
## INTRODUCTION

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In this issue, we look at surge and lightning protection for circuits. Since many of our applications are connected to AC power lines, and the quality of power and protection from surges or lightning varies, we will discuss strategies for reducing these effects. We will draw on some articles from previous newsletters, as some of the protection methods are the same for other events, ESD for instance.

The next issue will discuss reducing internal noise susceptibility of an application (i.e., one or more circuits affecting other circuits in a single system). This will include discussions on analog and digital circuits and some routing guidelines.

Please send any comments on this newsletter or prior issues or any ideas for future articles to: EMC@microchip.com.

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## WHAT IS A SURGE?

A surge is a type of electrical overstress that is conducted on wires usually in the form of rapid changes in current flow or voltage. Surges are transient events typically lasting no more than a few milliseconds. Most surges are generated by switching reactive loads or lightning strikes.

Surge is governed by the IEC 61000-4-5 specification from the International Electrotechnical Commission (http://www.iec.ch). This specification discusses the testing and measurement techniques for surge immunity testing. Surges are broken into two categories: switching transients and lightning transients.

Switching transients are those associated with:

- Power system switching disturbances
- Switching activity nearby instrumentation
- Load changes in the power distribution system
- Resonating circuits associated with switching devices (thyristors)
- Assorted system faults, such as short circuits or arcing

Lightning transients are made up of mechanisms that create surge voltages by:

- Direct lightning strikes that inject high currents into the application. This high current produces voltages by flowing through the earth ground or the impedance of the circuit itself.
- Indirect lightning strikes that induce voltage or current in conductors due to the electromagnetic field created by the strike
- Current flow induced into common earth grounds due to nearby lightning strikes directly to the earth ground

Without careful consideration of protection type and placement, dangerous levels of voltage or current can couple into the application circuit when the protection device is excited. Some of these protection devices include gas tubes, spark gaps, varistors, avalanche diodes, and thyristors. For more details see the article "*Know Your Transient Suppression Device*" in Issue 3 of this newsletter.

## *IN THIS ISSUE*

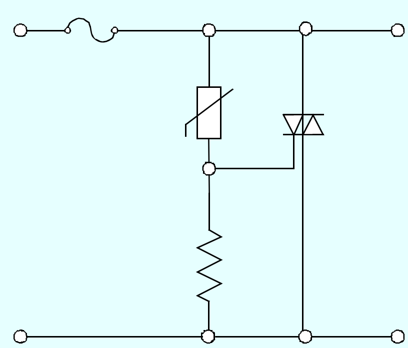


## *RECOMMENDED READING*

*Protection of Electronic Circuits from Overvoltages*
by Ronald B. Standler, ISBN 0-486-42552-5
The approach in this book is to work from the fundamental principles and the physics of overvoltage situations, and to discuss general design strategies and the philosophy of protection schemes. This book describes the various waveforms, properties of non-linear surge protective components, application of these components to various circuits, how to connect the surge protection components, and validating the protection scheme.

## *TIPS AND TRICKS*

The article, *"Protecting Circuits from Lightning (and Worse!)"* in this issue, discusses various type of transient suppressors and their selection criterion. If you need a transient suppressor that requires characteristics of a multiple transient suppressor, one solution is to use a hybrid system. The following figure shows an example implementation using MOV and Thyristor.



## PROTECTING CIRCUITS FROM LIGHTNING (AND WORSE!)

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### Introduction

Designing a circuit to withstand extreme high-voltage discharges can be very challenging. A lightning strike (i.e., a very fast, high-voltage pulse of tens of thousands of amps) is a powerful event, with enough energy to vaporize large chunks of metal! Printed Circuit Boards (PCBs) and Integrated Circuits (ICs) have no chance against direct lightning strikes; however, there are steps that can be taken to withstand the effects of an indirect high-voltage discharge event.

In contrast to the energy of lightning, the magnetic field of the wiring of a house, automobile or industrial plant stores much less energy, although the small physical size of the system (relative to the size of a cloud) supports nanosecond rise and fall times for kilovolt arcs. That energy is released in the form of localized electric arcs (plasma energy in the air) when switches, relays, or motor brushes interrupt current flow.

This article will discuss the magnitude of the problem that a lightning strike or other conducted electrical transient presents, conventional methods of diverting the bulk of electrical energy from a system, and approaches for minimizing the disruptive effects that fast transient high-voltage pulses can have on an electrical circuit.

### Lightning Physics

A typical lightning strike is actually a series of high voltage electrical discharges that take place over a fraction of a second.

A single discharge, or "stroke", is characterized by a very rapid rise (~1 µs), to a high peak current followed by a much slower decay (~500 µs), to near zero current.

Each stroke is preceded by a faint leader which establishes the path for the actual visible strike to follow. The energy in a stroke is about 100,000 Joules per meter, or 300 million Joules for the whole stroke, with each stroke lasting about 1 ms.

The magnitude of a lightning strike in terms of Volts and and Amperes is then:

$$Power = \frac{Energy}{Time}$$

$$V \times I = \frac{Joules}{Second}$$

$$V \times I = 3 \times 10^{11} J/S$$

where $V = 10{,}000{,}000\ Volts$ and $I = 30{,}000\ Amps$.

An extreme lightning strike can be many times this "typical" scenario, with cloud-to-ground voltages of many tens of millions of volts, peak currents of 200,000 amps, and peak rate-of-rise currents of 400,000 Amps/µs[1].

### Conventional Lightning Protection

The tried and true method of protecting an object against lightning is to intercept the lightning strike and conduct the bulk of its energy away from the object to earth ground, thus protecting the object and its contents. The most common implementation of this approach is the "lightning rod".

Extensive specifications, such as the National Fire Protection Association's "*Standard for the Installation of Lightning Protection Systems*" (NFPA 780), have been developed for the height and configuration of air terminals (lightning rods), the size of down conductors, and the implementation and characterization of the grounding system to provide adequate protection. These conventional systems effectively conduct the low frequency components of a lightning strike. The high frequency components of the strike will propagate through any structural metal or conductive material nearby and couple on to the power line.

Another side effect of these systems is the large electric fields that are generated by the rapid rise time of current through the high inductance of the down conductor. The magnitude of these electric fields can be calculated by considering the following conditions: A typical down conductor might have a resistance of 0.2 mΩ/meter and an inductance of 1000 nH/meter. For a 5.0 meter high building, R=1.0 mΩ and L=5000 nH. Using the lightning parameters for an extreme lightning strike from the previous section, the maximum electric field generated is on the order of:

$$V = RI + L\frac{dI}{dt} = (1 \times 10^{-3}) \times (200 \times 10^{3}) + (5000 \times 10^{-9}) \times (200 \times 10^{3} / 10^{-6}) = 1000 kV$$

Thus, the electric field would be about 200 kV/m[2].

### The Faraday Cage

A common approach to significantly reducing the effects of electric fields on a circuit is to construct a shield around the system.

The "ideal" shield would be a solid enclosure (no holes, slots, etc.) made of an ideal conducting material, whose surface has the same electrical potential at every point. With such a shield, electric fields or currents outside of the enclosure are cancelled and have no effect on an object inside the enclosure.

This type of enclosure is referred to as a "Faraday Cage" named for Michael Faraday, (1791–1867), the British physicist credited for the discovery of electromagnetic induction and the construction of the first Faraday Cage, among other things[3].

Although building an enclosure for a system or even adding a metal shield around a circuit on the PCB adds expense, this type of approach will significantly reduce the effects of electromagnetic interference when properly implemented.

## Other Fast Transient Sources

A circuit must survive transients that are even faster than lightning strikes. These transients surround us, in homes and automobiles and industrial plants. They are conducted through the power line as a result of locally arcing contacts in switches, relays, motors and circuit breakers, primarily due to inductive loads. As mechanical contacts open, inductive energy seeks a path to continue flowing and will create that path by arcing and sparking, repeatedly.

The amplitude of the inductance-generated kickback voltage can be calculated by : $Vpk = L*dI/dt$

The effects of these types of events is significant. If a 300A motor's inductance is 1 mH, the peak voltage can be thousands of volts when the motor is turned on and off, generating very large voltage spikes that are then conducted directly on the power line.

## Protection Requirements for Electronic Circuits

There are two relevant specs that define High-Voltage Fast Transient events:

- IEC 61000-4-4 Electromagnetic compatibility testing and measurement techniques - Electrical fast transient/burst immunity
- IEC 61000-4-5 Electromagnetic compatibility testing and measurement techniques - Surge immunity test.

These specifications quantify the level of fast transients and power surges that an electronic circuit should be able to withstand when subjected to high-energy disturbances on the power and interconnection lines.

There are a number of "test levels" or "classes" that are specified in the body of these documents, depending on the environment that a circuit is expected to operate in. The following table summarizes the test conditions of a "Level 4" environment, where the interconnections are running as outdoor cables along with power cables, and the power installation can be subjected to interference voltages generated by the installation itself or by lightning.

| Test | Specifications | Noise Source |
|---|---|---|
| IEC 61000-4-4 | $V_{(peak)}$ = 2 kV (into 50 Ω)<br>$t_{(rise)}$ = 5 ns<br>$V_{(decay)}$ = 1 kV/50 ns<br>Specified burst pattern for 1 minute | Switching noise of inductive loads, relay and switch chatter |
| IEC 61000-4-5 | $V_{(peak)}$ = 4 kV<br>$t_{(rise)}$ = 1.2 µs<br>$V_{(decay)}$ = 2 kV/50 µs<br>$I_{(SC)}$ = 2 kA<br>$t_{(ramp)}$ = 8 us<br>$I_{(decay)}$ = 1kA/30 µs | Lightning, power line and load switching |

Our task then is not to survive direct lightning strikes, but to implement PCB and IC systems that are robust in the face of fast transients, with surges of thousands of volts and amperes, rise times of hundreds of nanoseconds, and controlled durations.

## Voltage Transient and Surge protection

There are a number of solutions that can be implemented to address the problem of voltage spikes, transients and surges. These include shielded cable and twisted wires, crowbars, filters, and Transient Voltage Suppressors (TVS)[(4)].

| Solution | Advantages | Disadvantages |
|---|---|---|
| TVS Device | • Clamp surge voltage<br>• Fast turn-on time (<1 ns to 5 ns) | • Limited power rating<br>• Power rating proportional to capacitance |
| Crowbar Device | • High power rating<br>• Shunts surge current to GND | • Does not absorb energy<br>• Difficult to turn "off" |
| Shielded Cable/ Twisted Wire | • Increase RF immunity<br>• Decrease radiated emissions | • Cost<br>• High capacitance per meter |
| Filter | • Continuous noise filtering<br>• Attenuate surge voltage | • Does not clamp surges<br>• May distort data line signal |

Because we are interested in minimizing cost and protecting against power surges as well as fast transients, let's focus on TVS and crowbar devices.

### TVS DEVICES

Transient Voltage Suppressors (TVS) are semiconductor devices designed to provide protection against voltage and current transients. They are designed to operate in the Avalanche mode and essentially clamp a voltage to a set threshold. They typically use a large junction area to absorb large transient currents.

TVS devices are noted for their fast response time and low impedance. Some TVS devices can suppress transients in one direction (positive or negative voltage) or in both directions. One should also be aware of the different failure modes for these devices. For example, a Metal Oxide Varistor (MOV) will short, while the Zener Diode and TVS will typically open.

| Solution | Advantages | Disadvantages |
|---|---|---|
| • Metal Oxide Varistor<br>• (MOV) | • Low cost<br>• <1 ns to 5 ns response time<br>• Power rating α volume<br>• Power derating begins at 85°C | • Inherently bidirectional<br>• Aging characteristics<br>• High VCLAMP and ILEAKAGE |
| • Zener Diode | • Low cost<br>• Steady-state voltage rating | • Limited power rating<br>• Power derating begins at 25°C |
| • TVS Diode | • Optimized for power surges<br>• < 1 ns response time<br>• Low clamping voltage | • Limited power rating<br>• Power α silicon area<br>• Power α capacitance |

The MOV and Zener diodes are attractive solutions due to their low cost of implementation; however, their disadvantages, noted in the previous table, can be problematic when dealing with fast transients and high surge voltages. TVS diodes are slightly more expensive to implement, but their predictable behavior, low clamping voltage and speed of response makes them well suited to provide a first level of protection for electronic circuits with regard to voltage transients and surges.

### CROWBAR DEVICES

Crowbar devices conduct when threshold voltages are exceeded and then trigger to an ON state voltage drop for only a few volts (hence the name "crowbar"). These devices restore to a nonconducting state when the driving voltage and/or current is reduced with the passing of the transient. Spark gaps, Gas Discharge Tubes (GDT) and Thyristor's are crowbar devices.

| Solution | Advantages | Disadvantages |
|---|---|---|
| Spark Gap | • Low cost<br>• High surge current | • Variable breakdown voltage<br>• Short service life |
| Gas Discharge Tube (GDT) | • High surge current<br>• High off state impedance | • High cost<br>• Slow turn-on time<br>• High breakdown voltage |
| Thyristor | • Solid state reliability<br>• No life limit | • Difficult to turn off<br>• Medium turn-on time |

Since we are interested in minimizing cost while maintaining a fast response, the most useful crowbar device solution is the Spark Gap.

### Spark Gap

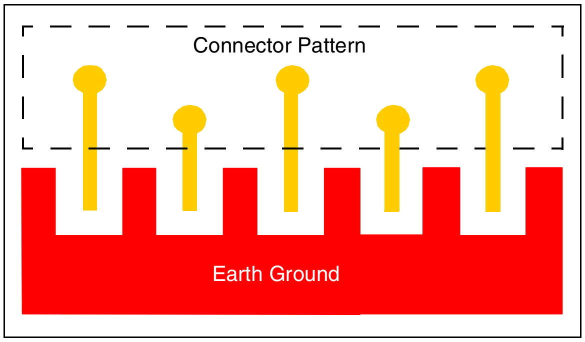
A spark gap can be implemented as a stand-alone device with overvoltage protection ranging from hundreds of volts to tens of thousands of volts. They also have peak current capabilities in the tens of thousands of amps, so they are well suited for protecting a circuit from the voltage and current surges defined in the IEC-61000 specification.

A spark gap can also be fabricated as part of the conductor pattern of a PCB, providing significant protection against voltage transients. Since it is part of the PCB, this is a very inexpensive method to implement. The main drawbacks are that the designer does not have as much control on performance, and performance can degrade over time.

The "gap" can have a nominal spacing of 0.005 to 0.015 inches, depending on what breakdown voltage is desired. The voltage breakdown of small spark gaps on a PCB is approximately V = ((3000 x p x di) + 1350), where "p" is the pressure in atmospheres and "d" is the distance in millimeters[5, 6].

The spark gap itself should be placed as close to the source of the power surge (e.g., external connector) as possible. Figure 1 illustrates a spark gap pattern from a connector, with the "gap" being formed between the trace copper and earth ground copper.

**FIGURE 1: SPARK GAP**




The combination of a crowbar and a TVS device may be the best implementation, providing the circuit with fast, predictable lower voltage protection of the TVS, as well as high voltage/current protection of the crowbar device.

## Summary

Designing for lightning and other high-voltage electrical transients can seem a daunting task at first, but there are common, conventional methods for protecting electronic circuits from these events.

First, the designer must determine what environment the system will be exposed to. Is there a mechanism for diverting the bulk of energy away from the circuit? Second, select and implement a method for controlling the fast high voltage transients that are conducted on the system level. In this way, the harmful effects of these types of events will be minimized.

## References

[1, 2] BOLT, Inc. (Business of Lightning Technology), http://www.boltlightningprotection.com

[3] Wikipedia, http://www.wikipedia.org

[4] Jim Lepkowski, ON Semiconductor, "*EMI/ESD Protection Solutions for the CAN Bus*", 2005 International CAN Conference Proceedings

[5] Bill Ehlers, PSC Inc., "*Spark Gaps Provide ESD Protection*", September 1997; EDN Access

[6] AirBorn Electronics, http://www.airborn.com.au

## DESIGNING AN ESD-SAFE ENCLOSURE

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### ESD

The article "*What is ESD?*" in Issue 1 of the EMC newsletter, provides background information on ESD or electrostatic discharge. The build up of static charge usually occurs over a period of time, and at some point it will result in a quick discharge. This discharge can be disastrous to a system.

One way of providing protection from static discharge is to limit or prevent charge build up. This approach is good for elements within the system; however, another potential source of ESD is external to a system. In this case, a protection mechanism would be to either block this discharge or divert it away from the sensitive system.

### System Enclosure

The most important element within a system for ESD protection is its enclosure. You need to consider the material used to build the enclosure and the design itself. The first important criterion is to select the proper material. The material should have sufficient dielectric strength to avoid direct discharge, and it should not break down under the discharge.

The first thing to consider is whether the enclosure will be grounded. If a system is ungrounded, a much higher dielectric strength is needed. A dielectric strength of 20kV or more is recommended. If the enclosure is grounded, the recommended dielectric strength is 1.5kV or more. The best option is to use a grounded metal enclosure as it prevents a charge build up. It also effectively blocks the external event (refer to *The Faraday Cage* in *"Protecting Circuits from Lightning (and Worse!)"* in this issue). It is also good at preventing radiated discharge (exterior discharge event can generate a radiated ESD event). However, in today's world lots of systems use a non-metallic enclosure.

Acrylic, the most common plastic used in today's enclosures, is a prolific static generator. As a side note, the generated static electricity also attracts dust, another important aspect to keep in mind for a clean room application. In many cases, the acrylic acts like Amber. Do you remember static electricity experiments in science class? Rubbing acrylic against clothing can generate a significant static charge.

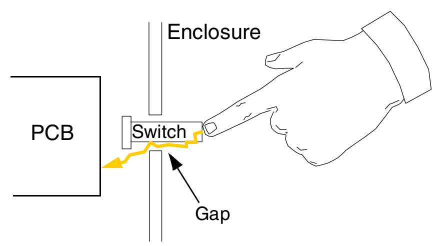
So what's the solution? Here are a few options:

1. Use a conductive coating. It provides a conductive (lower resistance) surface on non-conductive materials like plastic.
2. Use a static dissipative coating. It provides a moderate resistive surface on non-conductive materials like plastic.
3. Use a static dissipative material. An alternate material such as static dissipative PVC, conductive polymer, etc., can be used. These materials provide a much lower resistivity compared to plastic, but a higher resistivity compared to a conductor. It basically acts as a leaky medium, preventing charge build up.

The conductive, as well as static dissipative coatings, have been formulated to eliminate static electricity by decreasing surface resistance and volume resistivity. Depending on the material used, you will find a variety of coating options. For example, Electroless, electrolytic, conductive paint, vacuum metallizing, and so on. The right option must be selected based on cost, performance requirement and production volume. For a low volume, prototyping requirement, conductive (or static dissipative) spray or tape can be used. Both materials prevent static charge build up. Connecting it to ground or providing a discharge path through a resistor will serve to further increase its effectiveness.

### Enclosure Design

Most enclosures aren't just a plain closed box. This leads to the second part of our discussion; the design of the enclosure itself. Most enclosures have openings for a user interface, cables and connectors, etc. This can potentially create air gaps in the enclosure, providing a way for an ESD arc to enter into the system. The following illustration shows such an example.




As shown above, the switch installation creates an opening in the enclosure. When a user touches this area, the created ESD event may travel inside the system through this air gap. Try some of these suggestions to avoid this issue:

- Use a high-voltage proof silicon type or equivalent gasket to create an airtight connection
- Use an adhesive or sealant around openings to eliminate any air gaps
- Typically, an ESD arc of 15 kV can travel a distance of 1 cm. In favorable conditions, a higher ESD voltage may be able to travel further. In this case, the following two options can be used as preventative measures:
  - Keep sensitive PCBs and electronics at least 2 cm from the air gap. Avoid any other object in between that can act as a coupling medium.
  - Use a plastic knob with switches and a clear plastic rod with LEDs to increase its distance from the enclosure surface
- If a grounded metal enclosure is used, then ensure that joints and seams have no gaps

It is my hope that this article will prove useful to you when creating an ESD-safe enclosure for your system.

**NOTES:**

## Recent Issues

Current and back issues of this newsletter are available from the Microchip website at http://www.microchip.com.

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