ON Semiconductor®

Transient Overvoltage Protection

Chapter 1. The Nature of the Transient Overvoltage Problem

Overview of Hazards

Electrical transients in the form of voltage surges have always existed in electrical distribution systems, and prior to the implementation of semiconductor devices, they were of minor concern.

The vulnerability of semiconductors to lightning strikes was first studied by Bell Laboratories in 1961. [1] A later report tried to quantify the amount of energy certain semiconductors could absorb before they suffered latent or catastrophic damage from electrostatic discharge. [2] Despite these early warnings, industry did not begin to address the issue satisfactorily until the late 1970s.

All electrical and electronic devices can be damaged by voltage transients. The difference between them is the amount of energy they can absorb before damage occurs. Because many modern semiconductor devices, such as low voltage MOSFETs and integrated circuits can be damaged by disturbances that exceed only 10 volts or so, their survivability is poor in unprotected environments.

In many cases, as semiconductors have evolved, their ruggedness has diminished. The trend to produce smaller and faster devices, and the spread of MOSFET and gallium arsenide FET technologies has led to an increased vulnerability. High impedance inputs and small junction sizes limit the ability of these devices to absorb energy and to conduct large currents. It is necessary, therefore, to supplement vulnerable electronic components with devices specially designed to cope with these hazards.

Selection of the proper protective method should be made based upon a thorough investigation of the potential sources of the overvoltage hazard. Different applications and environments present different sources of overvoltage. The sources may be external, or they may be within the circuit.

Lightning

At any given time there are about 1800 thunderstorms in progress around the world, with lightning striking about 100 times each second. In the U. S., lightning kills about 150 people each year and injures another 250. In flat terrain with an average lightning frequency, each 300 foot structure will be hit, on average, once per year. Each 1200 foot structure, such as a radio or TV tower, will be hit 20 times each year, with strikes typically generating 600 million volts.

Each cloud-to-ground lightning flash really contains from three to five distinct strokes occurring at 60 millisecond intervals, with a peak current of some 20,000 Amperes for the first stroke and about half that for subsequent strokes. The final stroke may be followed by a continuing current of around 150 Amps lasting for 100 milliseconds.

The rise time of these strokes has been measured to be around 200 nanoseconds or faster. It is easy to see that the combination of 20,000 Amps and 200 nanoseconds calculates to a value, dI/dt, of 10^{11} Amps per second! This large value means that transient protection circuits must use radio frequency (RF) design techniques, particularly considerate of parasitic inductance and the capacitance of the conductors.

While this peak energy is certainly impressive, it is really the longer term continuing current which carries the bulk of the charge transferred between the cloud and ground.

From various field measurements, a typical lightning model has been constructed, as shown in Figure 1.

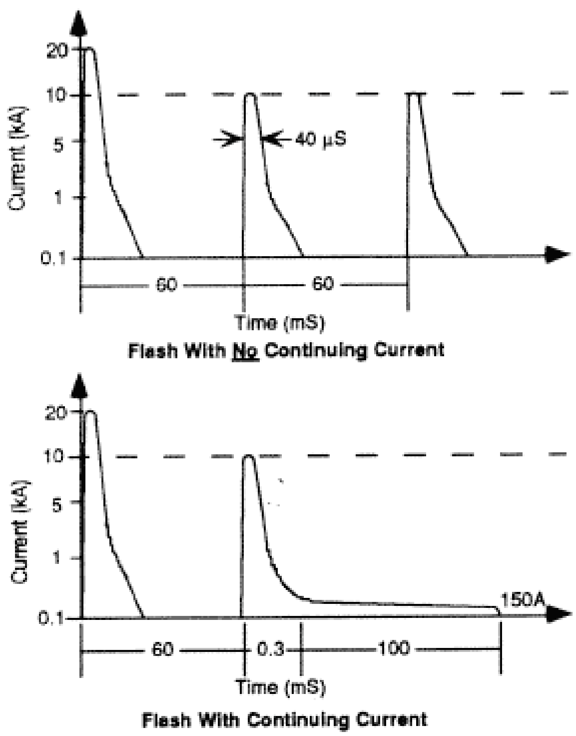

Figure 1 Typical Lightning Model, With and Without Continuing Current

Depending on various conditions, continuing current may or may not be present in a lightning strike. A severe lightning model has also been created, which gives an indication of the strength which can be expected during worst case conditions at a point very near the strike location. Figure 2 shows this model. Note that continuing current is present at more than one interval, greatly exacerbating the damage which can be expected. A severe strike can be expected to ignite combustible materials. A direct hit by lightning is, of course, a dramatic event, and probably non-recoverable. In fact, the electric field strength of a lightning strike some distance away may be excessive enough to cause catastrophic or latent damage to semiconductor equipment. It is a more realistic venture to try to protect equipment from these nearby strikes than to expect survival from a direct hit.

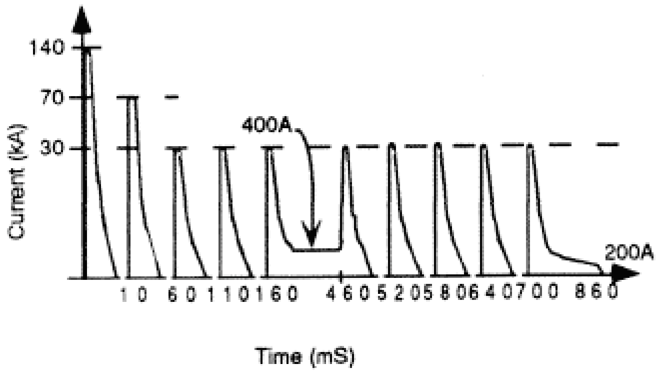

Figure 2 Severe Lightning Model

With this in mind, it is important to be able to quantify the induced voltage as a function of distance from the strike. Figure 3 shows that these induced voltages can be quite high, explaining the destruction of equipment from relatively distance lightning flashes.

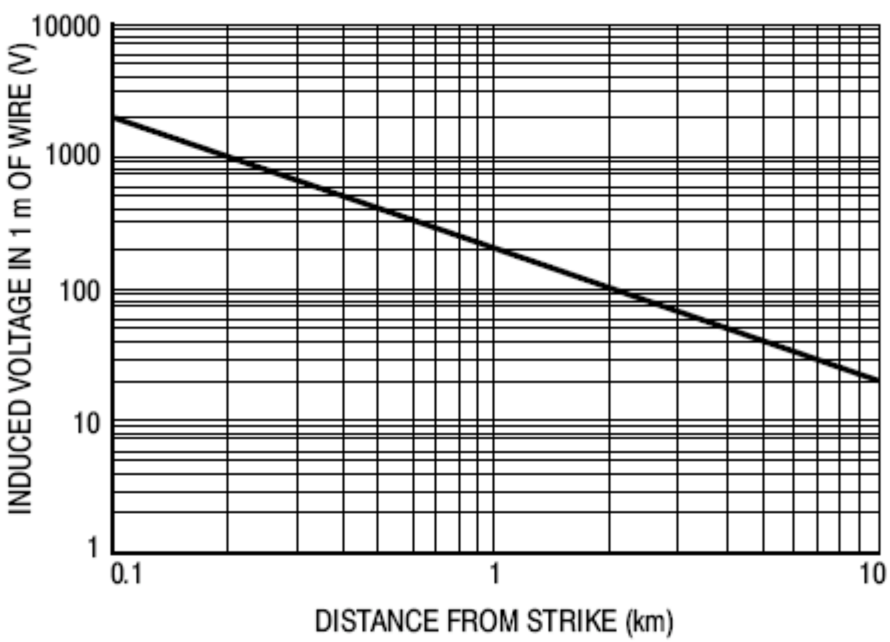

Figure 3 Voltage Induced by Nearby Lightning Strike

Burying cables does not provide appreciable protection as the earth is almost transparent to lightning radiated fields. In fact, underground wiring has a higher incidence of strikes than aerial cables.[3]

Protection against such hazards is a necessity for wired telecommunications. Primary protection devices such as carbon blocks and gas tubes have historically provided some degree of safety. Secondary and board-level protection has become the domain of a variety of semiconductor devices, including thyristor surge protection devices (TSPD). These are used at the termination of long wiring runs, for example on central office line cards, modems, etc. TSPD protection devices and techniques will be detailed in later chapters of this document.

Switching of Loads in Power Circuits

Inductive switching transients occur when a reactive load, such as a motor, solenoid or relay coil, is switched off. The rapidly collapsing magnetic field induces a transient voltage across an inductive load's winding which can be expressed by the formula:

$V = - L (dI/dt)$

where L is inductance in henrys and dI/dt is the rate of change of current in Amps per second.

Such transients can occur from a power failure, the normal opening of a switch or a load failure. The energy associated with the transient is that stored within the inductance at power interruption and is equal to:

$\omega = 1/2\ Li2$

where ω is energy in joules and I is instantaneous current in amps at the time of interruption.

As an example, a 1.4 to 2.5 kilovolt (kV) peak transient can be injected into a 120 volt ac (vac) power line when the ignition system of an oil furnace is fired. It has also been shown that there are transients present on these lines which can reach as high as 6 kV. In locations without transient protection devices, the maximum transient voltage is limited to about 6 kV by the insulation breakdown of the wiring.

Inductive switching transients are the silent killers of semiconductors as they often occur with no outward indication. A graphic example is the report of a large elevator company indicating the failure of 1000 volt rectifiers during a power interruption. In another area, power interruption to a 20 horsepower (HP) pump motor in a remote area was directly related to failure of sensitive monitoring equipment at that same site. [4]

The International Electrotechnical Commission (IEC) is now promoting their specification IEC 61000-4-4. This describes an inductive switching transient voltage threat having 50 nanosecond wide spikes with amplitudes from 2 kV to 4 kV occurring in 300 millisecond wide bursts.

Besides these particular regulatory specifications, many other application specific, functional tests exist. A supplier of transient voltage suppressor (TVS) components will be expected to perform to a wide variety of them. These components must be robust, because the hazard is dynamic and generally repetitive. TVS protection devices and techniques will be detailed in Chapter 2 of this document.

Electrostatic Discharge (ESD)

Electrostatic discharge (ESD) is a widely recognized hazard during manufacturing, shipping and handling of many semiconductor devices, especially those that contain unprotected MOSFETs, semiconductors for use at microwave frequencies and very high speed logic with switching times of 2 nanoseconds or less. In response to this threat, most semiconductors are routinely shipped in containers made of conductive material. This technique essentially maintains a common electrical potential between the device pins, eliminating any voltage differential.

In addition to various shipping precautions, electronic assembly line workers should be grounded, use grounded-tip soldering irons, ionized air blowers and other techniques to prevent large voltage potentials to be generated and possibly discharged into the semiconductors they are handling. Testing of the device presents yet another opportunity for static buildup and discharge.

Once the finished device is in normal operation, ESD damage can still occur. Any person shuffling his feet on a carpet and then touching a computer keyboard can possibly cause a software crash or, even worse, damage the computer hardware.

The electrical waveform involved in ESD is a brief pulse, with arise time of about 1.0 nanosecond, and a duration of 100 to 300 microseconds. The peak voltage can be as large as 30 kV in dry weather, but is more commonly 0.5 to 5.0 kV.6 The fastest rise times occur from discharges originating at the tip of a hand-held tool, while discharges from the finger tip and the side of the hand are slightly slower.[5]

A typical human with a body capacitance of 150 picofarads, charged to 3 microcoulombs, will develop a voltage potential of 20 kV, according to the formula:

$$V = Q/C$$

where V is voltage, Q is charge and C is capacitance. The energy delivered upon discharge is:

$$\omega = \frac{1}{2} CV2$$

where ω is energy in joules, C is capacitance and V is voltage.

It is interesting to note that most microcircuits can be destroyed by a 2500 volt pulse, but a person cannot feel a static spark of less than 3500 volts!

Protection devices, known as electrostatic discharge protectors (ESD Protectors) are small and inexpensive, and can be valuable insurance against ESD, especially around data ports and other pin connections which are accessible to the human touch. ESD protection devices and techniques will be detailed in Chapter 2 of this document.

Power Cross

Yet another source of electrical overstress is the accidental connection of signal lines, such as telephone or cable television, to an ac or DC power line. Strictly speaking, this phenomenon, known as a power cross, is a continuous state, not a transient. However, the techniques for ensuring the survival of signal electronics after a power cross are similar to techniques used for protection against transient overvoltages. For this reason, power cross is mentioned here.

Other Overvoltage Hazards

There are other sources of stress which will not be discussed in detail here due to their specialized nature. Microwave Radiation can disrupt electronics near high power microwave transmitters. Sunspots send out electromagnetic waves and have been known to create disturbances in sensitive equipment, especially during the height of their 11 year cycle.

Stress Waveforms

Double Exponential

A variety of industry standards have been developed to guide in the testing of systems exposed to stresses from lightning, surges from switching, electrostatic discharge and other stress. A review of some of these standards will be done in Chapter 3. Most of the standards use similar stress waveforms and some of these will be discussed here.

The most common waveform is the double exponential shown in Figure 4.

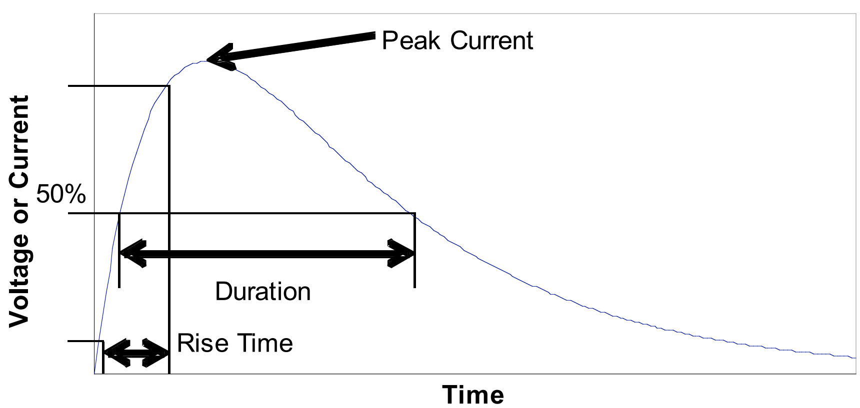

Figure 4 Double Exponential Waveform

Different standards may define the details somewhat differently but most include parameters similar to those in Table 1. Specific double exponential waveforms are often described by the shorthand, (rise time/duration), with the times in μs.

Table 1 Parameters used to describe double exponential waveforms

Parameter	**Measurement Condition**	**Description**
Peak Voltage	Into Open	Voltage at the peak of the double exponential
Peak Current	Into Short	Current at the peak of the double exponential
Rise Time	Open and/or Short	Rise time is often the time to rise from 10 to 90 % of peak current. Some standards specify a Front Time which is a rise time multiplied by a correction factor between 1 and 2.
Duration	Open and/or Short	Time from the beginning of the pulse until the pulse decays to 50% of the peak current or voltage.

Table 2 Common Double Exponential Waveforms.

Waveform (rise time μs/fall time μs)	Comments
Combination	This waveform has different rise and fall time definitions for measurement with an open or short 1.2/50 – Measured into Open 8/20 – Measured into Short
2/10	Same rise and fall for V and I
10/160	
10/250	
10/360	
10/560	
10/700	10/700 is for voltage into open, specification for short is 5/310
10/1000	Same rise and fall specification for V and I

100kHz Ring Wave

The ring wave is used to simulate fast events such as inductively coupled currents and voltages from the fast leading edge of lightning or capacitor bank switching on power systems. Its form is shown in Figure 5. The ring wave usually causes system upset rather than physical damage and is not intended for use on a surge protection device alone.

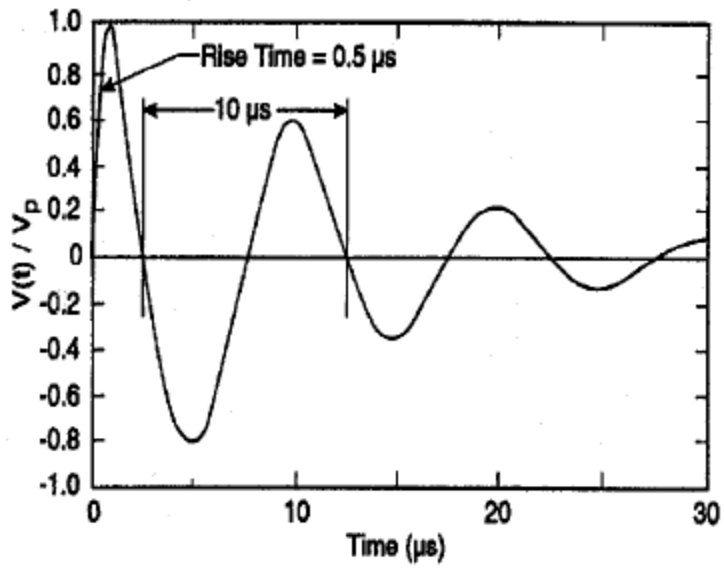

Figure 5 100 kHz Ring Wave (from IEEE C62.41.2-2002)

Electrical Fast Transient

The Electrical Fast Transient (EFT) waveform is intended to test for system immunity to interference. It does not represent a specific surge environment. As this is intended solely for system interrupt this stress is not appropriate for stressing components. The stress consists of short duration, fast rise time, double exponential pulses like those in Figure 4 repeated in a burst fashion. Each pulse has a 10% to 90% rise time of 5ns and 50% to 50% duration of 50ns. The burst pattern is shown in Figure 6

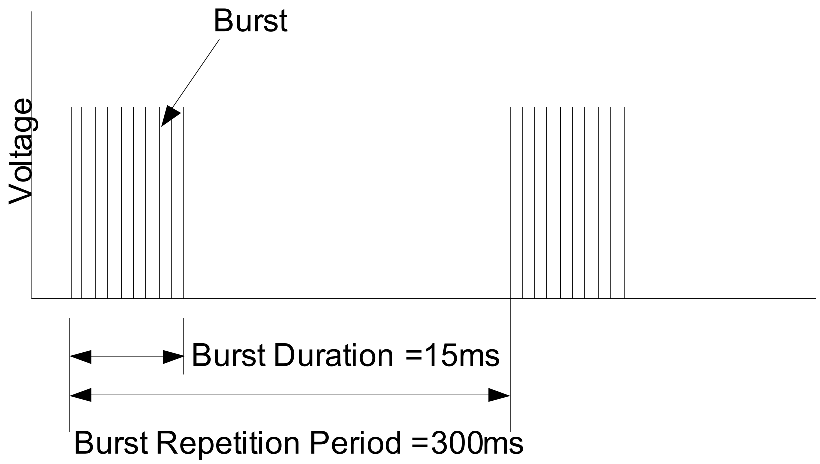

Figure 6 EFT Burst Pattern

Application of Surge Waveforms

The coupling of surge waveforms into a system under test has many variations and a full description is beyond the scope of this document. There are general concepts that will be discussed here. In practice all testing is done based on a specific test standard and the standards give detailed descriptions.

Surges can be applied to both power and data lines. The considerations are similar. The test setup must be able to deliver the stress to the system under test without interfering with system operation before and after the application of the stress. The test setup must also prevent damage or upset to electronics needed to exercise the system under test. This is done with a combination of a coupling network to apply the stress to the system under test and decoupling network to prevent damage or upset to auxiliary equipment. An example is shown in Figure 7 for stressing a set of data lines. The network in Figure 7 allows the stressing of any of the data lines with respect to any of the other data lines or ground. The parallel combination of the capacitor and the surge arrestor feeds the stress into the system. In most cases the arrestor is not included and the surge is coupled into the system capacitively. High speed data lines may not be able to tolerate the micro Farad sized capacitors needed for coupling. An arrestor, such as a gas tube, provides a low capacitive alternative.

Test setups for stress to power supply lines are similar. The values of the coupling capacitor may be larger and it is unlikely that the capacitance will be too large so that the use of arrestors for coupling is not needed. Resistors would not usually be used in the decoupling network and capacitive filters may be added between lines on the opposite side of the decoupling network from the unit under test.

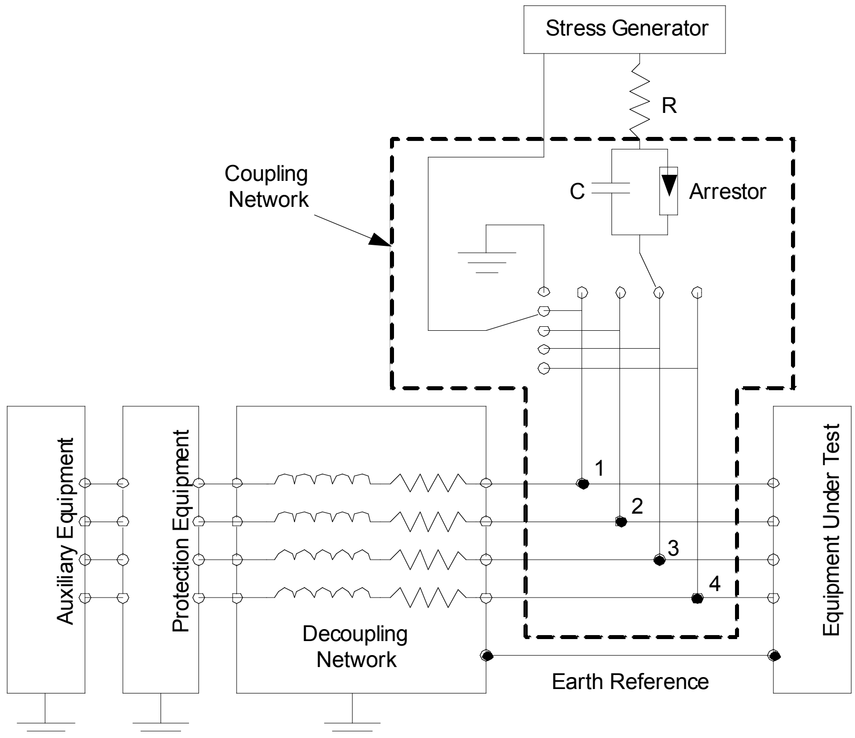

Figure 7 Sample test setup for surge measurements

The results of surge testing fall into 4 categories.

1. Normal equipment under test operation throughout the test procedure
2. Interrupt of equipment under test operation but operation returns to normal after the stress is removed without operator intervention.
3. Interruption of equipment under test operation which requires operator intervention to return to normal operation.
4. Non recoverable interruption of equipment under test operation due to physical damage to the hardware

System ESD Waveforms

The most common system level ESD test standards are IEC 61000-4-2 for a wide variety of commercial and industrial products and ISO 10605 for automotive applications. A representation of the waveform used to test systems for ESD robustness is shown in Figure 8. The current waveform is comprised of an initial current spike with a sub nano-second rise time and a longer lasting tail. For contact discharge IEC 61000-4-2 and ISO 10605 specify the same nominal initial peak with a peak current of 3.75A/kV and a 0.7 to 1 ns rise time. For the IEC standard the current tail starts with a current amplitude about a half of the initial peak and a decay time of about 50ns. The automotive standard has a tail whose current is about one sixth of the IEC current tail, but has a current decay time of 300 or 660 ns, depending on test conditions.

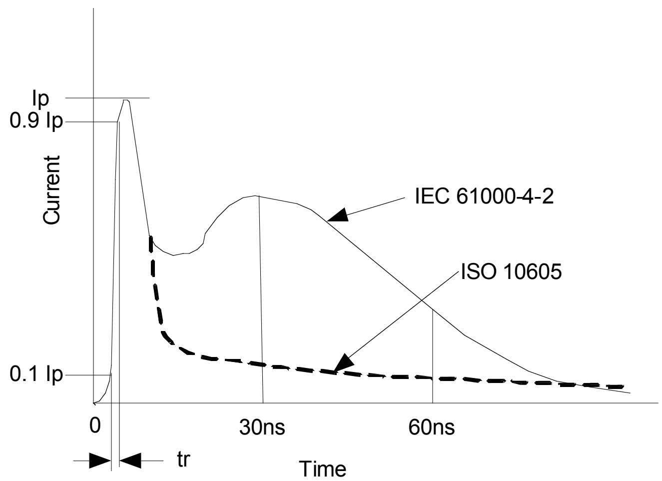

Figure 8 System level ESD waveforms

System level ESD stress is applied to the unit under test with a hand held pulse source, often referred to as an ESD gun. The IEC 61000-4-2 ESD test setup for table top or portable equipment is shown in Figure 9. A metal ground plane covers the floor and a wooden table sits on the ground plane. A metal horizontal coupling (HCP) plane electrically, connected to the ground plane with a pair of 470 kΩ resistors in series, is on top of the table. An insulator covers the HCP. The grounding cable of the ESD gun is connected to the ground plane. The system to be tested is placed on the table and is in operation during the test.

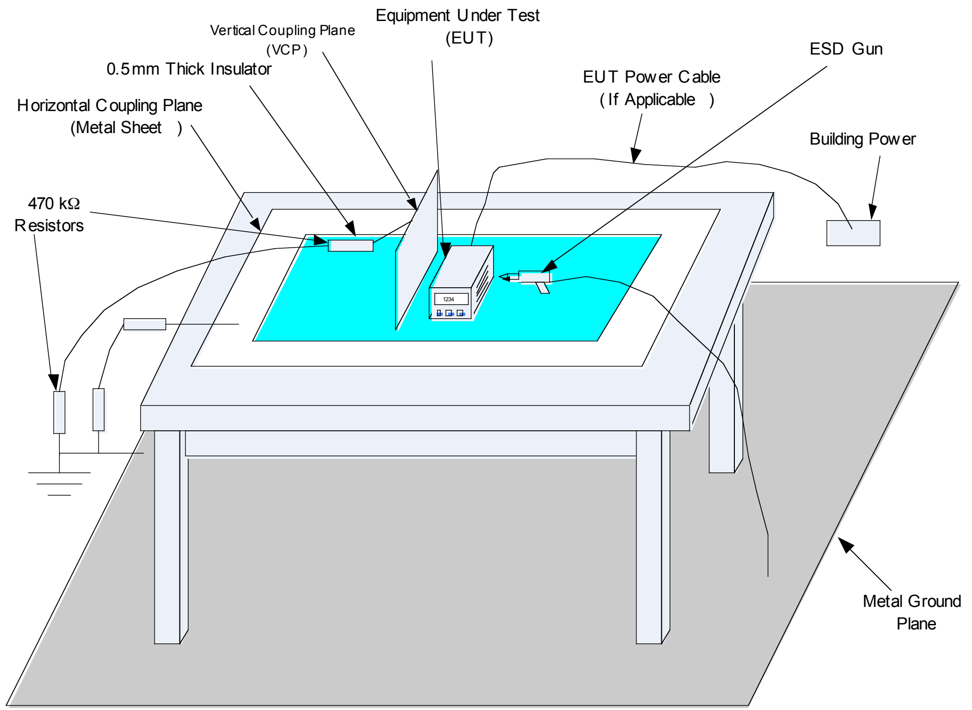

Figure 9 ESD test setup for IEC 61000-4-2 testing

ESD stress is done both directly to the unit under test and indirectly. Direct testing is done with contact discharge to conducting surfaces and air discharge is done to insulating surfaces. In contact discharge a pointed tip on the gun is placed against a conducting surface, the gun is charged to the test voltage and a relay within the gun initiates the stress pulse. In air discharge the gun is fitted with rounded tip. The capacitor inside the gun as well as the round tip, is charged to the test voltage and the gun is moved toward the system being tested. The stress current will be initiated by air breakdown.

Indirect discharge is contact discharge to the HCP or to a Vertical Coupling Plane mounted close to the unit being tested. This simulates disturbances that can be created by electromagnetic pulses to objects near the unit under test.

There is a separate test setup description for testing floor standing units. The test setup for bench testing automotive sub assemblies in ISO 10605 differs from the IEC setup but does have similarities. Separate instructions are given in ISO 10605 for the stressing of electrical components mounted in an automobile. The test results for system level test fall into the same four categories as the results for surge testing discussed earlier.

1. D. W. Bodle and P. A. Gresh, “Lightning Surges in Paired Telephone Cable Facilities,” The Bell System Technical Journal, Vol. 4, March 1961, pp. 547−576.
2. D. G. Stroh, “Static Electricity Can Kill Transistors,” Electronics, Vol. 35, 1962, pp. 90−91.
3. J. D. Norgard and C. L. Chen, “Lightning-Induced Transients on Buried Shielded Transmission Lines,” IEEE Transactions on EMC, Vol. EMC28, No. 3, August 1986, pp. 168−171.
4. O. M. Clark, “Transient Voltage Suppression (TVS),” 1989, pp. 6−7.
5. Clark, p. 7.

Chapter 2. Addressing Overvoltage

Introduction

Damage to electrical systems is due to a combination of voltage and current. High voltage can open unintended current paths such as forward or reverse breakdown of diodes or oxides reaching their breakdown voltage within integrated circuits. Once the unintended path is initiated by over voltage the resulting currents cause damage. Excess current can also cause thermal damage directly. Protection is done with either voltage activated circuit elements that open low resistance paths to prevent excess voltage, current limiting devices or a combination of the two. Protection strategy will be illustrated by considering the concept of Primary and Secondary Protection. After the discussion of Primary and Secondary protection the types of protection elements available will be reviewed, and then the use of protection devices in representative situations will be discussed.

Primary and Secondary Protection

The use of Primary and Secondary Protection is very common. It is used for lightning and surge protection in the telecommunications industry and it is used for ESD protection in advanced integrated circuit technology. A primary protection element, closer to the source of stress, is intended to carry the bulk of the current stress. The secondary protection element provides protection near sensitive circuits.

Figure 10 shows an example of primary and secondary protection for a data line entering a building. To prevent surges from lightning causing fires or electrocution in the building a protection elements is located at the building entrance. This is the primary protection. Protection elements that can carry the large current from a lightning induced surge normally do not have the fast turn on time and low trigger voltage needed to protect sensitive electronics. A protection element at a building entrance will also not be able to protect circuits from surges generated within the building. The secondary protection, located close to the sensitive equipment, protects against the let through stress from the primary protection and surges generated within the building. Secondary protection can be customized to the special needs of the circuit being protecting. Additionally voltage drops in the resistance between the primary and secondary protection, either parasitic or intentional, can help turn on the primary protection, as soon as the secondary protection begins to carry current. An additional level of safety can be obtained by placing a current limiting element between the primary and secondary protection elements.

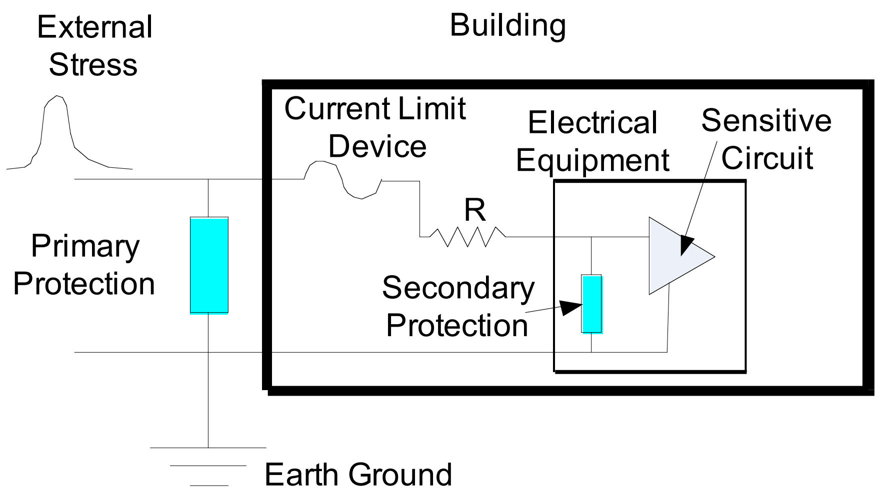

Figure 10 Primary and Secondary Protection for a simple data line entering a building

Having reviewed the basic roles of voltage and current limiting protection elements it is now appropriate to discuss the properties of protection elements and the various protection technologies that are available.

Protection Device Classification

Overvoltage protection products are classified with two classifications, unidirectional or bidirectional and voltage clamping or crowbar. Current limiting devices are divided into one time use and resettable.

Unidirectional and Bidirectional Protection

Protection requirements for electrical nodes with only positive or only negative voltage differ from nodes whose voltage extends above and below zero volts. Unidirectional and bidirectional protection elements address this issue and can be easily explained using diode based Transient Voltage Suppressors (TVS) devices as an example.

Figure 11 shows examples of unidirectional and bidirectional TVS protection of an input. The I-V curve for a unidirectional TVS device is similar to that of a standard diode. If a unidirectional TVS is inserted into the circuit as shown in Figure 11 the signal voltage will be undistorted if it remains between 0V and the TVS's reverse breakdown voltage. For negative voltage stresses the unidirectional TVS protects by forward bias operation. For positive stress on the signal line the TVS protects by reverse bias breakdown. If the signal ranges between 0V and a negative voltage, the unidirectional TVS device can be inserted with the opposite polarity.

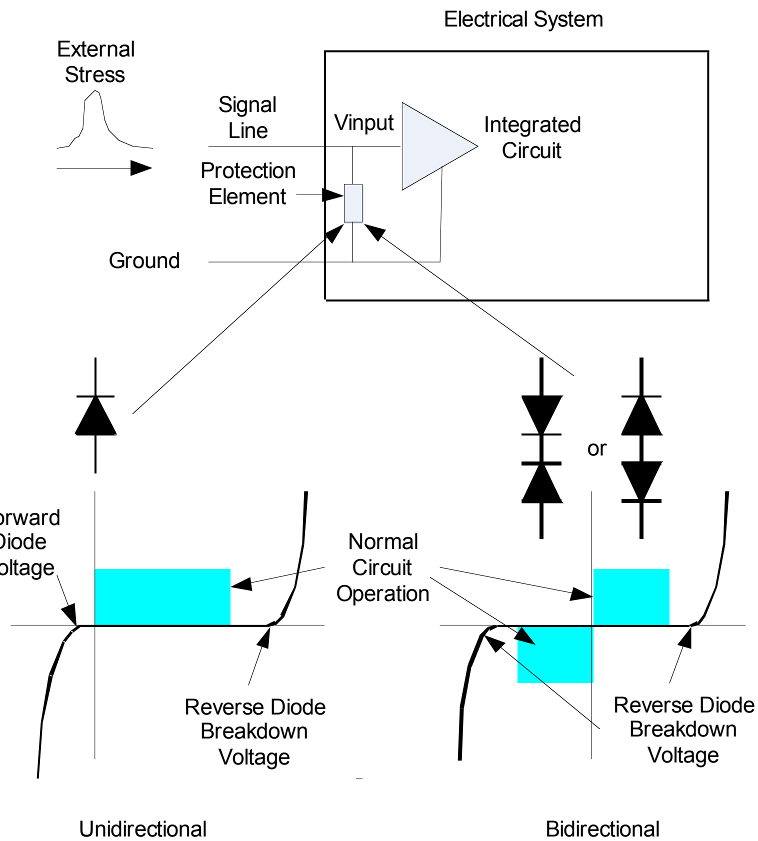

Figure 11 I-V curves and symbols for unidirectional and bidirectional TVS devices

A bidirectional TVS behaves as two anti-parallel diodes in series. If a bidirectional TVS device is used as the protection device in Figure 11 the input voltage can range over positive and negative values. Protection is provided by reverse bias breakdown in series with a forward bias diode in both polarities.

Clamp and Crowbar Devices

Protection devices are also classified as clamp versus crowbar. TVS devices are clamp devices; they clamp the voltage at a defined voltage during a stress event. A crowbar device attempts to create a short circuit when a trigger voltage is reached. It is like putting a metal crowbar across the high voltage to provide a short. Both cases are illustrated in Figure 12.

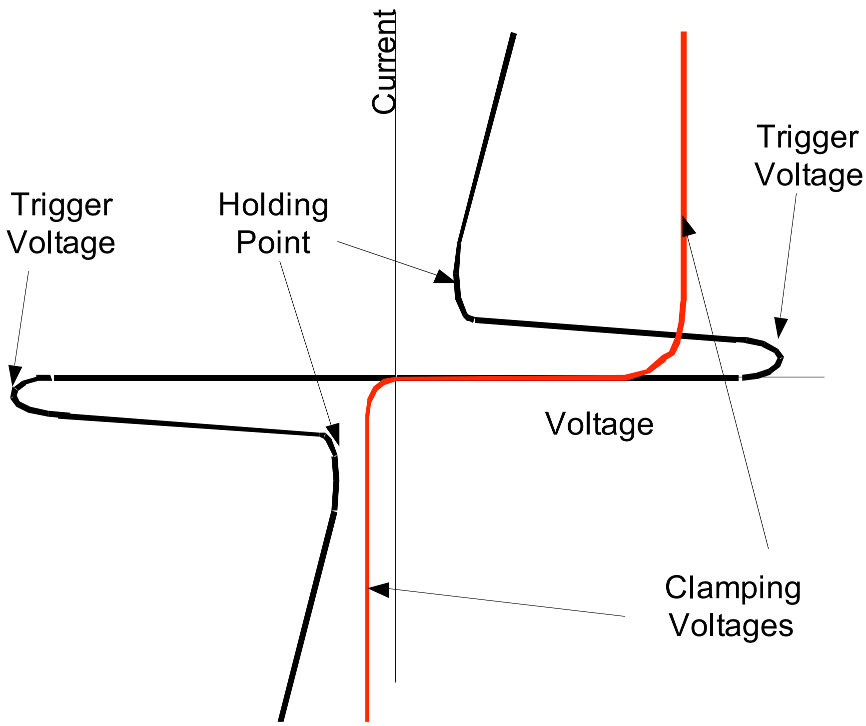

Figure 12 I-V characteristics of a bidirectional crowbar device (black) and a unidirectional voltage clamping device (red).

Some crowbar devices, such as thyristors, are very attractive for protection. Thyristors can have a low on state voltage and can keep voltage levels well below the critical values for sensitive electronic elements and carry considerable current without damage to the protection element due to low power dissipation. Care must be taken in the use of crowbar devices. The lowest current and voltage point that can sustain the on state of the crowbar device is an important parameter and is often called the holding point, see Figure 12. If the electrical node being protected can supply the voltage and current levels of the holding point, a crowbar device may not turn off after the electrical stress has been removed. Careful selection of the crowbar device is needed or other precautions must be taken to insure the protection turns off when the stress is removed and does not turn on during normal operation. The circuit being protected must also be able to survive the high voltage excursion needed to turn on the crowbar action.

Voltage clamp devices do not have the problem of not turning off after a stress, but they also must be selected with care. Clamp devices protecting in the reverse bias direction dissipate considerable power which they must dissipate internally. Clamp devices need to have very low dynamic resistance in the on state to insure that while carrying large currents the voltage does not exceed the allowed levels for sensitive circuit elements.

Applying Protection

Protection Product Selection

There are several considerations that must be taken into account when choosing protection elements. Consider the very basic circuit shown in Figure 13. An input of an integrated circuit is connected to a signal line that enters the system from an unprotected electrical environment. The signal line may be exposed to a variety of external stresses with voltage and current levels well beyond those that the input can withstand. The protection element is needed to insure that the voltage on the input remains within safe limits and shunt current away from the integrated circuit. The protection element choice depends on two things, the nature of the circuit being protected and the nature of the external stress.

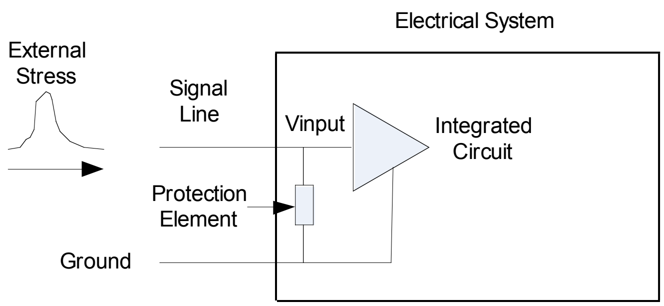

Figure 13 Example of protection element use

We will consider the properties of the input being protected first. Figure 14 illustrates the normal voltage range of the input, as well as the voltage beyond which damage will result. The onset of damage is usually not a sharply defined voltage. Voltage can extend to higher values if the excursion is very brief. Figure 14 also shows the I-V curves of two protection elements, a voltage clamping device and a crowbar device. For voltages within the normal operating range both protection elements' resistances are high, insuring input signal integrity. The voltage clamp protection looks well suited for this application because the voltage never enters the damage region. The crowbar device may be capable of protecting the circuit. Success of crowbar protection depends on how long the sensitive circuit can survive the turn on voltage of the protection element and how fast the protection element responds.

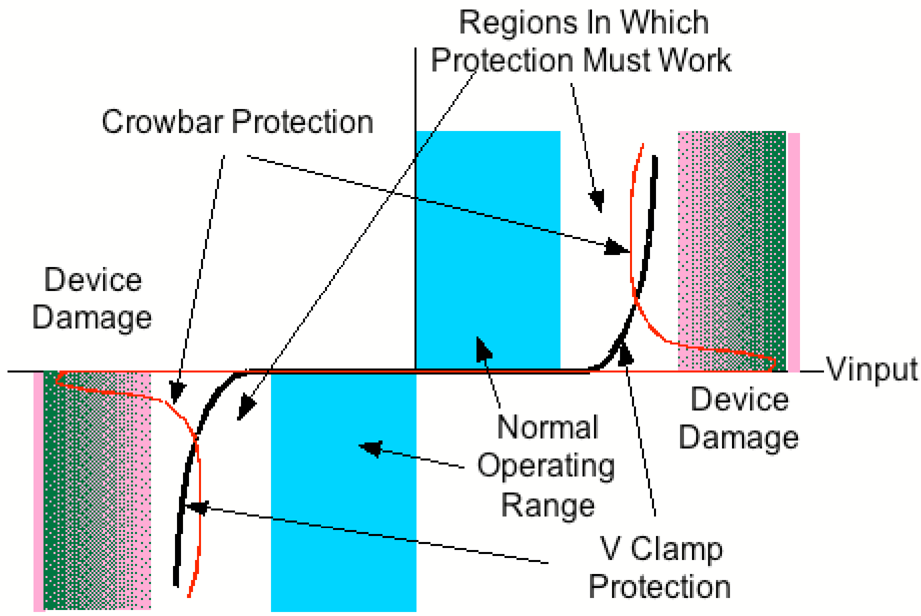

Figure 14 Voltage limits on circuit

How low the on resistance needs to be to prevent the voltage reaching the danger zone depends on how much current the external stress can provide. We therefore need to understand the nature of the external stress. The best way to define the external stress is to use the stress definitions in industry standard tests for system robustness to electrical stress. Test standards specify the voltage and current waveforms that a product needs to survive in a given environment. Consider the example in Figure 15. The system is required to survive a stress with a peak current of 20A. The circuit being protected has an input with an operating voltage of 0 to 3.6V and damage to the input is expected if the voltage exceeds 8V. The sample protection element turns on at 5V, safely above the normal operating voltage and can carry in excess of 20A without the voltage exceeding the unsafe operating voltage. This type of device should be very successful for protecting against an ESD stress.

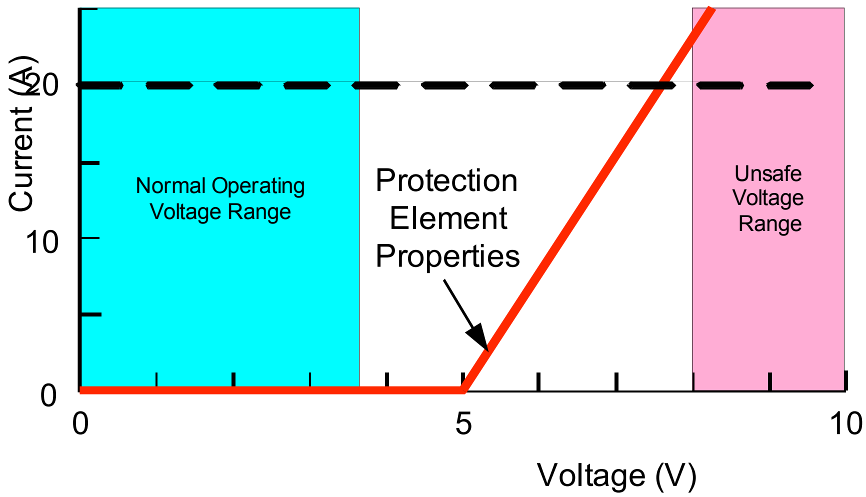

Figure 15 Example of the selection of a protection element for an application requiring a 20A peak current.

There are of course other considerations in the choice of protection elements. Most interfaces are more complex than a single line with respect to ground. Differential signals and systems such as the telephone network which use a combination of Primary and Secondary Protection need special considerations. The capacitance of the protection element is often more important than the low voltage resistance of the protection element, especially for high speed circuits. Physical size of the protection element, placement on the system board and cost are additional issues.

Knowing the properties of the system to be protected and the nature of the stress waveform allows an informed choice of protection devices. The protection must not turn on within the normal range of operation of the system node being protected, its capacitance must be low enough not to degrade high frequency signals, the protection element needs to be able to survive the stress itself, and the protection element must have low enough resistance in its on state to keep the voltage of the electrical node being protected below the danger region for the circuit being protected.

Protection Devices

Over Voltage Devices

Thyristor Surge Protection Devices

Thyristors are crowbar devices. Thyristors are based on a pair of intertwined bipolar transistors created by a 4 layer stack of n and p doped silicon regions as shown in Figure 16. The n doped region N1, p doped region P1, and n doped region N2 form the emitter, base and collector of an npn transistor while p doped region P2, n doped region N2, and p doped region P1 form the emitter, base and collector of a pnp transistor. With this arrangement the collector of each transistor provides the base of the other transistor. In this way any emitter to collector current of one transistor provides the base current for the other transistor. For a positive Anode to Cathode voltage, both emitter-base junctions, J1 and J3, are forward biased. Only the reverse biased junction J2 prevents current flow. If the Anode to Cathode voltage is increased to the breakdown voltage of the J2 junction currents will begin to flow directly into the bases of the two bipolar transistors. This turns both transistors on. With both transistors on the Thyristor's resistance drops, and the voltage across the Thyristor also drops. The resulting I-V curve for forcing a positive current from the Anode to the Cathode of a Thyristor is shown in Figure 17. A protection element with this form of I-V curve can provide excellent protection; when triggered the voltage drops well below the trigger condition and considerable current can be carried with very little power dissipation in the protection element. A caution is that the current or voltage must fall below the Holding Point, as shown in Figure 17, to return the Thyristor to its high resistance state.

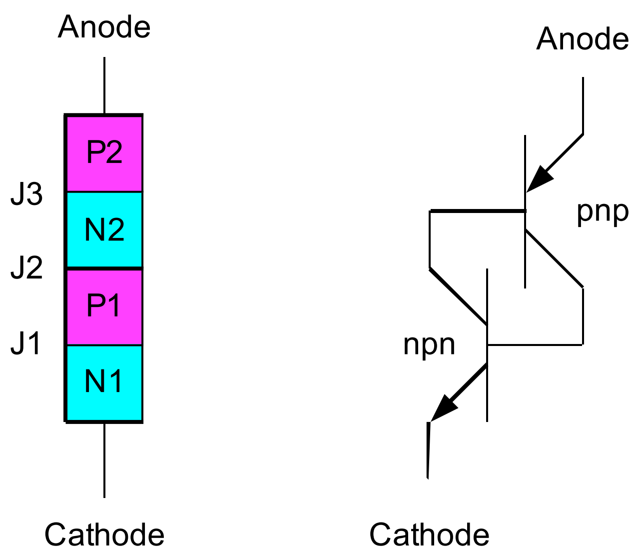

Figure 16 Thyristor physical structure and circuit

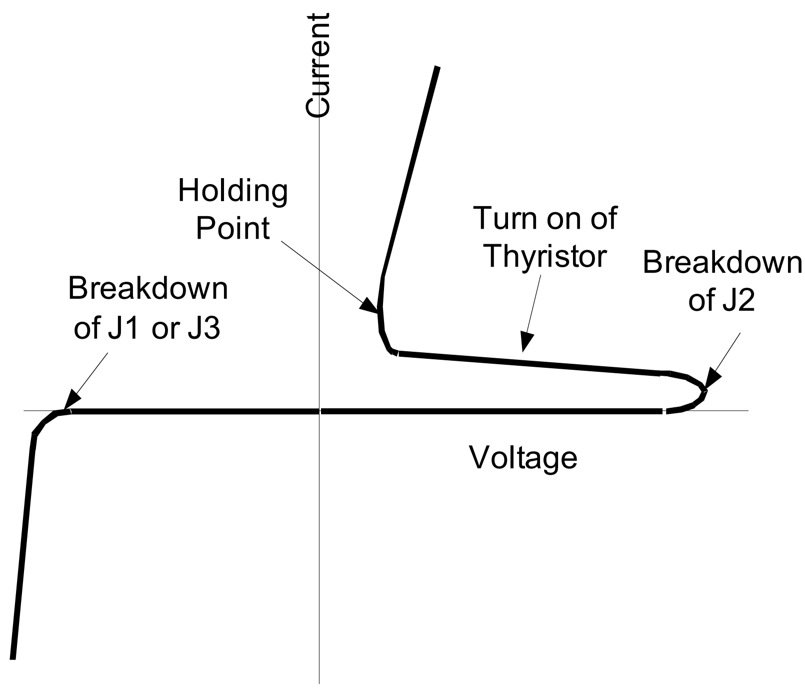

Figure 17 I-V curve for a thyristor biased Anode to Cathode

Under a negative Anode to Cathode voltage there is no regenerative feature and the I-V curve looks like a reverse bias diode breakdown as shown in Figure 17.

Figure 17 shows that the protection properties of a simple Thyristor are very asymmetric. To provide symmetrical crowbar behavior it is necessary to use two anti parallel Thyristors. This can be done with a pair of discrete Thyristors, as in Figure 18a, or it can be done with an integrated structure on a single piece of silicon including 5 doping levels, as illustrated in Figure 18b. The integrated device is usually called a Thyristor Surge Protection Device (TSPD) and its I-V characteristic is shown in Figure 19. Most TSPDs are of the symmetrical behavior but there are other options.

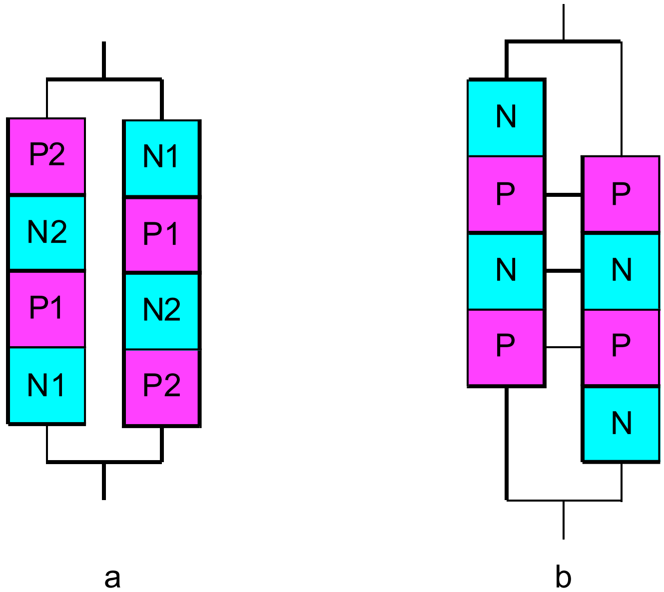

Figure 18 Illustrated versions of anti-parallel Thyristors. a) a pair of anti-parallel Thyristors b) anti-parallel Thyristors integrated into a single silicon device.

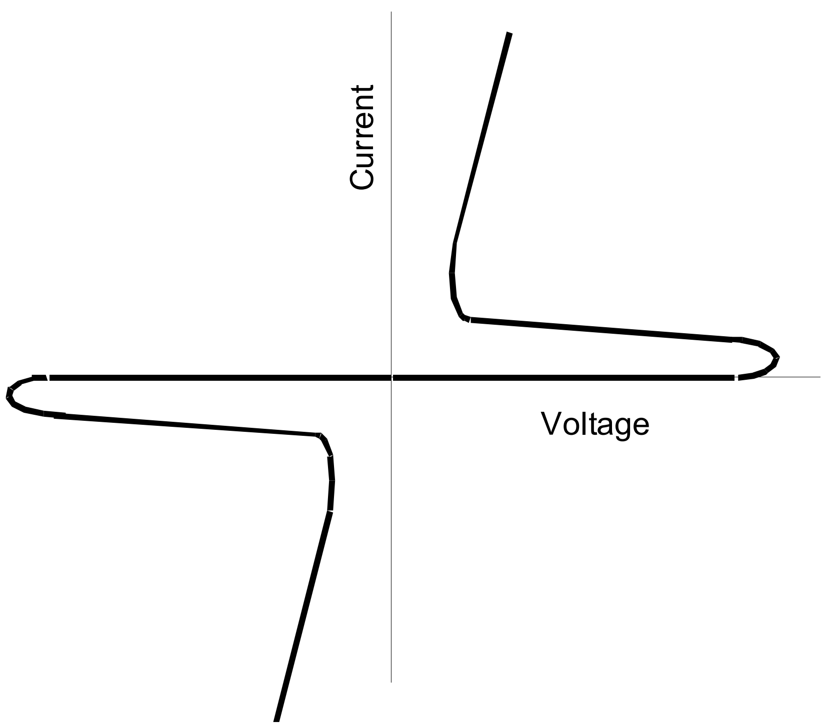

Figure 19 I-V curve of a pair of anti-parallel Thyristors

Transient Voltage Suppressors

Transient Voltage Suppressors are based on Avalanche and Zener diodes optimized for carrying high currents, tailored for specific breakdown voltages. Diodes are formed in a semiconductor, usually silicon, at a junction between n and p doped regions. TVS devices provide protection with a combination of forward bias and reverse bias breakdown conduction. TVS devices can also be manufactured with a variety of configurations as shown in Figure 20 to provide unidirectional, bidirectional and multi line protection. The basic I-V properties of TVS devices are shown in Figure 11.

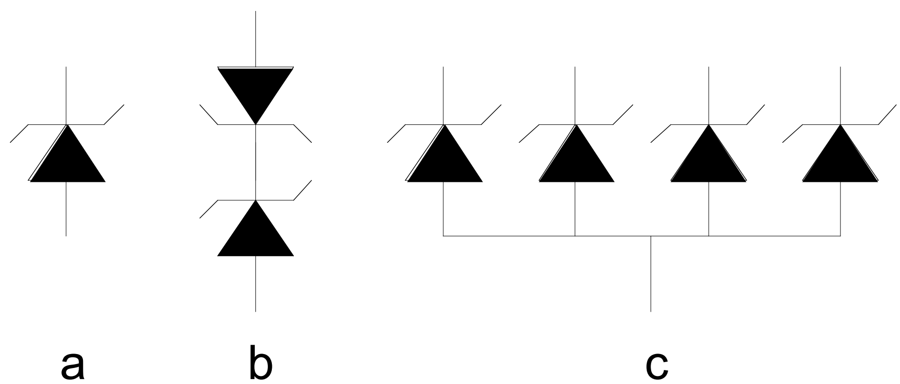

Figure 20 Sample of types of TVS devices

Metal Oxide Varistors (MOV)

The term varistor is a combination of variable and resistor. At low currents and voltages varistors have a high resistance but at higher voltages and currents the resistance drops dramatically. A varistor’s I-V curve is very similar to a bidirectional TVS device as shown in Figure 21. Varistors are usually made of a ceramic of zinc oxide grains in a matrix of other oxides as illustrated in Figure 22. The grains form diodes with the surrounding matrix, creating a complex array of parallel and anti-parallel diodes. At low voltage across the varistor each miniature diode has a very low voltage across it and very little current flows. At higher voltages the individual diodes begin to conduct and the resistance of the varistor drops dramatically. Factors such as grain size, the nature of the matrix material between the grains, the thickness of the ceramic and the attachment of leads to the ceramic determine the properties of a varistor.

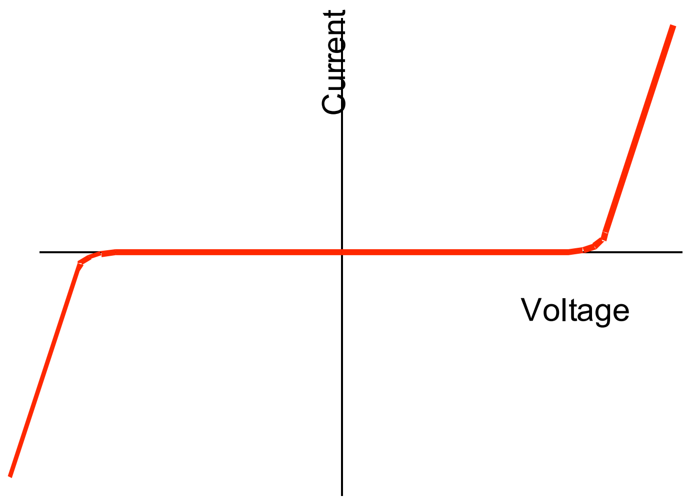

Figure 21 IV curve of a Varistor

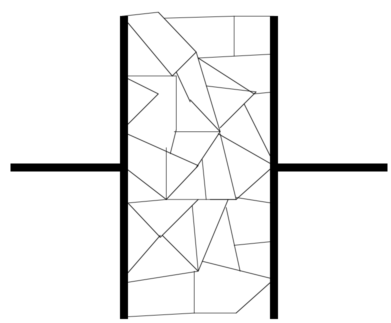

Figure 22 Diagram of a Metal Oxide Varistor

The bulk nature of the varistor resistive material allows them to carry considerable current without catastrophic failure. They do suffer from degradation upon multiple stresses, tend to have high capacitance and often have higher on resistances than TVS devices intended for the same application.

Polymer ESD Devices

Polymer ESD devices consist of a polymer embedded with conducting particles as shown in Figure 23a. At high voltage arcs between the particles create a low resistance path resulting in a drop in voltage. Polymer Devices are bidirectional crowbar devices as shown in Figure 23b. Polymer devices often have very high turn on voltages, often over 200V, but they turn on quickly, limiting the exposure to high voltage.

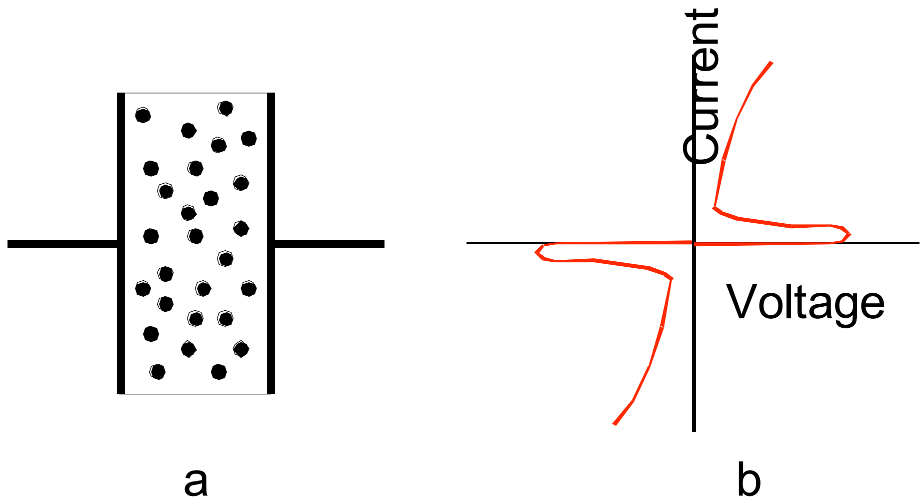

Figure 23 a) Polymer ESD construction, b) I-V curve of a polymer device

Gas Discharge Tubes

Gas discharge tubes are usually formed with a ceramic body filled with a gas mixture containing neon and argon and 2 or more electrodes as shown in Figure 24. When the voltage across the electrodes exceeds a specified value an arc occurs within the tube, providing a low current path. Gas Discharge Tubes with three or more electrodes can be constructed with a single volume of gas by having holes in the inner electrodes. The result is that an arc formed by a trigger voltage between any two adjacent electrodes will result in a low resistance path between all of the electrodes as the ionized gas fills the entire gas chamber. This can be an important feature for multi line signal ports which might be sensitive to large imbalances in the voltages between the lines. Gas discharge tubes have the bidirectional crowbar I-V similar to a bidirectional thyristor.

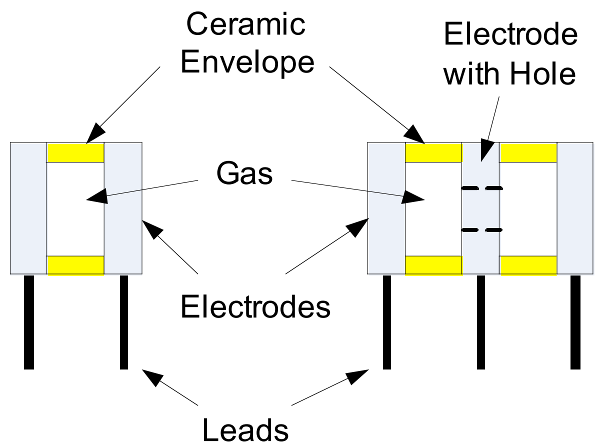

Figure 24 Simple cross section of two and three lead Gas Discharge Tubes

Gas discharge tubes can carry very large amounts of current and have very low capacitance resulting in very little signal loading. The lowest turn on voltage for a GDT is about 75V and the turn on time is relatively long. GDTs are also relatively large and more expensive than other surge protection devices. They excel as primary protection devices in conjunction with other faster turn on and lower voltage secondary protection elements.

Over Current Devices

Fuses

Fuses are a prime current limiting device. The active element of fuse is a metal conductor designed to melt and cause an open circuit if too much current flows in a circuit. Fuses come in a wide variety of configurations but the basic features are illustrated in Figure 25 for a cylindrical fuse. The fuse body can be made from a variety of insulating materials. For cylindrical fuses glass is a popular material since it is easy to see if the fuse has blown. The primary parameters for fuse characterization are the current carrying capacity and the rated voltage but other factors are also important. The current carrying capacity or rated current is the amount of current that the fuse will carry under steady state conditions. The rated voltage is the maximum voltage that can be maintained after the fuse has melted. The fuse's rated voltage must always be as high, or higher, than the system voltage.

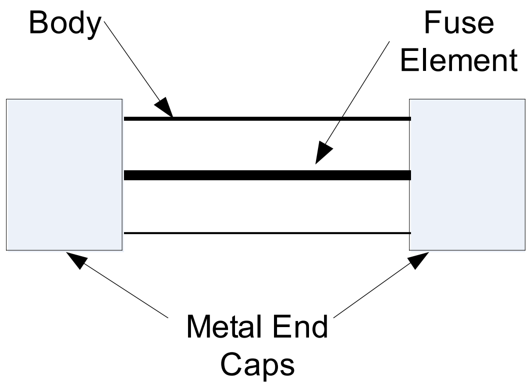

Figure 25 Diagram of a cylindrical fuse

The choice of the correct fuse can be complicated and it is advised to review literature provided by the manufacturer of a fuse being selected to ensure proper selections. One reason to review manufacturer literature is that fuses are specified according to different standards in different markets. In Europe the standard EN 60127 (or IEC 60127) standardizes fuses while in North America UL 248-1 and -14/CSA C22.2 No. 248.1, .14 are applicable. In Japan the Electrical Appliance and Material Safety Law (EAMSL) covers enclosed fuses.

Several considerations go into the selection of a fuse beyond the current carrying capacity and the voltage rating. Operating time is a major concern. The operating time is how long before the fuse presents an open circuit after the start of an over current condition. The operating time for a given fuse depends on how far above the current carrying capacity the current is, the ambient temperature and the type of fuse. Some fuses are designed to be slow blow or time-lag to allow for large inrush currents that occur for some load types such as inductive loads or possibly very large capacitance. Electronic systems are often sensitive to short over voltage and over current conditions and may need a fast operating fuse to prevent system damage. Also important is the Rated Breaking Capacity, also known as the “Interrupting Rating” and the “Short Circuit Rating.” This is the largest current that a particular fuse can interrupt. At currents above the Rated Breaking Capacity the current may not be interrupted due to a continued arc or the fuse may explode causing damage.

Positive Temperature Coefficient

Positive Temperature Coefficient (PTC) devices provide a similar function as a fuse, interrupting excess current, but have an automatic reset function. PTCs are made with a composite of conductive particles in a semi-crystalline polymer matrix as illustrated in Figure 26. At room or standard equipment operating temperatures the conducting particles touch, providing a low resistance path. If the temperature increases due to high current flow or ambient temperature change the polymer melts and becomes amorphous. In the amorphous state the volume expands and the conducting particles separate, increasing the resistance of the device. The advantage of a PTC is that after excess current has been removed the device will cool and return to a low resistance state.

Room Temperature

Elevated Temperature

Figure 26 Illustration of PTC operation

Comparison of Protection Devices

Table 3 shows a comparison of different types of surge suppression devices. The table is divided by device capabilities for high power surge events, such as the combination wave, 8/20 and 10/1000 types of stress, and fast, lower energy, ESD events.

Table 3 Comparison of voltage protection devices

Type		Speed	Voltage Accuracy	Current Capability	Size on Board	Lowest Crowbar Trigger Voltage	Wearout
High Power Surge Events - 8x20 µs, 10x1000 µs, ect.							
Gas Discharge Tube	GDT	Slow	Fair	High	Large	75V	Will fail after numerous stresses depending on severity
Thyristor Surge Protection Devices	TSPD	Fair	Good	Medium	Small	80V	No
Transient Voltage Supressor	TVS	Fast	Good	Low	Small	NA	No
Metal Oxide Varistor	MOV	Fair	Poor	Medium	Small	NA	Yes

Very Fast Surge Events – ESD (IEC61000-4-2)							
Polymer Device	PESD	Fast	Poor	Low	Small	~100V	Yes
Metal Oxide Varistor	MOV	Fair	Poor	Medium	Small	NA	Yes
Silicon ESD Suppressor	TVS	Fast	Good	Medium	Small	NA	No

Comparison of the effectiveness of different clamping devices is often very difficult. Data sheet parameters focus on the voltages at which protection elements turn on and the level of stress they can absorb. There is often very little on voltage clamping capability. Gas tubes and thyristors frequently clamp at voltage below the operating voltage of normal operation and therefore provide excellent protection during the time period that they are active. Protection elements designed for surge application are often specified with a clamping voltage, the peak voltage for a specified surge current such as 8/20 or 100/1000. The most difficult area for comparison is in the realm of ESD protection. ESD testing of product is done with the IEC 61000-4-2 standard. ESD protection elements are often characterized by their ability to withstand IEC current waveforms at specified levels. (This is done even though there is no standard to insure that the test is done in the same way between manufacturers.) With the IEC waveform, as discussed in Chapter 1, there is no clear way to define a clamping voltage. In the absence of a defined clamping voltage manufacturers have chosen a variety of ways to demonstrate the conductivity of their product during an ESD event. One of the more popular methods is to show a "screen shot" of the voltage measured across a protection element during an ESD event. A sample, comparing a diode based TVS device and a varistor is shown in Figure 27 for the same ESD stress. Even though the two products are aimed at the same application the diode based TVS shows clear advantage over the varistor in terms of protecting sensitive components from excess voltage.

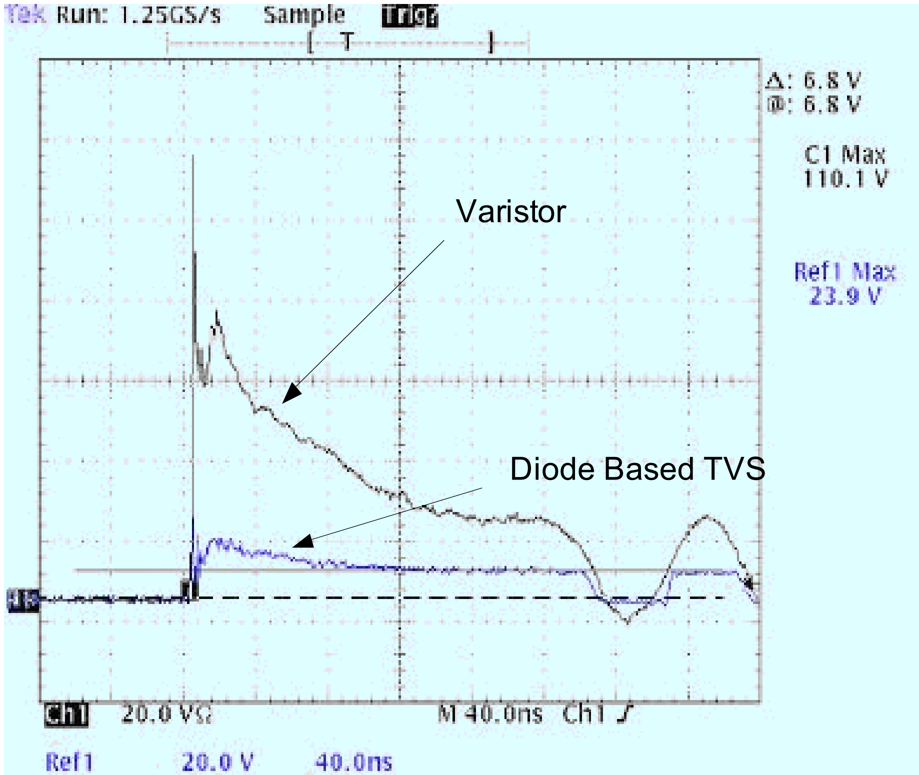

Figure 27 Comparison of Voltage measurements across a diode based TVS and a Varistor for the same ESD stress. Both products were intended for the same application

Another method that has been used to show the clamping ability is the use of voltage capture during a square stress pulse from a Transmission Line Pulse (TLP) system. This is especially popular with polymer type protection elements. The resulting curves show a dramatic drop in voltage from the initial trigger voltage of over 200V. The resulting voltage may still be quite high in comparison with the safe operating voltages of modern integrated circuits.

Protection Examples

There are many circuit configurations which require protection and it is impossible to cover them all. What is important is to see a few examples and see the considerations that go into protection design.

Differential Signal Pair

Consider a differential signal carried over a twisted pair as shown in Figure 28. Stress can occur in two ways. There can be a common mode signal on both the Positive and Negative lines with respect to ground and there can be a differential stress between the two lines. Protection options are shown in Figure 29. The example in Figure 29a has the advantage of only requiring two protection elements. The disadvantage is that twice the voltage can build up between the P and N lines as between either P or N and ground. This disadvantage is removed in Figure 29b by adding a dedicated protection element between P and N. For high speed lines there is a disadvantage because each signal line has the load capacitance of two rather than 1 overvoltage protection elements. The example in Figure 29c reduces the capacitive loading by placing the protection elements in series. For this arrangement the turn on voltage of the protection elements should be reduced from those that would be used in the Figure 29 a and b examples.

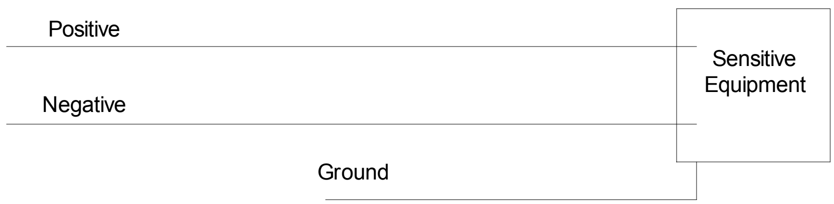

Figure 28 Basic Differential Signal

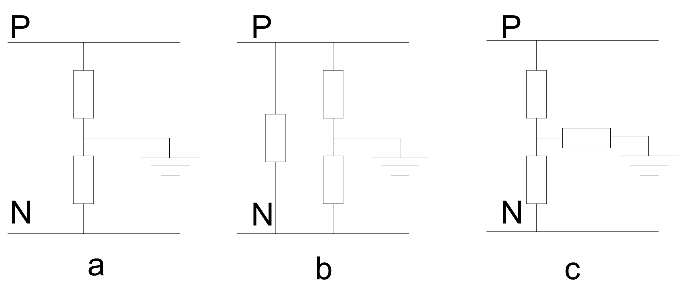

Figure 29 Overvoltage protection examples for a differential pair

Asynchronous Digital Subscriber Line

Asynchronous Digital Subscriber Line (ASDL) for providing both voice and high speed data over the same twisted pair telephone lines provides interesting protection challenges. Standard voice over telephone lines uses frequencies up to 4kHz, leaving a wide bandwidth to over a MHz available for data transmission. The data signal is separated from the voice signal with a transformer as shown in Figure 30. Standard telephones in the United States have a 48V DC voltage when the phone is "On Hook" or not being used. The ring signal is a 90Vrms signal. DSL Line Drivers typically operate in the 5V to 12V range. Protection elements need to be selected that will protect the low voltage DSL lines cards without interfering with the much higher voltage voice circuits. The protection strategy must also provide fire prevention and electrocution protection at the entrance to the building.

The protection requirements are slightly different between the central office and the customer premises, but the basics are similar. Figure 31 shows the protection strategy for a central office. The telephone line enters the building where protection is needed from lightning, power faults and switching noise. This is usually provided by Gas Discharge Tubes housed within the Main Distribution Frame (MDF). After passing the building entrance protection the twisted pair continues to the line card. The line card for an ADSL performs the separation of voice and data signals and connects the voice and data signals to the telephone network and the internet respectively. Current limiting devices, either fuses or resistors, are often placed at the input to the line card. Secondary protection at the input to the line card needs to protect the voice circuitry as well as the transformer. This secondary protection is usually performed by Thyristor Surge Protection Devices (TSPD). The final protection is on the far side of the transformer to protect the ADSL line driver and is typically a diode based Transient Voltage Suppressor (TVS).

The selection of the protection components depends on the nature of the circuits on the line card and the requirement that protection not degrade system performance. The choices are also guided by a variety of telephone industry standards which the equipment must pass. The Gas Discharge Tubes are typically chosen to have a turn on in the 600V range. This voltage is low enough and the Gas Tube fast enough to prevent physical damage to the building or harm to people in the structure. The protection devices located on the line card are intended to protect the card itself from damage. The TSPD devices must not turn on during normal operation. The 48V DC voltage and 90Vrms ring voltage dictates a turn on voltage in excess of 200V. How high a turn on voltage that can be tolerated depends on the properties of the voice circuit devices as well as the stress that the transformer can handle. Further protection is needed for the ADSL Line Driver. Line drivers typically operate in the 5 to 12V range, well below typical telephone voltages. The TSPD and the voltage reduction provided by the transformer can not be relied on to provide all the required protection for the line driver. The TVS, matched to the voltage range for the line driver, provides the final protection.

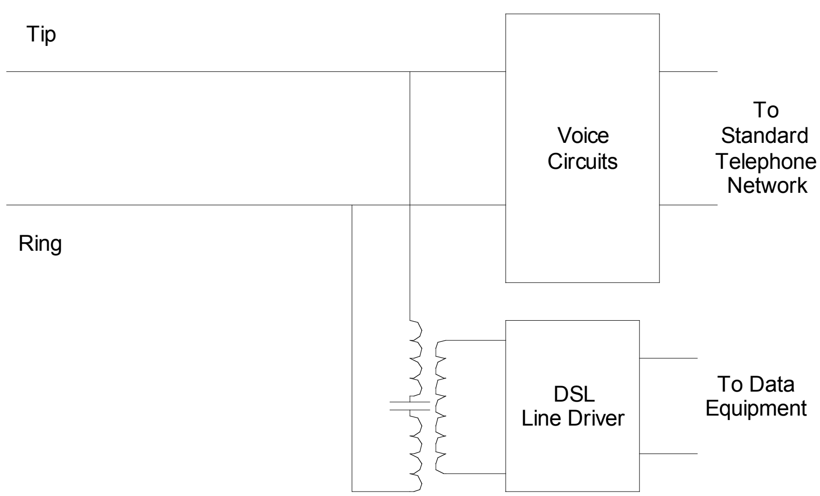

Figure 30 Separation of voice and date signals for ADSL

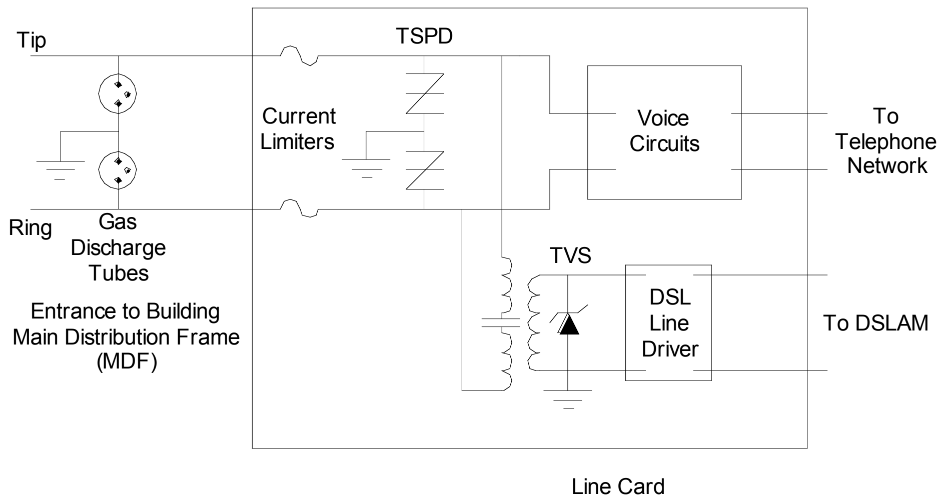

Figure 31 Protection Strategy for ADSL circuits in a Central Office (DSLAM is Digital Subscriber Line Access Multiplexer)

In the customer premises the situation is somewhat simpler, as shown in Figure 32. At the building entrance gas discharge tubes in a Network Interface Device can again provide the necessary protection from lightning and other surge threats. For standard telephones no further protection is needed. The remaining protection can be provided in the ADSL modem with an arrangement very similar to that provided on a line card.

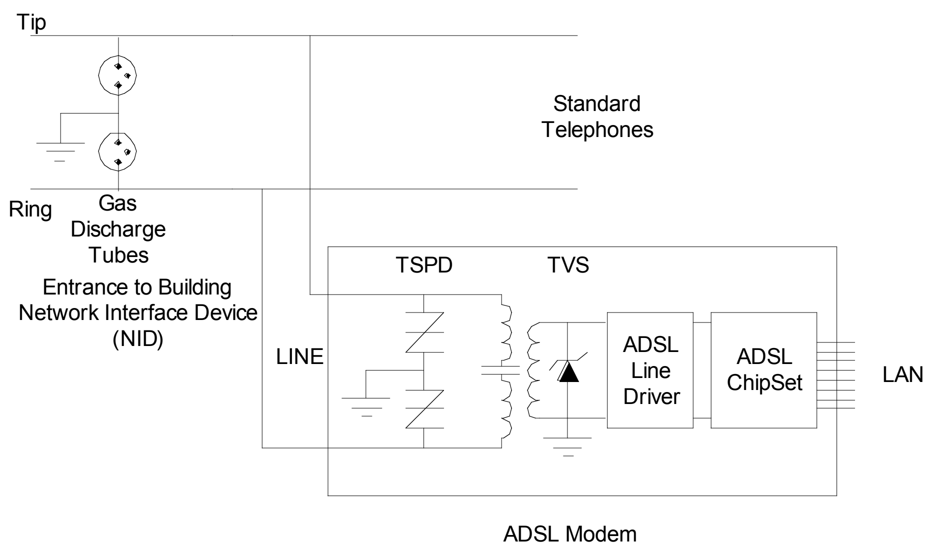

Figure 32 Example of ASDL Protection in a customer premises

TSPDs are available in a wide range of voltage and current ratings to match the requirements of each application. The NP Series of TSPDs from ON Semiconductor spans from 64 V to 350 V at 50, 80 and 100 A ratings, all available in the surface mount SMB package. The various devices are sized to serve central office, subscriber line interface circuit (SLIC), access equipment, customer premises equipment, private branch exchange (PBX), digital subscriber lines (DSL), data lines, security systems, phones, modems, fax machines, satellite and CATV set-top boxes.

USB Protection

Universal Serial Bus (USB) has become a very popular interface for connecting peripherals and portable devices such as cameras, cell phones and digital assistants to computers. The USB interface consists of 4 wires, power and ground wires and a pair of differential signal wires, as shown in Figure 33a. USB is only intended for local connections, having a maximum cable length of 5m. Since the cable will not be extending over long distances or outside of building there is no need to protect against surges such as lightning. The major concern is ESD damage. The biggest ESD concern is Cable Discharge Event (CDE). This occurs when a cable, and possible a portable device on the opposite end of the cable, become charged and discharge when inserted into the USB connector. USB ports therefore need ESD protection. There is currently no test standard for CDE, although the ESDA is working on one. Some testing of USB ports is sometimes done with modifications of the IEC 61000-4-2 test method.

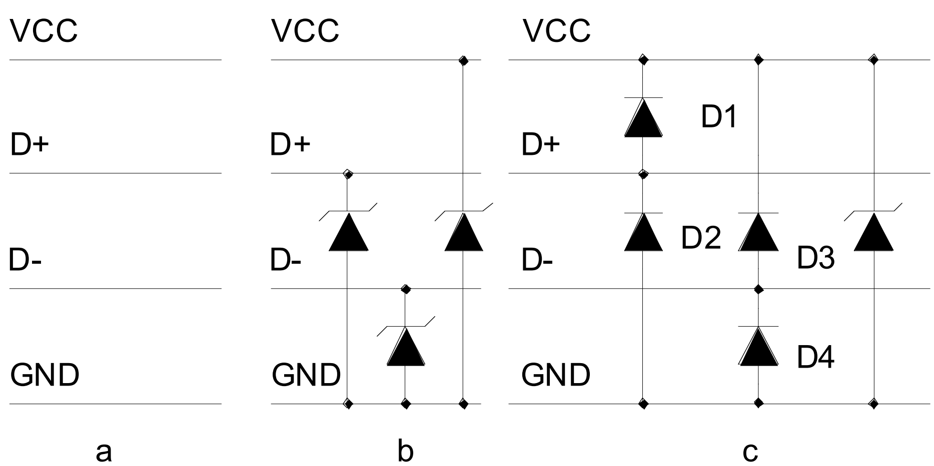

Figure 33 Protection of a USB port

The protection of a USB port must take into account that during normal operation there is a 5 V DC potential between VCC and GND. USB 2.0 has a data rate of 480 Mb/s. At these data rates the protection capacitance must be very low, no more than a few pF.

A straightforward protection strategy is to place low capacitance TVS devices between the D+ and D- and the ground rail as shown in Figure 33. The turn on voltage must be safely above the 3.6V maximum output high level and the protection elements must be able to tolerate the -1V to +4.6 V, 6MHz signal used to insure immunity to over and undershoot signals. A separate protection element may be employed for the VCC power bus to ground protection.

Another protection strategy is shown in Figure 33c. Each of the two data lines is connected by two diodes, one to VCC and the other to GND. As long as the data line voltages are between VCC and GND both diodes are reverse biased. If the data line potentials exceed VCC or go below GND by a diode drop a low resistance path is formed to either VCC or GDN. The protection strategy is completed with a Zener diode between VCC and GND. The Zener diode's reverse breakdown voltage must be 6V or greater to avoid turn on from normal power supply variability.

The arrangement in Figure 33c provides a low resistance current path between any two of the 4 wires which turns on with at most the Zener's reverse breakdown voltage plus two forward bias drops. Consider a positive stress between D+ and D- that significantly exceeds the Zener breakdown voltage. Current would flow through the forward biased diode D1, the reverse biased Zener diode in breakdown, and the forward biased diode D4.

The arrangement in Figure 33c has an additional advantage. As the breakdown voltage of a diode is decreased the diode's capacitance increases. The use of low voltage Zener diodes is therefore limited for high speed data lines. In the arrangement in Figure 33c the Zener diode is only between the VCC and GND terminals, where high capacitance is not a problem. The diodes D1 through D4 are only used in forward bias where diode resistance is inherently low. These diodes can therefore have a high reverse breakdown voltage and therefore low capacitance. This USB protection strategy can be implemented with discrete components but a number of suppliers provide integrated solutions which include the 4 standard and one Zener in a single package.

The development of low capacitance semiconductor devices tailored to the needs of high speed data line protection continues. ON Semiconductor now offers its ESD9L5.0ST5G , a 0.5 pF capacitance, sub-1.0 ns response time, unidirectional protection device in the tiny SOD923 package. It was designed specifically to protect voltage sensitive components from ESD and transient voltage events in USB 2.0 high speed and antenna line applications. Excellent clamping capability, low capacitance, low leakage, and fast response time, provide optimal ESD protection, while complying with IEC61000-4-2 Level 4.

Chapter 3. Standards

There are a large number of standards used to test systems for their immunity to overvoltage conditions. Groups of standards have developed based on location and industry. This chapter will review some of the most important standards. For additional assistance in selecting circuit protection products and solutions to meet global standards, contact your local ON Semiconductor sales representative or visit www.onsemi.com.

IEC61000-4 Series

The International Electrotechnical Commission (IEC) is one of the most important standards bodies. IEC has been traditionally regarded as a European standards body but it has truly global reach. The series IEC 61000 deals with electromagnetic compatibility with the series IEC 61000-4 covering testing and measurement techniques. Some of the relevant standards in this series are listed in Table 4. Passing these tests is often required for selling systems in Europe.

Table 4 List of some relevant standards in the IEC 61000-4 series on testing and measurement techniques

Standard	Topic
IEC 61000-4-1	Overview of IEC 61000-4 series
IEC 61000-4-2	Electrostatic discharge immunity tests
IEC 61000-4-4	Electrical fast transient/burst immunity test.
IEC 61000-4.5	Surge immunity test

IEEE C62 Series

IEEE was originally an acronym for the Institute of Electrical and Electronics Engineers. IEEE produces a wide variety of electrical standards. The series of standards IEEE C62 covers surge protection devices. The standards are divided into high voltage, >1000V AC or >1200V DC, and low voltage, <1000V AC or <1200V DC. The high voltage standards apply to high voltage power transmission lines. Only the low voltage standards are relevant to this discussion. The low voltage C62 standards cover, the nature of the surge environment, power line surge protection devices, communication surge protection devices, surge protection device components as well as guide on their use. The full C62 series is available on a single CD from IEEE. The low voltage documents are listed in Table 5.

Table 5. There is a great deal of educational information within these standards.

Table 5 IEEE Surge Protection Device Documents

IEEE Standard	**Title**
Power Line Surge Protection Devices	
IEEE Std C62.34 ™ -1996 (R2001)	Standard for Performance of Low-Voltage Surge-Protective Devices (Secondary Arresters)
IEEE Std C62.62 ™ -2000	IEEE Standard Test Specifications for Surge Protective Devices for Low-Voltage AC Power Circuits
IEEE Std C62.41.1 ™ -2002	Guide on the Surge Environment in Low-Voltage (1000 V and Less) AC Power Circuits
IEEE Std C62.48 ™ -1995	IEEE Guide on Interactions Between Power System Disturbances and Surge-Protective Devices
IEEE Std C62.41 ™ -1991 (R1995)	IEEE Recommended Practice on Surge Voltages in Low-Voltage AC Power Circuits
IEEE Std C62.41.2 ™ -2002	Recommended Practice on Characterization of Surges in Low-Voltage (1000 V and Less) AC Power Circuits
IEEE Std C62.45 ™ -2002	IEEE Recommended Practice on Surge Testing for Equipment Connected to Low-Voltage (1000 V and Less) AC Power Circuits
Telecommunication Surge Protection Devices	
IEEE Std C62.64 ™ -1997	IEEE Standard Specifications for Surge Protectors Used in Low-Voltage Data, Communications, and Signaling
IEEE Std C62.43 ™ -1999	IEEE Guide for the Application of Surge Protectors Used in Low-Voltage (Equal to or less than 1000 V rms or 1200 Vdc) Data, Communications, and Signaling Circuits

IEEE Standard	Title
jIEEE Std C62.36 TM -2000	Standard Test Methods for Surge Protectors Used in Low-Voltage Data, Communications, and Signaling Circuits
IEEE Std C62.38 TM -1994	IEEE Guide on Electrostatic Discharge (EDS): ESD Withstand Capability Evaluation Methods (for Electronic Equipment Subassemblies)
Surge Protection Device Components	
IEEE Std C62.31TM-1987 (R1998)	Standard Test Specifications for Gas-Tube Surge-Protective Devices
IEEE Std C62.32 TM -1981 (R2004)	Standard Test Specifications for Low-Voltage Air Gap Surge-Protective Devices (Excluding Valve and Expulsion Type Devices)
IEEE Std C62.33 TM -1982 (R1994)	Standard Test Specifications for Varistor Surge-Protective Devices
IEEE Std C62.35 TM -1987 (R1993)	Standard Test Specifications for Avalanche Junction Semiconductor Surge Protective Devices
IEEE Std C62.37 TM -1996 (R2002)	IEEE Standard Test Specification for Thyristor Diode Surge Protective Devices
IEEE Std C62.37.1 TM -2000	IEEE Guide for the Application of Thyristor Surge Protective Devices
IEEE Std C62.42 TM -1992 (R1999)	IEEE Guide for the Application. of Gas Tube and Air Gap Arrester Low-Voltage (Equal to or Less than 1000 Vrms or 1200 Vdc) Surge-Protective Devices
IEEE Std. C62.42TM -2005	IEEE Guide for the Application of Component Surge-Protective Devices for Use in Low-Voltage [Equal to Or Less Than 1000 V (ac) Or 1200 V (dc)] Circuits

UL 1449

Underwriters Laboratories (UL) is a United States based, not for profit, privately owned product safety and certification company. UL tests a wide variety of products for compliance with respect to standards that they have developed. UL 1449 specifies the performance criteria establishing the maximum voltage that can pass through a protection device after clamping has taken place for the United States market. Power outlet strips that include surge protection comply with this standard in the United States.

Telecommunication Standards

The telecommunications industry, with its large network extending from remote locations to within virtually all buildings, both commercial and residential, has its own standards for survival of stress. The standards are by their nature regional. Representative standards are listed in Table 6.

Table 6 Summary of telecommunication protection standards

Standard	Standard Body	Equipment Tested	Region
GR-1089-CORE	Telcordia	Central Office and Transmission	USA
TIA-968 / UL 60950	Telephone Industry Association Underwriters Laboratories	Customer Premises	USA
ITU-T K.20	International Telecommunications Union	Central Office	Europe
ITU-T K.21	International Telecommunications Union	Customer Premises	Europe
ITU-T K.45	International Telecommunications Union	Telephone Trunk Networks	Europe
YD/T 950	China Communications Standards Association	Central Offices	China
YD/T 993	China Communications Standards Association	Customer Premises	China
YD/T 1082-2000	China Communications Standards Association	Transmission	China

Automotive

The automotive industry has its own sets of standards with individual manufacturers often augmenting the standards. For ESD the ISO 10605 standard is most widely used. ISO 10605 uses ESD guns similar to those used in IEC 61000-4-2 standard but with different resistor and capacitor values deemed more applicable to the automotive environment. ISO 7637-1 2002-03, and ISO 7637-2 2nd DIS 2002-07, deal with electrical transients other than ESD for the automotive industry. Individual companies may add additional tests. Ford Motor Company, for instance, has developed a number of voltage transient overvoltage tests that are specific to the automobile environment. These are documented in ES-XW7T-1A278-AC, "Component and Subsystem Electromagnetic Compatibility - Worldwide Requirements and Test Procedures" which is available at www.fordemc.com.