# Characterization of Transient Voltage Surge Suppressors From a System Compatibility Perspective


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Significance
Part 6: Tutorials, textbooks and reviews
Part 7: Mitigation techniques

A comprehensive review of test programs (up to 1992) of surge-protective devices, including service-entrance SPDs and downstream SPDs.

Tests performed at Georgia Power facilities for surge withstand capability, TOV withstand, failure modes, and mechanical tests.

Test performed at the Power Electronics Applications Center (PEAC) on meter-base arresters, plug-in TVSSs (power port and communications port) and surge-reference equalizers.

# Characterization of Transient Voltage Surge Suppressors From a System Compatibility Perspective


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***Abstract*** *- Transient voltage surge suppressors are characterized from the point of view of electric utilities wishing to offer to their customers a comprehensive surge-protection plan. This plan involves a surge arrester installed at the service entrance and one or more plug-in suppressors installed within the premises, at the point of connection of a surge-sensitive appliance. Complementary tests were conducted at two laboratories to assess the compatibility of candidate devices with the needs of the utilities and the end-users. Basic, fundamental tests of protection performance and failure mode were performed for both suppressors and arresters. Mechanical and environmental tests were performed on meter-base arresters. In addition to obtaining data on test specimens, another outcome is the development of test protocols that can be used for systematic and consistent testing of other candidate devices.*


## BACKGROUND

The proliferation of electronics in residential power systems has increased the need to protect sensitive electronic equipment from damaging transient voltage surges. These surges can originate outside the residence (lightning, power system switching) or inside (load switching, faults). External sources are associated with greater transient energy than internal sources. However, given the low tolerance (immunity) of some loads, even these internal sources of surges should not be ignored.

In answer to this need for surge protection, products have been developed under the generic name of Transient Voltage Surge Suppressors (TVSS). Some of these can be installed by the occupant of the premises, typically as a plug-in device inserted between the wall receptacle and the power cord of the equipment to be protected. Other TVSSs are permanently-wired, typically installed at the service entrance panel or as a modified wall receptacle. Both types have been available for some time. Another type of service-entrance protection has emerged, which is incorporated into revenue-meter socket adapters. The protective socket adapter plugs into a standard meter base, and the meter plugs into the socket adapter.

Standards-writing groups are still in search of consensus on the names that should be used for the different types of devices. The acronym 'TVSS' appears to be well entrenched in the U.S. usage to describe devices installed on the load side of the main service disconnect (such as in the Underwriters Laboratories Standard UL 1449) but is denied international recognition. On the line side of the main disconnect, and further upstream towards the utility distribution system, the term 'secondary surge arrester' has generally been used (although the IEEE has not developed a definition of this term). The generic term 'surge-protective device' advocated by the IEEE has been condensed to 'SPD' in current drafts of the IEC. In this paper, we will differentiate a plug-in *suppressor* from a service-entrance *arrester*.

Much testing has already been devoted to plug-in suppressors, but this testing has generally been limited to a simple verification of the protective function, without much consideration for their overall performance in the system. There is even less information available on the more recent service-entrance arresters. As an outgrowth of power quality concerns, electric utilities have become interested in offering surge protection to their customers. Currently, about 13 utilities have launched programs of surge protection involving service-entrance arresters as well as matching plug-in suppressors.

Such an extensive program cannot rely on simple verification of the protective function, but requires an assessment of the overall system compatibility. A long-standing approach to compatibility has been developed by the engineering community of electromagnetic compatibility (EMC), from which the surge-protection programs can benefit.

The basic EMC philosophy is expressed in the definition of EMC: equipment should "have a high probability to function satisfactorily in its electromagnetic environment without introducing intolerable disturbances to anything in that environment" [IEC International Vocabulary 161]*. For SPDs, this philosophy can be expressed in simple terms: *Do the job of protection effectively, do survive in the process, and do not introduce undesirable side effects.*

† Technology Administration, U.S. Department of Commerce


* Citations are listed alphabetically at the end of this paper.

When an electric utility provides a device for public use, it is responsible not only for performance, but also for customer service and safety. Hence, a device capable of operating with the high energies available on the power system grid must be carefully chosen. The electric utility must consider physical characteristics, mechanical and electrical properties, and installation techniques.

On the other hand, plug-in suppressors are less exposed to high-energy faults than the service-entrance arresters because the wiring impedance reduces the available fault current. However, other compatibility issues arise with these devices, such as the side effects of involving the internal wiring of a building during the diversion of large surge currents [Martzloff, 1990], or the coordination of cascaded SPDs [Lai & Martzloff, 1991].

In response to these concerns, the characterization tests described in this paper have been conducted on meter-base adapter arresters and on plug-in suppressors. A process of interaction and iteration was involved during the performance of the tests. First, tests were conducted according to some preconceived test plan derived from existing industry standards and defined in a draft test protocol. This protocol included a list of expectations in the device performance, to be compared with the test results. As a result of this comparison, the protocol was amended to incorporate considerations emerging from observations made during the tests.

## SURGE-PROTECTION SCHEMES

Surge protection installed in the end-user premises can be implemented by several approaches. The simplest would be to connect a single SPD at the power port of selected pieces of equipment in the premises; each SPD would be specified one at a time regardless of other equipment protection. However, large surges originating outside the residence, associated with lightning or major power-system events, are best diverted at the service entrance. Surges generated within the premises can be diverted by suppressors located close to the internal source or close to the equipment in need of protection.

Figure 1 shows the principle of a two-stage protection scheme. The first stage provides diversion of impinging high-energy surges through the arrester, typically installed at the service entrance, or by a device permanently wired at the service panel. The inductance of the premises wiring inherently restricts the propagation of surges in branch circuits. The second stage of voltage clamping is provided by a suppressor of lesser surge-handling capability, which is typically located close to the equipment in need of protection as an add-on, plug-in device or which is incorporated within the equipment. This second stage completes the scheme for surges of external origin as well as for surges originating within the building.

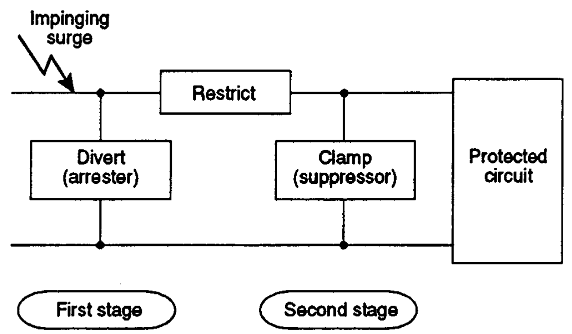
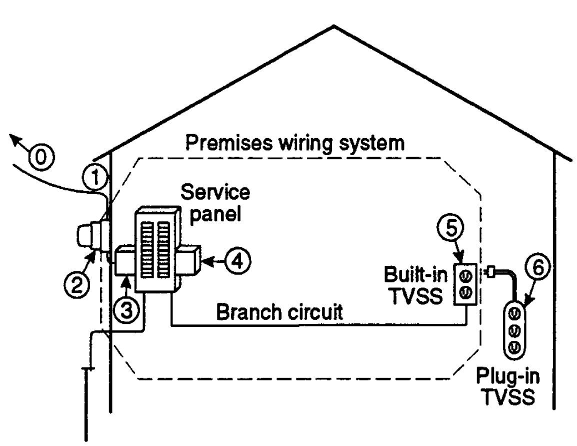



**Figure 1**
**Two-stage surge-protection scheme**

Accordingly, different sets of surge-stress levels are applicable to the first stage and to the second stage of the protection scheme. A second-stage device, if provided with both a power port and a communications port, is called a *'Surge Reference Equalizer'*. Possible locations for the SPDs range from the secondary of the distribution transformer to the cord connection of equipment. Figure 2 shows the various locations for installation of protective devices, starting at the weather head and ending at the wall receptacles, including plug-in TVSSs.

## ONGOING CHARACTERIZATION PROJECTS

Many organizations have recognized the need to characterize the performance of the myriad of TVSSs offered by many manufacturers. From time to time several trade magazines publish the results of surveys or performance tests.




LEGEND

0 Secondary arrester at transformer
1 Arrester at weather head
2 Meter-base adapter arrester
3 Permanently wired, line side
4 Permanently wired, load side
5 Permanently wired receptacle
6 Plug-in TVSS

**Figure 2**
**Possible locations for arresters and suppressors**

Underwriters Laboratories (UL) Standard 1449, which is the basis for UL listing of TVSSs, plays an important part in the design of TVSS. While the prime function of UL testing is to assess safety of products, the case of TVSSs is different because UL considers that inadequate performance of a TVSS could present a safety hazard to downstream equipment.

Now the electric utilities have taken an active role in characterizing the performance of suppressors as well as arresters. Two complementary programs are described in this paper, one conducted by Georgia Power, the other by the Power Electronics Applications Center (PEAC). The PEAC program has focused primarily on the electrical compatibility aspects. Georgia Power has expanded the scope to include compatibility with other environmental factors and utility concerns with service reliability, mechanical durability, and safety.

## TEST PROGRAMS

The two characterization programs conducted by Georgia Power and by PEAC have complementary and common elements for the service-entrance arresters. For the plug-in suppressors, the work reported here has been carried on by PEAC. Table 1 shows the principal tests conducted by the two organizations. A noteworthy aspect of the program is that, unlike some product evaluations conducted by consumer-oriented organizations, the tests specimens are obtained with the full knowledge and cooperation of the manufacturers.

This approach makes it possible to optimize the test program and, if appropriate, suggest improvements in the design, rather than to perform pass-fail tests without the benefit of manufacturer expertise and involvement. Tests on undefined black boxes may appear desirable as a generic, impartial, and uniform evaluation process. However, more useful results can be obtained when the test takes into consideration the expected behavior of the device.

**Table 1**
**Principal Characterization Tests Performed**

| TYPE OF TEST | ARRESTERS | PLUG-IN TVSS | PHONE SRE* | CATV SRE** |
|---|---|---|---|---|
| Vnom | GP - PEAC | PEAC | PEAC | PEAC |
| SURGE | GP - PEAC | PEAC | PEAC | PEAC |
| DURABILITY | GP - PEAC | PEAC | PEAC | PEAC |
| OVERVOLTAGE | GP - PEAC | PEAC | PEAC | PEAC |
| END-OF-LIFE | GP - PEAC | PEAC | PEAC | PEAC |
| IMPACT | GP | N/A | N/A | N/A |
| THERMAL | GP | N/A | N/A | N/A |
| CURRENT LOAD | GP | N/A | N/A | N/A |
| LET-THROUGH | N/A | N/A | PEAC | PEAC |
| POWER CROSS | N/A | N/A | PEAC | N/A |
| INSERTION LOSS | N/A | N/A | N/A | PEAC |

* SURGE REFERENCE EQUALIZER FOR TELEPHONE
** SURGE REFERENCE EQUALIZER FOR CABLE TV
GP: TESTS BY GEORGIA POWER
PEAC: TESTS BY PEAC
N/A: NOT APPLICABLE TO THIS TYPE OF DEVICE

## SERVICE-ENTRANCE ARRESTER CONCERNS

The arresters characterized in the two programs were meter-base types because ease of installation is a primary interest to the utilities. Meter-base extenders with built-in SPDs are the easiest for a utility to retrofit on customer premises. The basic mechanical design of the arresters is imposed by the application, configured as an adapter inserted between the meter and its socket. Nevertheless, there are many possible variations within that basic mechanical design. Likewise, the basic protection function can be obtained through many possible electrical designs. This degree of design freedom has two implications: on the one hand, it makes it necessary to assess the performance of various brands, and on the other hand, it offers the opportunity to optimize the design through the interaction between the testing organizations and the manufacturers.

The Georgia Power Research Center and Power Quality Departments worked together in this project. Several tests were deemed necessary before any device would be acceptable for residential use. Mechanical and electrical tests were devised to assess performance. Specifications for testing such a device were drawn up with reference to existing standards and laboratory testing.

Of particular concern was an "end-of-life" test. This test was devised to determine the response to power-follow when a surge-suppressor element fails in service. PEAC tests were performed by launching a thermal runaway and observing the resulting failure of the device while exposed to the normal line voltage. This approach met with limitations of the duration of the available fault current in the indoor facility (back-up breakers would trip before final clearing by the test specimen could occur). The Georgia Power approach, on the other hand, was conducted with less limitation on the duration of the available fault current, but with a device first punctured by a separate, prior exposure to a destructive level of overvoltage from a high-impedance source. The two test methods should ultimately be revised to eliminate the current limitation encountered at PEAC and the ambiguity of re-applying power to a cold, pre-punctured varistor as tested by Georgia Power.

The specifications of a service-entrance arrester should include some indication of arrester condition, ease of installation (including method of grounding), environmental resistance, and safety. Several arresters evaluated had neon-type indicator lamps. All lamps have a finite lifetime, in most cases less than three years. The arresters of interest will have a mean time before failure much greater than ten years. Therefore, the use of indicator lamps is undesirable.

If a switch is added, then its mechanical life, water tightness, possible physical abuse, and the extra step of having someone remember (or care) to operate the switch and check the lamps, are all open to question. One manufacturer has added a clear plastic window to the bottom of the meter base extender that houses the surge-suppression devices. When the protective fuses blow in the field or during a test, the clear window properly clouded over. This change from clear to clouded gives a noticeable indication of fuse operation and corresponding failed surge-protector condition. Thus, there is an opportunity for manufacturers to improve the concept and the design of their indicators.

The meter-base adapters simply plug in behind the electric utility meter. Grounding is accomplished by connecting a grounding pigtail to the service neutral, a grounding lug or hole provided in the meter base, or beneath a mounting screw in the meter base (the later method is still in question). The Georgia Power Meter Department rejected any idea of modifying the meter box to accept any of the surge-suppression devices that had multiple pigtails to wire-in. Since the power company is not allowed to work beyond the meter base, power distribution panel installations at the residence were not considered. Where surges entering the residence from the electric service are concerned, devices located at the service entrance instead of the power-distribution panel achieve better surge suppression.

Resistance to the environment should be considered. Susceptibility to moisture ingress should be evaluated. Some device designs featured epoxy encapsulation, O-ring seals, or coating with a dry tar-like substance. Resistance to ultraviolet radiation is a necessity, because of the sunlight exposure on the side of a house. Also, corrosion resistance is a necessary test. Evaluation tests should include a "salt-fog" test that will determine water tightness and corrosion resistance. The flammability of any device should be investigated before installation in the field.

Several mechanical properties of a service-entrance arrester must be considered. These properties include impact resistance, thermal withstand capabilities, and the ability of the meter-base extender jaws to maintain sufficient pressure on the meter blades to prevent overheating. If the meter-base extender jaws cannot maintain a low contact resistance with the meter blades, then progressive contact deterioration will further increase the resistance, leading to overheating to the point that extensive damage may occur.

## GEORGIA POWER ELECTRICAL TESTS

To evaluate the electrical characteristics of the surge arresters, Georgia Power performed four types of tests. These were: 1) nominal varistor voltage, 2) surge withstand, 3) temporary overvoltage, and 4) end-of-life failure mode.

### Nominal Varistor Voltage

Measurement of the nominal varistor voltage (the voltage across the varistor with 1 mA dc flowing in the varistor) identifies the voltage rating of the varistor used in each design. Changes in this voltage can indicate the degradation of a device after testing. This parameter was measured according to the IEEE definition of varistor voltage [ANSI/IEEE C62.33-1982]. By referring to varistor data tables, its was apparent that the arrester manufacturers used devices with ratings as low as 130 V and as high as 175 V.

### Surge Withstand

For the surge-withstand tests, two IEEE standards [ANSI/IEEE C62.41-1991; ANSI/IEEE C62.11-1987] were consulted. ANSI/IEEE C62.41 defines the 'Combination Wave' featuring an open-circuit voltage (OCV) waveform of 1.2/50 μs with an inherent short-circuit current (SCI) waveform of 8/20 μs. For the 'Category C' environment, the recommended SCI amplitude is 10 kA. ANSI/IEEE C62.11 specifies a test of discharge voltage at 1.5 kA and at 5 kA with an 8/20-μs wave, and a current-withstand test of 10 kA with a 4/10-μs wave.

Two types of surge-withstand tests were performed. The first consisted of the application of an 8/20-μs current wave with increasing amplitude until the device failed. One important unexpected event occurred during testing of some of the devices. At some point, the clamping-voltage level increased enough to cause internal arcing, usually on the printed circuit board used to mount the varistors. When this occurred, the device was considered to have failed because the power-follow available at the service entrance would destroy the device. Available power-follow currents at residential service entrances greater than 5 kA are possible.

The second test was a multiple surge-withstand test, performed at a level of 800 J per surge, with a modified cable fault locator ('thumper'). Each arrester section was surged individually, with 120 V ac applied before, during, and after the surge. The cable thumper was modified to provide a Combination Wave, 13-kV OCV and 5.5-kA SCI. A total of 100 surges at 6-s intervals was applied to the arrester. No excessive change of nominal varistor voltage occurred.

### Temporary Overvoltage

Because of neutral and/or connector corrosion problems in the past, which cause voltage shifts on the residential 120-V legs, the temporary overvoltage (TOV) characteristic of the device was of importance. Tests for TOV performance were made at a point just below where thermal runaway occurred. Although possible voltage shifts due to neutral or connector corrosion vary in each case, the devices with the highest TOV capability are often desirable.

The voltage step below which thermal runaway occurred was considered the TOV capability point, provided that the device demonstrated thermal stability for five minutes and constant standby current.

### End-of-Life Failure Mode

An "end-of-life" test was devised to determine the failure mode in service. Similar to the fault current withstand test in ANSI/IEEE C62.11, the metal oxide varistor is first punctured by overvoltage with a lightly fused ac power supply. Then, full available fault current is applied to the device at full rated voltage. The internal fusing of the arrester must clear the fault without catastrophic failure of the device or meter box housing and without phase-to-phase or phase-to-neutral arcing. If phase-to-phase or phase-to-neutral arcing were to occur in the field, then the high side transformer fuse would have to clear the fault. Not only would the premises lose service power, but, because of the long fuse curve of the high side fuse, the premises may sustain extensive damage at the service entrance location.

The test circuit was fed by a 167-kVA distribution transformer with a 120/240-V low side. This transformer fed a load-distribution center with an 800-A main breaker. Wired from the main bus was a 200-A fused disconnect equipped with two 200NLN Slow-Blow fuses. A 200-A meter box was then wired to the fused disconnect.

For testing, the specimen arrester was then mounted in the meter socket and the 800-A main breaker was used to energize the test specimen. The fault current through the test specimen for this test configuration was 2.8 kA rms. A video recorder was used to record the arrester failure mechanism, allowing a frame-by-frame post-mortem of the end-of-life test.

## GEORGIA POWER MECHANICAL TESTS

### Impact Resistance

In view of the handling procedures for meter adapters, impact resistance is an important parameter. Two industry standards were consulted for test techniques and impact force [ASTM Std. D2444; ANSI/NEMA Std. TC 8-1978]. Three different types of meter-adapter housings were evaluated. One type was constructed of fiberglass materials, while the other two were constructed of thermoplastic materials. In the tests, the thermoplastic housing could withstand at least four times more impact force than the fiberglass housings.

### Thermal Withstand

Two fiberglass and two types of thermoplastic meter adapter housings were placed in an air oven and heated for two hours at temperatures of 60°, 80°, 100°, and 125°C.

At the end of each two-hour period, the devices were examined and flexed by hand. All but one of the thermoplastic housings withstood the elevated-temperature exposures without showing signs of deformation or melting.

### Current Cycle Submersion

In the current cycle submersion test, the jaw and blade assembly samples were inserted into meter base assemblies with double jaws. Meter blade shorting bars were then inserted into the sample jaws. Then all the assemblies were connected in a series loop. A computer-controlled, constant ac current supply was used to drive current through the loop.

The samples were subjected to 50 load cycles consisting of a current-on period of one hour and a current-off period of one-half hour. During the current-off period, the loop was submerged in 4°C water. At the end of the current-off period, the loop was raised from the water and the current applied for the next cycle. The temperature of the jaws was measured at five-minute intervals during the current-on periods.

The contact resistance of the jaws is measured at the beginning of each test, after every ten cycles, and at the end of each test. The jaw temperature is also recorded with each set of resistance measurements so that the resistance values can be corrected to 20°C. The corrected resistance values and jaw temperatures are used to evaluate the performance of each jaw.

Two current levels, 200 A and 240 A, were used to evaluate the jaw and blade assemblies. The procedure was derived from those described in UL 414 Standard, Section 15, on heating of meter jaws. The largest application of interest is 200 A. After 50 load cycles at 200 A, the shorting bars were extracted and then reinserted 13 times while the meter jaws were still hot. Then, when the meter jaws were cool, the shorting bars were extracted and reinserted another 12 times. After this procedure, another 50 load cycles at 240 A were applied. It was found that working the jaws as provided by the UL standard reveals some hidden problems with some meter jaw designs.

## PEAC TEST PROGRAM

The tests at PEAC were performed on the basis of the test protocols being developed simultaneously with the test program. At the conclusion of the test programs reported here, two of these protocols reached sufficient maturity to be released for comment by interested parties. The first, identified as SC-110, *Surge-Protective Devices Used in Low-Voltage AC Power Systems*, covers all TVSSs test protocols. The second, identified as SC-120, *Surge Reference Equalizers Used in Premises Power-Communications Systems*, covers the test protocols used for tests on the telephone port or on the cable TV port of these devices.

## PEAC TESTS ON METER-BASE ARRESTERS

PEAC tested four brands of meter-base arresters. All the brands used metal oxide varistors (MOVs) as the surge-protective element. There were substantial differences in the designs. The surge-protective elements consisted of either multiple-paralleled 14-mm or 20-mm radial-lead type MOVs, or single 40-mm MOV discs. The MOVs were electrically connected by soldered or welded bonding, or by spring-loaded contact.

The first type of design, used in two products, had the MOVs connected between each line at the source-side of the meter and ground (Figure 3). A second design included another MOV connected line-to-line at the source-side of the meter. The third design used MOVs connected between each line at the load-side of the meter and ground. The voltage ratings of the MOVs used in the various brands included 130 V, 150 V, 250 V, and 275 V. Other significant design variations were fusing and failure indication. Failure indication ranged from an inspection window, to simple neon lights, to an audible alarm.

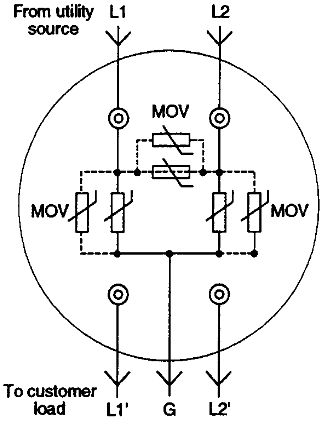



**Figure 3**
**Internal connections of MOVs in the meter-base arresters**

### Initial Characterization Tests

The SC test protocol calls for a characterization that serves as a baseline for assessing any change in the specimen during the test sequence. The two principal tests in this initial characterization are a determination of the nominal voltage (voltage at 1 mA dc) and a verification of clamping action with a 100-kHz Ring Wave.

### Clamping Voltage Results

Three samples of each arrester brand were surge tested with the Combination Wave, 6-kV OCV, 5-kA SCI. The clamping voltages for each brand tested ranged from 420 V to 860 V for the line-to-ground surges, and from 780 V to 1550 V for the line-to-line surges.

### Durability Tests

Three samples of each brand were subjected to 24 surges in each coupling mode with the Combination Wave at 6-kV OCV, 1.25-kA SCI. The interval between surges was sufficient to allow the samples to return to room temperature. Two of three samples of one brand failed (short circuited line-to-line) during the tests. All other samples withstood the repetitive surges.

### Failure-Mode Tests

Samples of each brand were intentionally operated at a controlled increasing voltage to initiate thermal runaway, thus causing device failure. The line-to-ground voltage at which thermal runaway began for the brands tested ranged from 170 to 345 V rms. Each brand was tested with available 60-Hz short-circuit currents of 500 A, 1700 A, and 3600 A rms. Results of the test ranged from no visible smoke, to some smoke with sparks emitted, to heavy smoke and sustained burning.

When smaller diameter MOVs failed (short circuited), they blew apart and cleared the circuit. When larger diameter MOVs failed (short circuited), they required the test setup overcurrent protection (not normally present in residential ac power service entrance applications) to clear the fault. Because of the nature of the indoor-facility test circuit, those products with internal fuses in series with the MOVs did not blow their fuses during any of the failure mode tests before the backup test circuit breaker opened. Products with encapsulated (potted) MOVs tended to prevent the failed MOVs from blowing apart sufficiently to clear the circuit.

## PEAC TESTS ON PLUG-IN TVSS

Two types of plug-in TVSSs were included in the PEAC characterization project. The first type was the simple power-port TVSS, plug-in construction. This device is inserted between the wall receptacle and the power cord of an appliance. The second type was the surge reference equalizer. This device combines into a single unit the protection of the power port and the communications port, eliminating voltage shifts between the reference 'grounds' of the two ports, a recognized cause of equipment failure.

## TESTS ON PLUG-IN POWER-PORT TVSS

Tests were conducted to determine surge clamping levels, durability, tolerance to steady-state voltage variations, and device failure modes. Other characteristics, such as consumer safety and packaging integrity, that may be included in product safety listing agency test requirements (such as UL 1449), were not evaluated as part of the tests conducted at PEAC.

Three brands of plug-in TVSS products were tested. All used metal oxide varistors (MOVs) as the surge-protective elements. The designs of the products varied substantially. Figure 4 shows an example of the circuit of a typical power-port TVSS. The products included various combinations of single or multiple, parallel-connected 14-mm or 20-mm MOV discs. These were connected line-to-neutral, line-to-ground, and neutral-to-ground. Other designs included inductors and/or capacitors to provide additional noise filtering. Some designs had two stages of MOVs, one on the input side of the inductor, and one on the load side of the inductor.

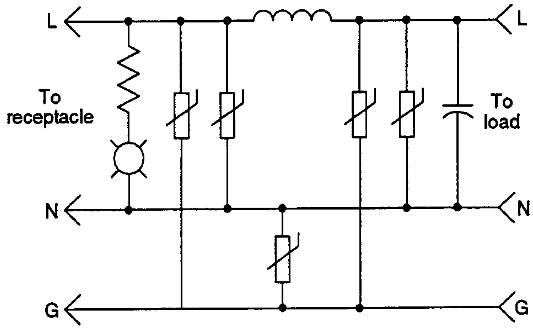



**Figure 4**
**Typical circuit of a power-port, plug-in TVSS**

The voltage ratings of the MOVs used in the various brands were either 130 V or 150 V. One TVSS design used 130-V MOVs connected L-N and N-G (Figure 4), and 150-V MOVs connected L-G. Some products contained no fuses, while others had fuses and a circuit breaker. Failure indication ranged from simple power-on lights to wiring diagnostics and MOV failure detection.

### Clamping Voltage Tests

Three samples of each brand were surge tested with the Combination Wave at 6-kV OCV, 500-A SCI. The clamping voltages for each brand tested ranged from 310 V to 400 V.

Three samples of each brand were also surge tested with the ANSI/IEEE C62.41 100 kHz Ring Wave, 6-kV OCV, 200-A SCI. The clamping voltages ranged from 90 V to 470 V for the line-to-neutral surges, and from 300 V to 420 V for line-to-ground and neutral-to-ground surges. The low line-to-neutral let-through voltages (90 V) were the result of an additional 100-kHz filter in the product rather than MOV clamping.

### Durability Test

Three samples of each brand were surge tested 24 times in each connection mode with the Combination Wave at 6-kV OCV, 125-A SCI. All samples withstood the repetitive surges without degradation, indicating reasonable durability.

### Failure Mode Tests

Samples of each brand were intentionally operated at a controlled increasing voltage to initiate thermal runaway, thus causing device failure. The voltage at which thermal runaway began for all brands was approximately 180 V. Each brand was tested with an available short-circuit current of 1700 A rms. Upon failure, one brand caused the test setup branch breaker to trip. Another brand caused slight charring of the cheesecloth wrapped around the units during the test to detect potential fire hazard. All brands emitted some smoke when the MOV(s) failed. Some product status lights did not indicate that the unit had failed.

## PEAC TESTS ON SURGE REFERENCE EQUALIZERS

The objectives of these tests were to determine the electrical performance of the communications port for a sampling of products on the market today and to develop appropriate performance criteria. The Surge Reference Equalizer (SRE) devices have two ports. The power port circuit is similar to the circuit of the simple TVSS shown in Figure 4. Figure 5 shows the circuit of a telephone port SRE. Figure 6 shows the installation of an SRE for a modem link to the telephone system.

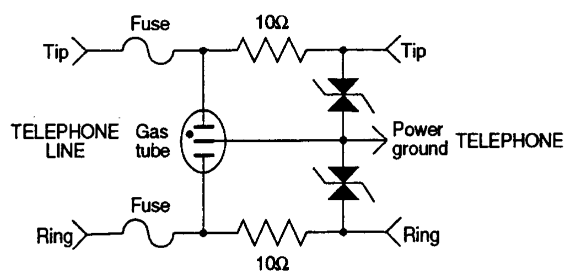



**Figure 5**
**Typical circuit for a telephone port SRE**

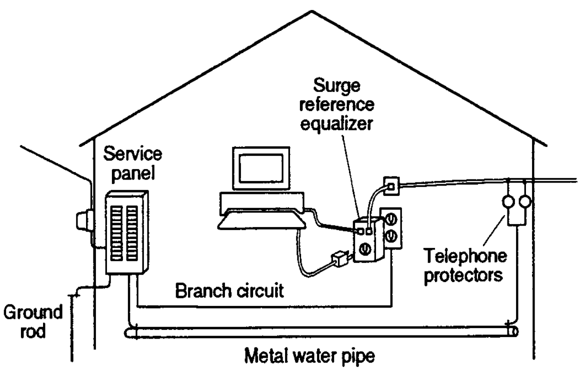



**Figure 6**
**Surge Reference Equalizer for telephone link**

The ac power ports of these devices were tested in accordance with the SC-110 protocol, with typical results similar to those described in the previous section on simple plug-in TVSSs. The communications ports were tested, in accordance with the SC-120 protocol, to determine clamping or let-through voltage performance, surge current handling capability, and basic compatibility with the intended communications circuit (such as telephone wiring overcurrent protection and cable-TV insertion loss). Other characteristics, such as consumer safety and packaging integrity, expected to be included in product safety listing agency tests (such as UL 1449), were not evaluated as part of the tests.

Three telephone port types and three cable TV (CATV) communications port types of each brand were tested. A total of six 120-V single-phase products were tested. There were substantial differences in the designs. For telephone ports, most products used a multi-stage surge-suppression circuit connected tip-to-ground and ring-to-ground. For the CATV port, each product design was different. Two products had the CATV shield solidly connected to the ac power ground; one connected the shield to power ground through surge-protective elements. Most products relied on a gas tube to provide CATV surge suppression. None of the products provided any indication of the surge suppression circuit status (On/Off or OK/Failed).

**Let-Through Voltage Tests**

Samples of telephone port SREs were surge tested in each mode (Tip-Ring, Tip-Ground, and Ring-Ground) with a surge of 10/1000 μs, 100-A and 200-A SCI. These two test levels are based on telephone industry standards [ANSI/EIA/TIA 571]. All three brands could withstand the 100-A surges, but only one could withstand the 200-A surges. The let-through voltage for the 100-A surges for each brand tested ranged from 230 V to 560 V.

Samples of CATV port SREs were surge tested in each available mode (shield-center conductor, and shield-ground, if not solidly connected) with the 100-kHz Ring Wave, 1-kV OCV, 33-A SCI. The let-through voltages for each brand tested ranged from 60 V to 990 V for shield-to-center conductor surges. The high let-through voltages were the result of the turn-on delay of the gas tubes used in the products.

**Power-Cross Overvoltage Test**

Each telephone port was subjected to a power cross overvoltage test, based on industry standards [UL 497A], to determine the ability to limit currents in the event of an accidental connection with power lines. The products were subjected to two test conditions: 520-V rms OCV, 40-A SCI for 1.5 s and 240-V rms OCV, 24-A SCI for 30 seconds.

Based on the UL 497A requirement, the products were expected to limit the current to less than the damage level of normal telephone wiring (simulated by a 0.6-A fuse), a safety requirement. All products failed to limit the current sufficiently for both test conditions.

**Insertion Loss Tests**

Any TVSS device inserted in the CATV circuit must not degrade the intended signal (insertion losses) under normal operation. Additionally, the device should not allow the intended signal to radiate high-frequencies or allow ambient noise to interfere with the signal. Each brand of CATV product was tested with a CATV broadcast signal and insertion loss was measured. The products were also tested with weak broadcast signals and weak CATV signals to evaluate qualitatively their insertion losses. Two brands had less than 1 dB insertion loss while the other brand had 3 dB insertion loss. None of the brands noticeably degraded the observed TV reception.

## RELATED TOPICS

**Simulation Projects**

The highly nonlinear response of MOVs defies intuitive circuit analysis beyond a simple case with very few components. This situation leaves the designer with the choice of testing with real components — ultimately, the final test that cannot be avoided — or making a numerical simulation. Several models for the varistor response, ranging from table look-up to closed solutions, have been proposed by different authors. In fact, there are so many models that citing a few presents the risk of offending the other authors. The IEEE Surge-Protective Devices Committee sponsors a working group devoted to the modeling of varistors.

**Low-Side Surges**

Initially unexplained failures of distribution transformers had been the subject of much research and controversy. Since the seminal paper [McMillen et al., 1982], many papers have been published, resulting in an increased awareness of the issue, now referred to as 'Low-Side Surges'. One of the conclusions that have been reached is that improperly coordinated installation of SPDs at the service entrance may be the cause of lightning-induced failures [Dugan, 1992].

This research led to a recommendation of providing a 480-V rated arrester for 120/240-V service [Marz & Mendis, 1992]. When combined with the concerns about excessively low clamping voltages selected for TVSSs installed at the end of branch circuits or SPDs incorporated into equipment, this situation leaves unanswered questions on the selection of the appropriate voltage rating for the service entrance arrester [Martzloff & Lai, 1992].

## THE DEVELOPMENT OF SYSTEM COMPATIBILITY TEST PROTOCOLS

The need to assess system compatibility, as described in this paper, led to the characterization projects involving tests focused on compatibility concerns. This family of test protocols has the common denominator of system compatibility, hence their 'SC' designations. The SC documents will provide a uniform approach to system-compatibility testing until the usual, slower standards development will have caught up with the fast-changing electronic technology [Key et al., 1992].

Each protocol presents an introductory background, general guidelines, and specific test guidelines. These test guidelines include a statement of the rationale for performing the tests, define the purpose and test procedure, and recite expected results. Three such protocols cover the subject of TVSSs, as summarized below. Interested parties can obtain copies from PEAC.

### SC-110: Surge-Protective Devices Used in Low-Voltage AC Power Systems

This test protocol applies to all low-voltage SPDs that may be installed in end-user premises, as illustrated in Figure 2. In addition to the principal tests performed by PEAC as described in this paper, this protocol includes a number of optional tests that may be selected for special cases. Recognition of the concerns about failure modes is an important aspect of this test protocol.

### SC-111: Surge-Protective Devices for Meter-Base Service Entrance

This test protocol, still under development, is intended to complement SC-110. The prime objective is to describe mechanical-environmental tests specifically focused on the service-entrance application. Electrical performance tests will also be included, similar to those of SC-110, to have a single document for the meter-base arresters. Failure mode, durability, and impact resistance, are important aspects for this application. The menu of proposed tests under consideration includes the following:

1. Ultraviolet resistance - ASTM G53 - 1000 hours
2. Salt-fog corrosion resistance - ASTM B117 - 1000 hrs
3. Flammability (self-ignition) - ASTM D1929
4. Impact resistance - ASTM Std. D2444
5. Thermal withstand - ≥ 125°C for 2 hours
6. Temperature rise - UL 414 Section 15
7. Current cycle submersion - 50 cycles at 240 A
8. Varistor voltage measurement
9. Temporary overvoltage measurement
10. Surge withstand to failure
11. Multiple surge withstand
12. End-of-life failure mode

### SC-120: Reference Equalizers Surge-Protective Devices for Power and Communications Systems

The increasing use of equipment that includes a power port and a communications port (cable TV receivers, smart telephones, Fax machines, desk-top publishing systems, distributed computer systems, industrial process control systems, etc.), as shown in Figure 6, has created a new problem in surge protection. Appropriate surge-protective devices correctly but independently applied to each of the two ports might not provide adequate protection against the problem of differences in the 'ground' reference voltages appearing at the two ports during operation of one protective device.

The SC-120 document describes a test schedule that exercises the protective devices of both the power port and the communications port (telephone or cable TV), separately *and* in combination.

## DISCUSSION

There is a great variety of TVSS products on the market today; most use MOVs as the basic surge-protective device. Within this common use of MOVs, there is a great diversity in the selection of the voltage ratings of the varistors incorporated by the TVSS manufacturers. One temptation is to seek low surge clamping voltages. However, lower clamping voltages are not necessarily better if they are accompanied by lower MOV ac rms voltage ratings. Too low an MOV voltage rating leaves the MOV vulnerable to high line voltage conditions and swells, increasing the likelihood of premature failure [Martzloff & Leedy, 1987; ANSI C84.1-1989; Davidson, 1991; Lagergren et al., 1992].

Arresters installed on the line side of the service entrance circuit breaker will be exposed to the available fault current in case of failure. Typical levels of this fault current range from 3 to 10 kA rms. It may be desirable to incorporate a fuse protection in the arrester package to remove a failed arrester from the distribution system. Such an arrangement raises the issue of designing a reliable indicator to signal to the end-user that protection is lost.

The alternative would be to have the fuse in series with the service. In that case, power to the premises would be interrupted, a situation that may cause more complaints than a promptly recognized loss of surge protection.

With plug-in TVSS products, unit overcurrent protection on the power port is not mandatory if the product is designed for the rating of the branch circuit outlet or overcurrent protection (15-A product for a 15-A receptacle). The product, however, should be designed with fusing for the MOVs or with other means to prevent a hazardous condition from occurring when the MOV fails. For SRE devices, overcurrent protection on the telephone port is a requirement for UL listing.

## CONCLUSIONS

The characterization of TVSSs has provided an opportunity to assess the compatibility of these devices from the point of view of the utilities. In the process, a set of test protocols for system compatibility has been developed by an inter-action among SPD manufacturers, utilities, standards-writing bodies, and, to some degree, end-users. From this, we present several findings and calls for action:

1. There is a wide range of products available for surge protection, but all are not equal. A comprehensive product-evaluation program would be necessary to provide complete information. Work is beginning in that direction, with the support of an increasing number of utilities.

2. Test protocols are now available, enabling interested parties to conduct or sponsor tests on an objective and consistent basis.

3. SPD manufacturers still have an opportunity to improve their products for greater compatibility. For instance, some designs were found to leave unanswered questions on the reliability of failure indication or fusing for protection against large fault currents.

4. Individual end-users have little leverage to influence the process of improving compatibility of products. However, the increasing interest of utilities in providing surge protection to their customers will increase this leverage above the critical mass.

5. By making available a process whereby products can be tested and the results communicated to the manufacturers, new possibilities are opened for a cooperative mood that will result in improved products to the satisfaction of all interested parties.

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