

AN-6

COMMON MISTAKES IN LIGHTNING PROTECTION OF PHONE LINE INTERFACE CIRCUITS

By Joe Randolph

Introduction

Lightning protection of phone line interface circuits is a complicated topic. The specific protection circuit that will provide the best protection at the lowest cost will depend heavily on the type of interface being protected, the circuits used to implement that interface, and the type of equipment in which the interface is installed.

Despite this complexity, there are certain common considerations that typically apply for a wide range of applications. The purpose of this note is to provide a very basic description of the types of lightning surges that appear on phone lines, and a description of some of the common mistakes that designers make when trying to protect a phone line interface from these surges. This note is *not* intended to provide a comprehensive tutorial on lightning protection, but the basic principles described here should be helpful to any designer who is trying to develop a protection circuit, or to manufacturers who are experiencing lightning failures in the lab or in the field.

Terminology

In order to discuss lightning protection of phone line interface circuits, it is necessary to first define some terms that will be used frequently:

Phone Line Tip and Ring

A regular analog phone line consists of a single twisted pair of copper wires called tip and ring. Sometimes these are called the A and B leads. The discussion here will focus on this type of 2-wire phone line, although the same protection principles apply to 4-wire arrangements such as T1/E1, HDSL, and even Ethernet.

Terminal Equipment (TE)

In general, “terminal equipment” refers to equipment that terminates the phone line tip and ring leads at the customer’s premises. Examples include telephones, modems, fax machines, and PBXs. For the purposes of this discussion, we will also consider as “terminal equipment” any equipment provided by the phone company that terminates the other end of the phone line, such as a central office feed circuit. This is a slightly broader definition of TE than is commonly used in the industry.

Common Mode (Longitudinal) Surges

Most lightning surges appear “common mode” on tip/ring. This means that the surge voltage appears equally on both tip and ring with respect to earth ground. In other words, if you could measure the voltage from tip to ring during a 1000 volt common mode surge, you would measure zero volts tip-to-ring, but if you measured between tip/ring and ground, you would measure 1000 volts tip-to-ground and 1000 volts ring-to-ground. The telecom term for a common mode surge is “longitudinal.”

Differential (Metallic) Surges

Sometimes a common mode surge gets converted to a differential surge that appears as a voltage difference between the tip and ring leads. For example, if a common mode surge of 1000 volts is applied to tip/ring, and an SCR protection device triggers and shorts tip to ground, tip will be at ground potential while ring remains at 1000 volts. This is called a “common mode to differential conversion.” Whenever there are protection devices installed tip-to-ground and ring-to-ground, there exists the possibility of a common mode to differential conversion, since no two protection devices will trigger at the exact same moment. The telecom term for a differential surge is “metallic.”

Surge Waveform

Test waveforms for lightning surges are typically referred to by the rise time, fall time, open circuit voltage, and short circuit current. For example, a 10x1000 uS, 1000 volt, 100 amp surge has a nominal rise time of 10 uS, a decay to 50% peak value in 1000 uS, an open circuit voltage of 1000 volts, and a short circuit current of 100 amps.

The design of accurate, repeatable laboratory surge generators is very difficult, but the basic principle is deceptively simple. A capacitor is charged up to the specified open circuit voltage, and then it is discharged into the phone line via a wave shaping network that includes a series limiting resistor. So, a surge generator for the above referenced 1000 volt, 100 amp surge will have an internal 10 ohm series resistor that limits its short circuit current output to 100 amps. As will be seen in the discussion that follows, it is important to consider both the open circuit voltage *and* the short circuit current when designing lightning protection circuits. In most situations, only one of these two parameters will dominate the failure mode for a particular surge.

DAA (FXO) and SLIC (FXS) Phone line Interfaces

There are two very different types of phone line interfaces used on regular analog phone lines. For TE such as telephones, modems, fax machines, and PBXs, the interface is typically called a DAA or FXO interface. These interfaces function as loads across the tip/ring leads, and they are typically *isolated from earth ground*. For the purposes of this discussion, we will call these DAA-FXO interfaces.

On the other end of the phone line, back at the phone company central office, there is a different interface called a SLIC or FXS interface. These interfaces provide DC power to the phone, and apply a high voltage AC ring signal to activate the ringer in the phone. These interfaces source power to the phone line, and they are typically *connected to earth ground*. For the purposes of this discussion, we will call them SLIC-FXS interfaces. The fundamental differences between DAA-FXO circuits and SLIC-FXS circuits call for very different protection schemes.

Primary Protector

Each end of the phone line is typically equipped with a “primary protector” at the point where the phone line enters the building. The job of the primary protector is to divert most of the lightning energy on the phone line to earth ground. Primary protectors have some form of crowbar overvoltage protection devices connected tip-to-ground and ring-to-ground. The devices used in primary protectors can be gapped carbon blocks, gas tubes, or SCR-type silicon devices.

In general, primary protectors that use gapped carbon blocks have the highest breakdown voltages. If the type of primary protector that will be present on a given phone line is unknown, it is customary to assume that it will be a carbon block protector. By industry convention, the maximum “let-through” of a carbon block primary protector is roughly 1000 volts differential and 1500 volts common mode. Most industry standards for lightning immunity of phone line TE assume that a primary protector is installed on the phone line. Thus, most industry standards focus on the “let-through” energy that gets past the presumed primary protector and can damage the TE.

How Lightning Appears On a Phone Line

Lightning almost never strikes phone lines directly. When it does, there is usually extensive damage including melted copper and scorched circuit boards. When a phone line gets a direct strike, there is pretty much no protection scheme that will protect the wiring and the equipment. None of the industry standard lightning test surges are intended to simulate a direct strike.

The vast majority of lightning surges on phone lines are *induced* on the phone line by lightning striking something nearby, such as a tree, a building, or the ground itself. The huge currents associated with the nearby strike generate intense electromagnetic fields that couple into the tip/ring leads by electromagnetic induction. Since the tip/ring wires are twisted together, the same voltage is typically induced in the tip lead as the ring lead, which is why lightning surges are typically induced as common mode surges.

Another mechanism by which lightning appears on phone line interfaces is called “ground potential rise.” When lightning strikes the ground, the huge currents flowing through the non-zero resistance of the ground will cause a momentary increase in the local ground potential. If the strike is near the point where the primary protector is connected to ground, this ground potential rise can effectively force current up the ground lead of the primary protector and onto the phone line, sort of like coming in the back door. Either way, a large common mode surge is induced on the phone line.

As mentioned earlier, if only one side of the primary protector triggers in response to a common mode surge, the surge will be converted from common mode to differential. This is why most telecom standards specify immunity to both common mode and differential surges.

Most industry standards for lightning immunity of phone line interfaces focus on how the TE will handle the let-through energy that gets past the primary protector. Lightning protection installed behind the primary protector is often referred to as the “secondary protection.” Secondary protection is typically included inside the TE near the point where the phone line enters the TE enclosure. Sometimes an external protector is installed near the TE, but if this protector is installed behind the primary protector it is still referred to as a secondary protector.

Some Common Mistakes

We have now defined the terminology we will use and have discussed how lightning gets induced on phone lines. The key role of the primary protector has been described, since assumptions about the primary protector affect the type of surge waveforms that the TE is likely to experience. We are now ready to discuss some of the common protection mistakes made by designers of phone line interface circuits.

1) *Focusing on Voltage Instead of Current*

Many designers focus their attention on the open circuit voltage of the surge, and do not give sufficient thought to the path that the surge current will take. Any time a voltage-limiting device is used for lightning protection, the dominant problem usually becomes one of managing the high peak currents that will travel through the protection device and return to the surge generator via some path through the TE.

It is very important to pay attention to the complete path that the surge current will take. For example, it is not a good practice to return lightning current through the logic ground plane of a circuit board. A current of 100 amps passing through the ground plane will develop significant voltage drops from one side of the board to the other, potentially causing upset or damage to sensitive circuits. While the digital ground usually must be tied to the chassis ground at some point, the location should be chosen in such a way that lightning return currents do not travel through sensitive circuitry.

One case where it is appropriate to focus on the open circuit voltage is for common mode surges on FXO interfaces. Since FXO interfaces are typically isolated from ground, it is possible to rely on the isolation barrier for protection against common mode surges. For example, an isolation barrier that provides 1000 VRMS (1414 volts peak) isolation when tested with a 50/60 Hz AC hipot test will usually handle a 1500 volt peak common mode surge without difficulty. In this case the protection strategy is to prevent any current at all from entering the TE during a common mode surge.

2) *Using Undersized Components*

The problem of undersized components is closely related to the need to study the path that the surge current will take as it passes through the TE.

Look carefully at every component that will carry lightning current, and confirm that it is capable of handling the current without damage. Of course, the surge protector itself is the first component to check, so study the data sheet carefully to confirm that the protector can handle the surge current it will see in the application. However, lightning return current typically also passes through other components on its way back to the surge generator. Every component in the lightning path should be evaluated, including connectors, diodes, resistors, relays, chokes, and ferrite beads.

For example, many designers mistakenly place small surface mount ferrite beads directly in the lightning path. Typically, these will blow off the board like popcorn when the first surge is applied.

Resistors in the surge path are a frequent problem, and must be carefully selected. A 10 ohm resistor with 50 amps passing through it will dissipate a peak power of $(50) \times (50) \times (10) = 25,000$ watts. While the entire surge event typically lasts less than 1 mS, this is still a lot of pulse power to handle.

Typically, a garden variety resistor can handle about ten times its steady state power rating for 1 mS. For example, just about any 10 ohm, 1 watt resistor can survive a 1 amp, 10x1000 uS surge (10 watts instantaneous peak). Beyond a peak-to-average ratio of about ten, it becomes important to use resistors that are specifically designed as “pulse withstand” resistors. Certain types of resistor construction, such as thick film and wire wound, are better suited to withstanding high pulse energy, especially if they are specifically designed for high pulse power. Determine the peak pulse power that the resistor will have to handle, and make sure that the specifications show that the resistor can handle that level of pulse power. When in doubt, request more information from the manufacturer.

3) Using Undersized Trace Width and Spacings in Board Layouts

There is much confusion among designers about what sort of trace widths and spacings are appropriate for handling lightning current. Sometimes the designer forgets to consider this at all, and an auto-routed circuit with 6 mil lines and 6 mil spacings suffers extensive lightning damage. On the other hand, some designers are more conservative than they need to be, and specify extremely wide trace width and spacings, causing excessive board area to be consumed.

In general, a minimum trace width of 15 mils in so called “one ounce copper” is required to handle a 10x1000 uS, 100 amp surge. For voltage breakdown, the spacing should be at least 25 mils for every 1000 volts of peak voltage that the spacing is intended to withstand. Note that depending on the protection scheme being used, the peak voltage differences in the circuit may be limited by the surge protectors.

4) Forgetting to Consider Both Common Mode and Differential Surge Events

Since lightning surges can be presented either common mode or differentially, it is important to consider how the circuit will respond to both types of surge. Some designers focus only on one type and forget to consider the other.

5) Forgetting That the Isolation Barrier Must be 3-Dimensional

In circuits such as DAA-FXO interfaces that rely on the isolation barrier for common mode protection, it is important to ensure that the barrier provides adequate spacing in three dimensions. Sometimes the designer will take great care to maintain the proper spacing in the board layout, but will forget to consider conductive parts that are mounted above, below, or next to the phone line interface. For example, the leads on a through-hole RJ-11 connector can protrude below the board and come close to the chassis or another circuit.

6) Neglecting Overshoot of Overvoltage Protectors

Most overvoltage protectors will limit at a lower voltage for a slow, low-current surge than for a fast, high-current surge. When analyzing the predicted behavior of an overvoltage protector, it is important to consider both the rise time and the peak current of the applied surge. For example, the actual trigger threshold of a GDT (Gas Discharge Tube) typically goes up significantly with faster rise times of the applied surge. The peak voltage across an MOV (Metal Oxide Varistor) will

be much higher for high currents than for low currents. In general, all overvoltage protectors exhibit overshoot to some degree, and this overshoot should be factored into the design of the protection circuit.

7) Inadvertently Placing Two Overvoltage Protectors in Parallel

If two overvoltage protectors are placed in parallel, all of the surge current will flow through the device with the lower threshold. Sometimes this leads to unexpected results when different operational modes of the circuit create different surge paths. For example, when a DAA-FXO circuit is in the onhook idle mode, a 300 volt protector across tip/ring is usually adequate to protect the ring detector and switchhook relay without creating false triggering on the peaks of the AC ring signal.

However, when the circuit is in the offhook active mode, normal loop current flows through the DC hold circuit, generating a voltage drop of only ten volts or so between tip and ring. In this condition, a differential surge will cause excess current to flow through the DC hold circuit, and can overwhelm the low voltage protection (if any) provided in that circuit. Since excessive current can flow at voltages well under 300 volts, the 300 volt protector that works fine for the onhook condition provides no protection at all for the offhook condition.

8) *Returning Surge Current to an Unreliable Ground*

It is best to avoid returning surge currents to a “ground” that may not be grounded. For example, if the protection circuit in a fax machine or desk top terminal adapter has common mode overvoltage protectors installed tip-to-ground and ring-to-ground, the path to ground typically relies on a grounded AC mains connector. In many consumer applications the presence of a grounded AC power outlet can not be guaranteed. If surge currents are directed to a “ground” path that in fact is not grounded, the surge current will seek any other path to ground that it can find. Sometimes this might be through a USB cable or serial port connected to another piece of equipment that does have a ground. Surge currents traveling through such paths typically cause extensive damage.

9) *Compromising Normal, Non-Surge Operation*

Sometimes designers use protection devices that compromise the normal operation of the circuit. For example, an overvoltage protector that triggers on worst-case peak voltages experienced during normal operation can cause spurious behavior of the system. Also, most surge protectors present some amount of capacitance to the circuit. In some cases this capacitance is voltage-dependent and causes nonlinear distortion. Capacitance and nonlinearity are typically not an issue for conventional DAA-FXO circuits or SLIC-FXS circuits, but they can cause problems for high speed circuits such as T1/E1 and DSL modems.

10) *Misunderstanding Balance Requirements*

In phone line interfaces, the concept of balance refers to matching the impedance from tip-to-ground to the impedance from ring-to-ground. If these impedances are not well matched, induced

50/60 Hz common mode noise on the phone line can be converted to differential noise that is audible to the user.

The issue of balance is very important for interfaces that connect to long outside phone lines. Since outside lines are sometimes routed in parallel with AC power mains for long distances, there is considerable opportunity for induction of 50/60 Hz common mode voltages on the phone lines.

In general, SLIC-FXS interfaces are more difficult to balance than DAA-FXO interfaces. Since SLIC-FXS circuits are typically not isolated from earth ground, the impedance from tip-to-ground and from ring-to-ground is usually less than 100 ohms. If the designer adds a 10 ohm, 10% tolerance resistor in series with the tip lead and a 10 ohm, 10% tolerance resistor in series with the ring lead, the result could be a 111 ohm resistance tip-to-ground and a 109 ohm resistance ring-to-ground. This mismatch is enough to cause audible hum on an outside line. In SLIC-FXS circuits that interface to outside lines, any added impedances usually must be matched *to within a fraction of an ohm* in order to maintain good balance. This matching is hard to achieve with some protection schemes.

For SLIC-FXS interfaces that only connect to short loops within a building, the amount of induced common mode 50/60 Hz noise will usually be low. In these applications, a higher degree of unbalance can be tolerated without causing audible hum.

DAA-FXO circuits are typically much less sensitive to added resistance because they are isolated from ground. In general, adding 10, 20, or even 100 ohms in only the tip lead or only the ring lead is entirely acceptable for a DAA-FXO interface, since the inherent impedances from tip-to-ground and from ring-to-ground typically exceed one megohm. When the inherent impedances are already very high, adding a small amount of resistance in only one leg is not enough to materially affect the overall balance.

In summary, it is possible to either underestimate or overestimate the need for the protection circuit to provide well matched impedances in tip and ring. In general, extremely good matching is required for SLIC-FXS interfaces that connect to outside lines. Failure to provide this matching can introduce audible hum. On the other hand, matched impedances in tip and ring are generally less of an issue for SLIC-FXS interfaces that connect to short inside lines, or for DAA-FXO interfaces regardless of line length.

11) Assuming That the Primary Protector is Working

As noted earlier, most of the industry standard lightning surges used for compliance testing assume that the primary protector is properly installed and working. It turns out that a small percentage of primary protectors, especially in residential installations, are not functioning. This is usually because the primary protector's connection to earth ground has been inadvertently disconnected by a plumber, electrician, or other contractor working on the house. Since a disconnected primary protector does not create any obvious problem with the phone service, these situations can remain undetected for a very long time.

When the primary protector is not functioning, common mode surges can reach 5000 volts or more, although the short circuit currents typically remain below 100 amps. For the best overall reliability in consumer applications, DAA-FXO interfaces that rely on the isolation barrier for common mode protection should withstand common mode surges of 5000 volts. Usually it is not difficult to enhance the isolation barrier to provide this level of protection.

12) Assuming That Inside Lines Never Experience Lightning Surges

As odd as it may seem, lightning surges can appear on phone lines that stay entirely within a building. Fortunately, the energy induced in inside lines is typically much lower than the energy induced in outside lines.

Recall that even for outside lines, the surge energy that appears on the phone line is typically induced by electromagnetic coupling from lightning that strikes a nearby object. In a tall office building with inside phone lines routed from the basement to the top floor, energy can be induced in the phone lines if lightning strikes the building and travels to ground through the steel frame of the building. The degree of risk for inside lines depends mostly on how long they are. In general, lines that are less than 100 meters long are probably at minimal risk, but the surge exposure grows as the length of the line increases.

Summary

Designing appropriate lightning protection for a phone line interface typically requires having detailed information about the circuit to be protected and the surges that it must survive. Without this information it is difficult to make general statements about what sort of protection circuit is best for a given application. Designers have available a wide variety of protection devices and protection strategies that can be combined for a successful solution.

In terms of general advice for designers, the important thing is to understand the expected surge events and then carefully analyze how the proposed protection scheme is likely to behave under surge conditions. Some designers underestimate the value of this type of analysis, and proceed directly to board layout and laboratory surge testing without doing the analysis first. This can lead to a long and expensive test-modify-retest cycle.

This note has provided some background on how lightning energy gets onto phone lines and what sorts of surge events typically appear at the phone line interfaces of terminal equipment. An effort has also been made to explain the differences between the various types of phone line interfaces, since these differences affect the available options for lightning protection.

With this background, several common mistakes in lightning protection have been described. Hopefully, readers can use this information to help them review their proposed circuits during the design phase. In addition, readers who are experiencing lightning failures that they do not presently understand may gain some insight from reviewing the above discussion.

About the Author

Joe Randolph is a consultant who specializes in the design of telecommunications equipment. He has extensive experience designing lightning protection for compliance with international regulatory requirements and with industry standards such as Telcordia GR-1089, ITU K.20, and ITU K.21. He also has considerable experience troubleshooting unusual lightning failures that occur in the field.

If you have questions about the topics discussed here, or if you want assistance with a specific lightning protection problem, you can contact Mr. Randolph directly:

Joe Randolph
Randolph Telecom, Inc.
Phone: 781-721-2848 (USA)
Email: jpr@randolph-telecom.com
Web Site: <http://www.randolph-telecom.com>