APPLICATION NOTE #175

Surge Protection Guidelines and Recommendations

INTRODUCTION

Application Note #175 supplements the recommended protection circuitry discussions currently found in Cermetek product data sheets. The contents of Application Note #175 originally appeared as a two part series in the August and September 2000 issues of Conformity Magazine. The articles were written by Isidor Straus of Curtis-Straus, LLC. Although reformatted and combined into this single application note, both articles remain essentially as they appeared in publication and are presented here for the benefit of Cermetek's customers.

OVERVIEW

Telecom equipment must be designed to withstand, or fail gracefully under, such "events" as lightning induced surges and power line crossing while maintaining a prescribed electrical isolation barrier. Protective circuitry must also be designed in such a way so as not to interfere with the operation of the equipment it is intended to protect. Regulatory standards that govern telecom equipment performance are: FCC Part 68/Industry Canada CS03, UL 1950/EN 60950, Bellcore NEBS 1089, and ETSI requirements.

TYPES OF EQUIPMENT

This application note is intended to provide assistance with devices that are connected directly to the public network. These devices can be divided into analog devices operating at audio frequencies (up to 57.KBPS) and digital devices operating at 1.5 MBPS (T1) or 2.048 MBPS (E1).

For audio telephony equipment, these devices can be further divided by type of service. This would include: whether they source loop current (reverse battery) or not, whether they loop or ground start, and whether they employ two or four wires. Application Note # 175 audio equipment discussions are limited in scope to issues concerning analog loop start equipment with a single 2-wire (i.e., TIP and RING) connection.

For digital T1 and E1 equipment, there is really only one type of service. Although there are two types of data format and framing, the basic signal levels (nominally ± 3 volts) and connections are the same for all T1 and E1 services. The T1/E1 line is a four-wire connection, comprised of two 2-wire pairs. Each pair operates half duplex, either sending or receiving data. Application Note # 175 discusses applications using both types of digital equipment.

PROTECTION REQUIREMENTS

Analog and Digital equipment must be protected against various categories of stress to ensure a minimum level of robust operation in the field. The stress conditions and the testing methodology mandated by various regulatory standards can divided into the following categories:

1. Metallic (or differential) surges.
2. Longitudinal (or common mode with respect to ground) surges.
3. Overvoltage stresses.
4. Dielectric (or Insulation) strength testing.

Essentially, the governing standards measure immunity to stresses via standardized tests. Some stresses must be withstood without degradation; for others, the equipment is allowed to fail gracefully (i.e., no fire, no shock hazard, etc.).

A summary of the most common requirements can be found in Tables 1 through 3. Table 1 describes surge, or transient tests. Table 2 describes the most commonly used overvoltage tests, and Table 3 describes the dielectric isolation interface (i.e., electrical isolation barrier) stand off voltage requirements.

TELCOM EQUIPMENT

Fuse and PTC (Positive Thermal Coefficient) component usage is essentially the same for both analog and digital equipment. However, the nature and operating requirements for analog loop start equipment is considerably more complex than for T1/E1 digital equipment.

Idealized DIGITAL T1/E1 Interface. Typical applications can be found in Figures 1 and 2. For each 2-wire pair, a transformer provides a dielectric barrier that isolates the telcom system (the TELCO side) from the user equipment (the USER side).

Table 1. Regulatory Surge Requirements (Partial List).

Standard/Test	Open Ckt. Voltage (V)	Short Ckt. Current (A)	Duration (uSec)	Comments
Part 68, Type B, Metallic	1000	25	9 x 720	Must survive, 2 repetitions
Part 68, Type B, Longitudinal	1500	37.5	9 x 720	Must survive, 2 repetitions
Part 68/CS03, Type A, Metallic	800	100	10 x 560	Survivability desirable, but optional
Part 68/CS03, Type A Longitudinal	1500	200	10 x 160	Survivability desirable, but optional
Bellcore GR-1089, 1st level	600, 1000	100	10 x 1000	Various, to 50 repetitions
Bellcore GR-1089, 1st level	2500	500	2 x 10	10 repetitions

Table 2. Regulatory Overvoltage Requirements (Partial List).

Standard	Open Voltage, Short Ckt. Current	Time Applied	Comments
UL 1950/IEC 950 M1/L1	600 V, 40 A	1.5 Secs	No fire or fragmentation
UL 1950/IEC 950 M2/L2	600 V, 7 A	5 Secs	No fire or fragmentation
UL 1950/IEC 950 M3/L3	600 V, 2.2 A OR 135% of fused current with fuse shorted (M3-L3)	30 Min	Maximum heating - check for fire hazard
Bellcore GR-1089	600 V, 60 A	5 Sec	No fire or fragmentation

Table 3. Dielectric Strength Requirements.

Standard	Voltage	Comments
FCC Part 68/CS03	1000 VAC for interface	Test with voltage limiting components or bridging components removed.
Safety (UL 1950, IEC 950)	1250 to 1500 VAC typical	Interface dielectric requirement depends on construction, country, and primary power.

Loop-Start Circuitry Operating States. Analog Loop start circuits have, for the purposes of Application Note #175, three operating states:

1. On-hook.
2. Ringing.
3. Off-hook.

In each of these states, the normal operating environment presents different voltages and currents to the USER equipment. Because of these varying requirements, protection against surges and overvoltage conditions is more complicated for loop start equipment. However, as with the case for digital equipment, the protective components must allow the equipment to operate properly while still maintaining protection against the various overvoltage and surge transient events.

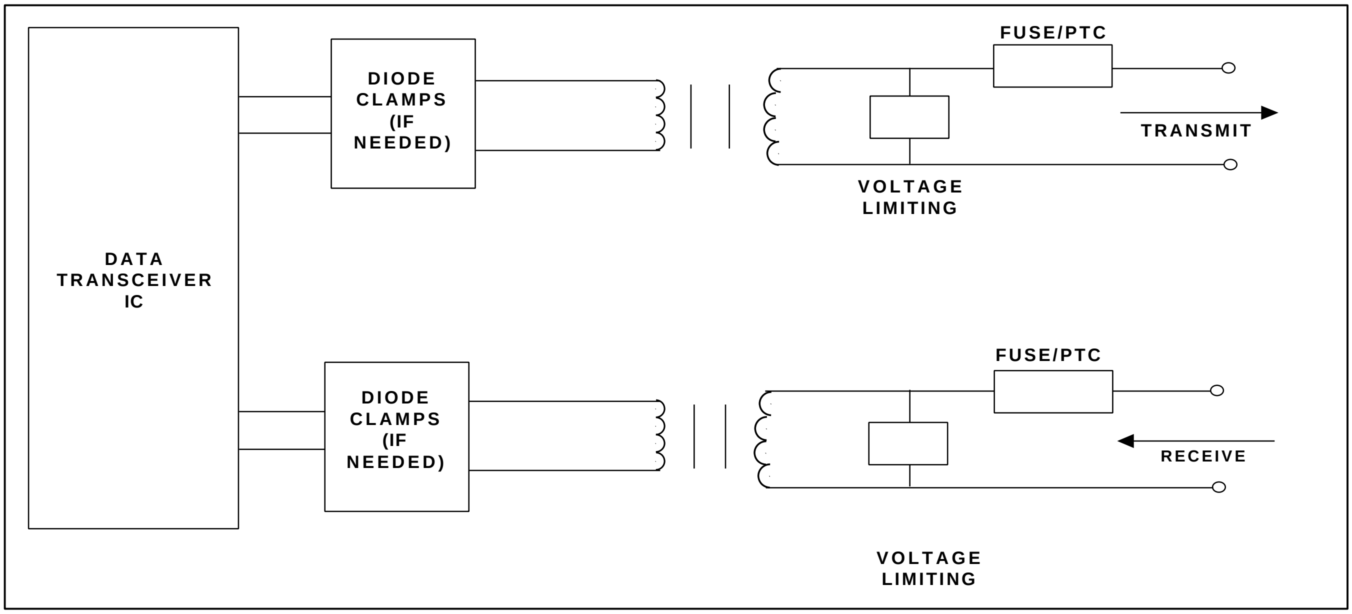

Figure 1. Typical floating T1/E1 interface design. In this figure, the USER side is to the left of the transformer and the TELCO side is to the right of the transformer. Differential surge protection is provided on the TELCO side by voltage limiting devices. The USER side protection functions as additional protection and is useful as protection against residual effects of the stresses. Longitudinal stress is withstood by the transformer dielectric.

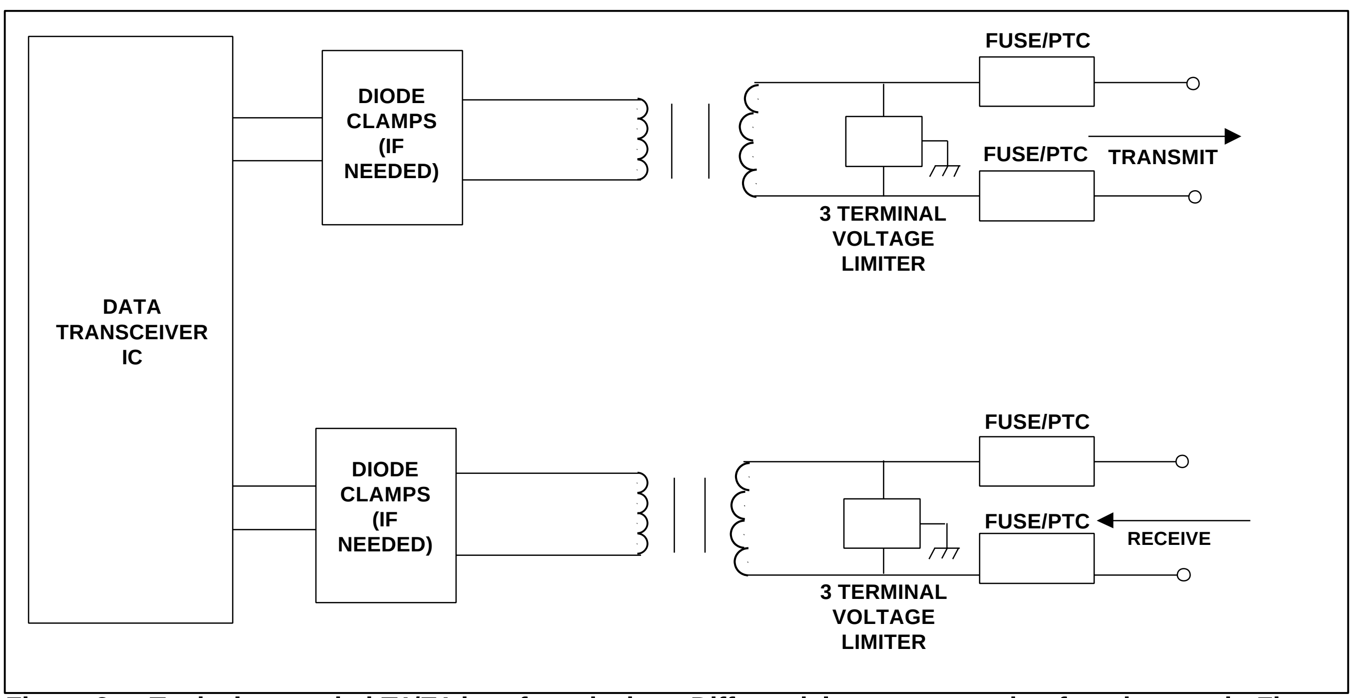

Figure 2. Typical grounded T1/E1 interface design. Differential surge protection functions as in Figure 1, but longitudinal stresses now result in current flow to ground via the third terminal of voltage limiting device. Although grounded voltage limiting is more robust, it requires extra components for proper implementation. Note that the transformer isolation must still meet the longitudinal stresses with the grounded protective component removed.

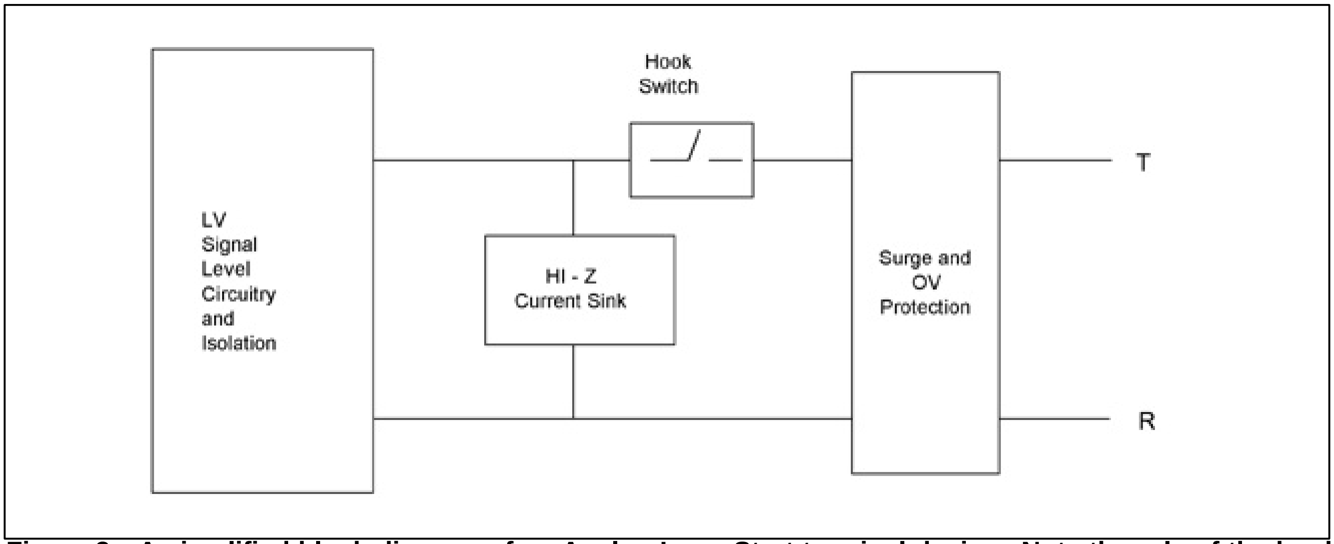

Figure 3. A simplified block diagram of an Analog Loop Start terminal device. Note the role of the hook switch. When open, (i.e., on-hook) the hook switch has to withstand the surge voltage up to the level of protection provided by the surge protector as well as any momentary pulses that may "sneak" past the surge protector. When closed (i.e., off-hook), the hook switch must absorb any current pulse caused by a voltage surge.

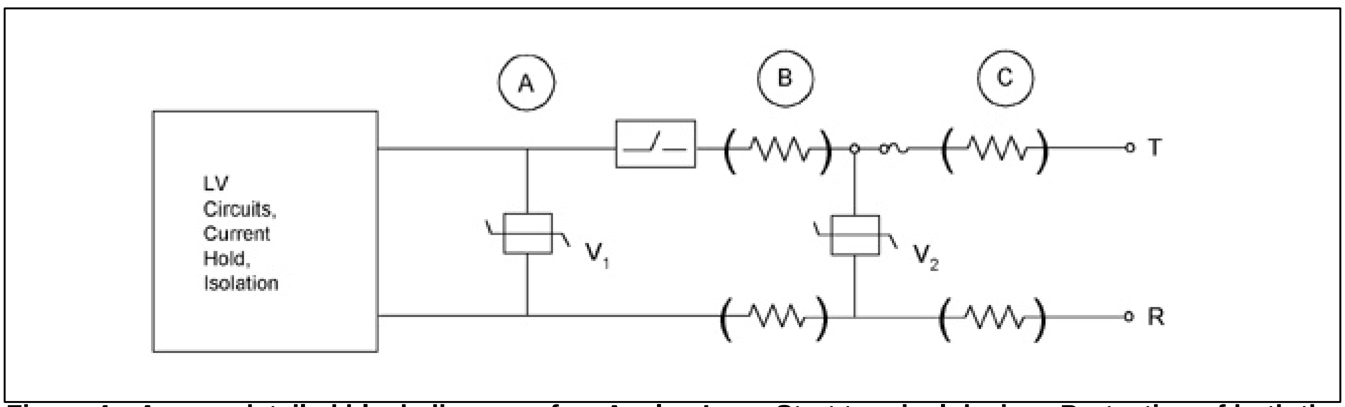

Figure 4. A more detailed block diagram of an Analog Loop Start terminal device. Protection of both the hook switch and the low voltage circuitry in the terminal device requires an additional low voltage clamping element (V_1, circled item A) and may sometimes require additional series resistance (circled items B and C). Note that the greater the resistance added, the smaller the ratio of energy delivered to the terminal device. Device V_2 is the primary voltage protection device.

Idealized Analog Loop-Start System. Figures 3 and 4 illustrate a typical Analog Loop Start terminal device application with surge and overvoltage protection. The essential characteristics of the PSTN system, with respect to DC operating point, are indicated in the diagram in Figure 5. In both the On-Hook and Off-Hook states, the network "looks" like a battery of approximately 48 volts (range between 42.5 and 56.5 volts) with a series resistance varying from 400 to approximately 1800 ohms, depending on the length and wire gauge of the subscriber loop. The minimum resistance is set at the central office to limit current for the case of close proximity subscribers; the maximum resistance occurs for customers who are several miles away. The positive pole of the central office battery is grounded. There is no ground at the subscriber end, so both differential and common mode surges must be considered.

On-Hook. In the On-Hook state, very little current flows. FCC Part 68 requires that the USER equipment exhibit multi-megohm resistance. The resulting circuit model for on-hook operation is a 48 volt(DC) signal applied differentially across TIP and RING, with a poor, high-resistance ground on the positive side.

Ringing State. For the case of the Ringing state, the On-Hook configuration in Figure 5 is further complicated with a ringing voltage superimposed on the battery voltage (See Figure 6). The most common ringing signals are 20 or 30 Hz at up to 130 VAC (A type ringer), or voltages up to 150 VAC (B type ringer). The terminal equipment's ring detector circuitry is AC coupled to the PSTN line.

Off-Hook. When the user goes Off-Hook (i.e., closes the hook-switch), a net DC loop current will flow through the terminal equipment's DC Hold Circuitry. The central office detects this loop current flow and stops the AC ringing signal.

The terminal equipment has decidedly different electrical characteristics when in the Off-Hook state. The Off-Hook state DC load characteristics can be determined by using the load line in Figure 7. The load line is composed of the Central Office battery, the loop resistance and the I-V characteristics of the terminal device (EUT). Typically, in the Off-Hook state, a current in the range of 20 to 50 mA flows through the loop and a voltage is developed across the EUT of less than ten volts.

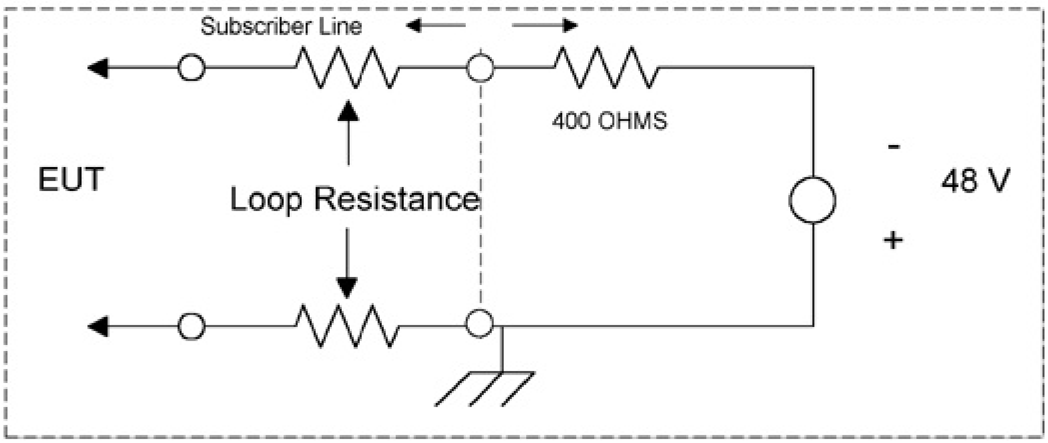

Figure 5. A simplified DC representation of the PSTN battery and wiring resistance. This representation is adequate for On-Hook analysis.

SURGE AND OVERVOLTAGE PROTECTION METHODOLGY

The TELCO side of the transformer is where the primary voltage limiting (such as sidactors, varistors, or gas discharge tubes) and current limiting components (usually a series of current limiting elements such fuses or PTC components) are located. The voltage limiting components are intended to prevent surge damage; the current limiting components protect against excessive current during overvoltage events. It is interesting to note that the overvoltage test – which simulates a power line crossing a telcom line – forces excessive currents through the interface components and is really an “overcurrent” test.

Protection against a voltage surge event is provided by voltage limiting devices. Thyristors, or avalanching devices (sidactors is a trade name for these components) are commonly used for this purpose. Their operation is quick, but not instantaneous. The primary advantage of thyristors is that they stay active until the stress voltage goes to zero. Varistors are quicker, but they are clamping devices only. Once the voltage recedes below the activation voltage, the varistor de-activates. With either a varistor or thyristor, it is possible for a voltage pulse to be coupled across the interface.

Protecting against excessive currents (i.e., from the overvoltage tests) is the job of the current limiting fuse or PTC.

The USER side of the transformer connects to either a low voltage data transceiver IC (digital TI/EI case) or to low voltage circuitry/Hold Current Circuitry (analog loop start case). Sometimes the TELCO side protection components are not sufficient to protect low voltage circuitry against surges (typically, metallic surges cause the problem) and additional protection is required on the USER side of the interface. Diode clamping is often employed on the USER side of the transformer when there is concern that voltage pulses will sneak into the

USER side before the overvoltage components have time to respond to the incoming surge. In this case, diode clamping to ground and to $+V_{CC}$ is quite effective. The diodes steer the excess energy back through the nearest bypass capacitor, keeping any voltage applied to the USER circuit(s) within a diode drop of the supply rail levels. As an additional precaution, series resistance may be added in the TIP/RING lines to limit overvoltage induced current flow.

Fuse/PTC Requirements. A fuse must be robust enough (i.e., have enough thermal capacity) to survive the desired surges, but open under the high current M1/L1 and M2/L2 tests. The M3/L3 test is a special case for fuses. If the fuse is rated at less than 2.2 A, it is jumpered, and the current is ramped to 135% of the fuse value for 30 minutes. The idea is to stress the interface with the maximum long-term current it could experience without opening the fuse. This is the worst case test for heating of the interface components. The most commonly used type of fuse is a 1.25 A rated slo-blo.

PTCs differ from fuses in that they don't open permanently. Instead, their resistance increases with heating from excessive current. Thus they are resettable – their resistance returns to normal once they cool down. They react slowly enough that they are unaffected by surges. They also have maximum current overload and voltage supporting capabilities. The most commonly used PTCs are rated at 600V, and are either 150mA or 160 mA devices.

PROTECTION IN THE OFF-HOOK STATE

In the Off-Hook state (i.e., the hook switch is closed), any differential surge experienced is passed through the hook switch to the LV terminal device circuitry. This low voltage circuitry is quite susceptible to overvoltage damaged, so it is common practice for an additional voltage limiting device, typically a zener diode or varistor in the 20 volt range, to be included for protection.

Large voltage transients due to lightening strikes or a high voltage power line crossing (i.e., directly contacting the PSTN line) may also produce an overvoltage induced current. In this case, a large current pulse, easily several tens of amperes, will briefly flow through the hook switch during the voltage surge. This current pulse is sufficiently large to destroy the hook-switch. The usual way to protect the switch is to limit the current pulse with additional resistance in the TIP and/or RING lines. Typical values are in the range of 10 to 33 ohms, or even higher, depending on the sensitivity of the hook-switch to current surges.

The effect of series resistance on the current that passes through the switch is three-fold.

1. It reduces the amount of current that flows through the switch for a given amount of transient voltage.

2. It preferentially steers the Off-Hook transient current to the main surge protector if these resistors are located on the switch side of the differential surge protector.

3. It increases the output impedance thereby reducing the TELCOM signal to noise ratio of the terminal device's transmitted signal.

WHEN IS GROUNDING NECESSARY?

Grounding provides more robust protection but implementation is more costly because additional components are required. Whether a ground is needed depends on several factors. Two of the more critical factors are discussed below.

Availability. Applications which do not use a three wire electrical connection, or do not have provisions for chassis grounding (such as those operating from battery eliminators), won't have access to electrical ground. In this case, grounding is not possible.

Protection of Insulation Barrier. If a floating interface is used, all longitudinal (common mode) voltages must be withstood by the insulation of the barrier formed by the transformer and the wiring. In this case, the insulation receives the maximum stress. Some designers prefer to divert longitudinal stresses to ground through the additional protective circuitry. This reduces the stress on the insulation and provides a designated path for current to flow. However, this approach is more costly, requiring an extra fuse/PTC and a more complex voltage protection component (or multiple single components.) Remember, even though this approach provides additional protection, the barrier dielectric must still meet the required isolation criteria with the protective components removed.

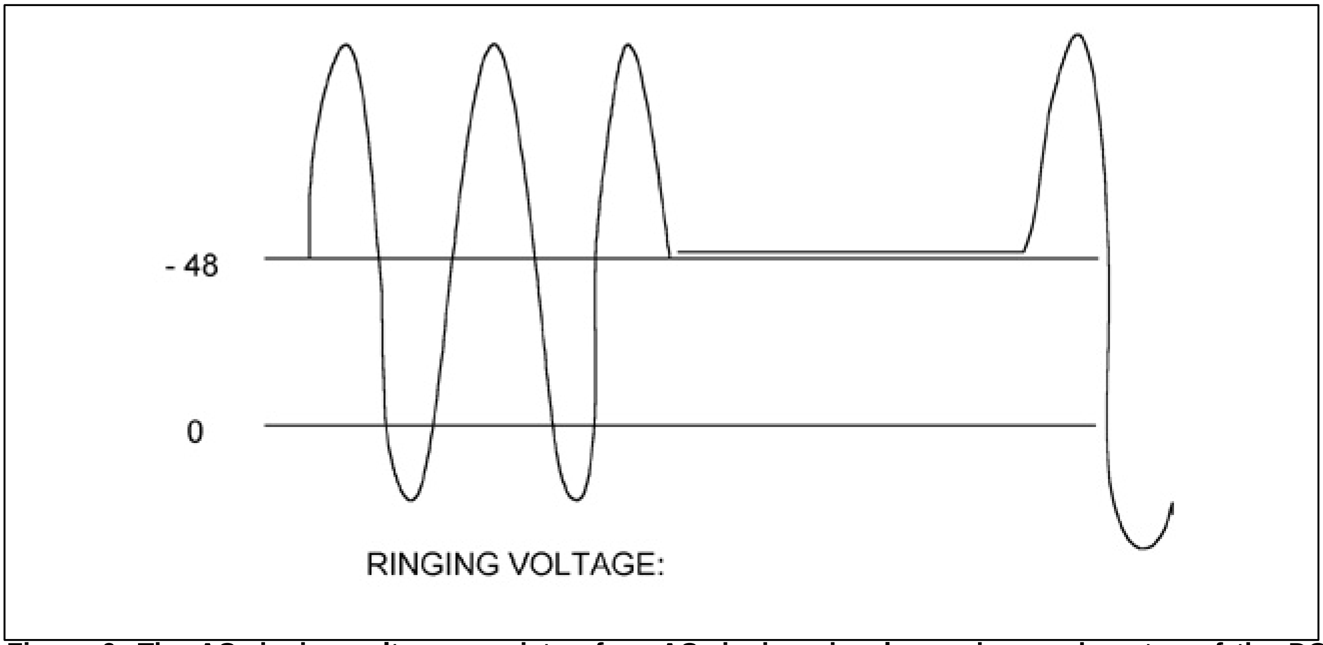

Figure 6: The AC ringing voltage consists of an AC ringing signal superimposed on top of the DC voltage provided by the central office battery.

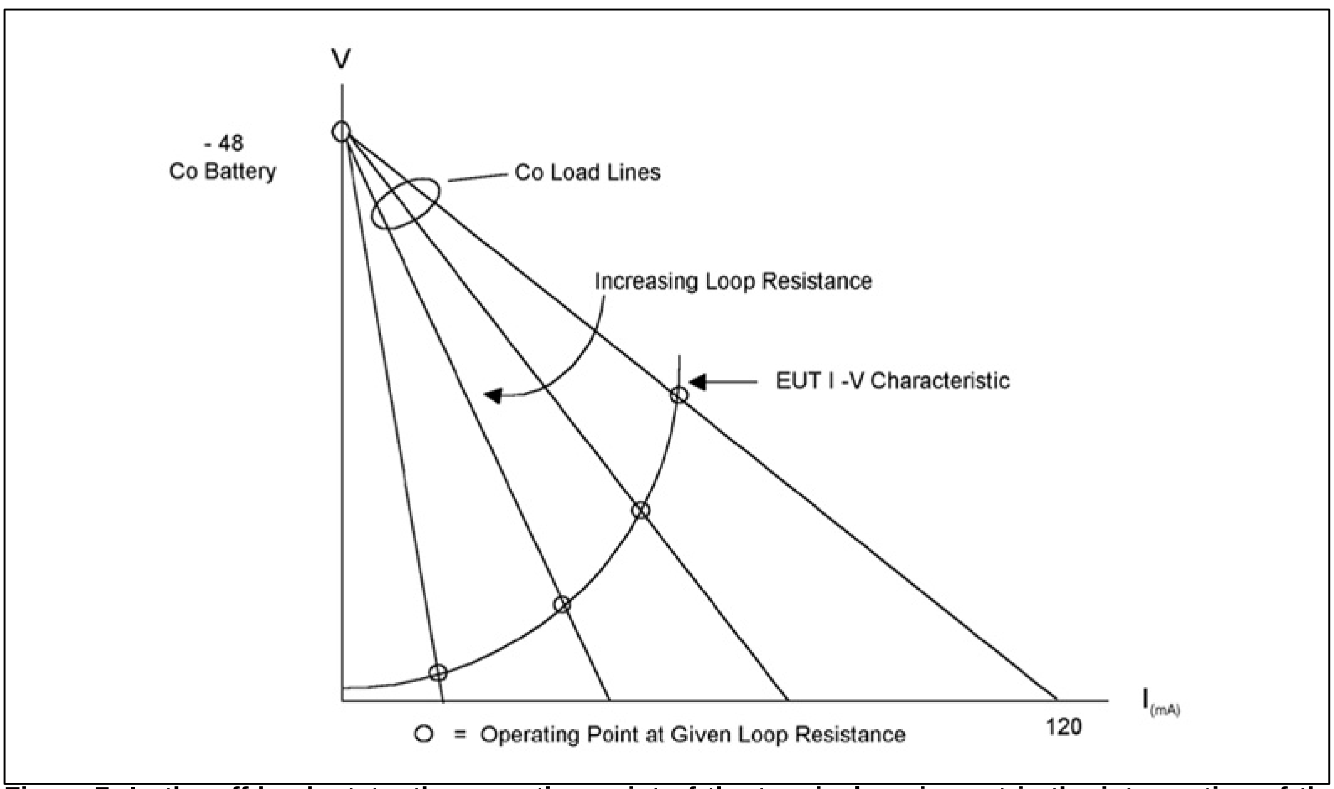

Figure 7: In the off-hook state, the operating point of the terminal equipment is the intersection of the load line of the telephone network and the I-V characteristic of the equipment.

SURGE PROTECTOR RATINGS

By analyzing the operating conditions of the Ringing, Off-Hook and On-Hook states the required performance characteristics of the surge protection circuitry can be determined. Surge protectors are of primary importance in the On-Hook and Ringing states.

Minimum Ratings. The lower bound or minimum voltage of the surge protection circuitry is set by the On-Hook and Ringing states and is a reflection of the need to pass the AC peak ringing signal to the telcom equipment's ring detector circuitry.

The peak ringing voltage is the sum of the battery voltage plus the peak ringing signal. For a 130 VAC ring signal, the peak ringing voltage is 240 volts; for a 150 VAC ring signal, the peak ringing voltage is 269 volts. Therefore, surge protectors shouldn't conduct significantly at less than 269 volts. Soft conduction, such as that exhibited by a varistor, is less problematic than the firing of an avalanching device, such as a sidactor or a gas discharge tube. This is because a varistor might conduct near the peak, but would not conduct after the voltage recedes; a sidactor or gas discharge tube, once activated, will continue to conduct current until the net voltage across the device goes to zero. See Figure 8.

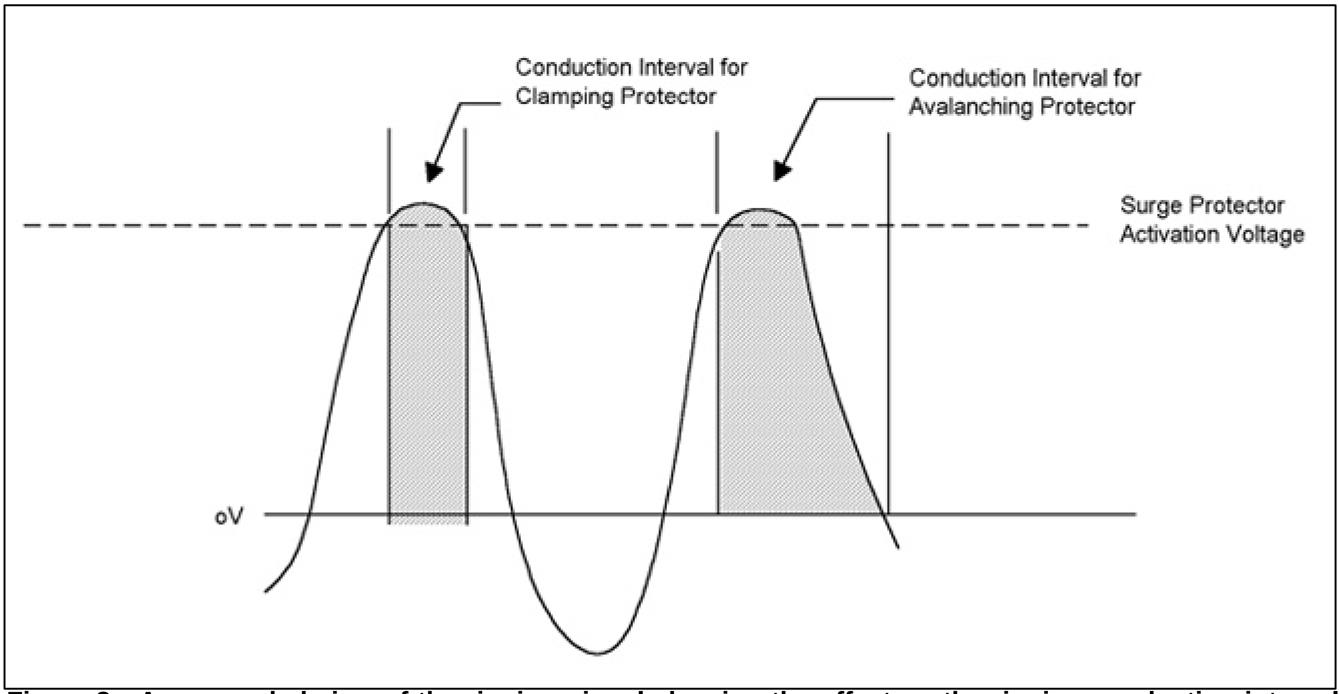

Figure 8. An expanded view of the ringing signal showing the effect on the ringing conduction interval of a Clamping device vs. an Avalanching device.

Additionally, FCC Part 68 requires that there be less than 3.0 mA of DC current flowing through the terminal equipment when in the On-Hook state. This added limitation is necessary because the Central Office interprets DC loop current flow in excess of 3.0mA as indicating the Off-Hook state. Incorrect operation of surge protectors may cause the AC ringing voltage to generate a loop current greater than the 3mA limit. This condition is called "ringing pre-trip." Unfortunately, ringing pre-trip falsely signals the Central Office to stop the AC ringing voltage prior to the terminal device going Off-Hook. Once the ring voltage stops, the current flow in excess of 3mA also stops. However, the terminal device is still On-Hook, therefore, the central office concludes (incorrectly) that the user hung up immediately after going Off-Hook and the central office terminates the incoming call. Ringing pre-trip is a particularly harmful false operation and care must be taken to avoid this condition.

Although the above discussion of minimum on-hook surge protector ratings considered only the case for differentially connected surge protectors, it is a system requirement that the users equipment work regardless of the polarity when connected to the system. Consequently, the same arguments apply to common mode surge protection (i. e., those connected from line to ground).

Maximum Ratings. No maximum rating is specified by regulation, but a practical a *de facto* maximum exists. Specifically, the maximum rating limit will depend on the maximum ratings of the hook switching element and the tolerance limit on the percentage variation of the surge protectors' activation voltage.

To illustrate this point, consider the simplified telecom device block diagram in Figure 3. The hook switch element determines the on/off hook state of the device. The hook switch operates as follows: when the hook switch is open (i.e., On-Hook), no loop current flows; when it is closed (i.e., the Off-Hook state), the hold current flows through the hold circuitry (often a FET or transistor current source connected through a diode bridge) and back to the central office.

In the On-Hook state, differential surges appear across the hook switch element. If the hook-switch is a manual switch or an adequately rated mechanical relay, no maximum need be specified. However, if a solid state device such as an optically coupled FET is used as the hook-switch, then the maximum drain to source voltage limit of the FET becomes the maximum allowed voltage. If the differential surge protector does not clamp or limit incoming surges to a value below this level, the hook-switch element is likely to be damaged during the surge event.

Required Surge Protector Limits. Essentially, the voltage range for a differential surge protection element must lie between the maximum peak ring voltage (i.e., the minimum rating of the surge protector) and the breakdown voltage of the hook switching element (i.e., the maximum rating of the surge protector).

BALANCE AND SHUNT CAPACITANCE

In digital networks, parasitic capacitance can cause problems with impedance, frequency response, and longitudinal balance. Recall that for digital networks the bandwidth of interest is 1.5 MHz for T1 and up to 2 MHz for E1, and the line impedance is 100 ohms. For loop-start telephone networks, the bandwidth is only 4 KHz. Consequently, the effect of shunt capacitance, both differentially and to ground, is much less significant for loop-start networks for a given amount of capacitance. Still, it is possible, although uncommon, for shunt capacitance imbalance to degrade the line balance even at 4 kHz. Practical experience has shown that capacitance imbalances of less than 1 nF (1000 pF) can usually be tolerated and will not adversely affect the minimum 40 dB transverse balance required by of the FCC.

SUMMING UP

Although there are many ways to design protection schemes for terminal equipment, adhering to a few basic principles will simply the design of the protective circuitry regardless of the specific application:

- Decide on topology – will earth ground be used?
- Surge protectors should be rated for at least 270 Volts (350V preferred) before substantial conduction occurs to avoid interfering with ringing.
- Pick the voltage-limiting device. There are three characteristics:
    1. Topology – two or three terminals: If grounding is to be used, then a three terminal device is required; otherwise a two terminal unit will suffice.
    2. Voltage rating: For digital lines, a varistor with the lowest voltage rating is usually best. All available voltages are well above the T1/E1 signal levels.
    3. Energy rating: The energy rating required of the varistor will depend on whether or not there is any additional resistance in the circuit. That is, is the varistor required to handle all of the surge by itself, or will current be limited by other series components (such as the resistance of a PTC, or any deliberately added resistance)?
- Solid state switches must be protected against excessive transient voltages. This sets an upper bound on the reliable firing voltage for the differentially connected surge protector.
- Additional surge protection, operating at a lower voltage, is frequently required to protect the low voltage circuitry on the USER side of the electrical isolation barrier (i.e., transformer) device.
- If a solid state hook switch is used, make sure it can withstand the transient currents delivered under FCC surge conditions or provide external current limiting.

- In general, transient currents delivered during FCC surge testing can be sharply diminished with additional series resistance.
- Fusing/PTC usage guidelines are similar for both digital and analog terminal equipment. A good starting point is to use a fuse which will survive all surges and blow under the low current (M3/L3) overvoltage test. A 1.25 Amp slo-blo fuse will usually pass both Type A and Type B of FCC surge testing. A 0.5 A slo-blo fuse will generally meet the FCC Type B surge, but not the Type A.
- Note that there is some variation in fuse surge handling capabilities, and a slightly higher value may be required with some manufacturers' components. Only one current limiting device is needed if the interface floats – that is, if a two terminal voltage limiting component is used.
- Check robustness of the interface by surge testing to see if (a) the protection components and transformer survive, and (b) auxiliary protection on the USER side of the interface (clamping diodes) is required to prevent harm to the transceiver IC and/or the LV circuitry.
- Make sure any capacitances to ground are balanced in both TIP and RING lines to within a few hundred picofarads, or at most 1 nF. This capacitance will be the sum of any RF bypassing as well as the capacitance in any surge suppression components. Varistors can have surprisingly high capacitance in the off state.

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