Introduction to Lightning and AC Power Fault Surge Protection for Telecom Signaling Cables

Joseph Randolph, *Member, IEEE*
Randolph Telecom, Inc.
Winchester, Massachusetts USA

Abstract - This paper provides an introduction to the types of lightning surges and AC power fault surges that commonly affect the signaling cables of telecom network infrastructure and terminal equipment. Discussion is limited to twisted-pair copper lines such as telephone tip/ring cables and Ethernet cables. Surge types addressed include induced surges caused by nearby lightning strikes, induced AC voltages caused by fault conditions in adjacent AC power cables, and events caused by direct contact with AC power mains.

The basic physical mechanisms that cause each type of surge event are explained, with attention to both theoretical predictions and real-world measurements. Interactions between the surge energy source and the connected equipment will cause various types of surge waveforms to appear on the affected cables. The resulting surges are characterized for both outside cable plant and for cables routed entirely within a building.

The ways in which various international testing standards attempt to simulate these surge events are described. Examples of some industry-standard test procedures and compliance requirements are presented.

Some general guidelines are provided for evaluating the surge tolerance of a given design based on an analysis of the applied surge and the available paths for surge currents to flow. This type of analysis will often identify potential weaknesses based strictly on a review of the proposed design, prior to performing any actual surge tests.

I. Introduction

High voltage transients are a common occurrence on twisted pair communication cables. In particular, lightning-induced transients can occur quite frequently. In geographic regions with high thunderstorm activity, such as the southeastern USA, South America, and Africa, the density of cloud-to-ground lightning strikes can exceed 10 strikes per square kilometer per year [1].

The magnitude of telecom cable surges depends not only on the geographic region where the cable is deployed, but also on a variety of other factors such as the length of the cable, its relationship to local earth ground, and nearby structures that can affect the path taken by lightning discharge currents.

Another type of surge event that can be experienced by telecom cables originates from the local AC power grid. Surges related to AC mains voltages can appear on telecom cables through induction or, in rare cases, by direct contact.

When designing an equipment's line interface circuitry for a telecom cable, these surge events must be taken into account. This paper describes the basic physical mechanisms that generate surges on telecom cables, and reviews some common laboratory tests that are used to evaluate the surge tolerance of a cable interface. Some simple procedures are described for identifying weaknesses in a given design prior to any actual testing.

II. Lightning Coupling to Cables

Lightning almost never strikes telecom cables directly. When it does, the result usually includes melted cable conductors, charred materials, and significant physical damage to the connected equipment. The current that flows in the lightning channel of a direct strike can be 100,000 amps or more [1]. There is little that can be done to protect telecom equipment from damage due to a direct lightning strike.

Fortunately, the majority of lightning surges that appear on telecom cables occur due an indirect coupling mechanism. Typically, one of three coupling mechanisms is involved when lightning creates a transient on a nearby cable:

1) Lightning strikes an object nearby and induces a transient via electromagnetic coupling.
2) Lightning strikes a building and travels to ground through the building's steel structure or a grounding cable. The high currents induce a transient via electromagnetic coupling.
3) Lightning strikes the ground near a building and causes the building's local ground reference to momentarily rise (known as "Ground Potential Rise" or GPR).

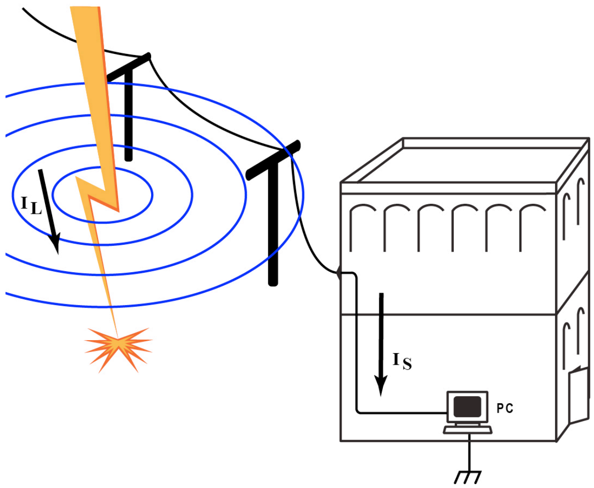

Fig. 1. Electromagnetic coupling into outside cable.

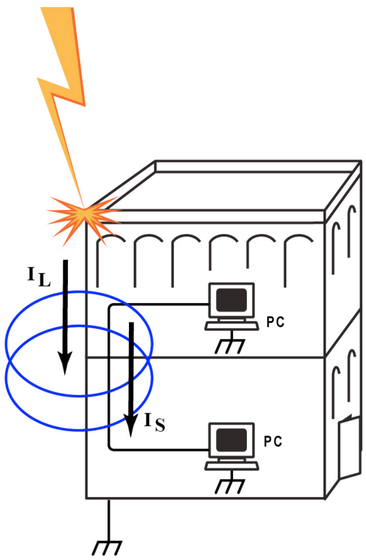

Fig. 2. Electromagnetic coupling from current in building structure.

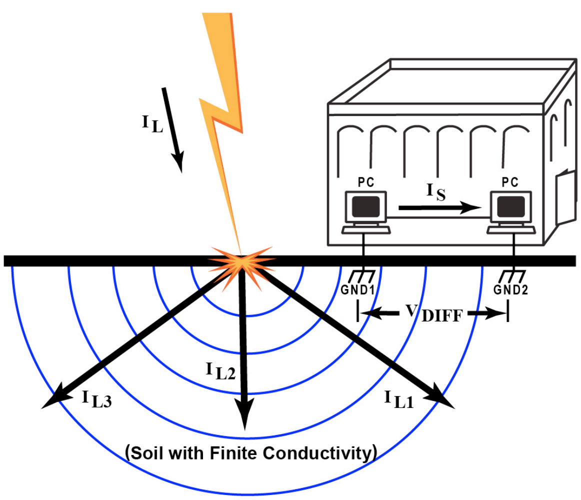

Fig. 3. Ground potential rise (GPR).

Fig.1 illustrates the first coupling method. The current I_L in the lightning channel can be 100,000 amps or more, with a very fast rise time on the order of a few microseconds. This extremely high di/dt generates an electromagnetic impulse that radiates outward from the lightning channel, coupling into a nearby cable to induce surge current I_S.

Note that this same electromagnetic pulse can also couple into cables located entirely within a building. Most building structures provide very little shielding from the electromagnetic pulse of a nearby lighting strike. Concrete and wood provide almost no shielding, although the reinforcing steel in a concrete structure can provide several dB of attenuation.

Fig. 2 illustrates the second coupling method, where lightning strikes a building and the lightning current I_L travels to earth ground through the steel structure or a grounding conductor. Again, the very high di/dt of the lightning current creates an electromagnetic impulse that couples into a nearby cable and induces surge current I_S.

Fig. 3 depicts a GPR situation where lightning strikes the ground near a grounded structure. Upon striking the ground, the lightning channel current I_L divides radially throughout a semi-spherical half-space with its origin at the strike point. This dispersion of the lightning current is represented in Fig. 3 by I_{L1}, I_{L2}, and I_{L3}. Since virtually all soils have a finite resistance, a voltage potential V_{DIFF} will develop between the two reference points GND1 and GND2, inducing possible surge current I_S. The potential difference V_{DIFF} can reach levels of several thousand volts per meter at locations near the strike point.

Note that while Fig. 3 depicts a case where the two different ground references are within the same building, the likelihood of having two different ground references is increased if a cable runs from one building to another.

Taken together, these three types of induced surges comprise the vast majority of lightning surge events on telecom cables.

III. Characteristics of Induced Surges

An introductory physics course usually covers the basic concepts for the types of coupling depicted in Fig. 1-3. The coupling in Fig. 1 and Fig. 2 might be described using Faraday's law for voltage induction, or Lenz's law for current induction. In both cases the basic principle is that a time-varying current in one conductor (the lightning channel) induces a corresponding voltage or current in a nearby conductor (the cable). In Fig. 3, Ohm's law might be used to describe the voltage difference between two ground references when a lightning current passes through soil that has a non-zero resistance.

These representations are very helpful for visualizing how coupling might occur, but they fail to model the true complexity of the real-world coupling mechanisms. Only a few general concepts from these simplified models are descriptive of the actual coupling mechanisms involved with most surges on telecom cables:

1) A current flowing in one location can induce current to flow in a seemingly unrelated conductor some distance away.
2) For the electromagnetic coupling depicted in Fig.1 and Fig. 2, the coupling mechanism is based on the rate of change of the lightning current and the physical proximity of the target cable. Faster rise times and closer proximity increase the coupling.
3) For the GPR mechanism depicted in Fig. 3, the surge coupling depends on the system having more than one ground reference.

Considerable effort has been made by others to develop accurate mathematical models to predict the characteristics of induced lightning surges. Real-world variables such as the lightning current rise time, relative angles of the strike current and the target conductors, soil impedance, and distance between the lightning source and the target greatly complicate the modeling problem. Most of the currently accepted models use antenna theory to model the electromagnetic fields generated by the lightning strike, and use either antenna theory or transmission line theory to model how these fields couple into a cable. The resulting models are exceedingly complex, and computerized numerical integration is usually used to perform the calculations.

References [2] and [3] provide a very good overview of the various methods that have been employed to model coupling into nearby cables. A brief review of these papers should convince the reader how remarkably complex the actual coupling mechanisms are. References [4] and [5] address coupling into cables located entirely within a building. References [6] and [7] address surges generated by GPR.

It is important to note that for a given lightning strike, the resulting surge that appears on a cable can be due to the superposition of two or more of the three basic coupling mechanisms. For example, lightning striking the ground near a cable system can induce a surge via electromagnetic coupling into the cable itself, and also through various ground paths excited by GPR. References [8] and [9] provide some very useful insight into this complex phenomenon.

Work on developing accurate models and simulations continues, but the methods described in the above references are far too complex for further discussion in this introductory paper. Field studies are also of great interest and can be very informative, although they are typically very location-specific and can be difficult to generalize.

Unfortunately, it is difficult to synthesize all the published studies into a single set of conclusions without getting mired down in the details about how each study was performed. For the purposes of the present discussion, we will simply state some general guidelines for twisted-pair telecom cables, based on the author's experience:

1) The 99 percentile for peak voltage amplitude is about 6000 volts.
2) The 99 percentile for peak short-circuit current is about 100 amps.
3) Surge waveforms typically have a fast rise time and a comparatively slower decay time.
4) The nominal duration of the surge ranges from about 10 uS on short cables to about 1000 uS on long cables. The greater duration on long cables is due to dispersion effects as the wave front interacts with the distributed impedance of the cable.

IV. Lightning Surge Waveforms

For laboratory testing of lightning surge immunity, most international standards such as IEC 61000-4-5 use a simplified double-exponential representation of the surge waveform, as shown in Fig. 4. The rising edge and falling edge each have an exponential shape. The nominal rise time T_R is the time it takes the waveform to reach peak value, while the nominal fall time T_F is the time it takes the waveform to decay to 50% of its peak value.

Note that the precise definitions of rise time and fall time differ among various standards. Most standards avoid using either the origin or the timing of the absolute peak value as reference points for specifying rise time and fall time. However, the intent of the various definitions is to define the waveform in a way that generally resembles Fig. 4.

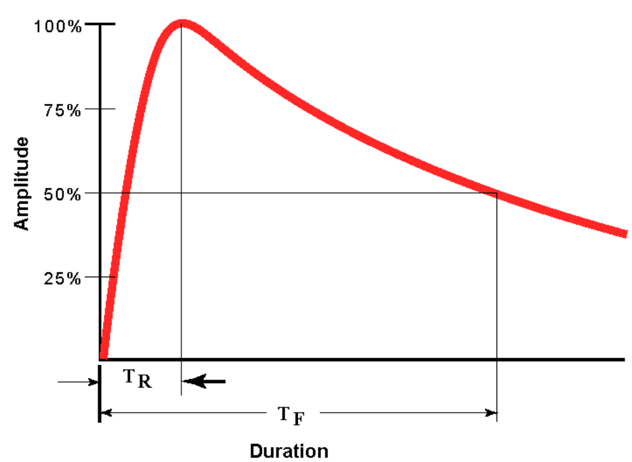

Fig. 4. Representative lightning surge waveform.

In industry parlance, a surge waveform that has a rise time of 2 uS and a fall time of 10 uS is referred to as a "2x10 uS" surge. Note that this description does not completely specify the surge, since it says nothing about the peak voltage or peak current. It also fails to say whether the specified waveform is the open-circuit voltage or the short-circuit current. All of these additional parameters would have to be specified to clarify the characteristics of the test surge. Most test surges are specified by their open-circuit voltage waveform and their peak short-circuit current, but this convention is not universal.

For the open-circuit voltage waveform of a laboratory surge generator, there are several different test waveforms in common use, such as 2x10 uS, 1.2x50 uS, 10x700 uS, and 10x1000 uS. The short circuit current delivered by the surge generator is typically 100 A or less.

V. AC MAINS POWER INDUCTION

Outdoor telecom cables are often routed along with AC power mains cables for distances up to 5 kilometers. This can lead to induction of common mode AC noise voltages at 50/60 Hz on the adjacent telecom cables. Given the low AC frequencies and the separation of the cables, the level of induced 50/60 Hz voltage on the phone cables is typically below 10 VRMS, with a very high effective source impedance.

However, there are certain fault conditions that can occur in the power grid that will greatly increase the amount of 60 Hz energy coupled into adjacent phone cables. If an AC power mains cable is downed and shorts to earth ground, very high currents will flow until the associated circuit breakers in the AC grid trip. These circuit breakers can take anywhere from a few hundred milliseconds to 30 minutes to trip, depending on the severity of the fault. During this interval, the induced voltage on adjacent telecom cables can exceed 600 VRMS, with available short circuit currents of several amperes.

Most regulatory standards do not require telecom equipment to survive AC mains induction, but focus instead on ensuring that such events do not present a fire hazard. Only a comparatively small number of standards worldwide call out AC induction tests that the equipment must survive without damage. Examples include Telcordia GR-1089-CORE, ITU K.20, ITU K.21, and Brazil's Resolution 442. Passing these tests can be quite challenging.

VI. AC MAINS POWER CONTACT

Another form of AC mains fault is the case of direct contact with adjacent phone cables. This type of fault is considered to be extremely rare but not impossible. In contrast to the induction scenario described above, direct contact can lead to far higher currents, ranging up to 40 amps. Regulatory standards do not require telecom equipment to survive direct contact with AC mains. The focus is usually on providing a fail-safe mechanism that prevents the equipment from presenting a fire hazard or electric shock hazard.

Note that the risk of AC mains power contact is not fully eliminated just because the telecom cables run entirely within a building. Some standards such as Telcordia GR-1089-CORE call out tests for AC mains contact even on inside lines, although the test voltages are typically lower in view of the lower voltages used on AC mains within most buildings.

VII. PRIMARY PROTECTION AND SECONDARY PROTECTION

In most parts of the world, a so-called "primary protector" is installed at the point where an outside telecom cable enters a building. The purpose of the primary protector is to provide the first line of defense from surges that appear on the cable. Primary protectors typically trigger at voltages between 400 and 1000 volts, and can handle peak surge currents up to 1000 amps. Older primary protectors use carbon block electrodes separated by an air gap of about 0.1 mm. Newer versions use gas discharge tubes.

For a typical 2-wire phone line, the primary protector is connected as shown in Fig. 5. Note that the earth ground path is usually a single conductor shared by both breakdown devices. This can lead to unintended side effects due to the finite inductance of the grounding conductor.

The protection devices P1 and P2 in the primary protector typically have a "crowbar" characteristic, meaning that when they trigger, they become effectively a short circuit and remain shorted until the surge current drops to a low level. This characteristic minimizes power dissipation in the protection devices, and allows them to handle very large surge currents without overheating.

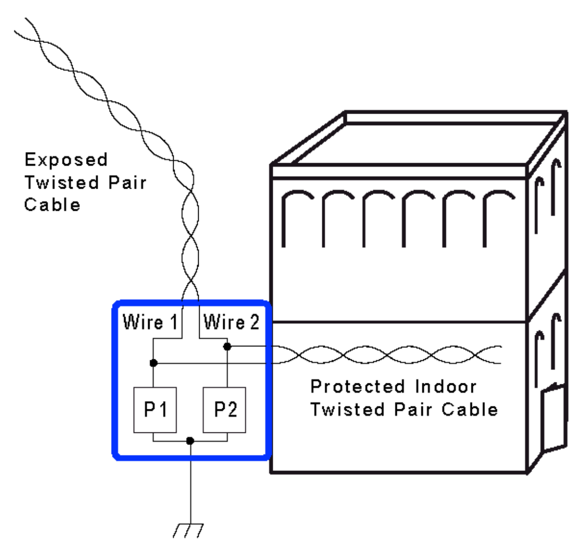

Fig. 5. Arrangement of primary protector.

For some types of telecom equipment, the protection provided by the primary protector is sufficient, but in most cases additional protection must be added within the equipment itself. This is typically referred to as "secondary protection." The purpose of secondary protection is to further limit the surge energy to a level that will not damage the equipment.

VIII. Let-through Energy of Primary Protectors

Secondary protection must be designed to handle whatever let-through energy can get past the primary protector. The surge voltages that appear on the protected indoor cable in Fig. 5 typically appear in one of two forms:

1) Differentially from one conductor to the other (also referred to as "metallic" surges).
2) Common mode on all conductors with respect to earth ground (also referred to as "longitudinal" surges).

Based on the worst-case primary protectors, the potential let-through energy is generally considered to have the following characteristics:

- Maximum differential voltage of 1000 volts
- Maximum common mode voltage of 2500 volts
- Peak current of 100 amps

For twisted pair cables, all induced surges begin initially as common mode surges, where the surge voltage appears between all the cable conductors and earth ground, with little or no voltage potential appearing between individual conductors. However, due to the operation of the primary protector, surges that appear on the protected side of the primary protector can be in the form of either common mode or differential surges. For a two-conductor phone line, Fig. 6 shows the difference between a common mode surge and a differential surge.

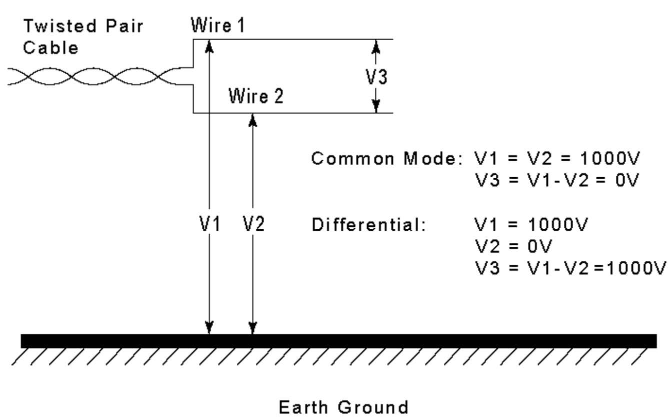

Fig. 6. Comparison of 1000 V surges in common mode and differential mode presentations.

The mechanism that creates a 1000 volt differential surge begins with a 1000 volt common mode surge induced on the cable, and envisions a primary protector that triggers at about 1000 volts. With reference to Fig 5, if the two surge protectors P1 and P2 do not have identical trigger voltages (and they are never exactly identical), a common mode surge on the cable can cause just one of them to trigger, which effectively shorts that conductor to ground.

If the protector on the other conductor does not trigger, the voltage on that conductor remains at about 1000 volts relative to ground. Thus, the instantaneous differential voltage between the two conductors becomes 1000 volts. This is an example of a "common-mode-to-differential-conversion" created by the primary surge protector, which is an important consideration in the design of secondary protection.

The mechanism that creates a 2500 volt common mode surge is not immediately obvious. With reference to Fig. 5, the cause is the finite inductance of a potentially long ground wire on the primary protector. When the primary protector triggers, there is an extremely fast rise time on the current that flows through the ground conductor. Experience has shown that the combination of fast rise time and this small inductance (typically less than 10 microhenries) can generate voltage drops on the ground wire of up to 2500 volts. Since this voltage appears on the ground wire that is common to both P1 and P2 in the primary protector, the equipment experiences it as a common mode surge that is typically less than 10 uS in duration.

Longer common mode lightning surges, on the order of 1000 uS, can be let through if the common mode surge voltage is low enough that the primary protector does not trigger at all.

In the case of induced or conducted 60 Hz AC power surges, the generally accepted maximum let-through of a worst case protector is considered to be 600 VRMS. While the peak voltage of a 600 VRMS sine wave is only 848 volts, the trigger threshold for a given protector is generally lower for a 60 Hz sine wave than for a fast rising lightning surge.

Note that if the primary protector in Fig. 5 were rated at 1000 V, it would let voltages of less than 600 VRMS pass through continuously if either one or both of the two protectors remained off.

IX. Representative Surges for Testing

When a circuit designer sets out to design a cable interface and evaluate it for surge tolerance, it is necessary to define a set of test surges that will be used for the evaluation. Sometimes these test surges are specifically called out in an applicable regulatory standard or industry standard, and sometimes they are self-imposed, based on the designer's experience and judgment.

For the purposes of the present discussion, we will define some specific test surges that are representative of those used in the telecom industry. Note that the names given to each surge are used for convenience in this discussion, and are not industry-standard names.

For telecom interfaces that connect to outside cables, the following surges are representative of the expected let-through of a worst-case primary protector. The lightning surges are specified as an open-circuit voltage waveform and a short-circuit peak current:

Common Mode Surges on Outside Cables

COM-1: 2500 volt, 2x10 uS, 100 amp (survive)

COM-2: 1000 volt, 10x1000 uS, 100 amp (survive)

COM-3: 600 VRMS, applied through 600 ohms for one second (survive)

COM-4: 600 VRMS, applied through 15 ohms for one second (no fire hazard)

Differential Surges on Outside Cables

DIF-1: 1000 volt, 10x1000 uS, 100 amp (survive)

DIF-2: 600 VRMS, applied through 600 ohms for one second (survive)

DIF-3: 600 VRMS, applied through 15 ohms for one second (no fire hazard)

For telecom interfaces that connect only to indoor cables, it is important to recognize that indoor cables typically have no primary protector installed. So, the representative surges must be based on the anticipated effects of various surge coupling mechanisms on a cable with no primary protector. The following test surges are representative of what is typically used for evaluation of a port for an indoor cable:

Common Mode Surges on Inside Cables

COM-5: 1500 V, 2x10 uS, 100 amp (survive)

COM-6: 120 VRMS, applied through 3 ohms for one second (no fire hazard)

Since there is generally no primary protector on inside lines, there is no external mechanism to convert an induced common mode surge to a differential surge. Such conversion is still possible if the equipment connected to either end of the cable has any form of common mode protection device connected between the cable and earth ground.

Note that the duration of the COM-5 lightning surge is much shorter than some of the surges for outside lines. This is because there is less dispersion on a short cable.

Another difference for inside lines is that induction from AC power mains is not considered to be a threat. There is little opportunity for induction because indoor cable lengths are much shorter and fault currents on indoor AC mains wiring are typically lower than for outdoor wiring.

The only AC power fault test that is considered to still be applicable for indoor cables is a direct-contact test, with the available voltage reduced to represent typical indoor AC mains wiring. For telecom cables routed entirely within a building, this type of direct contact test only appears in one published standard, Telcordia GR-1089-CORE.

The COM-5 and COM-6 surges have proven to be generally sufficient for most installations of indoor cabling, but recent field experience has shown a statistically significant incidence of lightning damage on indoor cable interfaces that were designed to survive the COM-5 surge. Most of the reported incidents were in residential installations rather than commercial buildings.

These failures have been the subject of much discussion among industry experts. At present there is no clear consensus for how surges larger than the COM-5 surge can appear on indoor telecom cables. One current theory is that GPR events are interacting with systems that have multiple grounds. Another theory is that consumer-grade surge protectors used in residential environments are somehow coupling transients from the AC mains onto indoor telecom cables.

Analysis of these unusual failures continues, but in the mean time, preliminary evidence suggests that the following test surge may provide adequate protection from these poorly understood situations:

High Level Common Mode Lightning Surge on Inside Cables

COM-7: 6000 V, 2x10 uS, 100 amp (survive)

X. Secondary Protection Strategies

Surge voltage alone is not sufficient to cause equipment damage. To cause damage, a surge *current* must somehow flow *through* the circuit, causing localized heating that exceeds the ratings of one or more components. Since current is what does the damage, there must be an *inlet* and an *outlet* for any surge to cause damage to equipment. This is a key concept to keep in mind when analyzing a circuit for its surge susceptibility.

Another key consideration is that any surge current that does flow will always follow the lowest impedance path through the equipment to earth ground. Sometimes this path is not the one that the designer intended.

Given the above considerations, there are only two possible methods that can be employed to protect equipment from a surge induced on a connected cable:

1) Block the surge current
2) Direct the surge current to known, safe path

This seemingly simple summary forms the basis of all methods that can be used to protect a circuit from surges that appear on a connected cable.

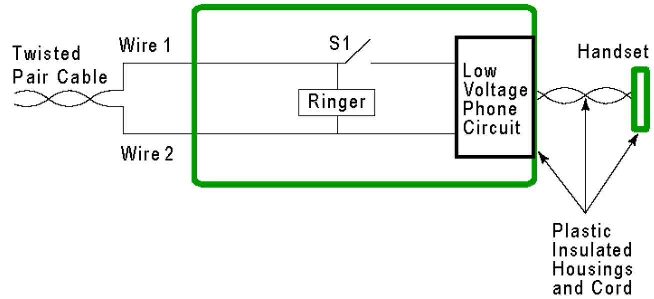

Fig. 7. Simple telephone without surge protection.

XI. Circuit analysis prior to actual testing

Many circuit designers mistakenly believe that the only way to evaluate the surge tolerance of a circuit is to build it and subject it to simulated surges. While testing is an essential step in the development of an interface circuit, considerable time and effort can often be saved by subjecting the proposed circuit design to careful analysis.

Often, a thoughtful inspection of the proposed circuit will reveal one or more predictable failure mechanisms that are easy to identify without any actual testing. To identify these predictable failures, all that is required is a methodical consideration of the expected path that current will take through the equipment when the equipment is subjected to various simulated surges.

Recall from the earlier discussion that voltage alone cannot cause damage. Damage occurs when current flowing through the circuit causes excessive heating in one or more components. So, the recommended method for analyzing a proposed protection circuit can be called "follow the current." Also recall that the designer's options are to either block the current or direct it to a known, safe path.

We will now apply this methodology to three simple examples of common telecom cable line interfaces. The first two examples will be a simple telephone and a simple SLIC (Subscriber Line Interface Circuit). These two port types often connect to outside cables. The third example will be an Ethernet port that connects to a cable running entirely within a building.

Example 1: Simple telephone

Fig. 7 shows a simple telephone in a plastic enclosure. The handset operates a mechanical switch S1 that connects the phone circuit to the line when the phone is in use. The ringer in the phone remains connected across the line at all times.

A big advantage for equipment that is floating with respect to ground is that common mode surges cannot damage it. Since there is no path to ground through the equipment, no current can flow.

Note that this immunity to common mode surges only holds true as long as the common mode isolation is greater than the applied common mode voltage. In the case of our hypothetical telephone, the plastic enclosure provides far more than 2500 volts isolation, so the phone is expected to survive all of the common mode surges defined above. This is an example of protecting equipment by blocking the surge current.

For differential surges with switch S1 open, all three surges DIF-1, and DIF-2, and DIF-3 are likely to damage the ringer circuit. A common solution is to place a crowbar-type voltage protector across the phone line to the left of the ringer. However, this protector must have a nominal trigger voltage of no less than about 300 volts in order to avoid false-triggering on the peaks of normal telephone ringing voltages.

While the selected surge protector may suffer damage from the DIF-3 surge, this is not necessarily a problem, since the passing criterion for the DIF-3 surge is only that there be no risk of fire. Some protectors can create a fire hazard in response to the DIF-3 surge, but others are designed to fail in a short circuited mode. Since power = (voltage times current), the short circuit failure mode minimizes power dissipation in the protection device and keeps it from becoming a fire hazard.

In some safety standards such as UL 60950-1, there is a concern that the high current that could flow through a shorted protection device during the DIF-3 test could cause the associated external phone wiring to overheat. This concern is addressed by limiting the amount of current that can flow in response to the DIF-3 surge. A typical method for complying with this requirement is to add a suitable fuse in series with the interface circuit. The fuse must be selected so that it survives the DIF-1 and DIF-2 surges, but opens safely for the DIF-3 surge.

Even with a 300 volt protector and a fuse added to the circuit of Fig 7 to handle the idle state surges, the phone circuit remains vulnerable when the phone is in use with S1 closed. In this case, current will flow through the telephone voice circuit until the voltage across that circuit reaches the 300 volt threshold of the ringer protector. Thermal damage to the voice circuits is highly likely. One possible solution is to add a second, low voltage surge protector on the voice circuit side of the switchhook.

Note that this second protector must be capable of handling the same DIF-1, DIF-2, and DIF-3 surge currents as the ringer protector, while maintaining a safe voltage across the telephone voice circuit. While low voltage protectors with high current-handling ability are available, they may have characteristics that are not suitable for protecting some phone circuits. An alternative is to use a low voltage protector that has lower current-handling capability, and to put a series resistor in front of it to limit the surge current.

Figure 8 shows a modified version of the circuit that is expected to pass all six of the applied tests. When S1 is open, P1 protects the ringer from overvoltages and the fuse opens to prevent a fire hazard for DIF-3. When S1 is closed, P2 protects the phone circuit, while R1 limits the surge current through P2.

It is important to look very carefully at the surges that R1 must be able to handle without damage. With S1 closed, surge current will flow through R1 until the voltage across R1 reaches 300 volts to trigger P1. If P2 is a crowbar-type device it becomes effectively a short circuit when it triggers. This means that the instantaneous voltage across R1 can be as high as 300 volts. This corresponds to an instantaneous power dissipation in R1 of (300x300)/20 = 4,500 watts. Most conventional resistors cannot handle this level of pulse power, but special surge-tolerant resistors are available that can handle such surges.

Another problem with R1 occurs during the DIF-3 test. In this case, the extended period of the surge can generate excessive heating in R1 and lead to a fire hazard. So, the selection of a suitable resistor for R1 typically requires that it be flame proof as well as surge tolerant.

Note that the AC peaks of the 600 VRMS DIF-3 surge will always trigger P1 in Fig. 8 and provide a reduced duty cycle for the heating in R1. However, a lower voltage level of 200 VRMS (283 volts peak) will not trigger P1. This is the case that typically generates maximum heating in R1. Some regulatory standards such as UL 60950-1 include DIF-3 tests at lower voltages in an effort to generate the maximum possible heating for evaluating a possible fire hazard.

At this point, readers may be convinced that adding a series resistor to help limit surge current is fraught with hidden complications, and should be avoided if possible. This is generally the case, but it is surprising how many designers add current-limiting resistors to their surge protection circuits without thinking through the stresses that the resistors must handle. This is an example of how some simple analysis can identify predictable problems in advance of any actual testing.

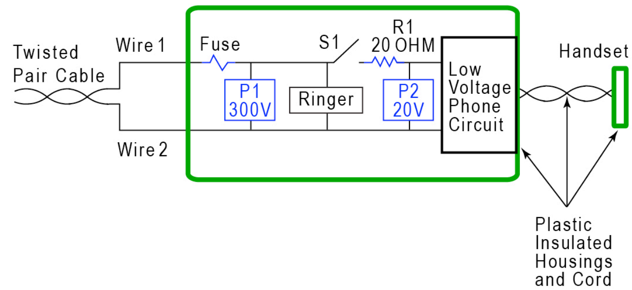

Fig. 8. Simple telephone with surge protection added.

EXAMPLE 2: SUBSCRIBER LINE INTERFACE CIRCUIT (SLIC)

We will now consider a simple SLIC that presents a different set of protection challenges compared to the telephone discussed above. By design, most SLIC circuits are referenced to earth ground, so unlike a simple telephone, SLICS are not inherently immune to common mode surges.

On a conventional phone line, the SLIC resides at the phone company's central office, and provides the DC loop current and AC ringing voltage necessary to operate a standard telephone. In these applications, the SLIC connects to outside cables.

Similar SLICs are used to allow ordinary phones to connect to the internet for VOIP (Voice Over Internet Protocol), and in network terminals used to provide ordinary phone service over fiber networks or cable TV coax. Most of these SLICs connect only to indoor cables, and could be designed with this simplification in mind. For the present example, though, we will assume that the SLIC connects to an outside cable.

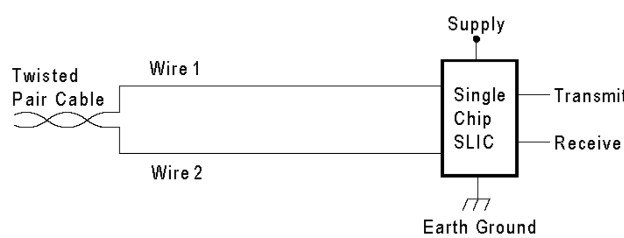

Fig. 9. SLIC circuit with no protection.

Fig. 9 shows the basic SLIC without any protection added. Note that the single-chip SLIC integrated circuit has its power supply referenced to earth ground. If we mentally apply the seven surges defined above for outside cables, we quickly find that all seven of the test surges are likely to damage the circuit. Since there is a path to ground through the SLIC chip, all of the surges will travel to ground through the SLIC chip and will likely damage it.

Fig. 10 shows a modified circuit that addresses all the above problems. The principal change is to add a protection device P1 that will trigger for both common mode and differential surges.

In this case, the protector is a type that is specifically designed for protecting ground-referenced SLICs. This is a crowbar-type protector that triggers whenever the voltage on either wire gets more than a few volts outside the power supply range of the SLIC chip. The protector P1 must be specified to handle the full surge current of all six test surges.

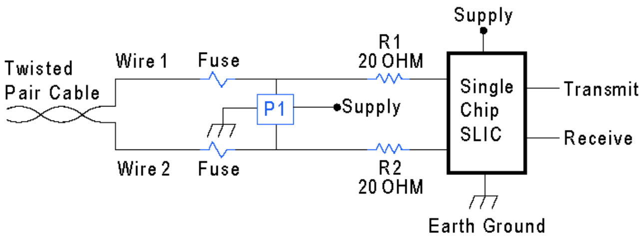

Fig. 10. SLIC circuit with protection added.

Resistors R1 and R2 help to limit any residual surge current that may enter the SLIC chip. In this case, the instantaneous voltage across R1 and R2 is limited to the few volts required to trigger P1. This means that the instantaneous power dissipation in R1 and R2 is quite low even under surge conditions, allowing the use of ordinary surface mount resistors.

Note that the surge power dissipation in R1 and R2 would be far higher if the resistors were simply relocated to the left side of P1, since the resistors would then be in the path of the full surge current as P1 directs that current to ground. This is an example of a seemingly minor topology difference that creates a major difference in the surge handling capability of the circuit.

Also note that in Fig 10 there is a fuse in each wire, while in the simple telephone circuit of Fig 8 there was only one fuse. This is because the SLIC has a path to ground, so surges can enter either wire and reach ground. In the simple telephone circuit, any surge entering on one wire must exit on the other, so only one fuse is needed to interrupt the current.

EXAMPLE 3: ETHERNET INTERFACE

We will now consider a very common indoor circuit, the Ethernet 100BASE-T connection. Ethernet cables are widely used for both local area networks within a building, and increasingly, as telephone extensions on systems that use VOIP technology to implement a business communication system.

Due to their inherent limitation of 100 meters in the IEEE 802.3 standard, conventional Ethernet connections are mostly limited to indoor applications. Various long haul Ethernet signaling systems are in use, but this example will focus on a conventional indoor Ethernet connection.

Figure 11 shows a typical Ethernet interface that has no explicit surge protection. Such circuits are quite common in many different types of information technology equipment. Interestingly, this circuit has a reasonable chance of holding up in a typical application, because the isolation barrier of the transformers T1 and T2, and the Smith capacitors C1 and C2, provide some inherent protection from common mode surges.

Since the IEEE 802.3 standard for Ethernet requires 1500 VRMS isolation (2121 volts peak), this circuit may pass the COM-5 and COM-6 tests with no changes.

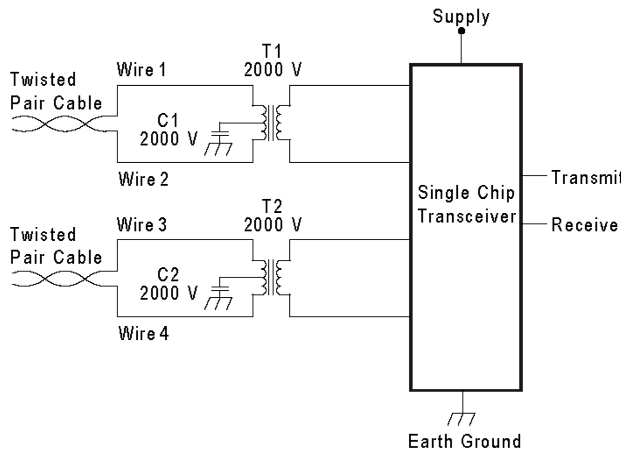

Fig. 11. Basic Ethernet interface.

Note that it would actually be counter-productive to add common mode protectors from the four cable conductors to earth ground. In addition to unnecessary added cost, the common mode protectors will create a mechanism for converting a common mode surge to a differential surge if one protector on a give pair triggers before the other. Furthermore, all four conductors might have to be fused to pass the COM-6 test. Common mode surge protectors connected to ground should be avoided on Ethernet interfaces.

As noted above, there is some evidence that the 1500 V COM-5 surge may not be an adequate test for some applications of inside cabling, particularly in residential environments. For these applications, designers may wish to self-impose the 6000 V COM-7 surge. Figure 12 shows how the Ethernet circuit could be modified to survive the COM-7 surge.

The principal change in Fig. 12 is to upgrade the existing isolation barrier to withstand a 6000 V surge. This requires using transformers with higher breakdown voltages, and Smith capacitors with higher voltage ratings.

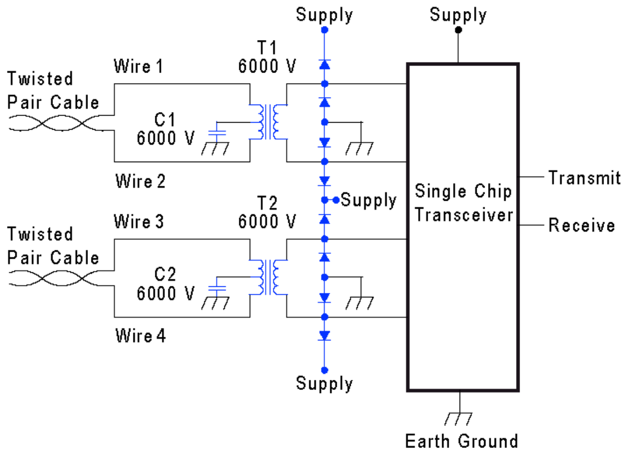

Fig. 12. Ethernet interface with added protection.

For such a large surge, there is the possibility of a small amount of let-through energy coupling through the inter-winding capacitance of the transformers. The diodes serve to catch any such transients and direct them to the supply or ground. If the sole intent is to handle capacitively coupled let-through currents from a common mode surge, these can be generic signal diodes such as a BAV99 because the surge currents they handle are small.

It is worth noting that in recent years, a variety of "Ethernet protectors" have appeared on the market. Typically these protectors include common mode protection in the form of individual surge protectors connected from each of the four Ethernet conductors to earth ground. Fig. 13 shows a representative arrangement.

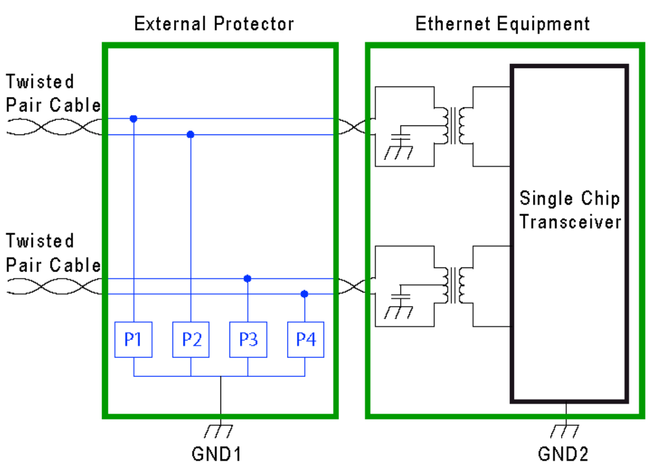

Fig 13. External Ethernet protector.

While the protector shown in Fig. 13 might appear to add some useful protection, it also creates some additional surge risks that would not otherwise be present. Recall that adding common mode protection to ground introduces a mechanism for common-mode-to-differential conversion of induced common mode surges.

In this case, asymmetrical triggering of P1 and P2, or P3 and P4, will create a differential surge on the associated transformer input in the Ethernet equipment, possibly damaging the Ethernet transceiver chip. Differential surges will tend to couple more energy through the transformers than common mode surges, since the inherent design of a transformer couples differential signals and blocks common mode signals.

Another risk with this topology is the risk of GPR creating an instantaneous potential difference between GND1 and GND2. GND1 and GND2 may not be physically close together and may not be well bonded to a single ground reference, creating an opportunity for GPR to damage the isolation barrier in the Ethernet equipment. Even if GND1 and GND2 are well bonded, there may be a "GND3" associated with the far end Ethernet equipment and possibly even a "GND4" if that equipment has its own external protector connected. A larger number of different ground references in the system will generally increase the susceptibility to GPR.

At the time of this writing, there is anecdotal evidence that the addition of external protectors as shown in Fig. 13 may actually increase certain types of surge-related failures rather than decrease them. In particular, it appears that such protectors convert common mode surges to differential surges that are more easily coupled through the transformers in the Ethernet interface.

As a result of this growing concern, the 2011 edition of Telcordia GR-1089-CORE has added a full suite of differential surges that an Ethernet port must be able to withstand. These tests apply for any application where there is the possibility that installers or users might add external Ethernet protectors. The only exemption applies to well controlled environments such as telephone network central offices where the network operator has complete control over the entire system.

XII. Summary

In this paper we have reviewed the basic mechanisms that cause lightning surges and AC power fault surges to appear on twisted-pair telecom signaling cables. The vast majority of these events are not caused by direct lightning contact with the cable. Rather, they are caused by indirect coupling from electromagnetic induction or from ground potential rise. Thus, the fact that a given cable is routed entirely within a building does not mean it is inherently protected from such surges.

The characteristics of these surges have been extensively studied by various researchers over the years. As a result, the telecom industry has developed some standard laboratory test surges that provide a simplified representation of the surges encountered in actual field installations. This paper has described a set of representative laboratory test surges, and then reviewed how these surges interact with some typical types of telecom cable interfaces.

It is important to understand that voltage alone cannot damage equipment. It is the resulting current that causes damage. Thus, the task of designing a cable interface to have adequate surge protection involves either blocking the current flow or directing the current to a known, safe path.

A key goal of this paper is to help circuit designers understand that weaknesses in the surge tolerance of a given cable interface can often be predicted in advance with careful analysis of the circuit diagram and the component data sheets. Each of the standard laboratory test surges can be mentally applied to the circuit in question to predict the magnitude of the surge current and the path that the current will take.

Using this systematic approach can often identify potential problems early in the development process, prior to actual surge testing of the completed product. This can save product developers considerable time and expense.

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