low Cost • Power Rating \propto Volume • Power Derating Begins at 85°C 	<ul style="list-style-type: none"> • Inherently bidirectional • Aging Characteristics • High V_{Clamp} and $I_{Leakage}$ 	<ul style="list-style-type: none"> • AC Power Lines • Automotive • ESD Protection
Polymer Varistors	<ul style="list-style-type: none"> • Very Low Capacitance • Small Packages 	<ul style="list-style-type: none"> • High Trigger Voltage • Limited Service Life • Limited Temperature Operating Range ($< 85^\circ\text{C}$) 	<ul style="list-style-type: none"> • ESD Protection • FireWire • USB
Zener Diodes	<ul style="list-style-type: none"> • Low Cost • Steady-State Voltage Rating 	<ul style="list-style-type: none"> • Limited Power Rating • Power Derating Begins at 25°C 	<ul style="list-style-type: none"> • Voltage References • Battery Packs
Avalanche TVS Diodes	<ul style="list-style-type: none"> • Optimized for Surges • < 1.0 ns Response Time • Low Clamping Voltage 	<ul style="list-style-type: none"> • Limited Power Rating • Power \propto Silicon Area • Power \propto Capacitance 	<ul style="list-style-type: none"> • ESD Protection • Cell Phones • Portable Equipment

Avalanche Diode EMI Filters

Avalanche TVS diode EMI filters offer the advantage of combining surge protection and filtering in a single device. Integrated TVS EMI filters are available in small surface mount IC packages to replace low pass filters that are implemented with discrete inductors, resistors, capacitors and TVS diodes. These filters use the capacitance of a diode

to form a low pass filter. An avalanche diode EMI filter reduces the component count and the required printed circuit board space. The decision to use either an LC or an RC filter is based on the amount of power that will be dissipated in the L or R elements. Figure 9 provides a schematic representation of an avalanche diode π filter.

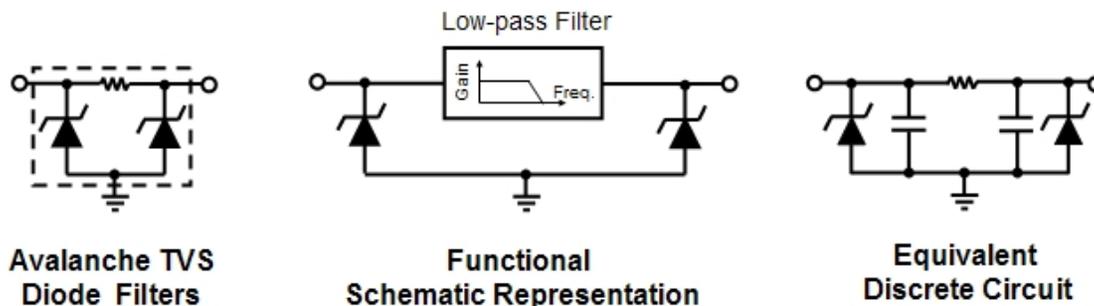


Figure 9. Example of an Avalanche TVS Diode Integrated π Filter

Table 5. Attributes of Avalanche Zener Diode EMI Filters

Device	Advantages	Disadvantages	Applications
Avalanche Diode EMI Filters	<ul style="list-style-type: none"> • Small IC Packages • "Ideal" Filter Response • Reduces Component Count 	<ul style="list-style-type: none"> • Cs are Small • Rs Cause Insertion Loss • Ls have Limited Power Rating 	<ul style="list-style-type: none"> • Cell Phones • PCs • ESD • USB

Multiple Protection Device Solutions

TVS devices can be combined to provide a hybrid device, as shown in Figure 10. This hybrid device solves the slow turn-on and high breakdown limitations of a GDT. The TVS diodes are used to turn-on quickly at a voltage below the damage point of the circuit and absorb the initial transient energy, allowing time for the GDT device to turn on and shunt the majority of the transient energy.

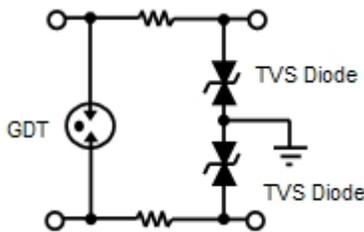


Figure 10. TVS Hybrid Device

Figure 11 provides a design example that uses multiple TVS devices to provide EMI protection. A shielded cable with twisted wire pairs minimizes the noise voltage induced on data lines. The filter connector serves to attenuate the noise before the signal enters the PCB. Next, TVS diodes, LC filters and a common mode choke are used on the PCB. The TVS diodes provide the overvoltage protection to ensure that a surge voltage is clamped to a safe value. The choke increases the transceiver's CMRR and functions as an effective device to provide filtering without distorting the differential signal. Finally, the capacitors located before and after the choke are used to increase the modules RF susceptibility immunity and lower the noise emitted from the PCB.

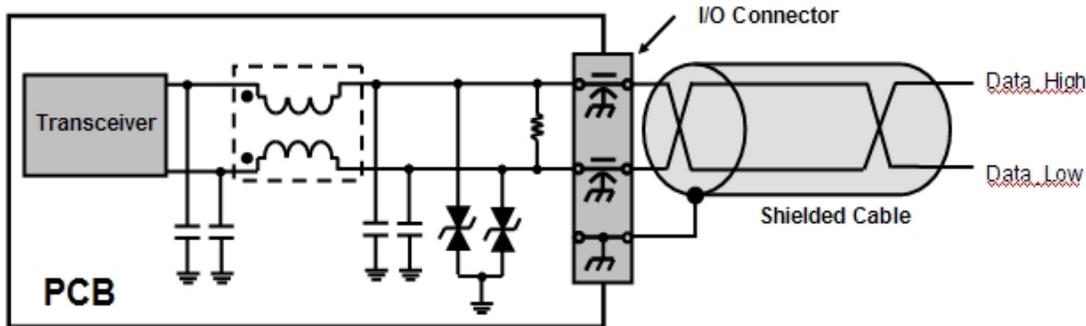


Figure 11. Multiple TVS Device Solution

TVS Selection Guidelines

1. Select a device with a working voltage that is greater than the maximum bus voltage.
2. Select a device with a clamping voltage less than the maximum specified surge voltage for the protected circuit.
3. A bidirectional TVS device may be required for differential amplifier circuits with a common mode offset voltage requirement. The common voltage specification is required when there is a significant difference in the voltage potential between the ground reference of the transmitting and receiving nodes.
4. Choose a TVS device that is capable of dissipating the energy of the surge pulse.
5. The power rating of most TVS devices decreases with temperature and a derating of the TVS's energy specification may be necessary.
6. The capacitance of the TVS device should be minimized for high speed circuits.

PCB Layout Recommendations

The PCB layout is critical to maximize the effectiveness of a TVS protection circuit. The following PCB guidelines are recommended:

1. Locate the protection devices close to the I/O connector. This allows the devices to absorb the energy of the transient voltage before it can be coupled into the adjacent traces on the PCB.
2. Minimize the loop area for the high-speed data lines, as well as the power and ground lines to reduce the radiated emissions and the susceptibility to RF noise.
3. Use ground planes to reduce the parasitic capacitance and inductance of the PCB.

Bibliography

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