ZENER DIODE BASED INTEGRATED FILTERS, AN ALTERNATIVE TO TRADITIONAL EMI FILTER DEVICES

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Introduction

Electromagnetic Compatibility (EMC) has become a major design concern for new products. Circuit designers are being challenged to meet stringent Electromagnetic Interference (EMI) and Electrostatic Discharge (ESD) standards and increase reliability, while reducing the size and cost of their products. In addition, new designs must be compliant with EMI standards that are more stringent than previous requirements.

This document provides guidelines to select a Transient Voltage Suppression (TVS) device to achieve higher EMI higher immunity levels, without significantly adding to the cost and complexity of the circuit. The attributes of traditional EMI filter devices will be compared to the features of TVS zener diode EMI filters. Zener diode integrated EMI filters provide a cost effective alternative to traditional EMI filter devices. These devices can be used to replace low pass filters that are implemented with discrete resistors, inductors, capacitors and zener diodes.

Problem Definition

Common Electrical System EMI Sources

Transient voltage surges are a major contributor to the early failure of semiconductor and other sensitive electrical components. EMI disturbances can also cause erratic behavior in control circuits because the system may not be able to distinguish a legitimate signal from a surge induced signal. Transient surge voltages result from the sudden release of stored energy. EMI transients can usually be attributed to:

- Severe and sudden load changes in adjacent circuits
- Power source fluctuations and pulses
- Short circuits
- Coupled electronic disturbances via cables
- Opening or closing of switch contacts
- ESD
- Lightning

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The immunity level required to protect against surge voltages will vary for each system; however, the automotive transient noise sources shown in Table 1 provide an example of the voltage spikes that can be expected to occur in a DC powered system.

Table 1: Typical Automotive Transients

Noise Source	Length of Transient	Energy	Voltage Amplitude	Occurrence	Test Pulse
Failed voltage regulator	Steady State		+18 V	Infrequent	
Jump start with a 24 V battery	5 min.		+24 V	Infrequent	
Load dump – disconnection of battery during charging	200 to 400 ms	> 10 J	+60 to +125 V	Infrequent	Fig. 1
Inductive load switching transient	< 320 µs	< 1 J	-300 to +80 V	Often	
Alternator field decay	200 ms	< 1 J	-100 to -40 V	Every turn-off	
Ignition pulse, battery disconnected	90 ms	< 0.5 J	< 75 V	Several times in vehicle lifetime	
Mutual coupling in wiring harness	1 ms	< 1 J	< 200 V	Often	
Ignition pulse	15 µs	< 1 mJ	3 V	Continuous	Fig. 3
Accessory noise	Burst of 50 ns pulses		< 1.5 V	50 Hz to 10 KHz	Fig. 2
ESD	< 50 ns	<10 mJ	15 kV	Infrequent	Fig. 4

EMI Immunity Tests

Electronic systems must be able to survive the high energy transients that are produced by non-repetitive and repetitive transient surge voltages, lightning and ESD. The definition of non-repetitive and repetitive surges is determined by the duration of the transient and the time in between surges. A non-repetitive surge is tested by a transient voltage with a pulse width of typically 50 to 2000 µs and a repeat rate of usually one pulse per second. Repetitive surges are represented by a burst of 15 to 300 ms of 50 ns transient pulses. Examples of non-repetitive noise sources include lightning, load dump, power switching, load changes and short circuit faults. Repetitive noise sources include inductive load switching, relay contact chatter and ignition system noise.

<u>Pass/Fail Test Criteria</u>

The pass/fail criterion of an EMI test is determined by both the operational status of the system and if any damage occurs to the circuits. In some systems, a fault is allowed during the EMI test surge; however, normal operation must resume after the completion of the transient event. The test criteria can also be defined by the maximum surge voltage that the system can be guaranteed to withstand without being damaged.

<u>Non-Repetitive Surge Immunity</u>

The non-repetitive surge tests are used to test a module’s transient immunity from either a switching or lightning induced surge voltage. The switching transients can be caused by power switching, sudden load changes or a short circuit fault in the power distribution system. For example, a DC motor can produce a surge voltage because it continues to rotate for a short duration because of inertia after the ignition is switched off. Figure 1 shows an example of the automotive ISO 7637-1 "load dump" waveform. A load dump transient occurs if the battery is disconnected from the alternator while the engine is running.

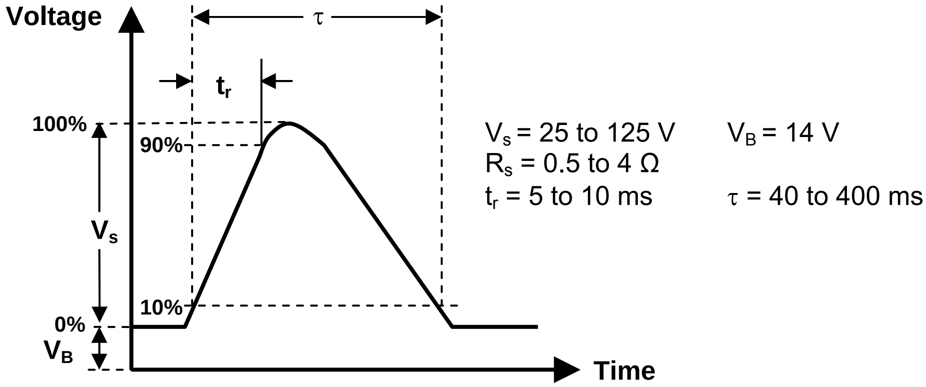

Figure 1: Load Dump Non-Repetitive Surge Test

Repetitive Surge Immunity

The repetitive or electrical fast transients (EFT) surge tests are used to test a module's transient immunity from noise sources such as inductive load switching, relay contact chatter and ignition system noise. Repetitive switching transients are typically coupled into the wiring harness because of the cable's parasitic capacitance and inductance. The recurring pattern of a burst of high voltage spikes of the IEC 61000-4-4 test, shown in Figure 2, can be used to determine the immunity level.

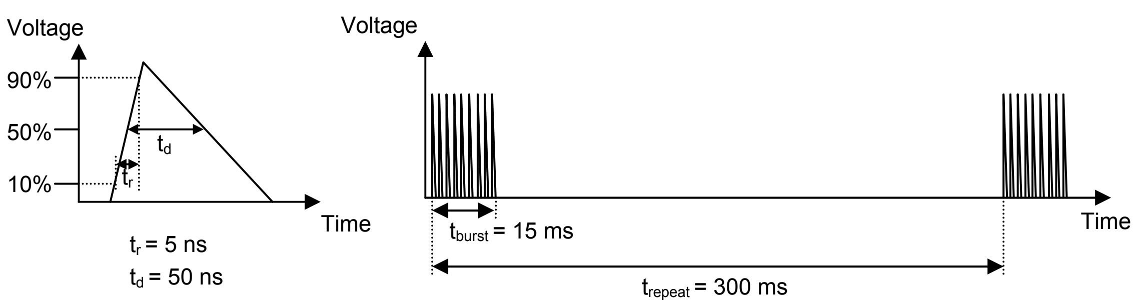

Figure 2: IEC 61000-4-4 EFT Test Waveform

Lighting

Lightning produces a transient surge voltage that can cause significant damage to an electronic system through either a direct or an indirect strike. A direct lightning strike requires a very high energy TVS device such as a gas discharge tube protection circuit. The indirect strike produces an intense electric and magnetic field that is coupled into the data and power lines, producing a large surge voltage. The magnitude of an indirect strike depends on the distance from the lightning strike and typically the energy is low enough that it can be absorbed by a TVS diode.

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The IEC 61000-4-5 specification serves as the standard test to verify the immunity of an electronic system to a non-repetitive surge such as lightning. This specification categorizes the severity levels of the surge event by the location of the cables and electronic system. The surge voltage is defined by a pulse that has an exponential rise to the peak, measured by the rise time from 10 to 90% and an exponential decay measured at the 50% point. The 8 x 20 μs waveform, shown in Figure 3, has a rise time of 8 μs and a decay time of 20 μs.

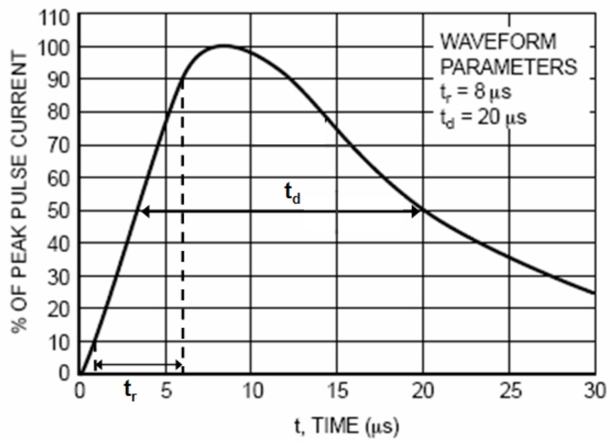

Figure 3: 8 x 20μs Lightning Test Waveform

ESD

The ESD immunity level can be specified by several different tests. The human body model (HBM) test often is listed on IC datasheets, while the International Electromechanical Commission (IEC) 61000-4-2 specification is typically used for system level tests. Both ESD specifications are designed to simulate the direct contact of a person to an object such as the I/O pin of a connector; however, the IEC test is more severe than the HBM. The IEC test is defined by the discharge of a 150 pF capacitor through a 330 Ω resistor, while the HBM uses a 100 pF capacitor and 1500Ω resistor. Figure 4 shows the ESD respond of a TVS zener with a breakdown voltage of 6.6 V.

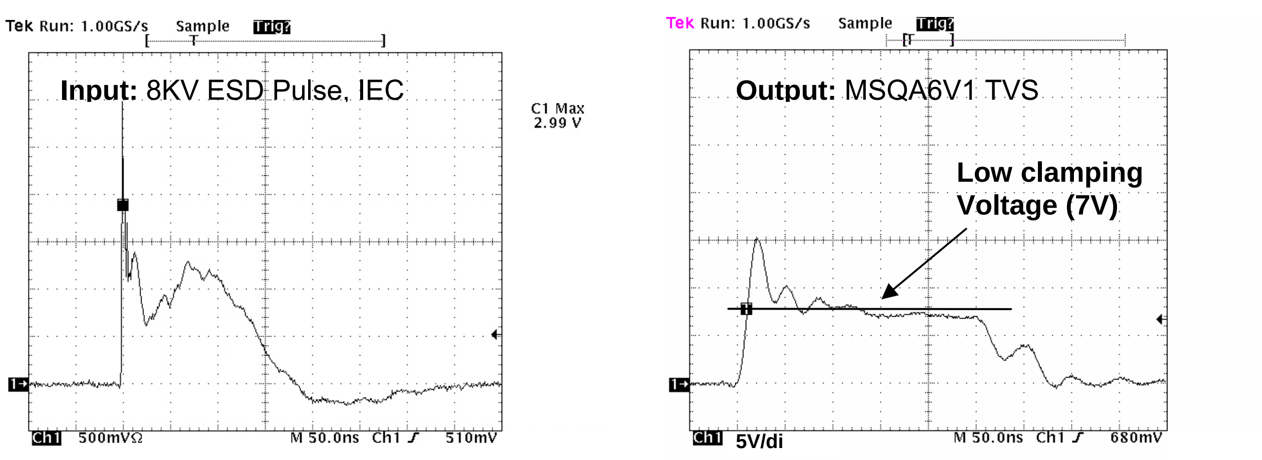

Figure 4: IEC 61000-4-2 ESD Test

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Table 2: Attributes of Popular Transient Voltage Suppression Devices

TVS Device	Type	Advantages	Disadvantages	Applications
Spark Gaps	Crowbar	• Low cost • High surge currents	• Variable breakdown voltage • Short service life	• Telecommunications • Power line meters
GDTs	Crowbar	• High surge currents • Can be combined with TVS diodes • “OFF” state C < 2 pF & R > 1 ΩG	• High cost • Slow turn-on • High V_{br} (200 – 900 V, typ.)	• Telecommunication • Lightning protection
TVS Thyristors	Crowbar	• High surge current • No service life limitations	• Difficult to turn “OFF” • Power line is shunted to ground	• Telecommunication
Feed-Through Capacitors	Filter	• Signal is filtered before PCB entry • Small impedance at ground connection • Effective in segmented chassis design	• High cost • Relatively large size • Difficult to use on PCB	• Engine controls
Filter Connectors	Filter	• Signal is filtered before PCB entry • Small impedance at ground connection	• Connector size increases • High cost	• Engine controls • PCs
Ferrite Beads	Filter	• Low cost • Available in wire “slip-on” package • Removes data line “ringing”	• Ferrite material saturates at high DC currents • Inductance can cause oscillations	• USB • High speed data lines
LC Filters	Filter	• Large current capability • Ls have small power dissipation • 2nd order LPF with -40 db / decade attenuation	• Filter may oscillate at self resonance frequency • Over voltage protection requires clamping TVS device	• Power supplies
MOVs	Clamping Device	• Low cost • Typically fail as an open-circuit • Wide range of breakdown voltages	• Inherent bi-directional clamping • Higher clamping voltage than zener • Single layer MOVs have limited life	• TVs • AC line protection • PCs
TVS Zener Diodes	Clamping Device	• Low cost • Fast response time (< 1 ns) • Variety of packages and power ratings • Low clamping voltage	• Limited power capability • Typical fail as a short-circuit • Power rating decreases with temperature	• Data line ESD • Cell phones • PCs • MOSFET protection
Zener Diode Filters	Clamping Device	• Low cost • Small IC packages • Low clamping voltage • Freq. response is “close” to ideal filter	• Cs are small, f_{-3db} > 100 MHz (typ.) • PCB routing complexity increases with multi-channel ICs • Rs have insertion loss	• Data line ESD • Cell phones • PCs • USB

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Protection Philosophy – Crowbar vs. Clamp vs. Filter

TVS devices can be categorized as either a crowbar, voltage clamping or filter device. A summary of the attributes of several popular traditional TVS devices and the relatively new zener diode based integrated filters is provided in Table 2.

Crowbar TVS Devices

Spark gaps, gas discharge tubes (GDTs) and thyristors 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, as shown in Figure 5. 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.

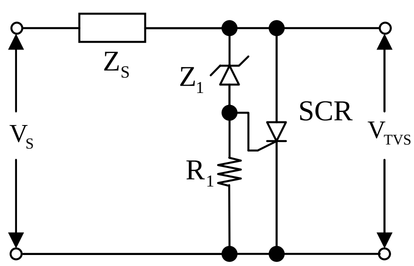


Figure 5: Example of a Thysistor Crowbar TVS device.

Spark gaps are constructed from two carbon block electrodes that are separated by an air gap of 3 to 4 mils. One electrode is connected to the signal line, while the other electrode is connected to ground. The surge voltage causes an arc to form that shunts the transient voltage to ground. GDT devices 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. TVS thyristors are constructed with four layers of p- and n-type semiconductor material. Most TVS thyristors consist of a SCR and a zener diode that controls the turn-on gate voltage.

Voltage Clamping TVS Devices

TVS zener diodes and Metal Oxide Varistors (MOVs) are popular voltage clamping devices. These devices function as variable impedances that are dynamically adjusted to maintain a constant clamping voltage. One advantage of clamping devices is that the protected circuit can still operate during the transient event. Clamping TVS devices function as a non-linear resistor. At low voltages below their breakdown voltage, they can be modeled as a very large resistance in parallel with a capacitance. When the voltage of the surge exceeds the breakdown voltage, the resistance of the device decreases to a low value. Figure 6 shows a schematic of a clamping TVS device.

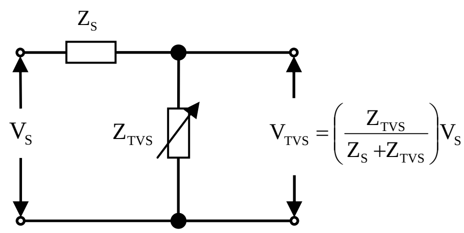


Figure 6: Example of a voltage clamping TVS device.

TVS diodes are designed with a larger junction than a standard zener diode, which provides the ability to absorb high peak energy. TVS diodes are designed to clamp a transient surge voltage, while a zener is designed to regulate a lower steady state voltage. 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 the devices clamping voltage (V_c).

Filter TVS Circuits

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 a zener 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.

The LC Pi filter is widely used in power supplies because it attenuates noise signals that are both entering and exiting the filter network. L_1 and C_2 form a filter that attenuates the high frequency signals entering the network via the cable, while L_1 and C_1 attenuates the high frequency noise that is exiting the network. Figure 7 shows a bi-directional Pi filter.

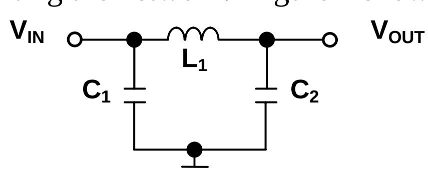


Figure 7: Example of a LC Pi filter.

Feed–through capacitors and filter connectors shunt the high frequency noise signals to chassis ground and the noise signal is filtered 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. A ferrite bead is a series filter device that provides high frequency attenuation with a small resistive power loss at DC. At low frequencies, they function as a resistor of 50 to 200 ohms, while at high frequencies they can be modeled as an inductor with impedance that increases with frequency.

Zener Diode Integrated Passive Device (IPD) Filters

Integrated IPD filters are now available in small SMT IC packages to replace low pass filters that are implemented with discrete inductors, resistors and capacitors. IPD filters reduce the component count and the required printed circuit board space. The decision to use either a LC or a RC filter is based on the amount of power that will be dissipated in the L or R elements. The voltage drop of the resistor in RC filters is often too large for high current circuits; thus a LC filter is the preferred device for applications such as power line filters. IPD filters use the capacitance of a zener diode to form a low pass filter. Figure 8 provides an example of an IPD filter.

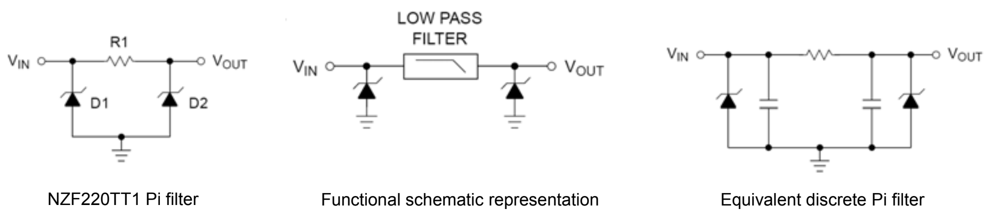


Figure 8: Example of a TVS zener diode IPD filter.

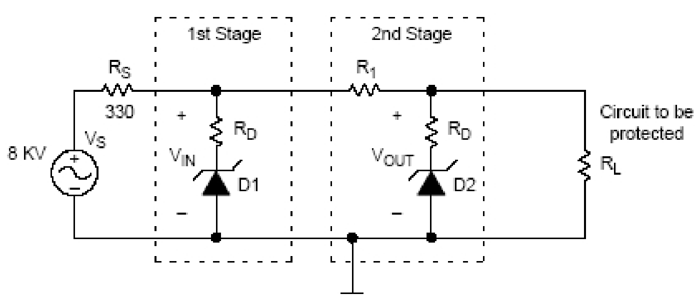
Design Examples of Zener Diode IPD Filters

<u>Surge Protection</u>

A Pi IPD filter that uses two zeners offers the advantage that a surge voltage will be clamped to a value that is within a few millivolts of the zener breakdown voltage. The protection characteristics of the NZF220TT1 Pi filter can be analyzed by considering the Pi circuit as two separate stages, as shown in Figure 9. The voltage at the first stage (V_{IN}) will have a peak or overshoot voltage that is significantly above the clamping voltage because of the dynamic resistance of diode D_1. In contrast, the voltage at the second stage (V_{OUT}) will be very close to the zener's clamping voltage because the R_D*I_P term is small in comparison to the magnitude of the R_D*I_P term of the first stage.

If: V_S = IEC 61000–4–2 voltage waveform = ± 8 kV
R_S = IEC 61000–4–2 source impedance = 330 Ω
V_{br} = breakdown voltage = 7 V
R_D = dynamic resistance of the zener = 1 Ω
I_P = peak ESD current
$R_1 = 100\ \Omega$, $C_1 = C_2 = 22$ pF, $R_D << R_S$ and $R_D << R_1$

Then: $V_{IN} = 31.2$ V
$V_{OUT} = 7.3$ V



$$V_{Clamping\_voltage} = V_{br} + R_D * I_P$$

$$V_{IN} = V_{br} + \left(\frac{R_D}{R_S + R_D}\right)V_S \cong V_{br} + \left(\frac{R_D}{R_S}\right)V_S$$

$$V_{OUT} = V_{br} + \left(\frac{R_D}{R_1 + R_D}\right)V_{IN} \cong V_{br} + \left(\frac{R_D}{R_1}\right)V_{IN}$$

Figure 9: ESD analysis of a TVS zener diode IPD filter.

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<u>Data Line Protection</u>

TVS diode array circuits can be used to provide protection to the data lines of a high speed bus such as the Controller Area Network (CAN), as shown in Figure 10. The bi-directional array is created from four identical zener TVS diodes. The clamping voltage of the composite device is equal to the breakdown voltage of the diode that is reversed biased, plus the diode drop of the second diode that is forwarded biased. Bi-directional TVS devices are usually required for applications that have long cables and use a differential amplification to solve any offset voltage that may exist from the difference between the two ground references of the transmitting and receiving modules.

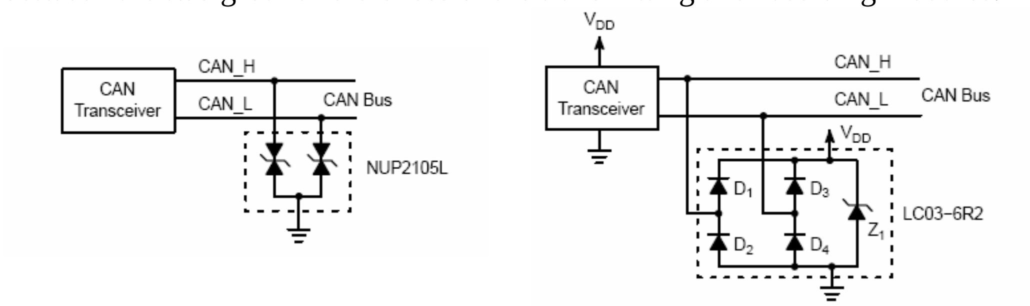

Figure 10: CAN Data Line Protection.

A diode array using standard diodes and a zener diode can also provide data line protection. The surge voltage on the signal lines is clamped to either a diode voltage drop above V_{DD} or a diode drop below ground. This circuit clamps at a voltage closer to the normal amplitude of the waveform and removes ringing on the signal lines. Diodes D_1, D_2, D_3 and D_4 have a low capacitance and are designed to have a fast turn-on time, while Z_1 is used to dissipate the majority of the energy during a surge.

<u>Hybrid TVS Devices</u>

Figure 11 provides an example of a hybrid TVS device that 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.

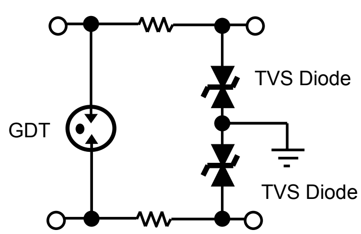

Figure 11: TVS Hybrid Device

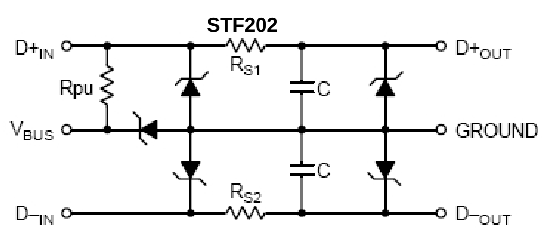

Figure 12: USB EMI Filter

<u>USB Filter and Line Termination</u>

Figure 12 provides an example of a zener IPD device that can provide ESD protection and the line termination for the USB communications port.

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 voltage for the protected circuit.
3. A bi-directional TVS device maybe required for differential amplifier circuits. 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 maybe necessary.
6. The capacitance of the TVS device should be minimized for high speed circuits.

<u>PCB Recommendations for Optimizing the EMI Filter Performance</u>

1. Filter all I/O signals entering and leaving the noisy environment.
2. Locate the EMI filter as close to the I/O connector as possible.
3. Minimize the loop area for all high speed signals entering the filter array.
4. Use ground planes to minimize the PCB's ground inductance.

<u>Optimizing ESD Protection</u>

1. Locate the TVS device as close to the I/O connector as possible.
2. Minimize the PCB trace lengths to the TVS device.
3. Minimize the PCB trace lengths for the ground return connections.
4. Use a fast turn-on device with a low clamping voltage.

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