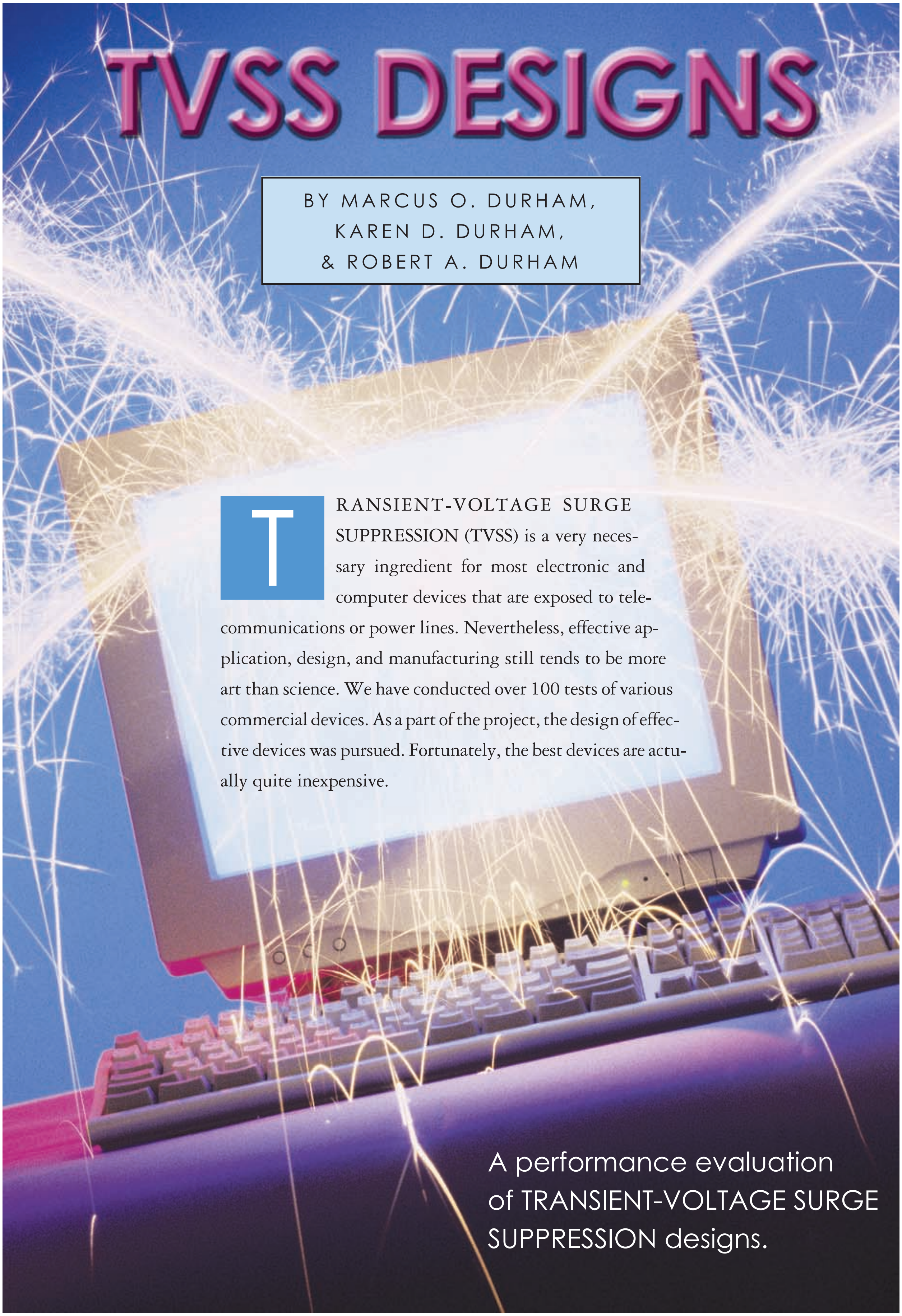


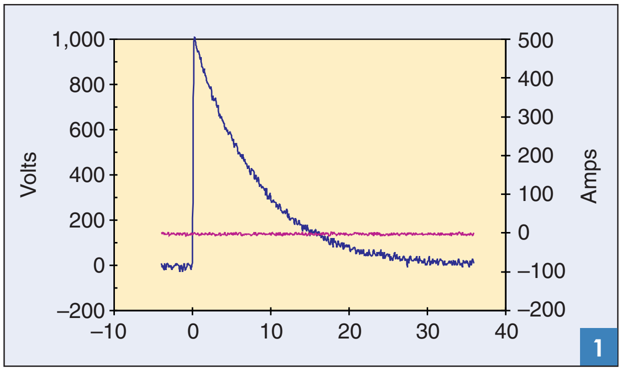
TVSS DESIGNS

BY MARCUS O. DURHAM,
KAREN D. DURHAM,
& ROBERT A. DURHAM

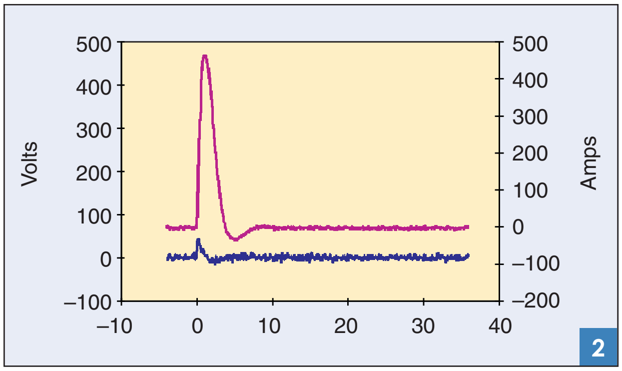
TRANSIENT-VOLTAGE SURGE SUPPRESSION (TVSS) is a very necessary ingredient for most electronic and computer devices that are exposed to telecommunications or power lines. Nevertheless, effective application, design, and manufacturing still tends to be more art than science. We have conducted over 100 tests of various commercial devices. As a part of the project, the design of effective devices was pursued. Fortunately, the best devices are actually quite inexpensive.

A performance evaluation of TRANSIENT-VOLTAGE SURGE SUPPRESSION designs.

1077-2618/02/$17.00©2002 IEEE



Standard 1.2/50 voltage.



Standard 8/20 current.

The purpose of the TVSS application influences the design. This may be to clamp voltage, shunt current, filter frequency, dissipate energy, or a combination. The elements may consist of air gaps, passive elements, or semiconductor electronics. Verification and performance testing is an area often overlooked. Proper installation, including grounding, is critical to the success of the circuit.

There are numerous devices on the market that make various claims. Most standards and traditional works address classical lightning arrester protection without detailed considerations of component design [1]-[5]. Most engineers do not have the instrumentation, equipment, laboratory, or resources to validate these devices for their applications. This article will discuss various approaches to protection system design. Numerous different components and systems were tested as a follow-up and result of research for several previous grounding papers [6]-[8]. Inadequate protection can result in equipment failure and downtime. Both cause lost revenue. Conversely, proper protection improves the bottom line.

THE PURPOSE OF TVSS APPLICATION DETERMINES THE DESIGN.

ANSI Standard Waveforms

Determination of the current capacity and wave response of protection networks requires very sophisticated laboratory instruments. Any comparison requires a standardized test procedure. ANSI C62 describes the industry-accepted waveform, applications, and test procedures [9]-[12].

A 1.2/50 wave-shape is used to evaluate open circuit or voltage responses. This is shown as channel 1 (volts) of the oscillographs. For short circuit or current responses, an 8/20 wave-shape is used. This is channel 2 (amps). Some oscillograph traces show an output voltage from inline devices on a third channel.

A 1.2/50 wave-shape describes an impulse signal that rises from virtually zero to its crest in 1.2 µs and declines to one-half crest value in 50 µs. The microsecond units are not usually applied to the designation of the wave.

Fig. 1. is a standard voltage waveform in response to an open circuit. The voltage peaks and dissipates in the standard period of time. There is no current flow.

Fig. 2. is the response to a short circuit. The voltage is very limited, while the current peaks and dampens very quickly with a very minor ringing or oscillation.

The test equipment applied both of these signals to the circuit. The resulting wave-shape was displayed and captured on a quad-channel digital recording oscilloscope.

The maximum deliverable voltage is selected prior to the test. After firing, the voltage and current maximum and minimums that passed through the suppressor were captured.

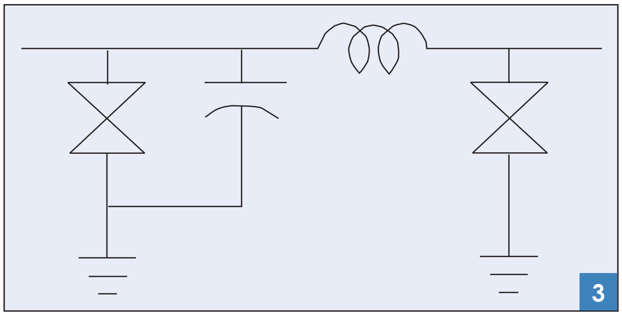
Protection Devices

Protection devices are added to an electrical system to aid in managing surges. The devices may shunt current, block energy from traveling down the wire, filter certain frequencies, clamp voltage levels, or perform a combination of these tasks [7].

Protection devices are selected based on the voltage, frequency, exposure, and ground system of the circuit. Regardless of the function, only a few basic components are available to economically protect an electrical system. Fig. 3 shows a complete system with all types of components.

The simplest protection arrangement is physical separation. Gaps may be used to provide arc paths above a certain level. These may be air gaps or may have a dielectric material between conductors. Classical lightning arresters fit in this category. The cross symbols in Fig. 3 represent these components.

Often the devices are built so that the path will become low impedance once breakdown occurs. Silicon carbide (SiC) is traditionally used in high-energy devices [10], [13].



Protection scheme.

One brand uses a unique insulation material. It is essentially sand with spaced out probes. This device provides virtually no protection.

Gas tubes and other break-over materials also fit in this air-gap category [12]. This is the slowest class of protection equipment, but the energy handling capability is very large for the cost. A performance curve for a 120-V device is shown in Fig. 4.

The test signal is an impulse while power system devices are rated root mean square (rms). To compare results, the peak voltage from a power circuit is $\sqrt{2}$ rms.

The most significant observation is that most devices do not provide any substantial current limitation and protection until two times the rated voltage or $\sqrt{2}$ times the peak is reached. As the impulse level is increased, the let-through voltage is as much as $2\sqrt{2}$ times the rated peak voltage.

Passive Elements

Capacitors shunt voltage to ground. A large capacitor greatly lengthens the time it takes for the voltage to return to zero (Fig. 5). Capacitors store the energy when hit with a surge. The energy must then dissipate once the impulse has passed.

Inline filtering uses inductors that block current changes. The inductor also provides a conductive, low resistance path. The basic shape of the inductor response is very similar to the short circuit of Fig. 6. A voltage is built up, and the substantial current is damped very quickly. Larger inductance permits a greater voltage build up, while the current is more limited because of the L di/dt effects.

The air-core inductor has less attenuation, a higher cutoff frequency, and is larger. However, it is preferred because ferrite-core inductors have a nonlinear response to the magnitude and frequency of the current to be dissipated.

A significant consideration is the resistance associated with the inductor. High resistance can cause very large power dissipation for large currents on power circuits. Conversely, the inductor must be large enough to limit the current. An inductor's power rating must be adequate for continuous operation.

$$P = I^2 R.$$

In control circuits, the resistance must be small enough to cause minimal impact on loop compliance. For example, the total loop resistance for a 4-20-mA circuit is typically 600 Ω. The instrument already comprises 250 Ω.

Filters

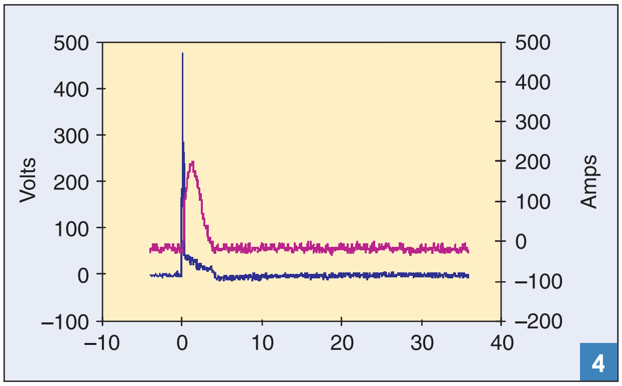
Bypass or bandpass filters are a combination of an inline inductor and a shunt capacitor. More surge protection is provided from devices with the lowest throughput energy at a particular frequency. Throughput is the amount of energy that gets past the protector onto the equipment being protected.

For power systems, the circuit must pass 60 Hz. Typical transients may be expected to perform similar to a 1-MHz signal. A filter would be constructed to block this high-frequency signal. Hence, the roll-off of a filter should have little impact on power or dc circuits. However, in control circuits, high frequency counters and analog circuits may be attenuated with this filter.

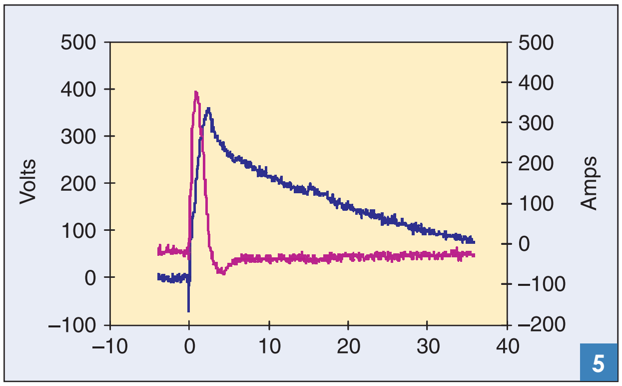
The combination of inductor and capacitor will create a tuned circuit with a resonant frequency. Care must be exercised to prevent the frequency from matching the frequency of the transients. The frequency of oscillation or ringing of the circuit is determined by the relationship

$$f = 1/2\pi\sqrt{LC}.$$

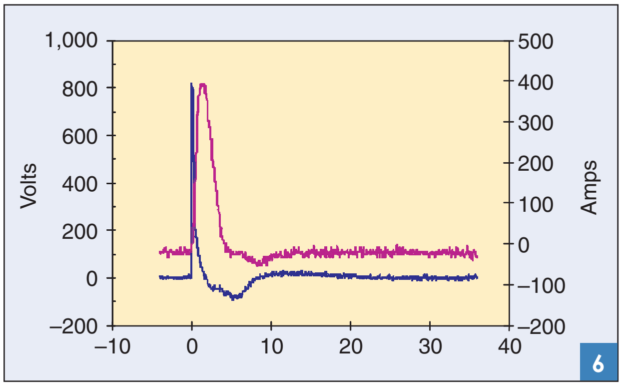
Fig. 7 illustrates the response of a device with a filter that resonates. Note that the output has a greater magnitude than the input and that it oscillates. There is also substantial noise on the current channel. This is not an acceptable protector. Because this will happen at some transient frequency, filters are generally not recommended.



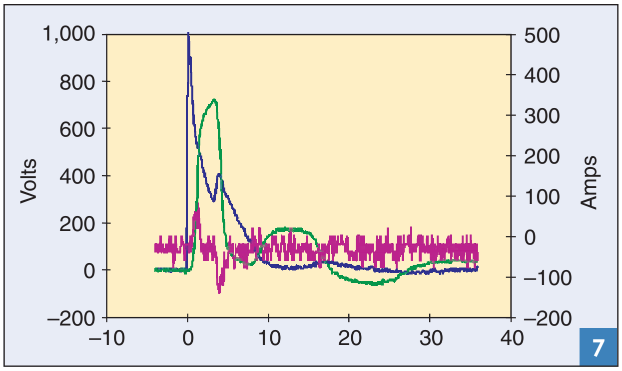
Gas tube response 500-V test.



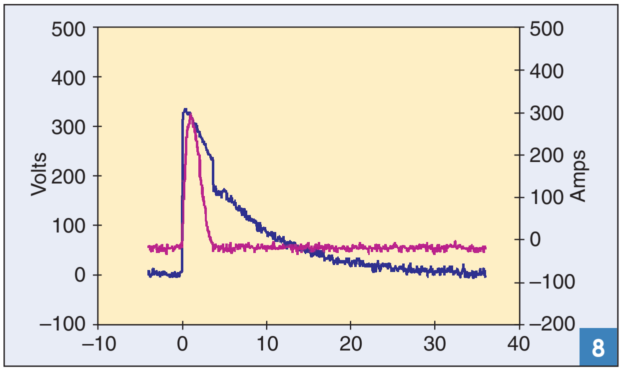
Capacitor response.



Inductor response.



Resonating filter response.



130-V MOV response.

Semiconductors

Semiconductor devices are faster than gap elements, but they generally handle less energy. Because of the limited range of operation, these devices must be more precisely specified. Silicon devices fit into two groups: voltage- and current-protective elements.

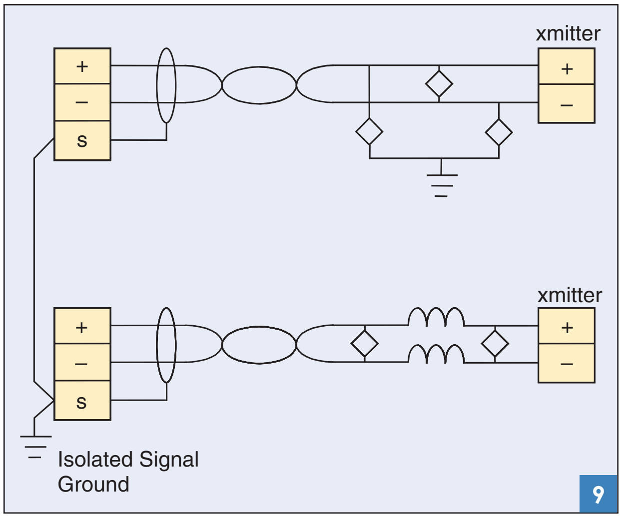
Metal-oxide devices are selected for a "turn on" voltage that is greater than the peak expected voltage from the power supply. They are manufactured to handle very precise quantities of energy (joules or watts per second). Each metal-oxide varistor (MOV) will have a resulting surge current rating. Typically the material is zinc oxide (ZnO).

The current capability is related to voltage by a nonlinear modification of the linear Ohm's law

$$I = kV^{\alpha}.$$

For SiC arresters, α is in the range of 10. For ZnO, the range is 25-60. This indicates that MOV devices are much more responsive than SiC arresters. In other words, they will conduct high current more quickly.

At very small currents, in the microamps, an MOV behaves like a linear resistor. At very large currents, in kiloamps, the current is fixed. In between, it is nonlinear. The response of a typical MOV used in a 130-V power protector is shown in Fig. 8.



Remote transmitter circuit.

The MOV device has an inherent capacitance. Higher energy units tend to have a higher capacitance. This creates a problem with high-frequency signals. At high frequency, the high capacitance will increase the impedance of the circuit and attenuate the signal. MOVs can handle more energy alone than other semiconductors. Nevertheless, at elevated energy levels, they must be used in conjunction with another arrester [8].

Zener, avalanche, or silicon junction diodes are current devices. They are much faster than varistors and tend to limit voltage surges to a lower level. However, they cannot sustain as much energy without failure.

Since the unit has essentially no energy dissipation rating, it is coupled with a primary arrester such as a gas tube. The diode will trigger first, and the energy will be dissipated through the gas tube. A typical circuit using a zener consists of a resistor or inductor placed inline and the zener shunting the output [7].

Grounds

For transient protection, a uniform, equipotential ground grid is desired under the entire area covered by the electrical system and all its connected equipment. The facility-grounding network provides this reference [6]-[8].

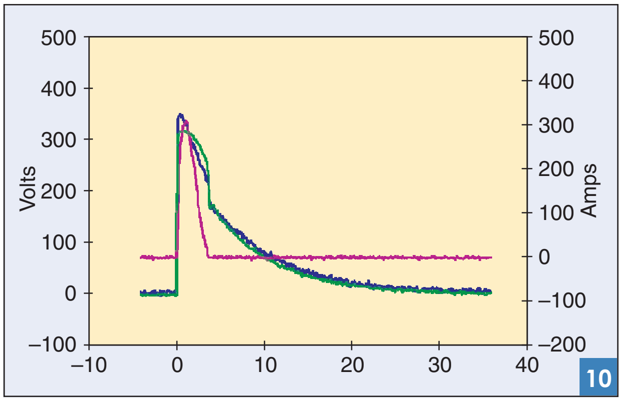
For typical systems, the ground terminals of the TVSS are tied together, and only one connection is made to earth. However, two different "grounds" are shown in Fig. 9. These are intentionally isolated in order to dissipate the energy or when there are different earth potentials on the ends of long conductors.

Local Instrumentation TVSS

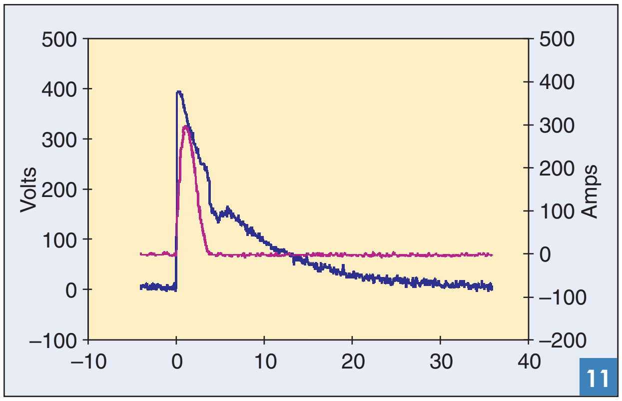
Electronic circuits that are fed from multiple cable pairs share the surge energy between the pairs; therefore, less energy is imposed on each piece of electronics. The mode of protection depends on the connection of the protection circuit. Differential-mode units are connected between the two signal wires of a circuit. A common-mode unit is connected between a signal wire and ground.

Where a common ground is available, as a minimum, a common-mode device should be placed on both ends of each conductor. This is shown in the top part of Fig. 9.

Many commercial protection modules have differential protection and an inductor to limit current changes. These inductors detrimentally impact the impedance and frequency response of the circuit.



Remote protector response.



Power TVSS response L-N.

Most commercial units have a common-mode connection to the earth. While this may be acceptable inside the plant ground grid area, it often contributes to failures on transmitters remote from the signal power source, because of circulating currents.

Remote Instrumentation TVSS

For remote instrumentation, the primary requirement is to isolate the unshielded cable from both the transmitter and the distributed control system (DCS) input card. Isolated inline protectors should be placed on the transmitter using differential mode. Shunt devices should be placed on the DCS ends of the cables using common mode.

A very effective inductor is 20 turns of the circuit wire. This should be on an air core that has a radius at least seven times the wire diameter. For typical instrumentation wire, this can be wrapped around a pencil for shape.

The preferred varistor for a 24-V circuit is a 36-V, 160-J device. With two MOVs across the line, the system shown in Fig. 9 has performed better than most commercial systems that were tested. The response of the protection circuit is shown in Fig. 10.

Two significant points are noted: the inductor causes the rounding of the output voltage, and the output performance curve is almost identical to the MOV performance curve. It is especially significant that the scheme dissipates the energy without any ground connection.

Power TVSS

The voltage, number of phases, and configuration describe the protection type. Generally, nonelectronics can be protected with shunt-type protectors.

Inline devices either failed or were ineffective in performance or packaging. Most inline devices actually had more voltage applied to the load than the voltage at the input of the protection circuit. The circuits would have been more effective as a shunt rather than an inline device.

For high-energy power systems, all components in Fig. 3 may be used. Because it is difficult to match the frequency and get low enough resistance for large currents, the inductor can often be removed from the circuit with little impact. This is particularly important since inline inductors are very expensive when built for low resistance and high current. A 130-V device is shown in Fig. 11. While the protection line to neutral is quite good, the line-to-ground voltage was twice as high (Fig. 12). This approach is common. Apparently the assumption in the design is that there will never be a voltage difference between the neutral and ground. Many papers on harmonics and other topics have illustrated that this is not the case [14].

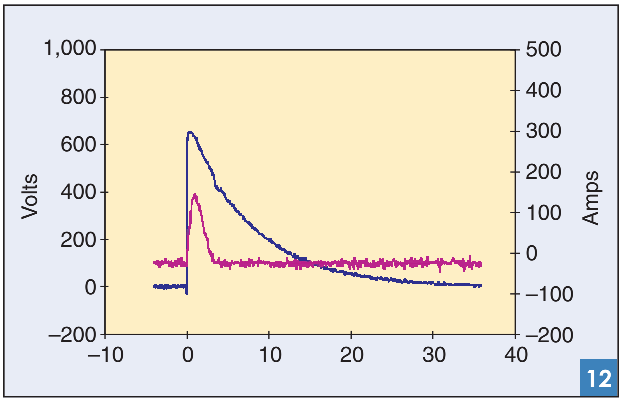
The most detailed design TVSS tested had a very sophisticated circuit. The device had MOV, gas tube, and capacitor across the line to neutral with an iron core inductor in the line. On the output side, it had MOVs across the line to neutral, line to ground, and neutral to ground. In addition it had a current-limiting transorb across the line to neutral. Theoretically, this should be the highest performing device. However, the voltage surge was clamped just slightly higher than other MOV devices. The ringing was less than other filter devices, apparently because of the transorb.

Motor TVSS

A variety of single- and three-phase devices have been previously evaluated for telephone and motor power systems [15]. The results of those tests are included to compare with recent technology devices.

One company requested a prototype design be evaluated. A complete system, including filters, designed for three-phase motor load was analyzed. With a 6,000-V surge applied, both the line-to-neutral and the line-to-line voltage were about 5,900 V. The current discharge was only 12 A. The system did little to protect the 480-V load.

With the grounds shorted together, there was a ringing for one cycle in both the current and voltage waveforms. It took 350 µs for the oscillation to stabilize. The peak voltage



Power TVSS response L-G.

was 5,679 V with a current of 544 A. It is very obvious that common grounds can cause a coupling back to the filter.

A pure resistive load was applied to the output. This caused harmonic spikes every 10 μs. This reflects the earlier discussion of sensitivity of the filter to tuned frequencies.

After a number of different scenarios, a very interesting observation was found; a TVSS with MOV arresters was as effective for a 60-Hz, 480-VAC circuit as the circuit with filters. In a more advanced design, primary arresters enhance the ability of the MOV to sustain large surges.

TVSS Challenges

Follow-Through

When a protector device fires, the arrester will continue conducting for an extended time. The protector shorts the circuit during the triggered time. Consequently, the system experiences false alarms and shutdowns. Gas tubes are particularly susceptible to this problem and may never shut-off. Specific arc-extinguishing circuits are required. By comparison, zener diodes clear very quickly while MOVs may take up to 15 s to clear.

Degradation

An MOV degrades with time as it ages from taking surges. Manufacturers grade MOVs on the amount of energy the MOV can withstand after so many hits. Select devices with the desired energy rating with a lifetime hit to exceed 100,000. As long as a zener's range is not exceeded, the device does not significantly age. However, because of the very limited current capability, a zener without a primary arrester will fail often.

Catastrophe

Silicon semiconductors, MOVs, and gas tubes will fail in a shorted mode when at the end of their life or when overpowered. At very excessive power levels, the device may melt and become an open circuit. Open circuits are seldom found until the device did not do its job. For gas tubes, the open occurs at power levels that deteriorate the elements so the gas will not ignite. Properly designed gas tube circuits can work to the limits of lightning levels.

Representative

A variety of TVSS devices were used. After analyzing the literature, it was determined the devices fit a particular design. During tests, the shape of the waveforms could usually be used to determine the circuits, even in potted units. Therefore, the results of the analyses appear to be representative of the state of the art.

Summary

There are numerous different considerations for each type of system. Nevertheless, there is a key concern for each. The goal is to make these seemingly conflicting requirements compatible. A complete TVSS system consists of shunt protectors on the input and output. Other components may include the input shunted with a capacitor and an inductor placed inline. The grounds are isolated on the input and output. For low energy systems, an MOV is often the only device used. This may be effective if it is adequately sized and has not deteriorated. For circuits exposed to higher energy and for power circuits, another primary arrester should be included. The fastest system uses avalanche diodes with a primary arrester to dissipate the larger energy.

For adequate protection, three conditions are critical. A semiconductor device is required. A high-energy primary arrester is used in conjunction. The configuration is arranged for all possible scenarios.

Finally, protection will generally be inappropriate without a very effective ground grid.

References

[1] R.T. Hasbrouck, "Lightning—Understanding it and protecting systems from its effects," Lawrence Livermore National Laboratory, Livermore, CA, Tech. Rep. UCRL-53925, 1989.

[2] *Lightning Protection Code*, ANSI/NFPA 780, 2001.

[3] *IEEE Recommended Practice for Grounding of Industrial and Commercial Power Systems (Green Book)*, ANSI/IEEE Std142, 1991.

[4] *IEEE Recommended Practice for Powering and Grounding Sensitive Electronic Equipment (Emerald Book)*, ANSI/IEEE Std1100-1992.

[5] *National Electrical Code*, ANSI/NFPA 70, 2002.

[6] M.O. Durham and R. Durham, "Grounding system design for isolated locations and plant systems," *IEEE Trans. Ind. Applicat.*, vol. 33, pp. 374-382, Mar./Apr. 1997.

[7] M.O. Durham and R.Durham, "Lightning, grounding, and protection for control systems," *IEEE Trans. Ind. Applicat.*, vol. 31, pp. 45-54, Jan./Feb. 1995.

[8] M.O. Durham and R.A. Durham, "Interaction and design of grounded systems for tanks and vessels," in *Proc. IEEE Petroleum and Chemical Industry Conf.*, 1999, pp. 195-202.

[9] *IEEE Standard for Gapped Silicon-Carbide Surge Arresters for AC Power Circuits*, ANSI/IEEE Std C62.1-1989.

[10] *IEEE Guide for the Application of Gapped Silicon-Carbide Surge Arresters for Alternating Current Systems*, ANSI/IEEE Std C62.2-1987.

[11] *IEEE Guide for the Connection of Surge Arresters to Protect Insulated, Shielded Electric Power Cable Systems*, ANSI/IEEE Std C62.22.1-1996.

[12] *IEEE Standard Test Specification for Gas-Tube Surge Protective Devices*, ANSI/IEEE Std C62.31-1987.

[13] *Distribution System Protection Manual*. Canonsburg, PA: McGraw Edison.

[14] M.O. Durham, R.D. Strattan, and D. Carter, "Harmonic impact on power system design," *Int. J. Power and Energy Syst.*, vol. 203, p. 1012, Feb. 1994.

[15] R. Sharma, "Transient voltage surge suppression analysis," M.S. thesis, Dept. Elect. Eng., Univ. of Tulsa, Tulsa, OK, 1996.

[16] D. Fink and W. Beaty, *Standard Handbook for Electrical Engineers,* 13th ed. New York: McGraw Hill, 1993.

[17] J. Rowland, *Linear Control Systems.* New York: Wiley, 1986.

Marcus O. Durham (mod@superb.org) is with THEWAY Corp. in Tulsa, Oklahoma, USA. Karen D. Durham is with NATCO in Tulsa, Oklahoma, USA. Robert A. Durham is with D^2 Technology in Broken Arrow, Oklahoma, USA. M. Durham is a Fellow of the IEEE. K. Durham and R. Durham are members of the IEEE.

This article first appeared in its original format at the 2000 IEEE Petroleum and Chemical Industry Technical Conference.