Protection of Electronics from Lightning and Other Large AC Power Pulses

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A lightning surge races up the power line and destroys dozens of boards in a computer system in California, at a cost of $4,000 in parts and six man-days. On the same circuit, other protected computers keep on running. Half a world away, in Taiwan, six of seven semiconductor memory testers suddenly fail catastrophically, while the protected one survives.

What ac line protection is needed to protect against lightning and other types of fast, high-energy power line disturbances?

Defining the Challenge

Luckily, much research has already been done in characterizing these pulses. The IEEE Standard 587-1980 (now ANSI/IEEE C62.41-1980) shows that despite wide variations, the wave shapes and amplitudes are predictable. They are a function of building wiring circuits, which are sufficiently standardized for this approximation. C62.41 is the best standard we have, and this is validated by the successful field performance of protective equipment designed to meet it.

Noise pulses are defined by where they are measured. This accounts for the inherent impedances and resonances of wiring circuits. Category C occurs outside the building and is not covered here. Sensitive electronics are commonly connected at Category A and B locations, which are depicted in Fig. 1.

Much greater pulse energies can be encountered near the service entrance or on dedicated branch circuits that are sometimes used for computers. Two types are typical:

1. A **ring wave** with a 0.5 μs rise time up to 6 kV and a 100 kHz frequency, decaying 40 percent each half cycle. The source impedance dictates a 500 A short circuit current.
2. A unidirectional **impulse** with 1.2 μs rise time to 6 kV and an exponential decay to half voltage in 50 μs. Short circuit capability here is 3,000 A, with a current rise time of 8 μs, decaying by half in 20 μs.

Of the two, the impulse is much more destructive due to its duration, unidirectional wave shape and large current capability.

For Category A locations, the energy levels are much less than in Category B, and there is only one wave shape. It is a ring wave with a 0.5 μs rise time up to 6 kV and 100 kHz frequency, as before. However, the increased line impedance of the smaller, longer wires to these locations limits the short circuit capability to 200 A. Figure 2 details these waveforms.

All of the above disturbances can occur at any phase position on the power line, in either positive or negative direction. They can also occur in either normal or common mode. The voltage amplitude is often less than 6 kV but will not generally exceed 6 kV since building wiring arcs over at this point.

There are many similarities between the EMP pulse and lightning pulses when it comes to power line protection. Both pulses have steep wave fronts. Lightning can rise to peak in as little as 150 ns, and EMP can be significantly faster. Amplitudes for EMP can be 25 kV, but durations are generally shorter.

Design of Effective Power Line Protection Devices

These pulses occur as common-mode pulses where there is a sudden rise in potential between ground and neutral or phase. Protection of the load requires isolation of the secondary circuit and shunting the impulse back to ground. Surge arrestors located at the service entrance to the building can sometimes help, but a well-shielded, well-insulated isolation transformer can reduce these impulses to levels that today's ever more sensitive electronics can survive.

Good transformer design demands that careful consideration be given to spacing, dielectrics and shielding. Spacings within the transformer between coil and shield, for example, enhance the performance of the insulation used. And all the work put into making a high-isolation transformer can be lost if the connection wiring allows the impulse to arc over to the secondary, bypassing the isolation transformer.

Insulating materials must be properly selected and applied as well. Double and triple varnished magnet wires eliminate pinholes which can cause breakdowns. Nomex* paper has higher dielectric strength

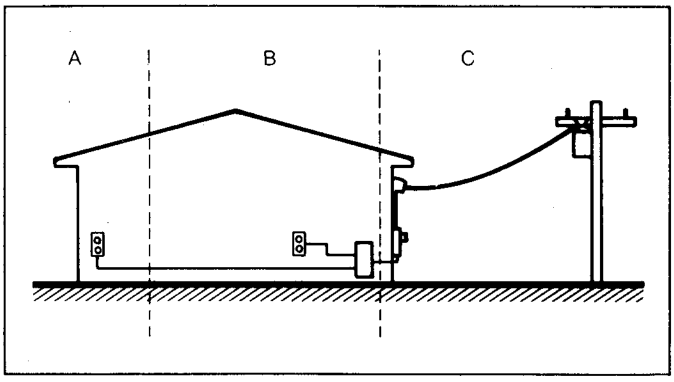

Figure 1—Location Categories

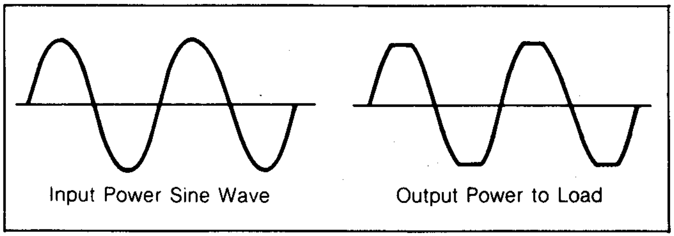

Figure 2—Effect of Filter with Excessive Source Impedance Increment

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(e.g., 700 V/mil) than less-expensive Kraft papers. One "space-age" material increasingly used in high-performance transformers lately is Kapton,* which is mechanically inferior to Nomex but has a dielectric strength exceeding 8 kV/mil. High-performance silicone glass sleeving over connection wires and extra isolation of components is also effective.

How Many Shields Does a Transformer Need?

The major trick in a transformer shield is to make it a good conductor and keep the electrostatic field between primary and secondary coils to a minimum. Box shields "completely" enclose the transformer's wiring. "Completely" is in quotes because it is never quite true. The shield is a one-turn metallic conductor around a flux-carrying core. It is generally either copper or aluminum. If the energized transformer has 1 V per turn on its coils, then the shield has 1 V across its open ends. Should the shield be closed by touching these ends, a shorted turn results which can burn up the transformer. There must therefore be some intervening dielectric space where some electrostatic field will find its way through.

So that's why "triple shields" are sometimes used? Yes, but if one shield is properly designed and built, there is no need for extra shields in the case. Space within the core is at a premium, and it should be used for the best dielectric and shield materials available.

It is the authors' opinion that there has been a specsmanship race to see who can quote the highest dB isolation or the lowest picofarad level of capacitance while ignoring the real world of spikes and surges. Multiple box shields of thin aluminum Reynolds wrap give impressive shield credentials. But how does a 1 mil aluminum foil shield stand up to a common-mode lightning impulse? Shields should be made of rugged copper ribbon, capable of carrying the hundreds or thousands of amps, if required, without fusing. Reynolds wrap is better for sandwiches.

Solutions to Normal-Mode Disturbances

Shielded isolation transformers may be the best answer to common-mode impulses, but using them alone can be harmful to the computer's health. If you hit one with normal-mode (line-neutral) fast rise time pulses, it will respond by ringing at its resonant frequency. Unless they are well-loaded, "isolation" transformers will actually **amplify** input spikes!

Attaching simple EMI/RFI filters to the line won't correct this situation. In fact, these devices must be properly loaded or they, too, will resonate. Since bothersome power line disturbances are generally in the 10 kHz to 10 MHz frequency range, the best answer is a nonlinear filter with resonance suppressing capabilities.

Series inductance in these L-C circuits as well as the transformer must be kept to an absolute minimum, however. Most modern computers now use switched-mode power supplies which draw their current in high-frequency gulps at the positive and negative peaks of the power sinusoid. Since the frequency of these current pulses approximates 1 kHz, any series inductance in the line tends to make the load current flatten the voltage sine wave as shown in Fig. 3.

This flattening produces undesirable harmonics and reduces the peak voltage, and switching supplies respond to peak voltage rather than rms. The voltage change caused by excessive source impedance increment (also known as **transfer impedance**) is given by:

$$\Delta V = \Delta I(2\pi fL)$$

Since f is much higher in frequency than the 60 Hz power sine wave, the inductive reactance ($2\pi fL$), a high value, multiplied by a high peak current ΔI (which occurs only when the rectified peaks of the sine waves exceed the voltage on the power supply's input shunt capacitor), gives a ΔV large enough to cause problems.

High-quality equipment incorporating normal- and common-mode surge protection while maintaining low source impedance increment is commercially available. An example is pictured in Fig. 4.

Sources and Types of Power Line Disturbances

Several groups of investigators have gathered data on power line noise. They have been thoroughly cited in other papers and will

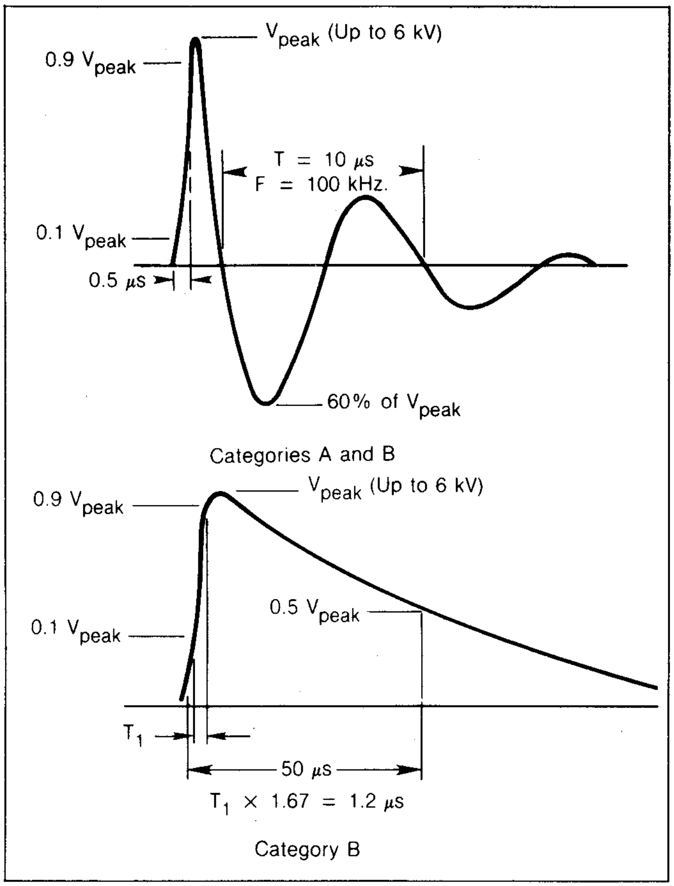

Figure 3—Standard Disturbance Waveforms

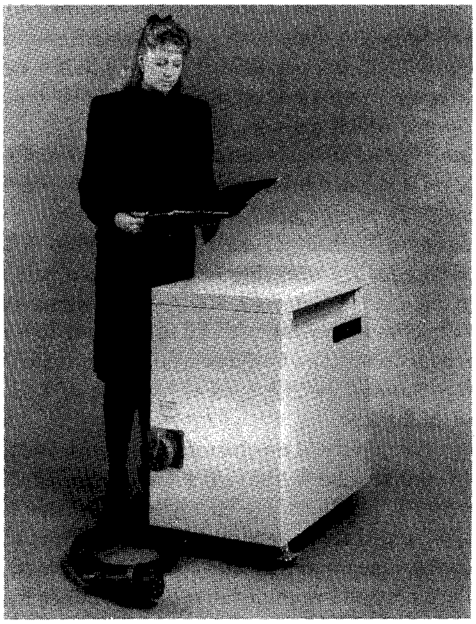

Figure 4—Modern Low Impedance Filter Protects Against Common- and Normal-Mode Pulses and Noise. (photo courtesy of Teal Electronics Corporation, San Diego, California)

not be discussed here other than as bibliographic listings. However, it is useful to review the basic types of noise and their sources.

Normal-mode noise is a disturbance potential between two power lines in the same circuit (phase to neutral), and common-mode noise consists of equal and in-phase potentials between two lines of a circuit and ground. Although Fig. 5 shows this for single-phase power, three-phase is analogous.

Most of us are aware that there are many man-made sources of noise, e.g., motors starting up, utility companies switching banks of capacitors to correct power factor, switching of large loads, bouncing contactors, electric arcs, laser devices and even nuclear detonations. Inductive pickup leads to normal-mode noise, and capacitive pickup to common-mode noise.

It is sometimes difficult to visualize how common-mode noise can exist at all inside a building. With neutral and ground tied together at the service entrance, as in Fig. 6, how can there be a potential between them?

Power lines are designed to carry 60 Hz, but they can have significant inductive reactances at higher frequencies. Because high-frequency currents tend to travel on the surfaces of conductors (**skin effect**), the conductivity of the wire also decreased markedly. High-frequency noise sources can have their signals picked up by wires acting as antennas, as shown in Fig. 7.

Common-mode noise problems occur when a pulse finds a lower impedance path to ground through the load than by other means. The grounded shield in the isolation transformer offers a lower-impedance path than the interwinding capacitance, shunting the pulse to ground.

"It's an ill wind that blows no good," however. The high inductive reactance of the lines at high frequencies, coupled with the line-to-line distributed shunt capacitance, tends to form a natural low-pass filter that attenuates the same very high frequencies. This time we got something for nothing.

Performance Testing is Necessary—and Possible

Published specifications for noise and spike suppression capabilities of commercial protection equipment are misleading at best. This is because there are few real standards and because assumptions behind the claims are rarely included. The assumed conditions have little to do with the real world, anyway.

Luckily, several quality manufacturers are now making equipment that produces realistic, repeatable power line disturbances, allowing objective comparisons between the many alternative technologies that are available for a particular application. This includes generation of the large ring waves and impulses in the ANSI/IEEE Standard C62.41-1980 reviewed earlier. Unfortunately, these machines tend to be large, lethal and relatively expensive.

It is possible to obtain a spike generation device which offers small size and low cost in exchange for limited flexibility and power. An example is the TEAL SG-863, which puts out an 800 V (peak to peak) decaying 12.5 kHz ring wave. The fast 150 ns rise and fall times add frequency components up to 2 MHz. The spike is put directly onto the peak of the 60 Hz, 120 V sine wave as shown in Fig. 8.

Although the generator's primary function is not for destructive testing, it does enable one to determine if various protective devices really do divert, clip or absorb spikes on the power line. We have been able to correlate data obtained by using this device with the results obtained using other surge generators whose monthly rental fees exceed the cost of building this smaller one. And since it puts a spike on each positive 60 Hz peak, you don't need an expensive storage scope to see the results. It can be used to observe both normal- and common-mode impulses.

Dedicated Grounds and Personnel Safety Issues

The National Electrical Code is written around the safety of the human user rather than the sensitive electronic loads. But is it possible to protect both? One technique that some people use is the

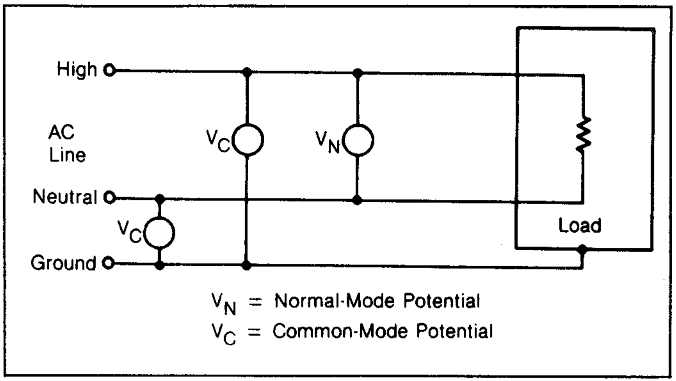

Figure 5—Definitions of Normal- and Common-Mode Noise

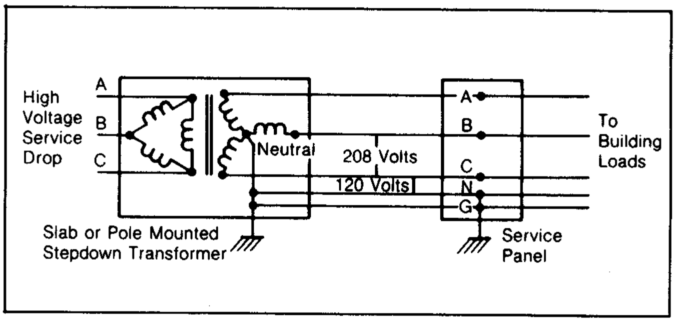

Figure 6—Three-Phase Power Wiring Showing Neutral to Ground Bond

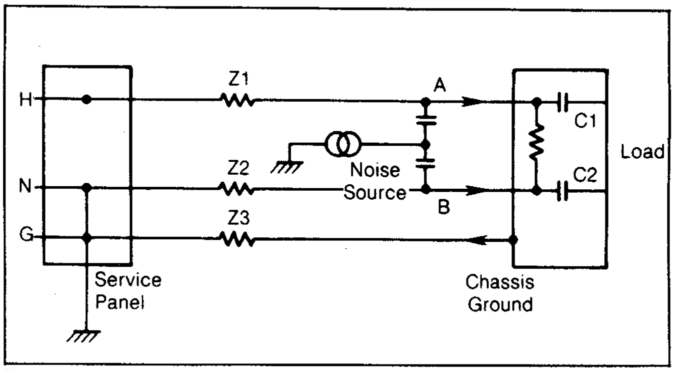

Figure 7—How Common-Mode Noise Potentials Exist and Disturb

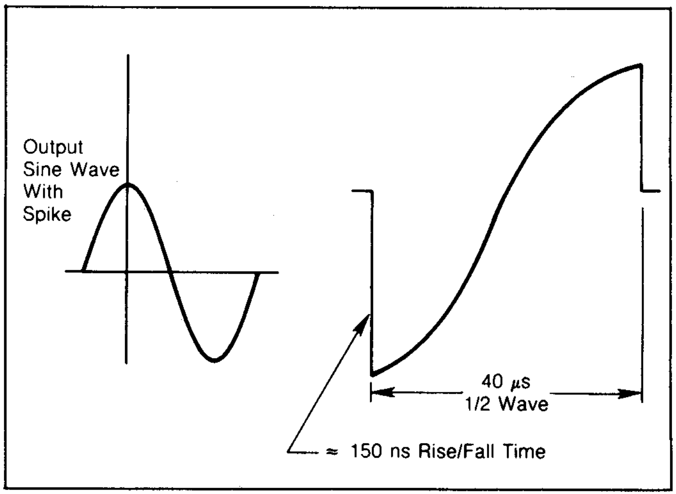

Figure 8—Spike Generator Output

dedicated ground. The rationale is that the building ground system is so bad that it is better to construct a new, good ground than to try to fix the old one. Generally, this is combined with an isolation transformer as in Fig. 9.

There is an element of danger involved. Sizable potential can exist between the two grounds, and a person could be touching both at once. This could be an especially significant problem in the event of a lightning strike when ground potentials can differ by thousands of volts. It is better to have just one ground and use heavy-gauge wire (for greater surface area), terminated at a good building ground rod driven into wet earth.

Conclusion

Destructive surges on the line caused by lightning and other high-energy impulses can be modeled with validity. Good, shielded isolation transformers can protect against these impulses if properly designed and built. However, use of these isolation transformers also requires the use of low-impedance, normal-mode filters. A new type of spike generator is available, allowing performance testing of circuits to be accomplished quickly and inexpensively. When designing grounding systems to protect sensitive electronics, personnel safety is an important issue to consider.

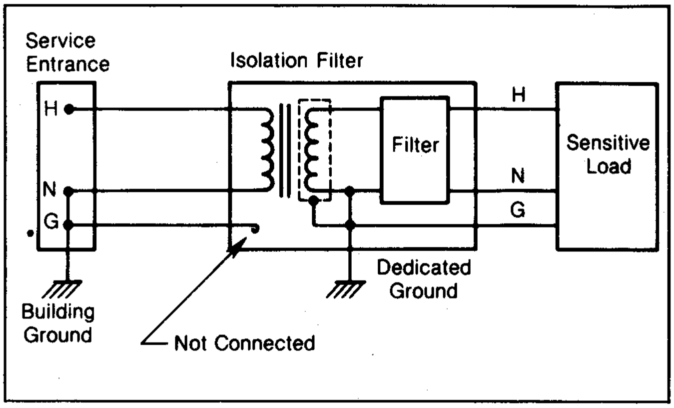

Figure 9—Isolation Filter with Dedicated Ground (Use of building ground is recommended.)

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3. National Fire Protection Association. "1987 National Electric Code." Quincy, Massachusetts: 1986.

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