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Proceedings

Open Forum on Surge Protection Application

Editor:
François D. Martzloff

U.S. DEPARTMENT OF COMMERCE
National Institute of Standards and Technology
Electronics and Electrical Engineering Laboratory
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Co-sponsored by:

Computer Business Equipment Manufacturers Association

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IEEE Standards Coordinating Committee 22 on Power Quality

IEEE Surge-Protective Devices Committee

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Table of Contents

INSTALLATION PRACTICES

COORDINATION OF CASCADED DEVICES

FOREWORD

The Open Forum on Surge Protection Application was convened by the National Institute of Standards and Technology and several co-sponsors for the purpose of bringing together contributors to a consensus-building review of current topics on surge protection application. On this occasion, the complete set of interested parties, ranging from manufacturers of surge-protective components, manufacturers of packaged assemblies, manufacturers of surge-sensitive equipment, and users of both sensitive equipment and surge-protective devices were offered an opportunity to exchange information on their respective needs and capabilities in a context of unrestricted, informal, and constructive discussion.

In keeping with this approach, the papers contributed as discussion starters have been collected in this publication by the convenor but have not been peer-reviewed, except for any review that the authors may have sought before submitting their papers for inclusion in these proceedings. Thus, the opinions, positions, descriptions, and recommendations of the contributors are their sole responsibility, without any implied endorsement by the convenor and co-sponsors.

Appendices A and B provide further information on the Forum structure, identifying the participants, their stated interest. Appendix C is a record of the expectations expressed by the participants at the opening of the Forum, and Appendix D is a record of their wishes for possible actions resulting from the Forum.

The interest demonstrated by the co-sponsors in convening this Forum, the contribution of papers and participation of attendees in the discussions are acknowledged, with the hope that these proceedings will assist in attracting attention to current issues and building consensus among groups involved in standards development.

Inquiries concerning this Forum and feedback on the action wish list are welcome and should be adressed to the convenor:

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POWER QUALITY COMPARISON

1979 VS 1991

A comparison of the
Goldstein-Speranza (AT&T)
and National Power Laboratory
Power Quality Studies

POWER QUALITY COMPARISON
1979 vs 1991

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ABSTRACT

National Power Laboratory is currently conducting the world's largest power quality study. This paper compares the first 270 site months of NPL data to the 270 site month Goldstein-Speranza (AT&T) power study. The scope and framework of each study is discussed. The data from both studies is presented using identical event threshold levels. Results of the comparison show major changes in the numbers and types of disturbances over the past ten years. The NPL and AT&T studies confirm the need for power conditioning and UPS equipment to protect computers and other sensitive loads.

INTRODUCTION

Previous power quality studies have identified and classified a variety of AC power disturbances. Many of these disturbances are capable of causing equipment damage or disrupting operation of computers and other sensitive electronic loads. Commonly recorded disturbances include:

1) Undervoltages - RMS voltages that fall below nominal levels;
2) Overvoltages - RMS voltages that rise above nominal levels;
3) Impulse - A sub-cycle event (Oscillatory decay, Spike, Transient, etc.) having a momentary steep rising or falling departure from the typical AC sine-wave;
4) Outages - a zero voltage condition on the power line.

Although the definitions and threshold levels for disturbances may differ from study to study, the existence of disturbances is consistently verified. Two of the most widely recognized power studies documenting these disturbances are the 1969-1972 Allen-Segall (IBM) study (ref 1) and the 1977-1979 Goldstein-Speranza (AT&T) study (ref 2).

One of the conclusions reached in the IBM study stated: "UPS equipment is required for reliable continuous operation of electronic equipment through the wide range of disturbances found on power lines (ref 1)." The AT&T study also recommends the use of power conditioning and UPS equipment at data processing and computer installations.

Using the prior studies as a reference, National Power Laboratory (NPL) is currently conducting the world's largest power quality study. The NPL study will provide current information showing the number, type, and duration of AC power disturbances found in today's electrical environment. Data is collected at the standard wall receptacle. The disturbances found at this point of utilization would be seen by computers or other sensitive electronic equipment. The NPL data will provide important information for product designers, systems managers, and consultants.

This paper compares the first 270 site-months of NPL data to the 270 site-month AT&T database using the AT&T thresholds and definitions. The following study elements are analyzed:

1) **Monitors.** The basic technology, and a review of recording, text, and graphics capabilities;

2) **Threshold Parameters.** Voltage and duration boundary conditions used to define each type of disturbance;

3) **Database Profile.** An explanation of each study's data potential;

4) **Disturbance Data.** Using the AT&T report boundary conditions.

MONITORS

The monitor used in the AT&T study was the microprocessor-based Dranetz 606-3. This monitor provided a paper tape printout of disturbance activity. The paper tape printout provided a classification of the type of disturbance along with voltage and time stamps. Three isolated inputs could measure up to three single-phase power lines. Aside from changing paper rolls and on-site data collection, the monitor was fully automatic.

The monitor being used by NPL is an enhanced Dranetz 626Rx. This monitor has many capabilities not present in the 606-3. These include:

1) Disturbance event duration measuring capability;
2) Computer displayable text and graphics reproduction of disturbance data;
3) Telephone retrieval of stored disturbance data;
4) AC line isolation and a high limit of 6000 volts.

Table 1 compares the 606-3 and 626Rx monitors.

	AT&T	NPL
Dranetz Model	606-3	626Rx
Threshold Selection Means	Manual	Remote - via PC
Data Storage	Paper Tape	Remote - via PC
Data Retrieval	Manual	Remote - via PC
AC Line Isolation	No	Yes
High Impulse Limit	4KV	6KV

Table 1. Monitor Comparison.

THRESHOLD PARAMETERS

Threshold parameters are the preset voltage levels and duration points which classify power line disturbances. Any disturbance on the AC power line which falls out of the preset detection window is recorded. The disturbance detection window in the NPL study is smaller than previous studies. This allows NPL to make direct quantitative comparisons using the reported threshold values of previous studies. Table 2 describes the threshold parameters used to compare the AT&T and NPL databases.

Disturbance	Voltage Level	Duration
Sags	≤96 V rms	≥1 cycle
Surges	≥130 V rms	≥1 cycle
Impulses	>200 V peak	.5 to 100us
Power Failures	0 V rms	≥1 cycle

Table 2. AT&T Threshold Parameters.

Sags and Surges

AT&T defines sags and surges as increases or decreases in power line voltage that exceed a specified voltage level and duration. The duration of these events is equal to the number of cycles that the voltage is above or below a specified level.

AT&T set the 606 monitor to record all sags and surges outside a ±5 volt rms window. The actual levels that were reported in their paper were 96 volts or less for sags, and 130 volts or greater for surges.

The NPL monitors record all sags and surges which are not within the recommended ANSI and CBEMA utilization voltage windows of 104 - 127 Vrms (ref 3,4). In this paper, sags to 96 volts and less, and surges to 130 volts and greater are the levels used for an exact comparison to AT&T data.

Impulses

AT&T defines an impulse as a short-term disturbance with a rise time between 0.5 and 100 microseconds. The AT&T monitors recorded all impulses with amplitudes between 200 and 4000 volts peak.

NPL monitors record all impulses between 100 and 6000 volts peak. The 100 volt level is intentionally low to record all disturbances that may affect sensitive electronic components. For direct comparison of the NPL and AT&T data, only the impulses between 200 and 4000 volts were counted.

The NPL monitors also record impulse duration and graphics data for each event. The AT&T monitors did not have graphics or duration-monitoring capabilities.

Power Failure (Outage)

AT&T defines a power failure (outage) as a zero-volt condition that lasts more than one cycle. Only power failures that were at least one hour apart were counted. This reduced 113 recorded power failures to 100 (ref 2). For an exact match comparison, the NPL database was sorted to include only one power failure per hour.

NPL monitors can record all power failures greater than four milliseconds in duration. The monitors also record the exact time the outage began and ended. For extended power failures, the 626Rx memory chips have a special built-in lithium battery. This ensures that data is not lost when the normal backup batteries become depleted.

DATABASE PROFILE

The stated goals of the AT&T study were:

- "To permit the selection of appropriate and cost-effective power-conditioning equipment for use in a rapidly increasing number of Bell System data-processing centers.
- To facilitate evaluation of the impact made by various types and numbers of AC power line disturbances with respect to computer operations (ref 2)."

The AT&T objectives included collection of enough field data to provide an accurate description of the frequency, magnitude and duration of power line disturbances. Secondary objectives were to develop a model that would apply to any particular site.

During their study, AT&T collected three-phase data from 24 sites (mostly Bell operating companies) over a 25-month period. Sites were carefully inspected prior to monitor installation. This insured proper grounding and the presence of normal utilization voltage levels (115-125 Vrms). The 24 AT&T sites yielded 270 monitor-months of data from twelve southern, midwestern, and eastern states. Table 3 lists the AT&T study monitor locations.

Kentucky
Louisiana
Massachusetts
Maryland
Michigan
Missouri
New Jersey
New York
Ohio
Tennessee
Texas
Virginia

Table 3. AT&T Site Locations.

For comparison to the AT&T study, the first 270 months of NPL data was used. This data came from ten population regions of 25 to 30 million people across the U.S. and Canada. The 270 NPL site-months include data samples from 51 locations in the 30 states and provinces listed in Table 4.

Arizona
California
Colorado
Connecticut
Florida
Georgia
Illinois
Indiana
Kansas
Massachusetts
Maryland
Missouri
Mississippi
North Carolina
North Dakota
New Hampshire
New Jersey
New Mexico
New York
Ohio
Oklahoma
Pennsylvania
Texas
Vermont
Virginia
Washington
Wisconsin
***New Brunswick**
***Nova Scotia**
***Ontario**

***Canadian sites**

Table 4. NPL Site Locations.

In the NPL study, single-phase power is monitored at each location. A "correct wiring" check is performed at each site prior to installation of the NPL monitor. A random site selection process gives NPL a broad cross section of: 1) Utility feeder types; 2) Building size and age; 3) Rural and urban locations; 4) Residential, heavy industrial and light industrial mix; 5) Population distribution; and 6) Building equipment profile.

Tables 5 and 6 profile the NPL sites for the first 270 monitor-months of the study.

Type		Construction		Age (Years)	
18%	Residential	20%	Frame	21%	0 - 5
20%	Small Business	33%	Brick	16%	6 - 10
25%	Light Industrial	20%	Reinforced Concrete	21%	11 - 25
2%	Heavy Industrial	20%	Structural Steel	26%	26 - 50
35%	Other	7%	Other	16%	51 +

Table 5. NPL Building Information.

Population		Neighborhood	
4%	0 - 2500	27%	Residential
12%	2500 - 10,000	14%	Light Industrial
27%	10,000 - 50,000	2%	Heavy Industrial
18%	50,000 - 100,000	10%	Industrial Park
21%	100,000 - 500,000	33%	Metropolitan
18%	Over 500,000	14%	Rural

Table 6. NPL Location Information

DISTURBANCE DATA

The Goldstein-Speranza (AT&T) study presents data as percentages of total recorded events. Table 7 shows the percentage comparison of NPL and AT&T data using the disturbance definitions and thresholds reported in the Goldstein-Speranza paper.

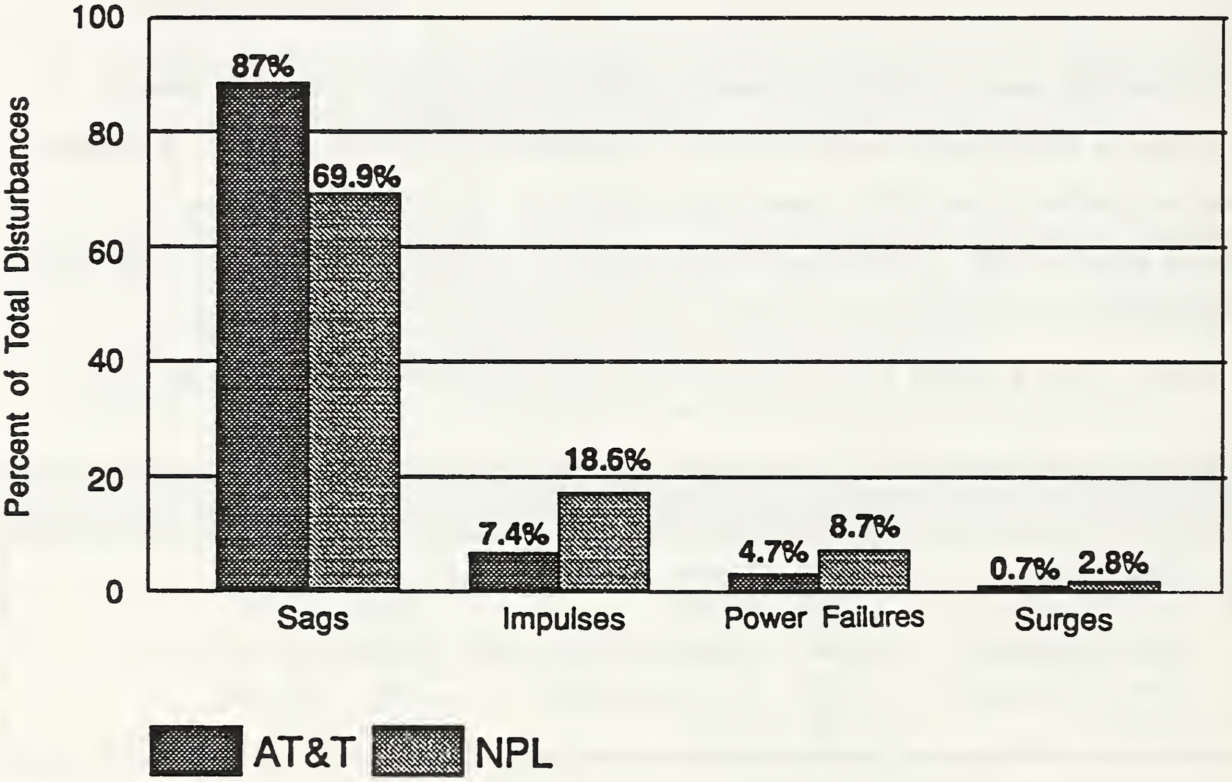

Table 7. Disturbance Percentage Comparison.

The percentage of NPL sags compared to the AT&T percentage shows that sags are down 20%. Impulse percentages have gone up 151%. Outage percentages are up 151%, and surges are up 300%. Reasons for these changes may be related to site, source, or load factors. As additional NPL data is accumulated, a more comprehensive distribution picture will emerge.

STUDY COMPARISON

Although the AT&T study is one of the largest power quality studies ever undertaken, its total database and geographic representation is limited. Upon completion, the NPL power study will be over six times larger than the AT&T study, and will provide new insights to important power quality issues. Table 8 summarizes the scope and magnitude of each study.

Study Elements	AT&T	NPL
Total Study Period	1977-1979	1990-1995
Total Site Months	270	1800
Number of Locations	24	235
Total Number of States	12	50 + Canada
Selection Process	Telco Installations	Random
Text Data	Yes	Yes
Graphics Data	No	Yes
Scrubbed Sites	Yes	No
Computer Sorting	No	Yes
AC Line Isolation	No	Yes
High Limit	4KV	6KV

Table 8. Power Study Comparison.

CONCLUSIONS

The AT&T report contains several general recommendations to minimize or protect against power line disturbances. These include careful AC distribution system planning, power conditioning, and UPS protection. Based on the increase of product and data-endangering disturbances, NPL strongly supports the AT&T recommendations.

Approximately 15% of the projected 1800-month NPL database was used for this power study comparison. As the database continues to grow, more changes are expected. The final NPL database should provide valuable new product susceptibility data which will aid product designers, systems managers, and power consultants.

---

1 REFERENCES

1) G. W. Allen and D. Segall, "Monitoring of Computer Installations for Power Line Disturbances", C74 199-6, IEEE PES, 1974

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3) ANSI C84.1-1982, American National Standard for Electric Power Systems and Equipment-Voltage Ratings (60 Hz)

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VOLTAGE SURGE GENERATED BY STATIC CONVERTERS

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Abstract

The concerns over voltage surge in static converter applications are peak voltage and rate of change of the surge (dv/dt). The cause of voltage surge involves interruption of inductive current by power semiconductor switching. It can be either

- Line Commutation, in Phase Controlled Rectifiers or
- Forced Commutation, in PWM Inverters or
- Diode Recovery, in Choppers and Inverters.

An optimally designed snubber or voltage suppression circuit may find itself inadequate along the product life due to change in switching characteristic of semiconductor devices. This unexpected change may cause failure in the converter itself or interfere with other equipment in the same power system. The discussion in this paper will focus on the effect of switching characteristic, mainly reverse recovery, on the peak voltage and dv/dt. A retro-fitting scheme will be presented.

1.0 Causes of Voltage Surge in Static Converters

1.1 Line Commutation

This commutation process occurs in DC Motor Drive Applications using Phase Controlled Rectifiers. In this process, the current flowing in one ac line is commutated to another line by the ac line voltage itself. Figure 1 shows that the surge across the ac lines occurs as a result of change in Thyristor reverse recovery current flowing in the ac source inductance. This surge is normally controlled by RC Snubber and MOV's. The surge voltage of a typical design is shown in Figure 2. The snubber allowed 44% voltage overshoot at assumed worst case Recovery Current (Irr) of 120 Amps and 3 micro-seconds positive slope recovery time (tB).

1.2 Forced Commutation

This type of commutation process takes place under controlled-turn-off of semiconductor switch or external commutation circuit. The rate of change of current can well be in the order of several hundred amperes per micro-second. Without proper clamping, a few micro-henries of inductance in the current path can generate over one thousand voltage of surge across the device. A uni-directional RDC clamping circuit is normally used in this application.

1.3 Diode Recovery

This process occurs when reverse voltage is suddenly applied across a conducting diode, forcing the diode to recover from forward conducting state. Similar to Line Commutation process, the surge voltage developed across the diode depends on the rate of change of diode reverse recovery current and the amount of wiring inductance in the circuit. RC Snubber is usually employed as voltage suppressor.

2.0 Effect of Recovery Characteristic on Surge Voltage

Over years of progress in semiconductor technology, the switching frequency of these devices has changed from a few hundred Hertz in early generation of PWM Inverters to near Mega-Hertz in state-of-the-art Power Supplies. The need for faster switching devices also includes faster recovering diodes. Until device manufacturers are able to deliver fast device with soft enough recovery, snubber design in some old products may not be sufficient for the new snappier components. The effect of peak reverse recovery current (Irr) and Recovery Time (tB) on the peak surge voltage and dv/dt of a typical snubber design is shown in Figures 3 and 4 respectively. As Irr increases 25%, peak voltage overshoot jumps from 44% to 61% while maximum dv/dt increases by 21%. The excess peak voltage can cause additional dissipation or failure in other voltage suppression devices in the same power system. The increase dv/dt level may interfere with the operation of the converter itself and other nearby equipment.

3.0 A Possible Retrofit Scheme

The snubber can be redesign to handle the new recovery characteristic. Since the new snubber is likely going to be larger, the old package may not be able to accommodate the new design due to space and/or heat dissipation problem. A bucket suppressor shown in Figure 5 is a good candidate for retro-fitting purpose. The circuit does not require access to any internal connection points inside the converter. Nor does it need minimum wiring inductance to be effective. However, the dv/dt remains unchanged. The performance comparison (peak surge voltage and dv/dt) of the original RC snubber design, the redesign RC snubber, and the original snubber plus bucket suppressor is shown in Figure 6. The surges voltage shows that if Irr increases by 25% and tB is 50% snappier, the voltage overshoot in the original RC Snubber circuit increases from 44% to 57%, dv/dt increase by 67% and wattloss in the snubber circuit increases by 18%. The redesigned RC Snubber yields 43% overshoot, 27% increase in dv/dt and 47% increase in snubber loss. The bucket suppressor yields 46% overshoot, 67% increase in dv/dt and 40% increase in wattloss.

Conclusion

The reverse recovery current of free-wheeling or anti-parallel diode or Thyristor together with wiring or line inductance is the primary source of voltage surge generated by a converter. New snappier semiconductor device may cause the existing snubber circuit to be inadequate for transient voltage suppression. A properly design bucket suppressor may be one of the easiest and most effective retrofit to the voltage surge problem.

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2. C.W. Lee and S.B. Park, "Design of a Thyristor Snubber Circuit by Considering the Reverse Recovery Process", IEEE Trans. on Power Electronics, Vol. 3, No. 4, October 1988.
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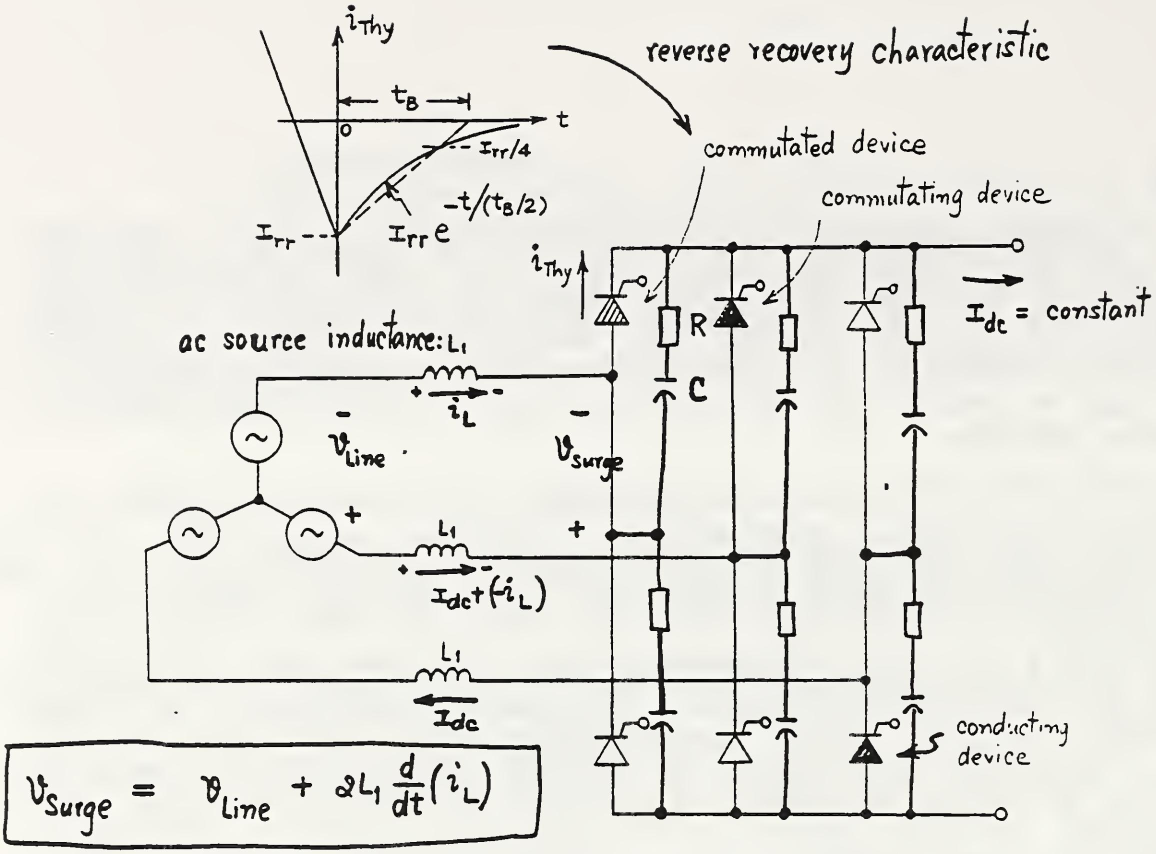


$$\boxed{v_{Surge} = v_{Line} + 2L_1\frac{d}{dt}(i_L)}$$

Figure 1 : A Phase Controlled Rectifier Circuit during commutation.

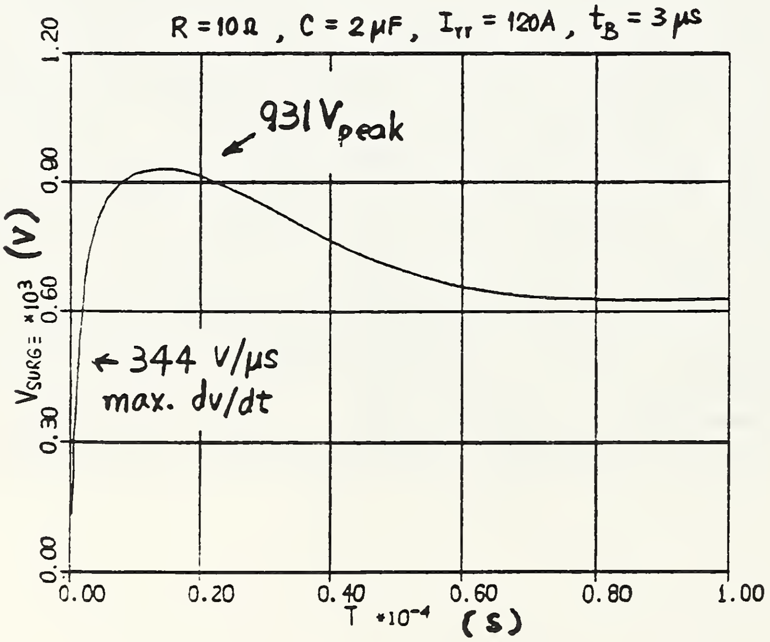


Figure 2 : Voltage Surge on a Typical RC Snubber Design.

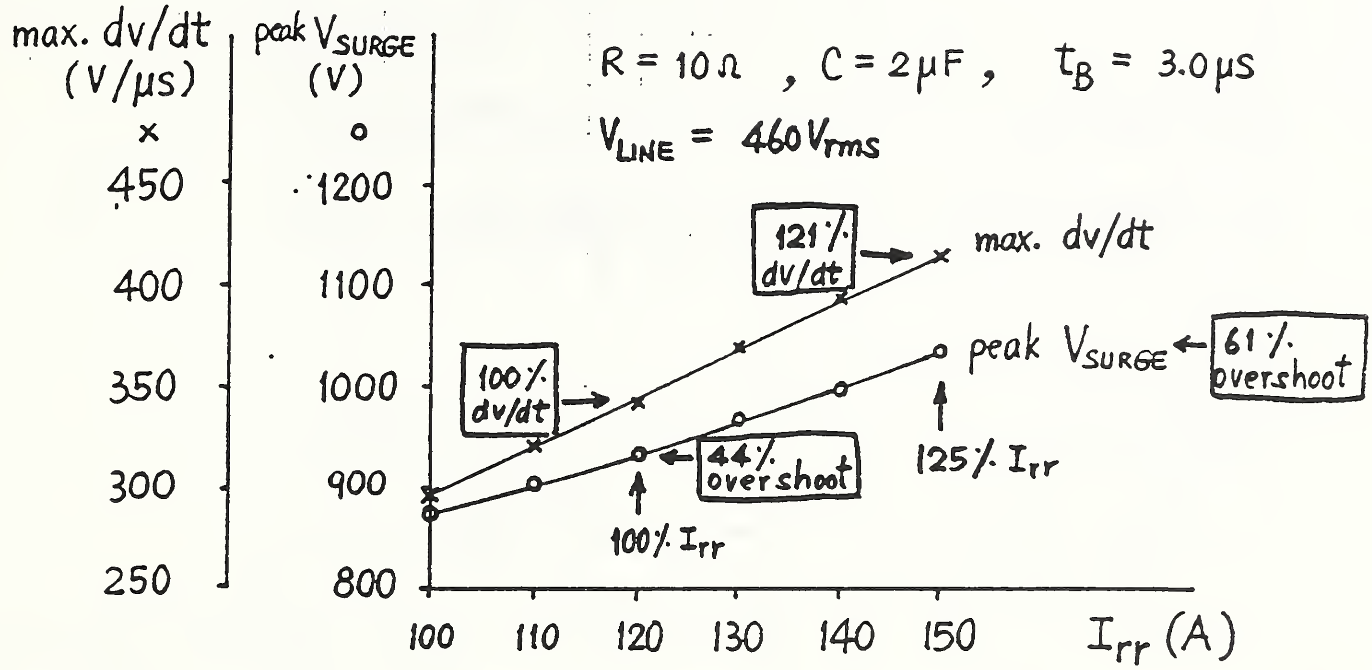


Figure 3: Surge Voltage vs. Reverse Recovery Current.

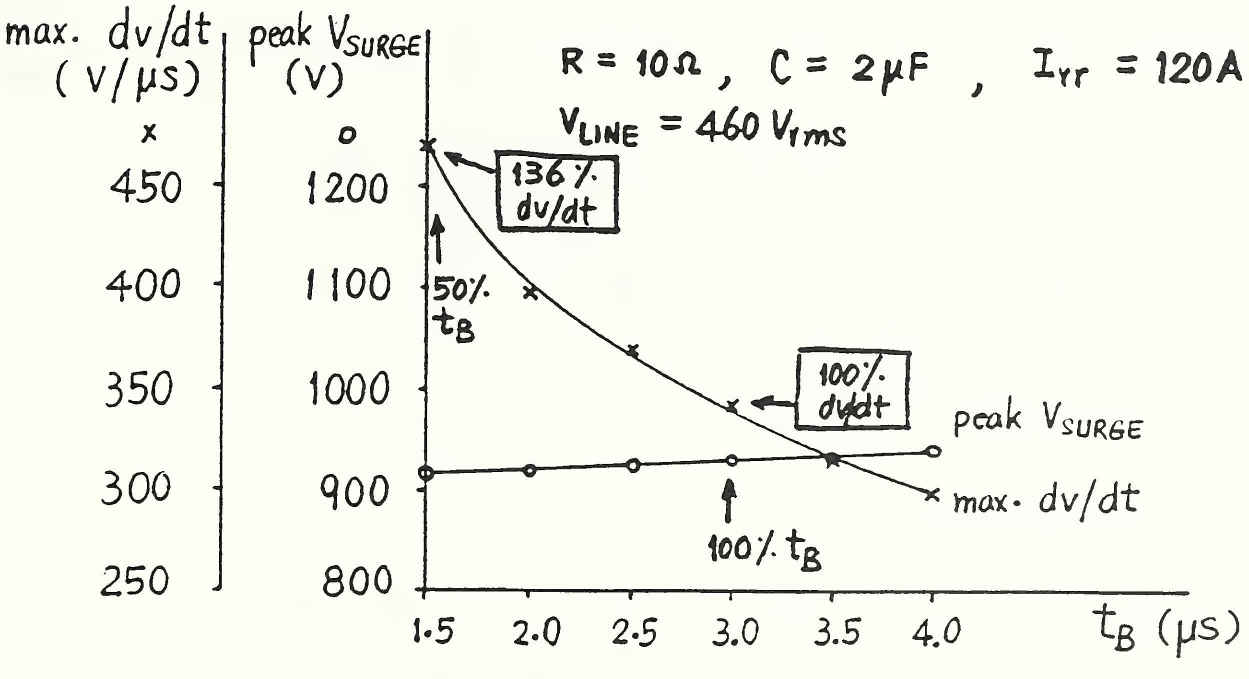


Figure 4: Surge Voltage vs. Recovery time.

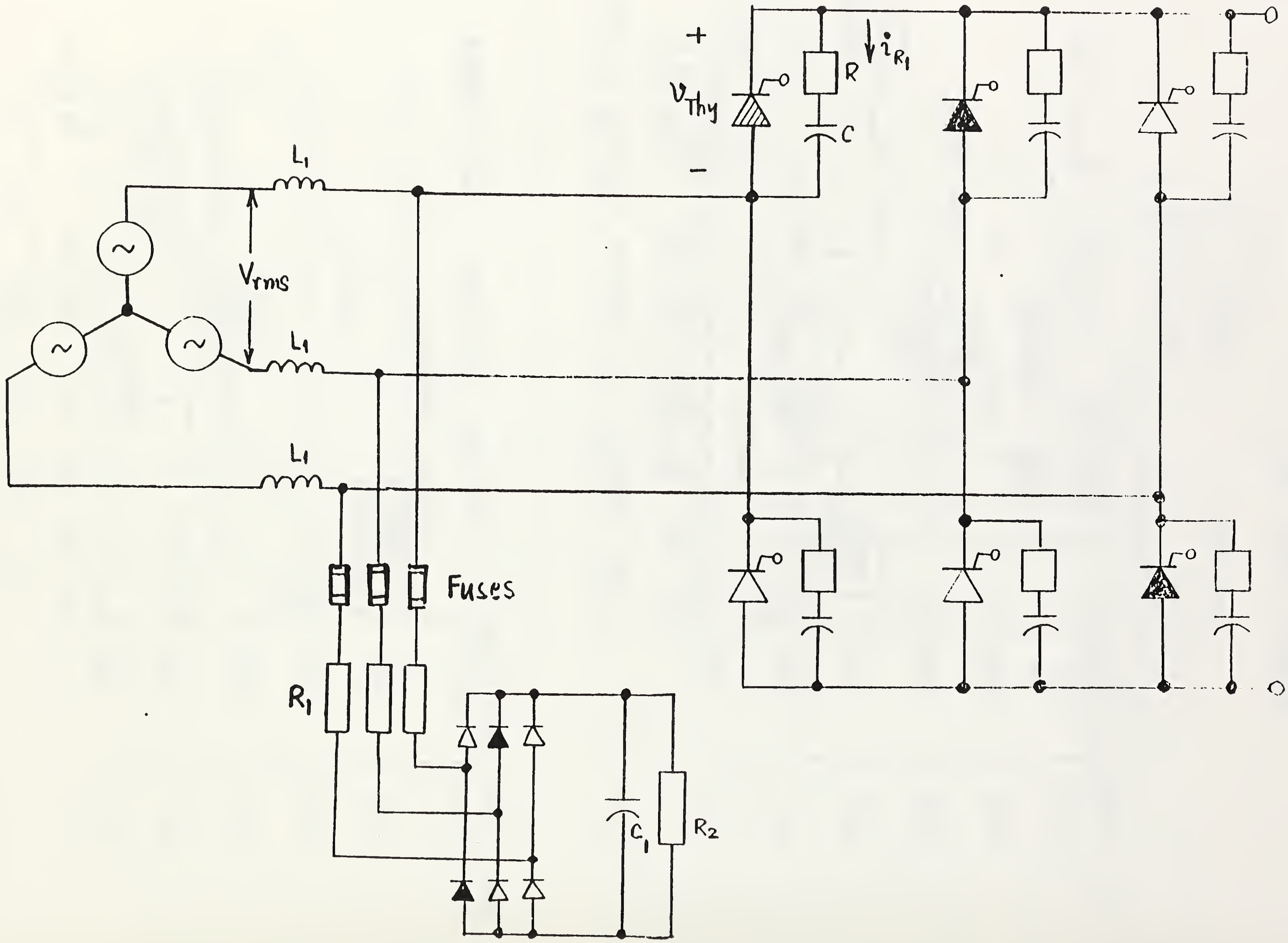
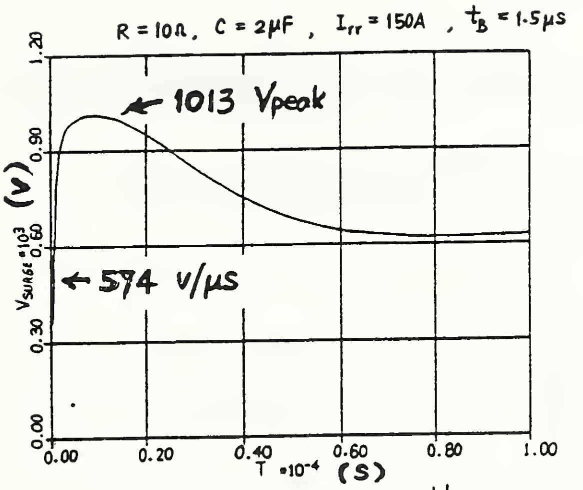
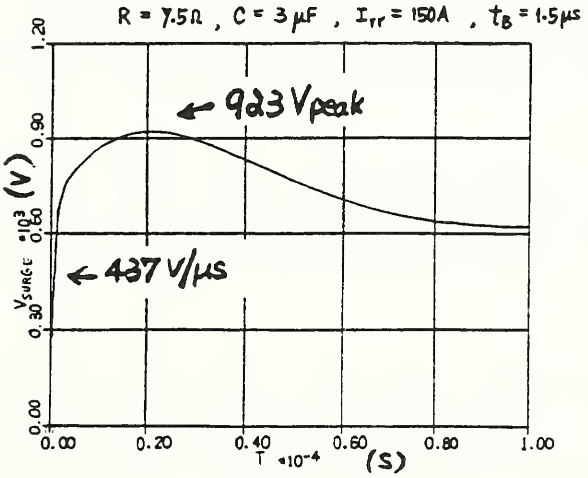


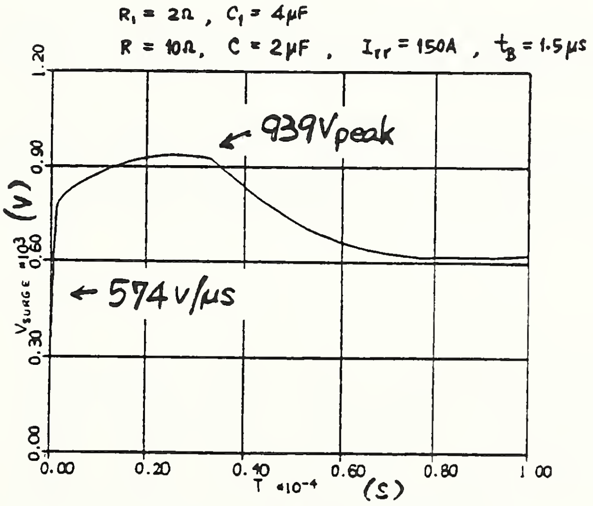
Figure 5 : Phase Controlled Rectifier with RC Snubber and Bucket Suppressor.



a) with original RC snubber



b) with new RC snubber



c) with original RC snubber plus bucket suppressor.

Figure 6: Voltage Surge with different suppressor design.

On the Propagation of Old and New Surges

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National Institute of Standards and Technology

INTRODUCTION

The revised IEEE Recommended Practice on Surge Voltages [1] has introduced a new generation of surge waveforms; how they travel in low-voltage power systems will affect some of the earlier tenets on surge propagation characteristics. The recent emergence of cascaded surge-protective devices [2], [3], [4], [5], raises a new set of concerns in which propagation characteristics play an important role. Until recently, the application of surge-protective devices was primarily based on the tenet that the classical 8/20 μs current waveform presents the most severe stress to the device. Whenever two devices were to be installed in a system with one device at the service entrance and one further into the building (the so-called cascade connection), system designers had relied on the inherent impedance of the wiring between the two devices to provide the electrical separation necessary to obtain coordination.

During the development of the revised IEEE Recommended Practice, some reluctance was encountered in deleting the mention of wire diameter for the branch circuits. The wire size was included in the definition of the 'Location Categories' given in the 1980 version of the IEEE Guide [6].

The objective of this paper is to review the propagation characteristics of the old and the new generation of surges waveforms encountered in low-voltage ac power systems. To complement information developed on this subject over the last ten years, measurements results are reported for the new 10/1000 μs waveform, and the effect (or, rather, the lack of effect) of wire diameter is documented by a simple experimental demonstration.

THE PROPAGATION OF SURGES — OLD AND NEW WAVEFORMS

Users of the new Recommended Practice now face the need to consider five representative surge waveforms. This section presents a summary of the propagation characteristics, with relevant references. These characteristics should be kept in mind during the discussions at this Forum.

1. The 100 kHz Ring Wave

The short duration of the first half-cycle of this waveform (0.5 μs rise time, compared to the travel time in a typical building) produces a propagation characteristic similar to that of traveling waves in transmission lines: reflections at impedance mismatches, and peak enhancement at unloaded (or lightly loaded) ends of lines [7], [8]. The subsequent oscillations at 100 kHz do not present these characteristics. For shorter lines (30 m or less), the inductance of the wiring is the dominant factor in the propagation.

2. The 1.2/50 μs — 8/20 μs Combination Wave

The relatively slow rise time of the voltage waveform, 1.2 μs, is long compared to the travel time in building wiring systems (200 m/μs propagation speed). Reflections die down during the rise time, so that there is no enhancement of the peaks (nor attenuation) at the open ends of the branch circuits [9]. The dominant parameter is the inductance of the wire. At the equivalent frequency of the 8 μs rise time of the current, typical wiring offers an impedance of about 0.2 Ω/m. Thus, a substantial driving voltage would be necessary to force a full 3 kA crest surge in a long branch circuit. The sparkover of wiring devices (or of a [gap + silicon carbide] arrester at the service entrance) will limit the driving voltage so that large 8/20 μs current surges are not expected in long branch circuits [10]. This conclusion had been at the root of the cascade coordination studies performed until recently.

3. The 5/50 ns burst of the Electrical Fast Transient (EFT)

This test waveform was initially developed in the IEC community for revealing any deficiency in the electromagnetic compatibility (susceptibility) of electronic equipment. The new IEEE Recommended Practice has endorsed the EFT as an 'Additional Waveform' to be considered. The fast rise of this waveform results in substantial stretching of the rise time, as well as attenuation of the surge peak, when more than a few meters of propagation are involved [11], [12]. Thus, the domain of application of this waveform is limited to interactions between adjacent equipment within the same building and propagation characteristics relieve users from concerns about EFT surges of remote origin.

4. The 5 kHz Ring Wave

This waveform has been included, as an 'Additional Waveform', in the new IEEE Recommended Practice. While there is an abundance of data from computer simulations of capacitor switching transients, little experimental data are available on the propagation of this waveform [13]. However, the relatively low frequency of this waveform makes it readily amenable to theoretical analysis based on simple lumped parameters of the power system, provided of course that the nonlinear characteristics of varistors are included.

5. The 10/1000 μs Unidirectional Wave

This waveform has been included, as an 'Additional Waveform', in the new IEEE Recommended Practice. Its relatively longer rise time, and more important, its long duration, raise new questions about a coordination based on the inductive impedance separating two cascaded devices [4]. Refer to the measurements reported in the next section, showing that inductance still dominates the initial portion of the 10/1000 μs event, but that the long tail of the waveform will force a resistive element, rather than an inductive element, to enter in a successful coordination scheme.

IMPEDANCE MEASUREMENTS FOR DIFFERENT WIRE SIZES AND WAVEFORMS

Three pieces of "Romex" cable [2 conductors + ground] of different conductor diameter (AWG #14, 12, and 10), each 10 m long and having its two current-carrying conductors joined at one end, were connected in series. The ground conductor was left floating. This set of three was then connected across the output of a surge generator capable of producing the 100 kHz Ring Wave, the Combination Wave, or the 10/1000 μs Unidirectional Wave (Figure 1). Thus, all three cables were exposed to the same current waveform. The impedance of this load circuit caused a departure from the nominal short-circuit waveforms delivered by the surge generator, which was recorded in each case.

A differential voltage probe was used to record the voltage drop at the origin of each cable (Figure 1), corresponding to each of the three successive current waveforms (Figures 2-4 and Table 1). Note in the voltage traces that during the portion of the waveform when current is changing, there is little difference in the voltage drop along the three cables #14, #12, and #10. In other words, the length of the cable is the dominant factor, in spite of the nearly 3:1 difference in the specific resistance of the #10 (3.3 Ω/km) and #14 (8.3 Ω/km) conductors. If any skin effect is involved in the propagation, that factor is also included in the comparison.

This lack of difference for *surge propagation* should be contrasted with the concerns about *voltage drop for 60 Hz loads*, covered in a fine print note [1] of the National Electric Code [14]. In keeping with the accepted practice in the surge-testing community, the ratio of current and voltage *peaks* is reported as the *effective impedance* for that particular waveform.

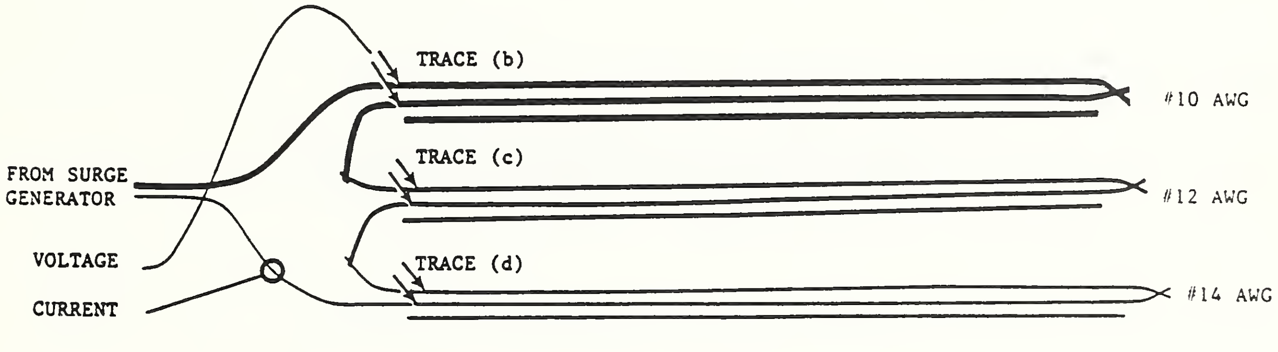

Figure 1. Series connection of test cables

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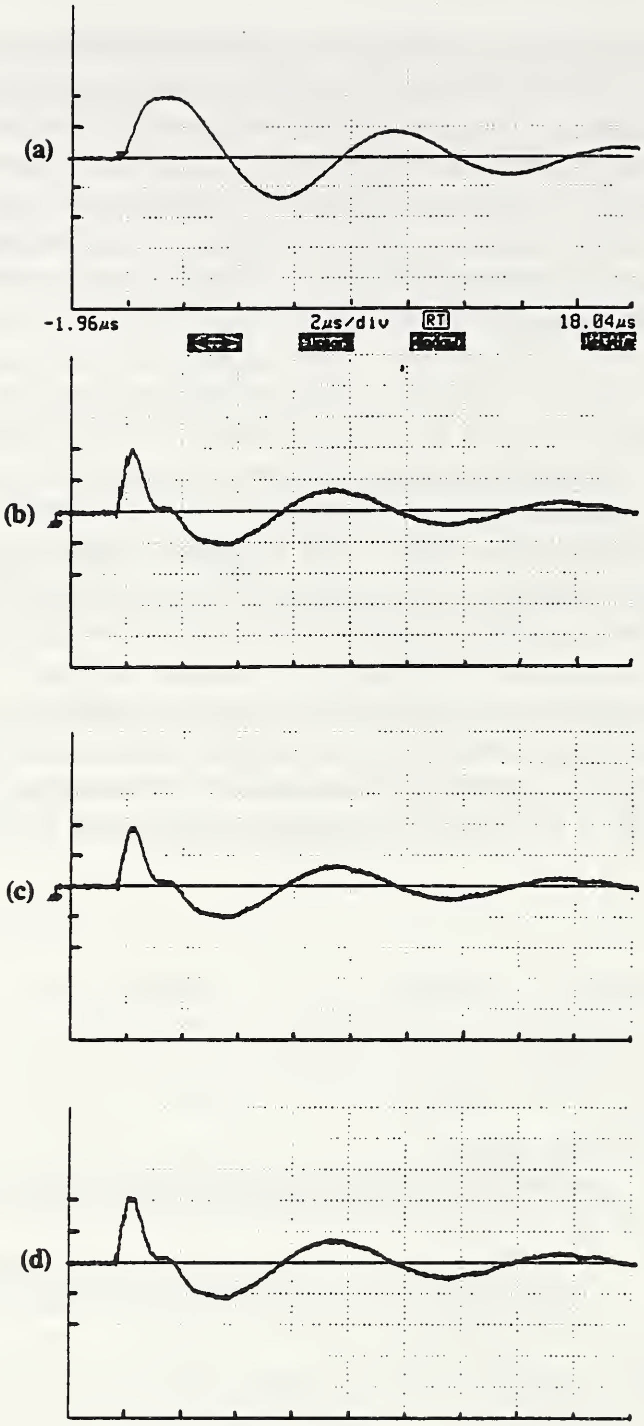
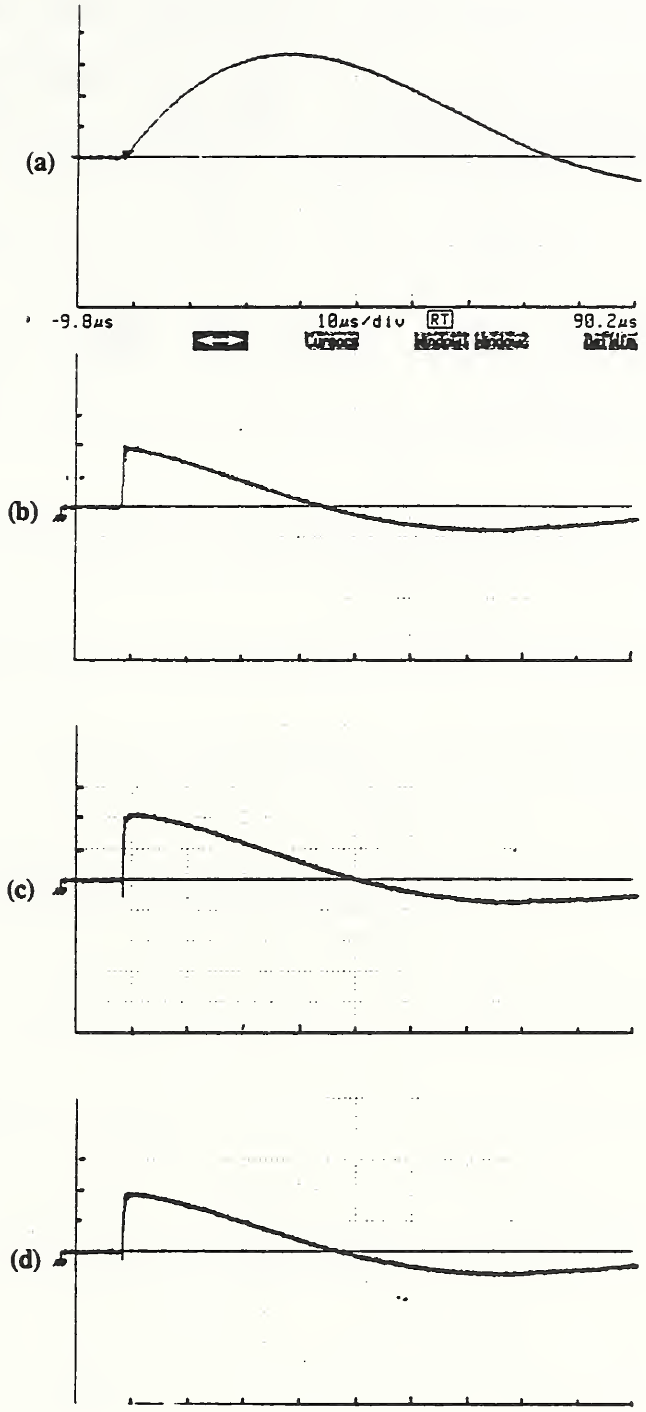
[1] *Fine print notes (FPN) of the NEC are only 'Explanatory Material', in contrast with 'Mandated Rules'.*



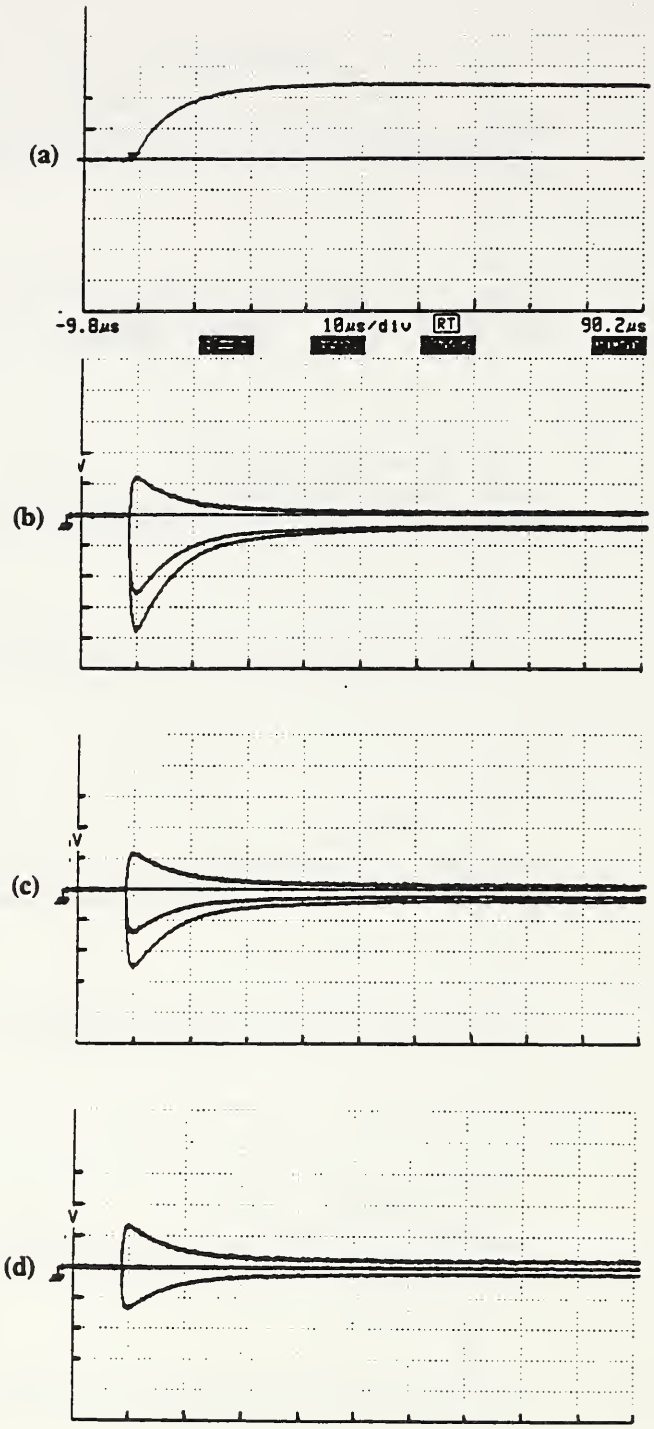
(a) Current trace: 50 A/div
(b) Voltage trace, #10)
(c) Voltage trace, #12) 400 V/div
(d) Voltage trace, #14)
(All at 2 μs/div)

Figure 2. Voltage drops with Ring Wave



(a) Current trace: 50 A/div
(b) Voltage trace, #10)
(c) Voltage trace, #12) 400 V/div
(d) Voltage trace, #14)
(All at 10 μs/div)

Figure 3. Voltage drops with Combination Wave



(a) Current trace: 50 A/div
(b) Voltage trace, #10)
(c) Voltage trace, #12) 400 V/div
(d) Voltage trace, #14)
(All at 10 μs/div)

Figure 4. Voltage drops with 10/1000 μs unidirectional wave

TABLE 1
MEASURED CURRENTS AND VOLTAGES, CALCULATED IMPEDANCE (10 m CABLE)
FOR THREE WIRE SIZES AND THREE WAVEFORMS

Nominal generator waveform	Ring Wave			Combination Wave			10/1000 μs Wave		
Peak current, I_p (A)	100			170			120		
Actual rise time of current (μs)	0.8			22			25		
Wire size (AWG)	10	12	14	10	12	14	10	12	14
Peak voltage during surge (V_p)	800	790	800	760	780	800	100	100	110
Effective impedance V_p/I_p (Ω)	8.0	7.9	8.0	4.5	4.6	4.7	0.8	0.8	0.9

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POSITION PAPER

TRANSIENT VOLTAGE SURGE SUPPRESSOR SPECIFICATIONS; REALISTIC PERFORMANCE OR SMOKE AND MIRRORS?

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INTRODUCTION

There are few segments in the recent history of the electronics industry with such diverse opinions and methods as the transient voltage surge suppression (TVSS) field, yet, this technology should be merging toward a reasonably defined science. However, it disappointingly remains disjointed and nebulous. In fact, transient suppression is looked upon by some as being a "smoke and mirror" act with frequent pot-shots taken at the industry by the electrical and electronics community. For example, Mark Waller, in his text Computer Electrical Power Requirements, in referring to transient voltage suppression devices states "The retail marketplace is full of (transient suppression) devices that are practically useless." and Shyamala Reddy in the March 1989 issue of LAN Magazine adds, "Surge suppressors are probably the most popular and least useful of all power protection devices." One would conclude from these adverse comments that the TVSS field has a challenge to improve its image.

On the other side of the coin, there are many documented cases in which equipment has been protected from severe electrical disturbances by TVSS assemblies.

Why, then, are there such diverse opinions? Probably because TVSS product applications extend over such a broad spectrum with many applications and market segments. These range, for example, from a commercial 480V three phase power entry protector which must sustain 10,000A transients on the high end, down to an outlet level protector for consumer electronics requiring only minimal protection.

In a rapidly growing market, this diversity allows the latitude for a broad range of product types, suppliers, specsmanship and quality; however there is no excuse for the existing confusion resulting from the absence of a common language which is necessary in describing the ratings and performance of a TVSS. Until all TVSS suppliers use the same clear, concise terminology for specifications, confusion will continue to reign and this industry will sustain the aroma of smoke and mirrors instead of the aura of professionalism.

Many of the inconsistencies, omissions and areas of misinterpretation are discussed in the following paragraphs along with suggested corrective measures that could be implemented by the TVSS community. Accurate and descriptive terminology would simplify the selection process from the users perspective and also define exactly what is being purchased and what level of performance can be expected.

WHAT IS ADEQUATE PROTECTION?

As one peruses the specifications of TVSSs on the market, it appears that the industry operates largely in a specsmanship mode with premium products providing the lowest clamping voltages. Published values vary from less than 200V (rms?) to the 300V plus range. Are these low clamping levels really needed or is it mostly specsmanship to entice the customer ? Low clamping levels may not needed according to Scott Muller. According to his text Upgrading and Repairing PCs, most PCs survive spikes up to 6,000V.

Significant problems may result from using suppressors having voltages which are marginal for a system. This is illustrated by F. Martzloff's warning to the IEEE Transient Suppression Committee in his correspondence of October 21, 1987 which states "...users need to know that the best protector is not necessarily the one claiming to suppress surges to the lowest level." With a suppressor breakdown level too low in voltage, high-line voltages lasting for milliseconds to seconds, normal for a power system, can drive the suppressor into breakdown for an extended period of time causing failure.

For improved overall TVSS performance and reliability, higher rated operating voltages, which are associated with proportionally higher clamping voltages, can be selected so that high-line voltage disturbances do not pose a threat. However, with the conditioning of the user to place a premium on lower clamping voltages, a move in the opposite direction by suppliers may be unpalatable and also confusing.

A second, major area of concern is an accurate definition of requirements for modes of protection. Protection modes, i.e., line-to-neutral, line-to-ground and neutral to ground are three ways in which a tvss can be wired. Most of the low cost TVSSs from discount stores provide only line-to-neutral protection. Since most consumer electronics are connected with two wires, line-to-neutral protection is adequate in some applications. Commercial systems with ground wires require line-to-neutral plus neutral-to-ground protection for capacitors in EMI/RFI filters.

In the subsequent section, electrical parameters will be listed along with definitions and commentary on what should be included and the significance of particular ratings or characteristics.

ELECTRICAL PARAMETERS

1. OPERATING VOLTAGE

This parameter normally defines the nominal operating voltage of the TVSS and usually without any definition of tolerance on the high side to accommodate normal high-line excursions. Since overvoltage for one-half cycle can destroy most TVSSs, this should be a mandatory parameter for the TVSS specification. In extreme electrical environments this parameter may be critical to the survival of the TVSS and the continued performance of that which it protects. The upper level of the steady state operating voltage should be specified.

2. CLAMPING VOLTAGE

This is a parameter which is often misused and misrepresented to enhance the overall specifications of a product. For example, one manufacturer lists the minimum breakdown voltage of the protector element, 190V, as the clamping voltage for a 120V rms rated TVSS. Uninformed and naive persons looking for the best performer could easily be misled by such distorted information.

Clamping voltage parameters should always be defined at the pulse current and the TVSS specification should include the maximum clamping voltage at the maximum rated surge current. The clamping voltage must be rated for the finished assembly and not for the best performance of the internal elements.

3. SURGE CURRENT RATING

This is another area where some suppliers take advantage of the users lack of knowledge in the suppression field. One TVSS intended for consumer use was labeled with a 4500A rated capability. Upon opening and examining the suppressor, it was found that the protector element had a <u>single surge rating</u> of 4500A. To make matters worse, the unit bore a UL listing label giving the user a false sense of security.

Where multiple components are internally used, some suppliers rate maximum current handling capability as the total current rating of all of the protector elements. Ratings should be based on a protection mode basis and on a per phase basis to clearly define surge current performance.

Maximum surge current ratings should be sufficiently conservative to provide surge capability over the expected life of the TVSS. The vast majority of all voltage stresses will be at the low end of the spectrum while very few will occur at the high end. The TVSS design should accommodate these conditions.

4. RESPONSE TIME

Response time is one of the most misused parameters of all. Most suppliers use the reported response time of the internal suppressor component and not the overall response time of the assembly. Many are specified as responding in less than one picosecond. This may sound great, but this statement is somewhat ridiculous. For example, it takes light one picosecond to traverse a distance equal to the thickness of about 50 sheets of paper.

Response time values in data sheets are primarily used for sales hype without regard to the true performance of a TVSS. Proof of performance to this parameter should be required.

The response time of the assembly should be the time interval between the start of the transient waveform until the voltage drops to the specified protection level of the protector assembly. It should not be the optimum response time of the internal component measured under ideal conditions. The term "response time" needs to be carefully defined as it can be easily misinterpreted.

5. EMI/RFI ATTENUATION

EMI/RFI attenuation is inadequately defined in many TVSS specifications, usually taking the form of a general statement to the effect that there is some attenuation included in the performance of the assembly. If specified, this parameter should be well defined in terms of minimum db attenuation at several points over a frequency range. This claim should be backed up with hard data. If possible, this should be linked into the needs of the protected equipment. Typically it is the lower quality electronics which is in greater need of additional EMI/RFI filtering in normal environments; however, noisy environments may require additional filtering for all grades of equipment.

6. STRESS TESTING

Stress ratings or life cycling should be required to define surge withstand capability over a spectrum of surge current levels. This should range from the lowest surge levels expected in normal service up through the higher, most severe limits in the environment for which the TVSS is rated.

For this parameter, the surge life ratings of the protector elements supplied by the manufacturer should be acceptable. For elements in parallel, their surge capability is not directly additive as there may be losses due to mismatch. Data should be submitted to prove capability since there is a variation in performance dependent on the degree of voltage matching.

A life curve over the surge current ratings should be included as is provided for components. Ratings should be also defined as to mode, i.e., line-to-neutral, etc. All modes should be included.

7. LIFE EXPECTANCY

Life expectancy of the TVSS in various environments such as those defined in ANSI/IEEE C62.41 should be included. This can be provided in a format defining the number of surges the TVSS will withstand at a given level such as at the Category A or Category B levels. Factored into this should also be the level of exposure, i.e., high, medium or low (also from ANSI/IEEE). This will be of particular help to the user who has unusually stringent requirements to meet, such as outlet protection in a small remote structure.

8. FUSE PROTECTION

Placing fuses in series with protective elements, especially metal oxide varistors, is common practice to prevent overheating and possible conflagration of components and packaging in the event of excessive overstress. UL no longer requires status indicators to monitor failure of the protective components and subsequent loss of protection, so a TVSS can lose its effectiveness without the user knowing it.

This is misleading to the user, providing a false sense of security and should be so indicated on the packaging. Removing the status indicators places the protected equipment in jeopardy in the event of protective element failure and its subsequent removal from the protective circuit.

9. END OF LIFE

End of life of a TVSS which has a status indicator is easily determined; however, without status indication, how is one to determine whether or not a TVSS is still providing protection or has failed? Without opening the TVSS, which is not recommended except by experienced personnel, it is impossible to determine good/bad status. Positive means should be available to readily determine the status of a TVSS by the average user.

10. INSTALLATION

Installation of TVSS assemblies is relatively simple for cord attach configurations. However, the user should be aware that the power cord length between the outlet and the TVSS is a transient radiator and sensitive data lines should be kept at a distance from this unprotected section of the power line.

Wire-in assemblies can be difficult to install for optimum performance. For example, if the protector output wires are placed in close proximity to the "dirty" input wires, transients can be coupled into the adjacent output wires reducing the effect of the suppressor and adding to the clamping voltage.

Another shortcoming of incorrect installation of wire-in TVSSs is the frequent use of long connecting wires between the protected lines and the protector. A wire has about one microhenry per meter which is small but can produce significant L(di/dt) effects under the high lightning currents for which these rugged TVSSs were designed.

Installers should be given specific instructions on how to optimize the protection installation through correct wiring and also bonding to the ground window of the protected equipment.

CONCLUSION

The specifications used by manufacturers to describe the electrical parameters of TVSS protector assemblies leave much to be desired in terms of continuity throughout the industry. There is too much latitude for interpretation of terms such as response time and clamping voltage, leaving them vulnerable for broad extrapolation.

Order can be brought out of chaos, but it will require a significant amount of time and effort on the part of all who share this market, including both suppliers and users, to make a significant course correction.

Time Response of TVSS Devices

by

Hans J. Steinhoff

Abstract

Surge protective devices for use on AC power lines of 120 to 600 volts sometimes use silicon avalanche diodes to achieve advertised response times of 5 picoseconds or less. This paper takes a look at the relevance of such claims and where they came from, and presents the results of surge testing some devices with and without silicon avalanche diodes. Three transient voltage surge suppressors which use both metal oxide varistors and silicone avalanche diodes were tested with surges having three different rates of voltage rise, they were tested again with the silicon avalanche diodes disconnected. The results showed that no significant difference in suppression voltage was observed when the silicon avalanche diode was disconnected.

* * * * * *

Much is made these days of the response time of transient voltage surge suppressors (TVSS) or of their components. Some manufacturers claim that their surge protective device or transient voltage surge suppressor has a response time of 5 nanoseconds. Some claim a response time of 5 picoseconds. Typically a claim of 5 nanosecond response time means the manufacturer is using metal oxide varistors (MOV's) as the suppression element in his TVSS. A claim of 5 picosecond response time, or any time in the picosecond range, indicates the manufacturer has used at least one silicon avalanche diode (SAD) in his device. Do these claims have any validity as to performance parameters? Are they anything that can be verified in a laboratory? Can they be verified using equipment that a reputable manufacturer of TVSS devices could be expected to own? Are 5 picosecond response times of any significance to the user of the TVSS?

Where did the response time figures which TVSS manufacturers claim come from? Quoting from the Panasonic ZNR Manual, Second Edition, "The response speed of ZNR is extremely fast. The conduction occurs very rapidly, in the order of 1 nanosecond or less. Measurements in this time region are very difficult. Device capacitance and lead inductance will predominate, so the varistor needs to be examined in disc form. At this time, response below 1 nanosecond has not been evaluated. In any event, it is of academic interest only with respect to a packaged varistor with electrode leads. Response speed of ZNR is, therefore, specified as 50 ns. and below. However, in actual application, the estimation of overshoot is more important than that of response speed." The Siemens (S10V) Metal Oxide Varistors for Surge Voltage Protection Catalog (CP4 20M 2/90) lists as the first feature, "Switching Response Time, < 15 µ sec. with minimal lead length". The Sanken Varistors SNR Series Catalog Second Edition - Improved Characteristics states: "Typical Response Time: < 15 µ sec.". The Harris Transient Voltage Suppression Devices Catalog of 1990 states "Response times of less than 1 picosecond are claimed for zener diodes, but these claims are not supported by any data measurements. For the varistor, measurements were made down to 500 picoseconds with a voltage rise time (dv/dt) of 1 million volts per microsecond." The Thomson-CSF Components Transient Voltage Suppressors Selection Guide 1981 claims, "A very low clamping time (on the order of 1 ps)" for their silicon avalanche diodes. The General Semiconductor Industries, Inc. Semiconductor Product Databook - 11th Edition says for the commonly used 1.5KE series, "The response time of Transzorb TVS1 diode clamping action is theoretically instantaneous (1 x 10^{-12} sec)."

Will it make a difference if the surge suppressor has a 50 nanosecond response time, or 5 nanoseconds, or 5 picoseconds? Let's look at the generally accepted 6 kV 1.2/50 microsecond voltage waveshape simulating lightning. The 1.2 microseconds represents the time from 10% of the 6 kV to 90% of the 6 kV times 1.25. This works out to 5 kV/µs, which is 5 volts per nanosecond. For an arrester with 50 nanosecond response time, this would theoretically add 250 volts to the suppression voltage of the device. For a 5 nanosecond response time arrester, 25 volts would be added to the suppression voltage of the device. So we can see that for voltages generated by lightning, response times faster than 5 nanoseconds do not add any significant voltage to the suppression voltage of the device.

Are there voltage rates of rise on AC power systems that are faster than 5 kV per microsecond? Yes, a common one being the 500 ampere 100 kHz ring wave of ANSI/IEEE C62.41. The rate of rise of the ring wave is about twice that of the combination wave. Are there still faster waveshapes? Yes, there are. These can result from relay bounce or electrostatic discharge. The International

Electrotechnical Commission (IEC) recommends a test pulse of 5/50 nanoseconds to simulate some of these events. However, as stated by Francois Martzloff in "Protecting Computer Systems Against Power Transients", IEEE Spectrum April 1990, nanosecond pulses do not propagate very far in power systems and picosecond response time is a feature that is not important in a power system.

This paper reports on tests performed on several products that employ both metal oxide varistors and silicon avalanche diodes. The SAD's used in these products have relatively low current handling capability compared to metal oxide varistors. The MOV's used in these products can conduct a single current pulse of 6,500 to 30,000 amperes. The SAD, on the other hand, can conduct a pulse of only 41 to 80 amperes on the same 8/20 microsecond current waveform. Since this surge current capability is insufficient to handle the surge current expected on AC power circuits, the SAD is always used in parallel with one or more MOV's. If the SAD were connected directly in parallel with the MOV, the SAD would fail, typically as a short circuit, on surges with relatively low current.

Several methods are employed to protect the SAD. One method is to use a resistor to limit the current through the SAD. The problem with this approach is that the resulting suppression voltage is not the suppression voltage of the SAD, but is the sum of the voltages across the SAD and the resistor. This is equal to the voltage across the MOV. Another approach to protecting the SAD, and this is employed by more than one manufacturer, is to use two or more SAD's in series. This results in the SAD's starting to clamp at a higher voltage than the MOV's. SAD's with clamping voltages of 300 to 400 volts have been used in parallel with MOV's whose 1 mA varistor voltage is 200 volts ±10%. Another method to protect the SAD's is to use a positive temperature coefficient resistive device in series with the SAD in the hope that the SAD can provide some clamping advantage at low currents and the PTC can prevent the destruction of the SAD. This approach would be effective only if the PTC had very low resistance until the current approaches the maximum current capability of the SAD and then can change to a high resistance in nanoseconds. One manufacturer uses a fuse in series with a string of SAD's. The SAD's on this product do not conduct any current until the current through the parallel MOV reaches a value of between 50 and 1,000 amperes. The SAD's failed in a shorted mode and the fuse blew when a current surge of around 3,000 amperes with an 8/20 μs waveshape was applied to the device. This device gives no indication that the SAD fuse had blown.

Three TVSS devices were tested with a 500 ampere 8/20 microsecond combination wave, a 500 ampere 100 kHz ring wave, and an impulse having a 1 kV per nanosecond rate of rise. They were first tested without any alteration and then tested again with the SAD disconnected. Two of the devices tested are hard-wired shunt connected surge protection devices. One of these devices, herein designated device "L" is intended by its manufacturer for the distribution panel. The other hard-wired unit, designated as device "D", is intended for sub-panels. The third device, designated device "E", is a plug-in protector. All three of these devices employ both MOV's and SAD's. The hard-wired devices were connected to the surge generator with AWG #8 solid wire 18 inches long from the device enclosure to the generator and the voltage was measured at the generator end of the wires. The voltage for the plug-in device was measured at the out-put receptacle of the device.

Figure 1 shows the current of the 500 ampere 8/20 microsecond IEEE C62.41 combination wave applied to device "L". The resulting voltage is shown in the same figure with the time base of 5 microseconds per division. Figure 2 shows the same current applied to device "L" with the SAD disconnected. There is no discernable difference in the response with and without the SAD. Figures 3 and 4 show the test repeated with the oscilloscope sweep rate set at 1 microsecond per division. Again no difference was observed. Figures 5 and 6 show no discernable difference with the sweep rate increased to 500 nanoseconds per division. Figures 7 through 12 show the same tests for device "D". Figures 7 and 8 seem to indicate a difference, but increasing the sweep rate to 500 nanoseconds per division shows there is no difference whether the SAD is connected or disconnected. Figures 13 and 14 show that there is no difference in response in surging the plug-in device "E" with the combination wave.

The three devices were then tested with the faster rising 500 ampere 100 kHz ring wave of IEEE C62.41. The peak voltage increased dramatically, but again the oscillograms show no significant difference between the silicon avalanche diode in the device being connected or disconnected. Figure 15 is with the SAD for device "L" and figure 16 is without the SAD. Figure 17 is with the SAD for device "D" and figure 18 is without the SAD. Figures 19 and 20 show the plug-in device "E" with and without the SAD respectively.

The three devices were last of all tested using a generator which is normally used for testing gas tube devices with a voltage rate of rise of 1 kilovolt per nanosecond. With the MOV devices connected to the generator the voltage rate of rise was approximately 700 volts per nanosecond. The current delivered by the generator for these tests was about 250 amperes for a duration of about 50 nanoseconds. Figure 21 shows the results for device "L" with the SAD and Figure 22 without the SAD. Figure 23 shows the results for device "D" with the SAD and Figure 24 without the SAD. Figures 25 and 26 show the results for the plug-in device "E", with and without the SAD, respectively.

The manufacturers of the three devices tested did not claim that their devices had response times of 5 picoseconds or less. These devices were tested because they were available and are similar to other devices whose manufacturers make such claims. One device which was purchased because the advertising literature stated that it had three stages, one of which had a 5 picosecond response time, turned out to have only two stages and no silicon avalanche diodes. The manufacturers of the three devices tested do make the claim that these devices have the feature called "sine wave tracking". A look at the oscillograms shows that sine wave tracking did not work with any of the waveshapes used for these tests.

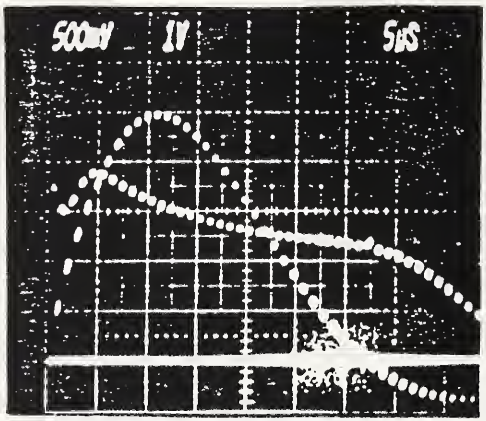

Fig. 1. Device "L"
100 volts/division
100 amps/division

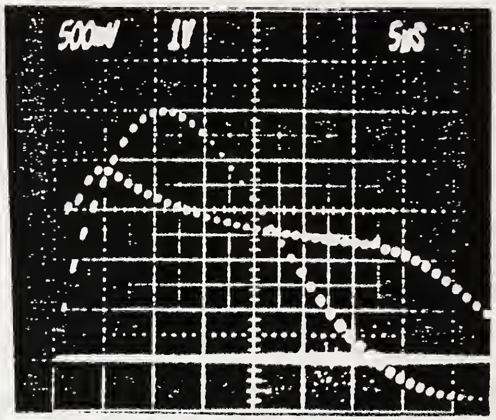

Fig. 2. Device "L" no SAD
100 volts/division
100 amps/division

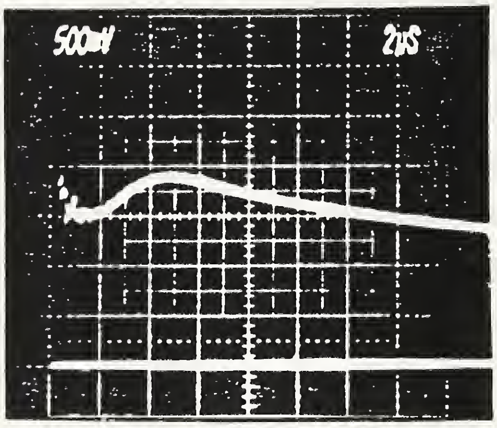

Fig. 3. Device "L"
100 volts/division
500 A 8/20 μs

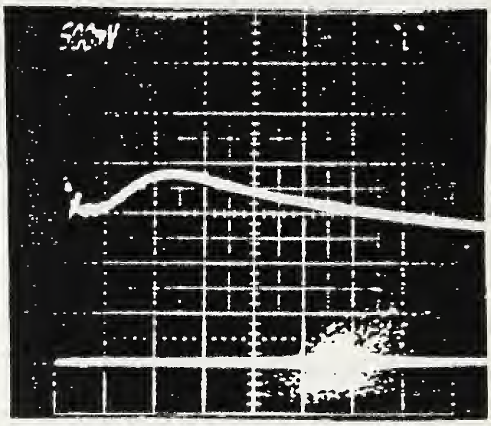

Fig. 4. Device "L" no SAD
100 volts/division
500 A 8/20 μs

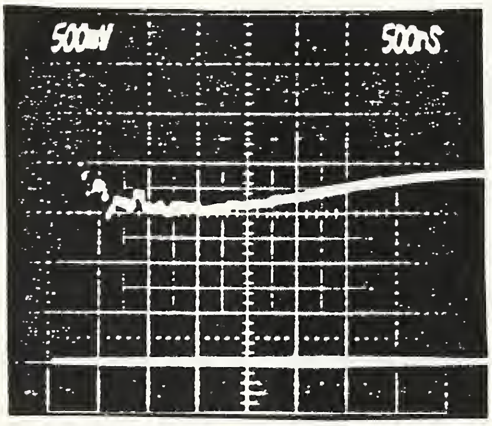

Fig. 5. Device "L"
100 volts/division
500 A 8/20 μs

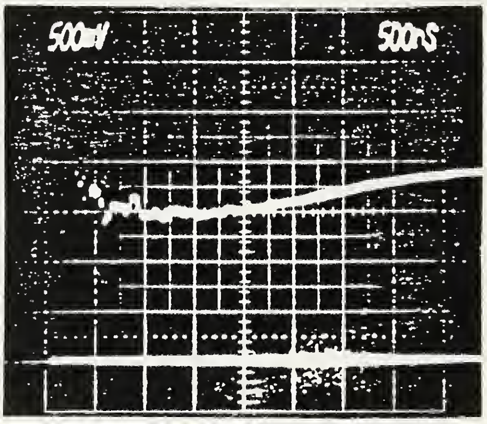

Fig. 6. Device "L" no SAD
100 volts/division
500 A 8/20 μs

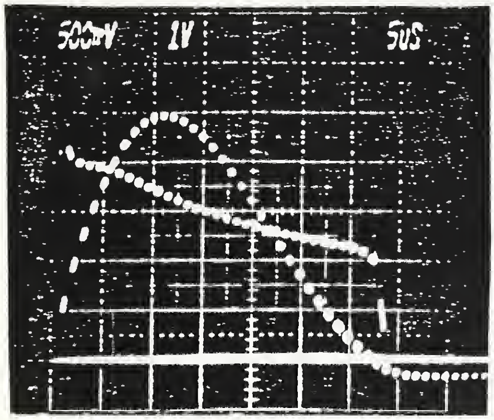

Fig. 7. Device "D"
100 volts/division
100 amps/division

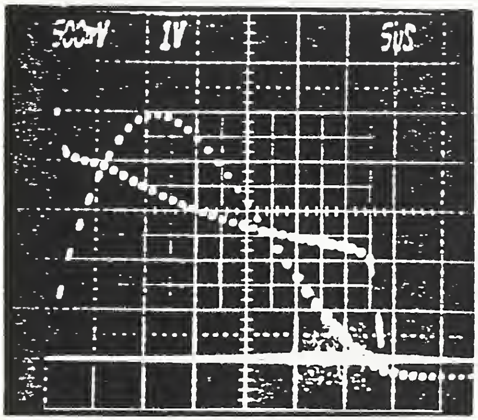

Fig. 8. Device "D" no SAD
100 volts/division
100 amps/division

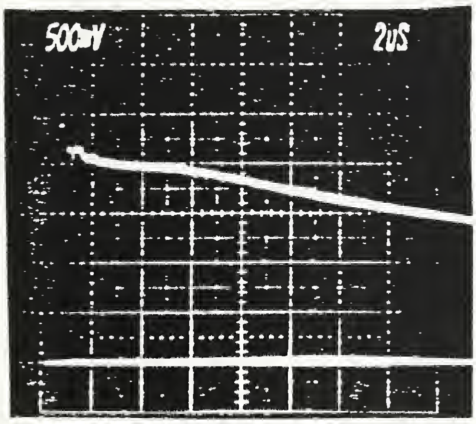

Fig. 9. Device "D"
100 volts/division
500 A 8/20 μs

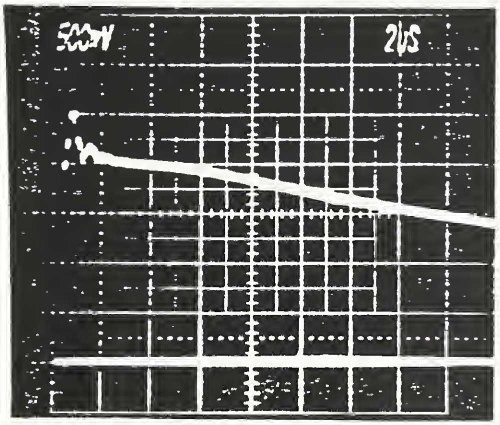

Fig. 10. Device "D" no SAD
100 volts/division
500 A 8/20 μs

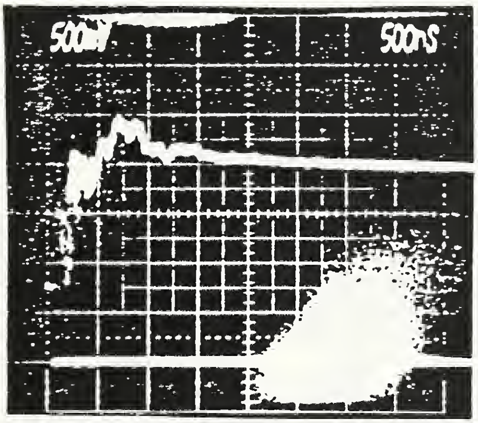

Fig. 11. Device "D"
100 volts/division
500 A 8/20 μs

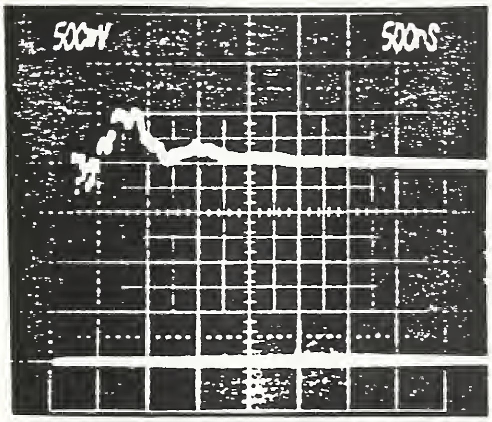

Fig. 12. Device "D" no SAD
100 volts/division
500 A 8/20 μs

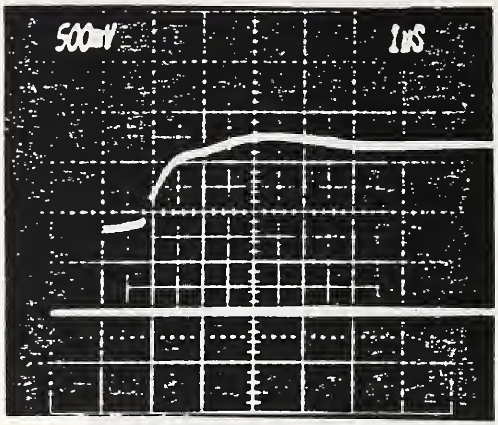

Fig. 13. Device "E"
100 volts/division
500 A 8/20 µs

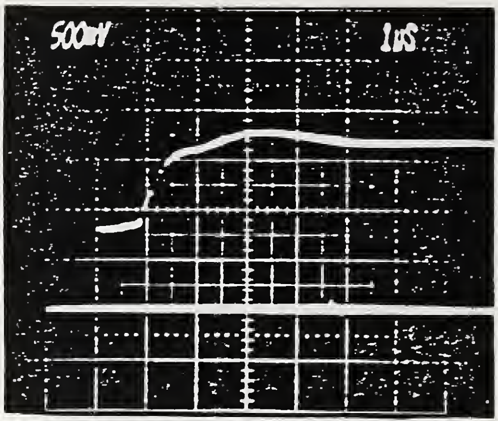

Fig. 14. Device "E" no SAD
100 volts/division
500 A 8/20 µs

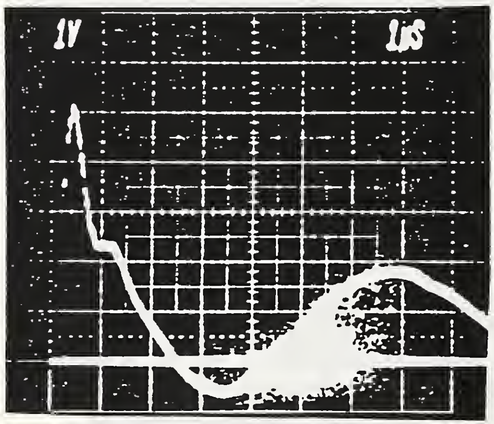

Fig. 15. Device "L"
200 volts/division
500 A Ring Wave

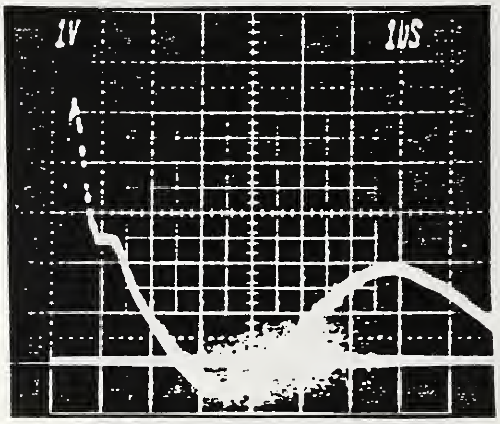

Fig. 16. Device "L" no SAD
200 volts/division
500 A Ring Wave

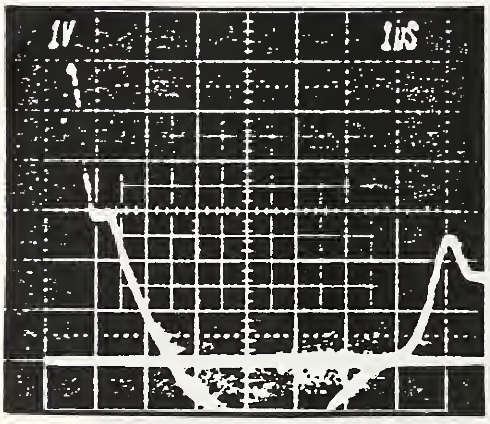

Fig. 17. Device "D"
200 volts/division
500 A Ring Wave

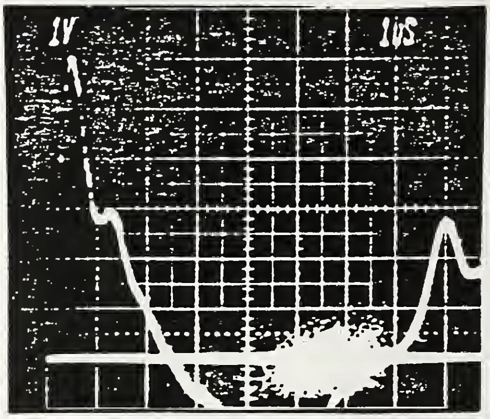

Fig. 18. Device "D" no SAD
200 volts/division
500 A Ring Wave

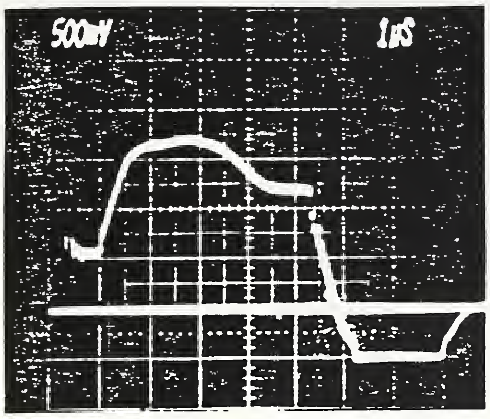

Fig. 19. Device "E"
100 volts/division
500 A 8/20 μs

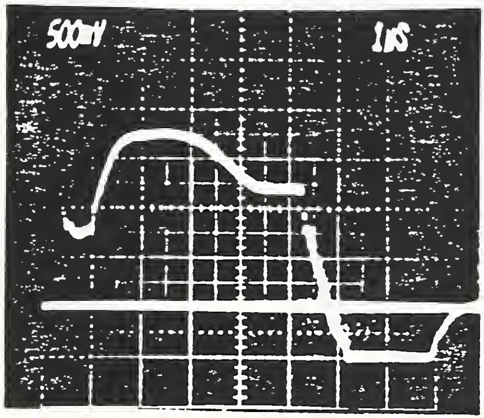

Fig. 20. Device "E" no SAD
100 volts/division
500 A 8/20 μs

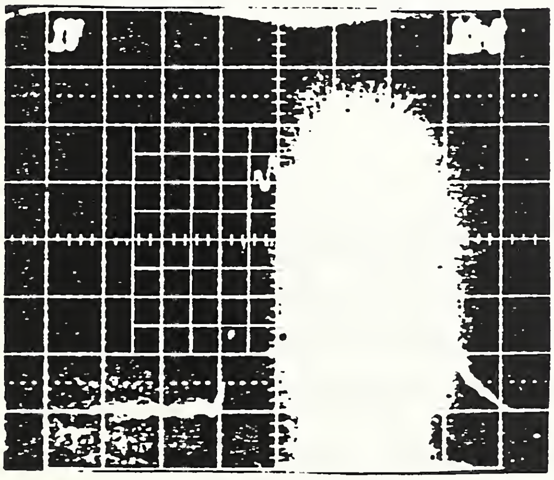

Fig. 21. Device "L"
1000 volts/division
1 kV/nanosecond

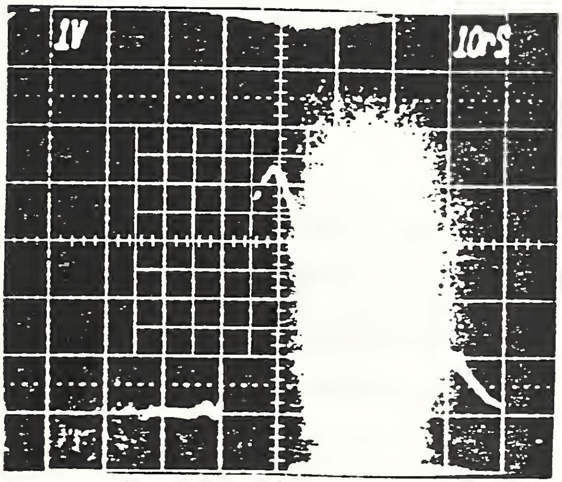

Fig. 22. Device "L" no SAD
1000 volts/division
1 kV/nanosecond

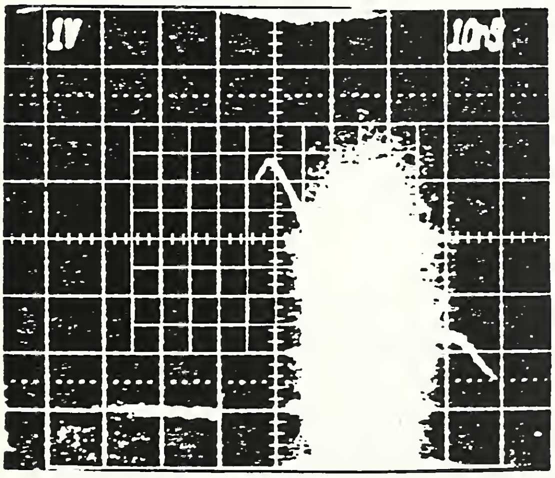

Fig. 23. Device "D"
1000 volts/division
1 kV/nanosecond

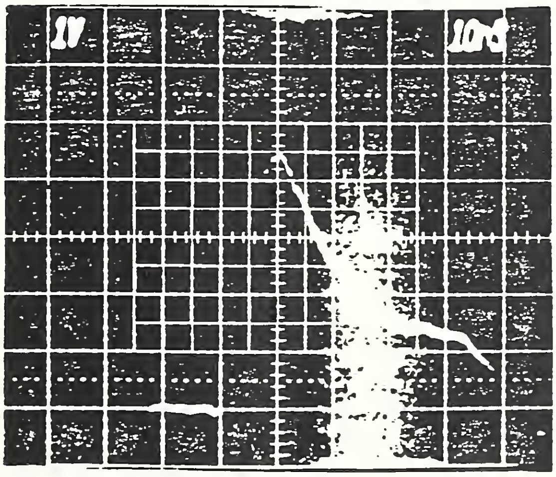

Fig. 24. Device "D" no SAD
1000 volts/division
1 kV/nanosecond

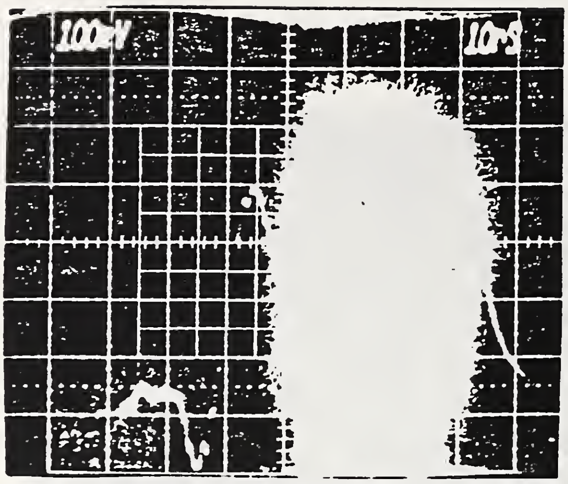

Fig. 25. Device "E"
100 volts/division
1 kV/nanosecond

Fig. 26. Device "E" no SAD
100 volts/division
1 kV/nanosecond

Conclusion

The claims of 5 picoseconds or less response times of devices or components are not relevant for surge protective devices used on AC power systems. The three devices tested showed no difference in the peak suppression voltage when tested with and without the silicon avalanche diode connected. This is not to imply that silicon avalanche diodes are not valuable or necessary in other circuits or surge protective devices. They just do not provide any observable advantage in devices also employing metal oxide varistors, when they are used for the sole purpose of making claims of picosecond response times.

PERFORMANCE OF MOV SUPPRESSORS IN LOW-VOLTAGE AC CIRCUITS

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Surge voltages on indoor ac power distribution lines can arise from both external and internal sources. Service entrance arresters help to reduce the effects of lightning but do not eliminate a need for suppressors at the location of sensitive equipment. Protective characteristics are improved by cascaded stages of arresters and suppressors regardless of the strategy used for coordination.

Introduction

Microprocessors are raising the productivity of our workplaces and introducing greater convenience to our homes. At the same time, microelectronic structures inevitably have less resistance to upset or damage by transient surge voltages on the ac mains. The surge voltage threat is being abated effectively using metal-oxide varistor (MOV) devices.

Characteristics of Surges

The highest surge voltages are caused by lightning which does not have to strike a powerline directly. The radiated electromagnetic field of a stroke can couple lightning to unconnected circuits. The possible severity of lightning surges can be predicted from an ANSI/IEEE standard (1980). Surge voltages also are frequently caused by switching of reactive loads. Switching events can occur within a facility, or they can be generated externally by power utility equipment. Sensitive equipment needs protection against all surges.

Fast Response of MOVs

MOVs are ultrafast solid state semiconductor devices. They can clamp combination wave test impulses representative of lightning without overshoot, as illustrated in Fig. 1. In fact, laboratory tests have shown that MOV elements respond practically instantaneously, even to voltage impulses as fast as about 500 ps risetime (Levinson and Philipp, 1986).

PERFORMANCE OF MOV SUPPRESSORS IN LOW-VOLTAGE AC CIRCUITS

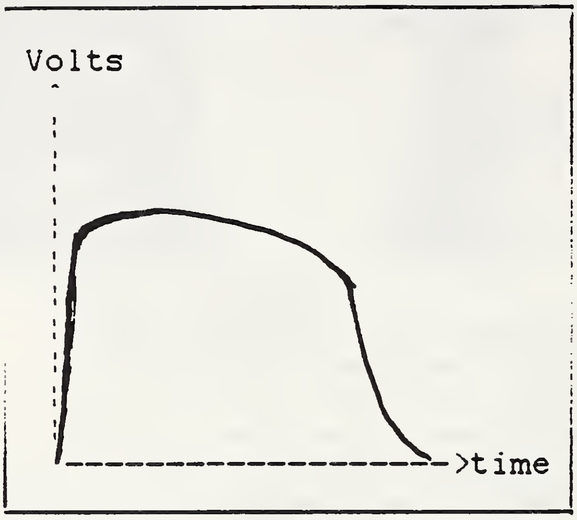


Fig. 1 Fast Response of MOV

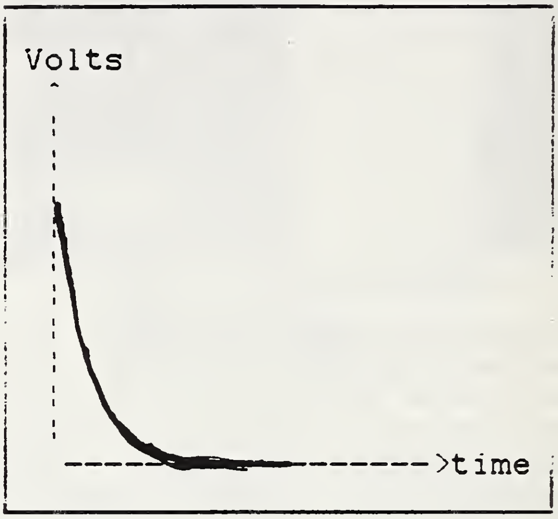


Fig. 2 Response of Inductor

In some applications where the rate of rise of the surge current is high, a significant voltage can be developed in the inductance of the lead wires connecting the mains to the metal-oxide elements. The voltage across an inductor. illustrated by Fig. 2, when added to the response of an MOV element can create the impression of a response time delay.

For example. when the response of MOV distribution arresters to 60 ns risetime pulses was measured by Miller. Fan and Barnes (1991). a very large spike was observed on the front end of the voltage across the arrester. However. it was shown that the spike was due to the inductance of the housing and measurement system. When a conductive tube of similar dimensions was substituted for the arrester. the voltage and current traces were very similar to before. except that the residual voltage after the spike was approximately zero. Hence. it was concluded that the MOV material had come to a full conducting state within the same time as the risetime of the pulse.

Impedance of AC Mains to Surges

The branch circuit wiring of the ac mains has an inductive impedance to surges. the magnitude of which depends on the rise time of the current wave. and which can greatly exceed the resistance to power frequency current. Martzloff (1983) measured the inductance and resistance L-N of a 75 M length of line of a type used for branch circuit wiring. The results can be reduced to a per unit basis giving values on the order of 1 uH/M and less than 0.01Ω/M respectively.

PERFORMANCE OF MOV SUPPRESSORS IN LOW-VOLTAGE AC CIRCUITS

A phenomenon occurring in low-voltage ac circuits is that surge impulses can be converted into oscillatory waves. As described by Martzloff (1983) this is due to reflections in branch circuits caused by the typical mismatch between the characteristic impedance of the line, about 100Ω, and the terminating impedance, which might range from open to very low depending on the loads connected. A test waveform of 0.5us-100 kHz is recommended by ANSI/IEEE (1980). The impedance of the mains is very significant for surges with high frequencies. A branch circuit 10 M long would present an expected impedance of about 2Ω to the front of an 8/20 current impulse and about 6Ω to a 100 kHz oscillatory surge wave shape.

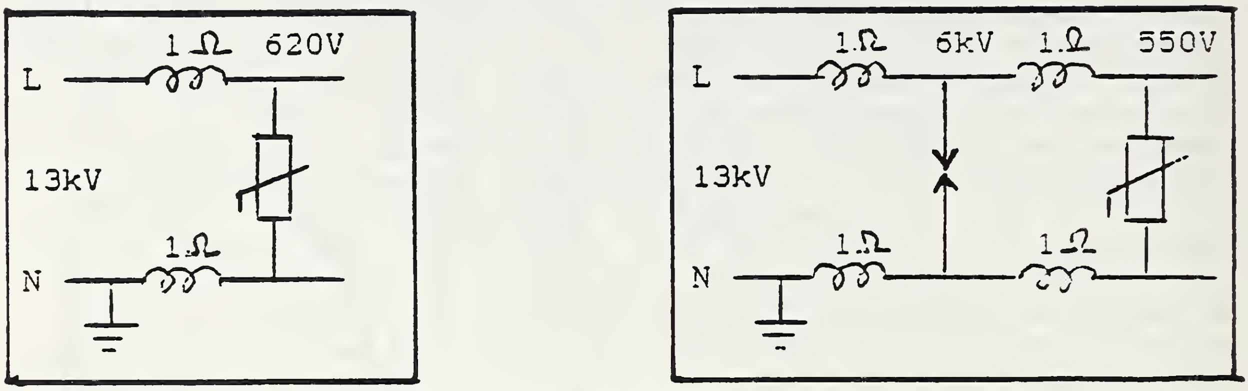
Protective Characteristics of MOVs

Models of the indoor ac low voltage surge environment seen by MOVs were analyzed by Martzloff (1985). Incident lightning surge characteristics were assumed to have a rate of surge occurrence versus voltage according to ANSI/IEEE guidance (1980). The wiring impedances, shown as resistances in Fig. 3, had values representing the impedances to an 8/20 us current wave shape. For a service entrance arrester the analysis predicted a maximum clamping voltage of 620 V for a 32 mm diameter MOV rated 150 Vrms, Fig. 3a). For a branch circuit suppressor 10 M farther away, with no arrester but with flashover of clearances at 6 kV, the predicted maximum clamping voltage of a 20 mm, 150 V rated MOV was 550 V, Fig. 3b).

It is instructive to consider the effect of substituting a 32 mm MOV for the 20 mm size in the suppressor, Fig. 3c). By use of the tables of calculated values in the Martzloff (1985) analysis, predicted clamping voltage would be 480 V, a significant reduction from 550 V.

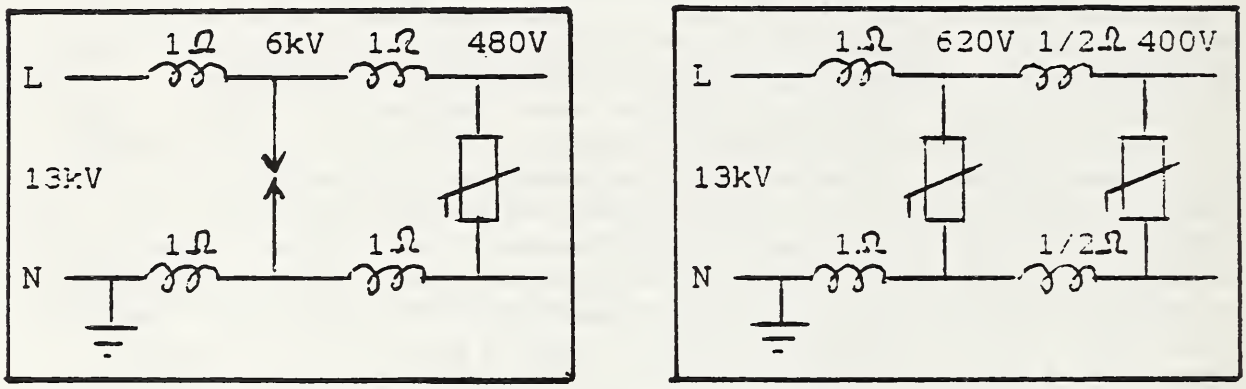
Devices can be combined for two-stage protection. It must be noted that clamping action in the first stage tends to increase the impulse duration seen by the second stage, and consequently the impedance of the branch circuit to surges might be cut about in half. A more sophisticated model and empirical verification, such as by Stringfellow (1991), is needed for precise determination of surge response values. However, the simplified model of Fig. 3d) can serve to illustrate concepts and to make tentative predictions. The arrester will draw most of the total peak current with a clamping voltage of up to 620 V. The suppressor MOV current will be on the order of 200 A, and the expected clamping voltage near to 400V.

PERFORMANCE OF MOV SUPPRESSORS IN LOW-VOLTAGE AC CIRCUITS



a) 32 mm MOV Arrester

b) 20 mm Suppressor



c) 32 mm MOV Suppressor

d) Arrester&Suppressor 32mm

Fig. 3 Predicted Clamping Voltage of 150 V Rated MOVs in Surge Model from ANSI/IEEE C62.41. Source: Martzloff (1985)

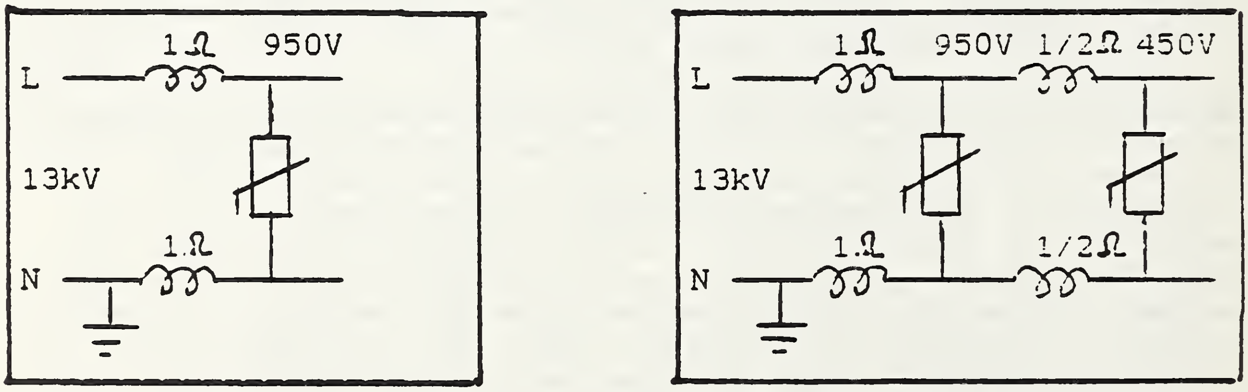


Fig. 4 Predicted Clamping Voltage of 250 V Rated Arrester MOV. and with 150 V Rated Suppressor MOV in Surge Model from ANSI/IEEE C62.41: derived from Martzloff (1985)

Note: inductive values are shown as impedance to 8/20 surge: for clarity. fuses and other devices are not shown.

PERFORMANCE OF MOV SUPPRESSORS IN LOW-VOLTAGE AC CIRCUITS

Voltage Coordination of MOVs

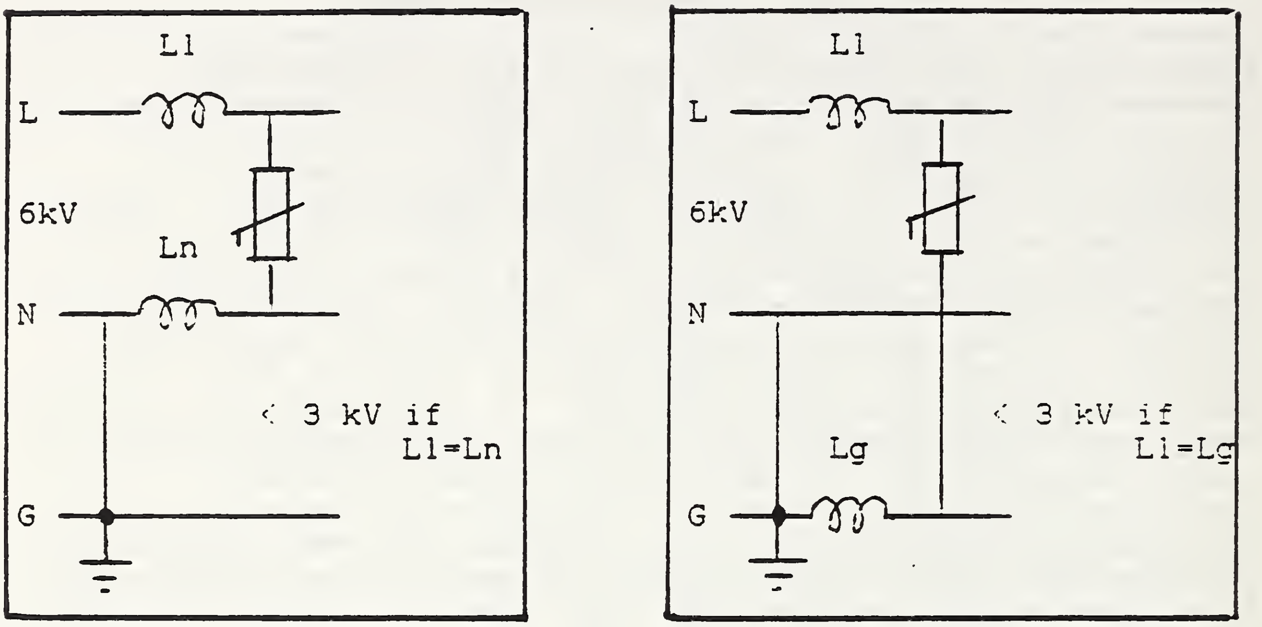
Historically, the arresters used on 120 V rms nominal service voltage have often been of higher voltage rating than the suppressors. For example, Fig. 4 considers the case of a 32 mm 250 V rated arrester MOV, alone and in combination with a 20 mm 150 V rated suppressor MOV. The predicted maximum clamping voltage is 950 V for the arrester and 450 V for the suppressor when the surge current is assumed to be 8/20 us waveshape. However, for installations exposed to long duration surges the effective impedance between the arrester and suppressor is only the small resistance of the ac mains wiring. In that case the suppressor would conduct most of the surge current, and a larger diameter MOV, 32 mm or more, might be needed.

An alternative approach to coordination has been described by Standler (1991), in which the arrrester is designed with a voltage rating, such as 150 Vrms, that is lower than that of the suppressors downstream. In such a case the arrester tends to conduct the largest share of the surge current, even for long duration surges. Consequently, smaller size MOVs could be used in the suppressors.

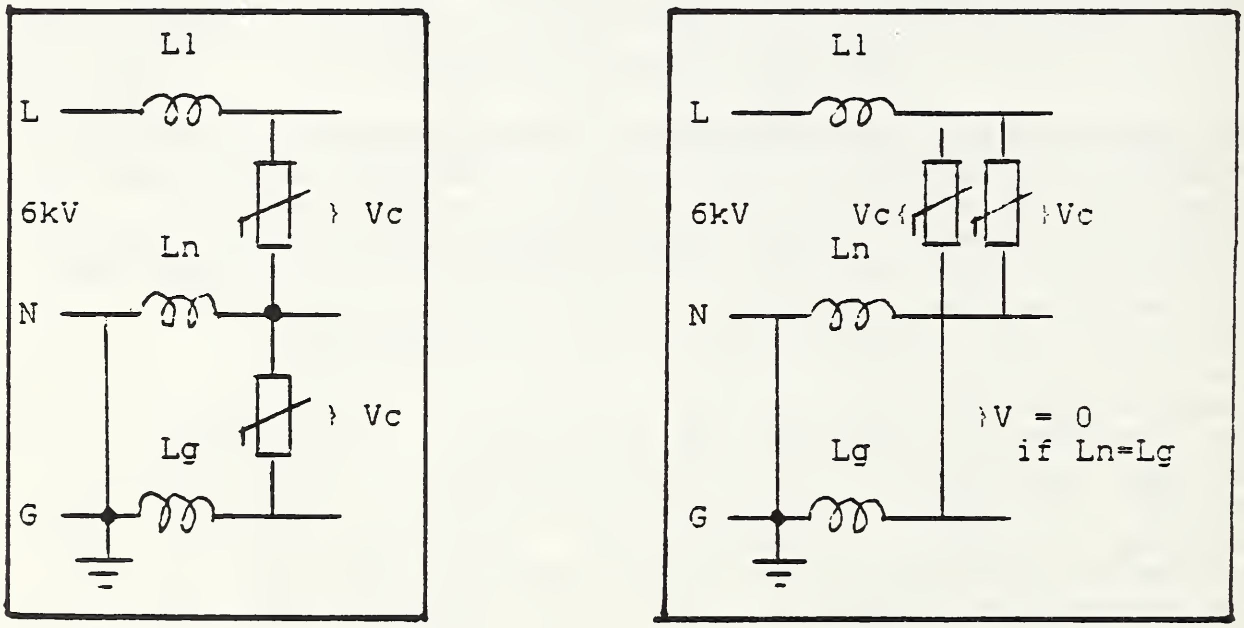
Mode Conversion of Surges

By application of the ANSI/IEEE (1980) category B test impulse in a laboratory simulation, Martzloff (1983) has shown how L-N surges can be converted to N-G surges in branch circuits when suppressors divert a L-N surge. Mode conversion occurs because the applied L-N surge voltage is divided among the impedances to the surge of the mains wiring and the clamping voltage of the suppressor.

Consider the cases illustrated by Fig. 5. In situation a) the surge current flowing L-N could cause a N-G surge voltage approaching 3 kV in peak magnitude. Diverting the surge to a branch circuit grounding conductor G instead of N does not avoid the problem, see b). Suppression of N-G surges has been installed in many applications, with ratings similar to the L-N device, as in c). However, the protective level L-G is the sum across L-N and L-G devices which is 2Vc. Circuit d) protects in L-N and L-G modes, but the N-G surge voltage depends on the values of the circuit impedances Ln, Lg and the clamping voltages at L-N and L-G. The model predicts that N-G surge voltage due to mode conversion could approach zero if circuit values happened to match. In many applications suppression is installed in all modes: L-N, L-G, N-G.



a) N-G Surge from L-N Surge b) N-G Surge from L-G Surge



c) N-G Surge Suppression d) N-G Surge from L-N. L-G

Fig. 5 Equivalent Circuits of AC Mains Illustrating How Mode Conversion Occurs

Note: for clarity. fuses and other devices are not shown.

Neutral-Ground Bonding

As Fig. 6 shows. N-G surges originating outside a building will be shorted and not conducted to interior branch circuits. if there is a N-G bond at the service entrance. However, surges originating inside at a branch circuit location can be largely isolated from the bonding point. For instance, if the radiated field of a lightning stroke coupled fast rising surges to internal building wiring circuits the bond or arresters at the service entrance could be ineffective because of parasitic inductance in the wiring. Other mechanisms also could be a source of N-G surges which would not be shorted by the N-G bond. and surges in other modes might not be suppressed by arresters at a service entrance. Hence, sensitive equipment served by a feeder line or branch circuit is likely to need suppresion at the service outlet or within the equipment. including suppression for the N-G mode.

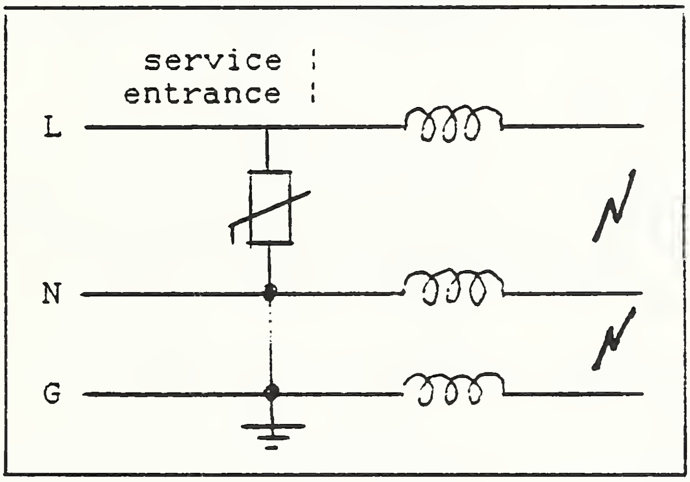


Fig. 6 AC Wiring Circuit With Neutral-Ground Bond

Application Considerations

When a surge protective device responds. the surge current injected into the path of circulating current creates an electromagnetic field which could cause interference (EMI) effects in sensitive equipment. An obvious way to minimize interference is to reduce the magnitude of the current in long loops. Lightning is likely to cause the highest surge current. and most of it can be diverted directly to ground with an arrester at or near the service entrance.

PERFORMANCE OF MOV SUPPRESSORS IN LOW-VOLTAGE AC CIRCUITS

Conclusions

The surge protective characteristics of MOVs are used to maximum advantage when surge arrester MOVs are combined with suppressor MOVs at distribution panels or branch locations serving sensitive equipment. This plan results in two or more stages of protection against lightning surges and achieves significantly lower clamping voltages.

Coordination of surge protective devices involves many factors. technical and economic. and is a complex subject in the province of the MOV user. However. the presence of two stages does allow greater flexibility in coordination of voltage ratings. Because protective levels are lower with two stages. a downward auction on ratings can be avoided. For the best suppression. MOVs are used in L-N. L-G and N-G modes where consistent with other requirements.

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POWERLINE PROTECTION WITHIN THE ELECTRONIC RECEPTACLE FOR THE GENERAL USER OF SENSITIVE EQUIPMENT

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ABSTRACT

Transient protection of sensitive equipment has become an international issue accelerated with the growth of the PC. It is impractical to suggest a UPS for every terminal. With over 150 million microprocessor-based devices installed, a general need exists for localized protection within the receptacle. A transient voltage surge suppressor (TVSS) receptacle is currently available from multiple wiring device vendors in the USA and Europe. The TVSS is installed in the wall outlet port between the commercial branch power source and the equipment cordset plug. As a hardwire device, the TVSS is always dedicated to the sensitive system. Although varistor-based, certain TVSS design features vary.

INTRODUCTION

Microprocessor chip density has increased roughly two orders of magnitude, and decreased from 4.5 micron to sub-micron architecture in ten years. Increases in chip complexity and density have been the result of decreasing semiconductor line widths from about 25 microns in 1960 to about 1.5 microns in 1987. In 1965 printed board feature size relationship was about 30 times larger than the comparable semiconductor value. This value increased to 50:1 in 1975 and to nearly 100:1 in 1985. The microprocessor vulnerability to electrical overstress from transients has become considerable.

A computer tolerance envelope developed to give the user minimum/maximum ranges of acceptable powerline tolerance for sensitive electronic equipment performance predicts up to two voltage disturbances per year exceeding the computer tolerance. (CBEMA* IEEE Type I disturbances: spikes and surges).

Several studies suggest that the frequency of occurrence of various powerline abnormalities justifies the general use of transient protection for sensitive equipment.

The electrical wiring device industry internationally has developed the TVSS receptacle for installation at the node between the facility power source and the equipment line-cord plug.

THE TVSS ELECTRONIC RECEPTACLE FOR GENERAL APPLICATIONS

The transient voltage surge suppressor (TVSS) receptacle diverts high energy overvoltages appearing on the powerline to ground, and can be fitted within an existing wall outlet box [Figure 1]. Because of the impinging effect of a common mode surge induced from the normal mode^2, this paper offers an over-simplified illustration of the need for neutral - ground protection [Figure 2] which is a zero differential only at the service entrance.

NO REGULATORY REQUIREMENTS AGAINST TRANSIENTS

Equipment compliance to the regulatory requirements for power supply noise emissions to minimize electromagnetic and radio frequency interference onto adjacent equipment is mandatory (FCC Rules, IEC, VDE) but much of the frustration with the powerline phenomena might have been avoided had there been regulatory requirements for transient protection. This does not exist and it is up to the equipment or protection vendors to set their own specifications: protection is the responsibility of the end-user.

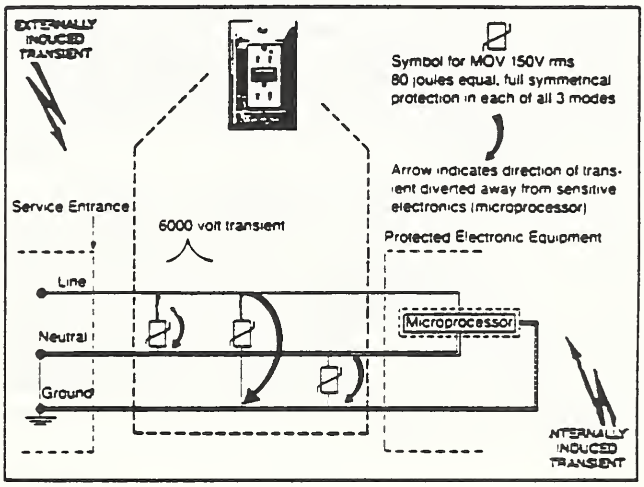


FIGURE 1
General schematic of TVSS receptacle in branch circuit.

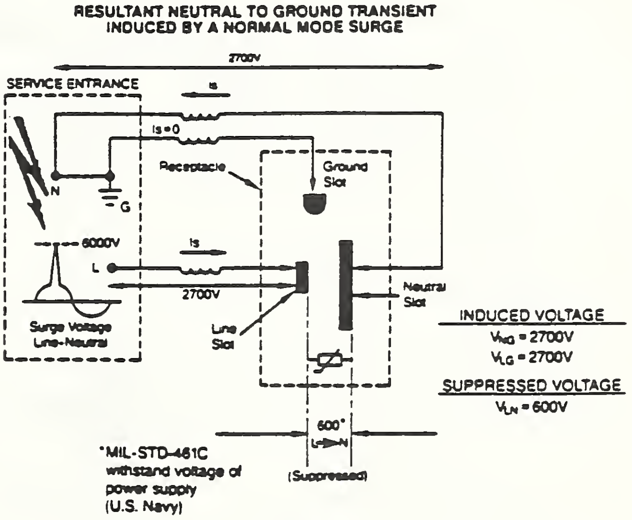


FIGURE 2
Illustration of impinging effect of normal mode transient induced from common mode.
(Neutral - ground consideration).

INDUSTRY'S INVOLVEMENT WITH TVSS DEVICES

A study of 2,000 end-users of personal computers by the Lotus Corporation in 1987, concluded that 64 per cent used some kind of TVSS as the first level of protection from adverse powerline phenomenon. Clearly, users were concerned about the adequacy

[*Computer and Business Equipment Manufacturer's Association][1] of the transient protection designed into their equipment. However, there was a concern of the nomadism of portable devices, intended or untended movement from the equipment, cable clutter and the cost of UPS systems.

Between 1986 and 1988 a wiring device manufacturer visited over 290 facilities in an attempt to understand the end-user's perception of the effectiveness of TVSS protection devices. Sites were selected as known to be high lightning exposure geographic areas or information-system intensive from a micro computer installation base.

THE DRAMATIC AND THE INNOCUOUS

While lightning, power factor correction capacitor banks, and "powerwheeling" are dramatic hostile causes of transient damage to microprocessor based equipment, there is evidence of an increase of internal transient propagation through branch wiring.

Commercial equipment switching, such as HVAC duty-cycling, vacuum cleaners, vending appliances, elevators, motor or transformer-based inductive devices, may cause disruption or destruction of sensitive loads resulting in mysterious equipment interruptions or permanent damage to the hardware. Transients may result in soft failure, hard failure or latent damage.

IBM AND AT&T POWERLINE STUDIES

Confusion on cost-effective protection devices has been compounded by the "apparent" difference in conclusions of two well known studies. The IBM study (Allen-Segall) of commercial facilities suggested that 88.5 per cent of powerline problems were transient-related. The AT&T study (Goldstein-Speranza) of telephone facilities described the opposite, 87 per cent were sags or undervoltages.

Unless the user is informed of the objective and procedure of studies such as the above, his decision may be biased into investing in an uninterruptible power supply instead of a more economical transient suppressor.

The Winter 1988 IEEE Transactions published a summary of nine major powerline studies performed over 20 years including the IBM and AT&T studies.[3] Transients as high as 5,600 volts, highest current in hundreds of amperes and fastest transient rise-time in nanoseconds were recorded.

VARISTOR BASED PRODUCT CHARACTERISTICS

Svante Arrhenius advanced the theory of activation energy which is an inverse linear relationship between temperature and the logarithm of a variable[4,5]. The implication is that if a failure mode is subject to the principle, a test for a given time at an elevated temperature is equivalent to a test for a much longer time at its normal operating temperature. The acceleration factor can be as high as 500; a test of 200h duration at 150° may be equivalent to 11 years of operation at a normal operating temperature of 55°C.

The Arrhenius model of life predictability applied to varistors with almost 20 years of extrapolation data, is used to test the varistor under very high stress levels of accelerated temperature and AC bias conditions [Figure 3]. By stressing the varistor above its maximum ratings, the model can confirm the varistor's long-term ability to meet these ratings.

A statistical application of this life/stress model to predict varistor reliability in typical lightning and switching environments assuming a 50/50 lightning/switching transient ratio, concluded with a conservative life time estimate of 28 years for the 32 mm varistor installed at the service entrance[6]. A conservative approximation for the 20 mm varistors installed in the branch circuit for a 10/90 lightning/switching transient ratio resulted in an estimated life time of 20 years [Figure 4].

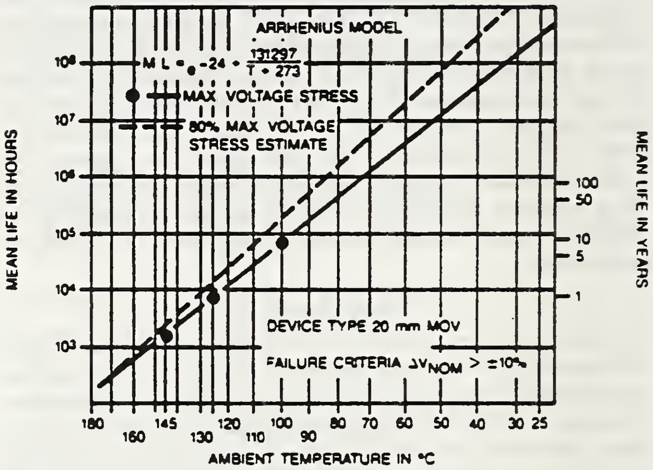


FIGURE 3
Arrhenius model of varistor mean life vs. temperature.

LIFE CONSUMPTION 20mm 150V RMS GE-MOV — Medium Exposure
— Catagory B

LIGHTNING (10%)

Voltage Surge Level V	No. of Surges Per Year Above Level	Total Occurences Per Year At Level	Occurences Due To Lightning (Bi-Wave)	Clamping Voltage of Varistor	Available Driving Voltage	Surge Current 2 Ω Amps	Rated No. of Pulses for this Surge Current	Percent Life Consumed
900	1000	900	90	450	450	225	9000	1.0
1500	100	90	9	470	1030	515	700	1.29
3000	10	9	.9	500	2500	1250	60	1.5
5000	1	.9	.09	550	4450	2225	9	1.0
6000	.1	.09	.009	570	5430	2715	7	.13
6000	.01	.009	.0009	570	5430	2715	7	.013
								4.933

SWITCHING (90%)

Occurences Due To Switching (Ocillatory)	Surge Current 12 Ω Amps	Rated No. of Pulses for this Surge Current	Percent Life Consumed
810	37.5	5,000,000	.016
81	85.8	500,000	.016
8.1	208	9,500	.085
.81	370	2,000	.041
.081	452	900	.009
.0081	452	900	.0009
			.1679

Cumulative Life Consumption/Year (Lightning)	4.933
Cumulative Life Consumption/Year (Switching)	.1679
Total Cumulative Life Consumption/Year	5.10
Time to Reach Rated Life -	19.61 Years

FIGURE 4
Life consumption: 20 mm varistor (Branch Circuit).

NOMINAL RATINGS

Due to the high-end tolerance allowed of the USA utility power source which may be as high as 132 volts or the potential damage of sustained overvoltages as high as 140 volts for periods of greater than 3 line cycles ("swell"), a nominal varistor rating of 150 volts is recommended for device longevity and safety [Figure 5].

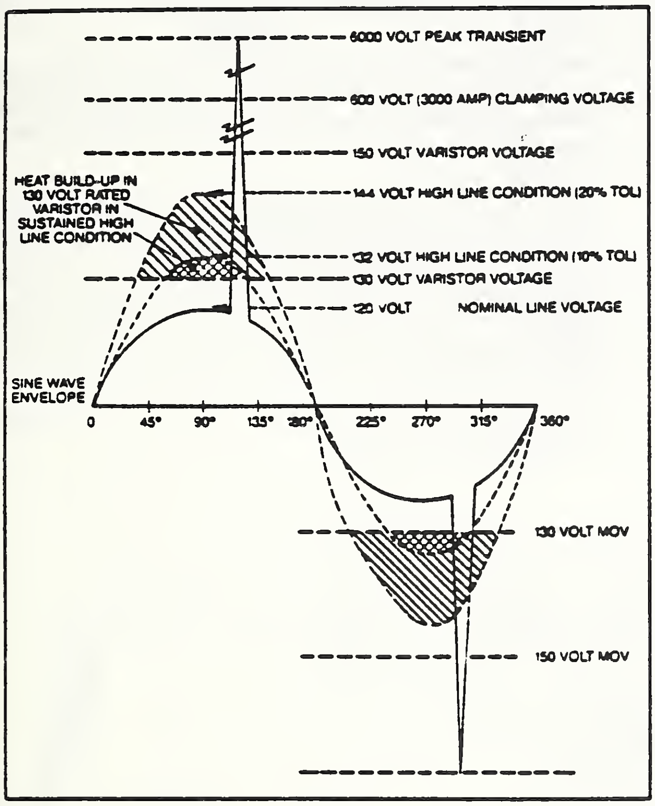


FIGURE 5
Illustration of 150 volt varistor versus 130 volt varistor in high line condition.

A lower rated varistor constantly activated below this level could rapidly degrade.

An industrial plant with poor voltage regulation, and equipped with main transformers set for an output of 460/480 volts when fully loaded, could increase the no load voltage to 490/500 volts over a weekend. This in turn would raise the voltage on the control transformer 115 volt winding to somewhere between 130 and 137 volts. In this circuit equipment utilizing 130 volt varistors may have a high probability of failure.

CLAMPING RATING

Users are cautioned from using varistors with clamping voltages which may be too low.[7]

Lightning has been characterized as 200,000 Volts/80,000 Amps remotely, 10,000 to 20,000 Volts/Amps outside the service entrance, and as high as 6,000 Volts/3,000 Amps within a facility, levels above which receptacles may arc over.

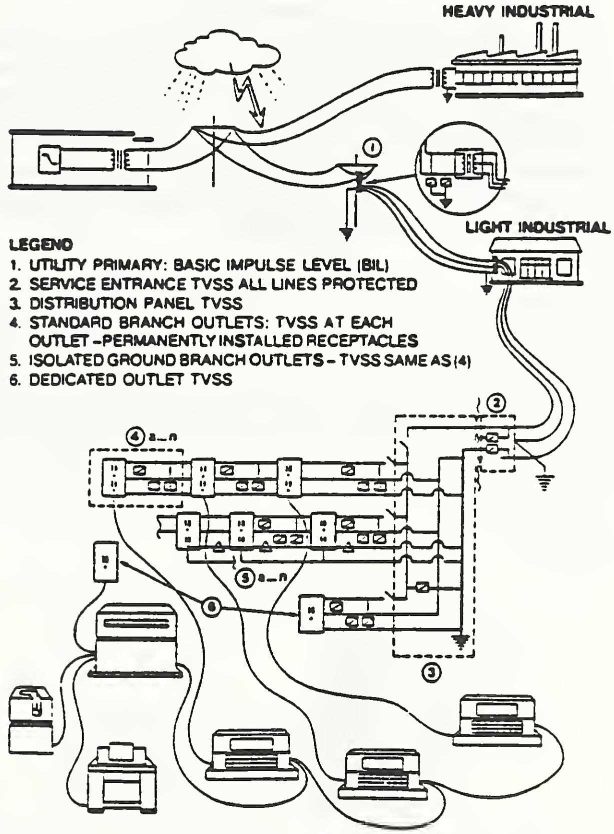
Considering the current handling capability of branch copper gauge wire, the strike and creep clearances of metallic contacts within receptacles and the propagation speed of electricity in a copper conductor, it is possible to design a TVSS receptacle for the worst case transient energy stress of electronic systems installed in the branch circuit.

The TVSS receptacle, when tested at the IEEE and UL level of 6,000 Volts open-circuit voltage and 3,000 Amps short-circuit current, must be capable of diverting to ground any overvoltage above 600 Volts before it reaches the sensitive electronics.

To adequately protect sensitive equipment from lightning, the author recommends the coordination of 32 mm varistors installed at the service entrance and 20 mm varistors at each wall outlet into which sensitive equipment is plugged [Figure 6].

POWERLINE "PROTECTION DECISION-TREE"

One of many models on helping the end-user identify cost/performance tradeoffs from effective to maximum protection includes the TVSS receptacle at the equipments point-of-use, through the UPS for critical loads [Figure 7].[8]



COORDINATED TVSS DEVICES AT THE SERVICE ENTRANCE, DISTRIBUTION PANEL AND AT EACH OUTLET OF STANDARD, ISOLATED GROUND OR DEDICATED RECEPTACLE, PERMANENTLY INSTALLED UNDER THIS SCHEME. DATA LINE IS NOT EXTERNALLY PROTECTED.

FIGURE 6
Facility service entrance and branch protection.

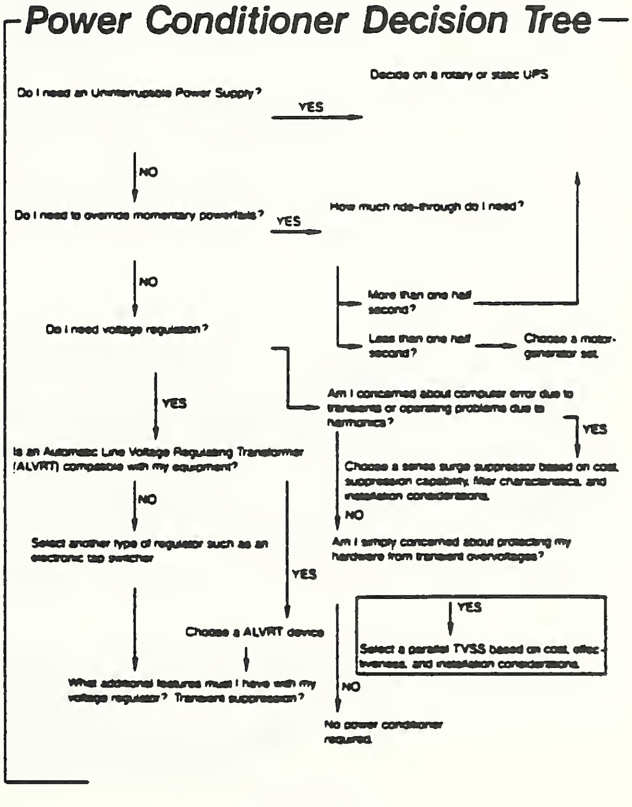


FIGURE 7
Powerline "Protection Decision - Tree".

COST OF EQUIPMENT MAINTENANCE DUE TO POWER SURGES

The original personal computer's estimated board replacement cost was $100 to $200 if the diagnostics performed by the trouble-shooter did not resolve equipment malfunction. To replace the newer MCA board may cost up to $2,000. The FIPS 94 document cites that service engineers typically report "no fault found" in more than 90 per cent of their calls for unscheduled maintenance. A recorded transient rarely coincides with the time of occurrence of a computer system malfunction.[9]

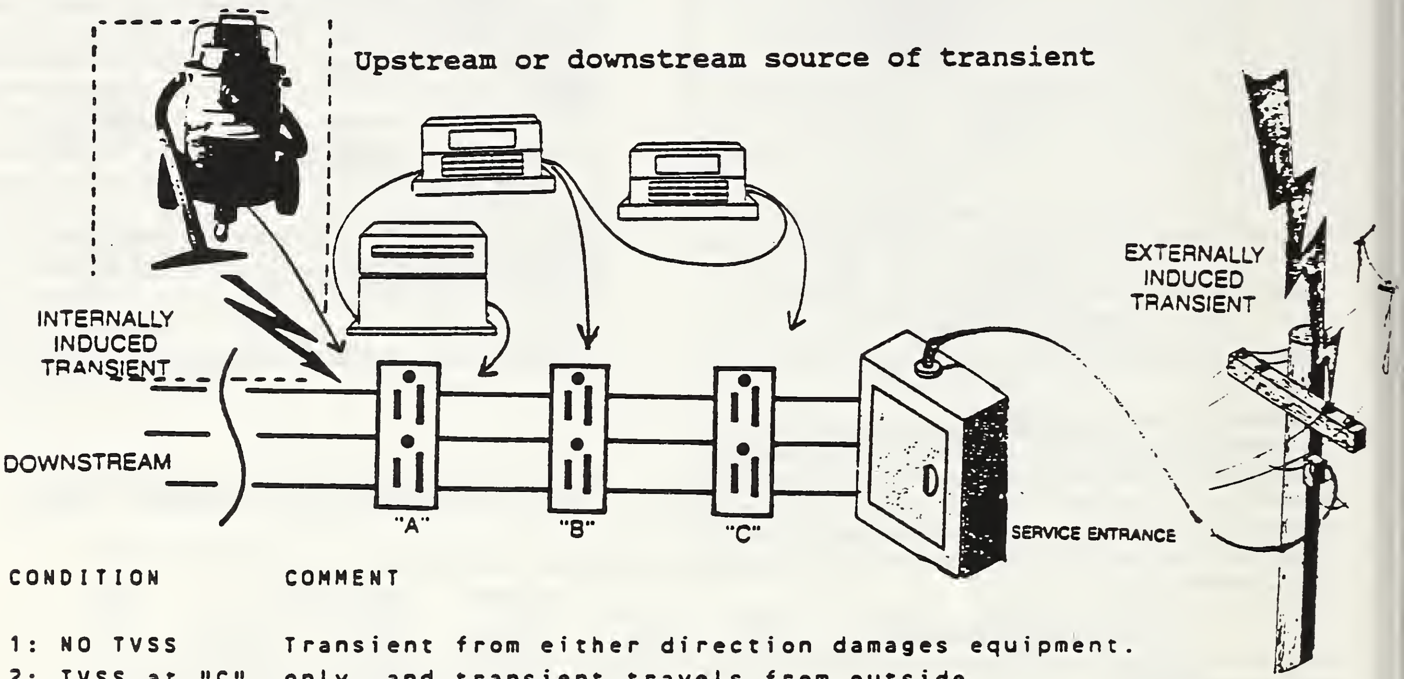
TVSS INSTALLATION CAVEATS

Full, equal and symmetrical protection is desirable in all three modes of branch wiring (line and neutral, line and ground, and neutral to ground) since a transient may occur in any leg. A reasonable level of common mode high frequency noise filtering is recommended. Mixing application-dependent and uncoordinated components in a single "black box" may be undesirable. The matching of nominal voltages for suppressor devices at low values of test current doesn't assure effective current sharing under high current surge conditions. Unmatched varistors for parallel connection result in imprecise values of dynamic impedance from the V-I characteristic curve published by manufacturers without uniform batch characteristics and proper process control during manufacture.

Recommended features include a built-in fuse to disconnect a failed protection device while the outlet continues to function as a powered receptacle, and a solid state LED monitor to indicate that protection is intact.

Since it is impossible to predict the direction of propagation of a transient which can occur upstream or downstream within a facility's branch wiring, the TVSS receptacle is not designed to offer downstream feed-through protection. It has been demonstrated that in the case of a high voltage transient, thousands of volts could destroy an intervening workstation if the source of the transient is not in the direction in which the first outlet is a TVSS [Figure 8].

Proper grounding, wiring, shielding and bonding are prerequisites for equipment performance.



CONDITION	COMMENT
1: NO TVSS	Transient from either direction damages equipment.
2: TVSS at "C"	only, and transient travels from outside.
RESULT:	FULL downstream protection.
3: TVSS at "C"	only, and internal switching transient travels to receptacle "A" first.
RESULT:	"Let-through Voltage" damages "A" and "B"
4: TVSS at "A"	only, and transient travels to "A" first.
RESULT:	FULL upstream protection.
5: TVSS at "A"	only, and transient travels from panel.
RESULT:	"Let-through Voltage" damages "B" and "C".
6: TVSS at "B"	only, and transient travels towards "A" or "C"
RESULT:	"Let-through Voltage" damages "A" or "C" while "B" protected
7: TVSS at "A",	"B" and "C": FULL PROTECTION AT ALL OUTLETS.

Figure 8 (a)

Transient considerations for equipment installed in unprotected wall outlets.

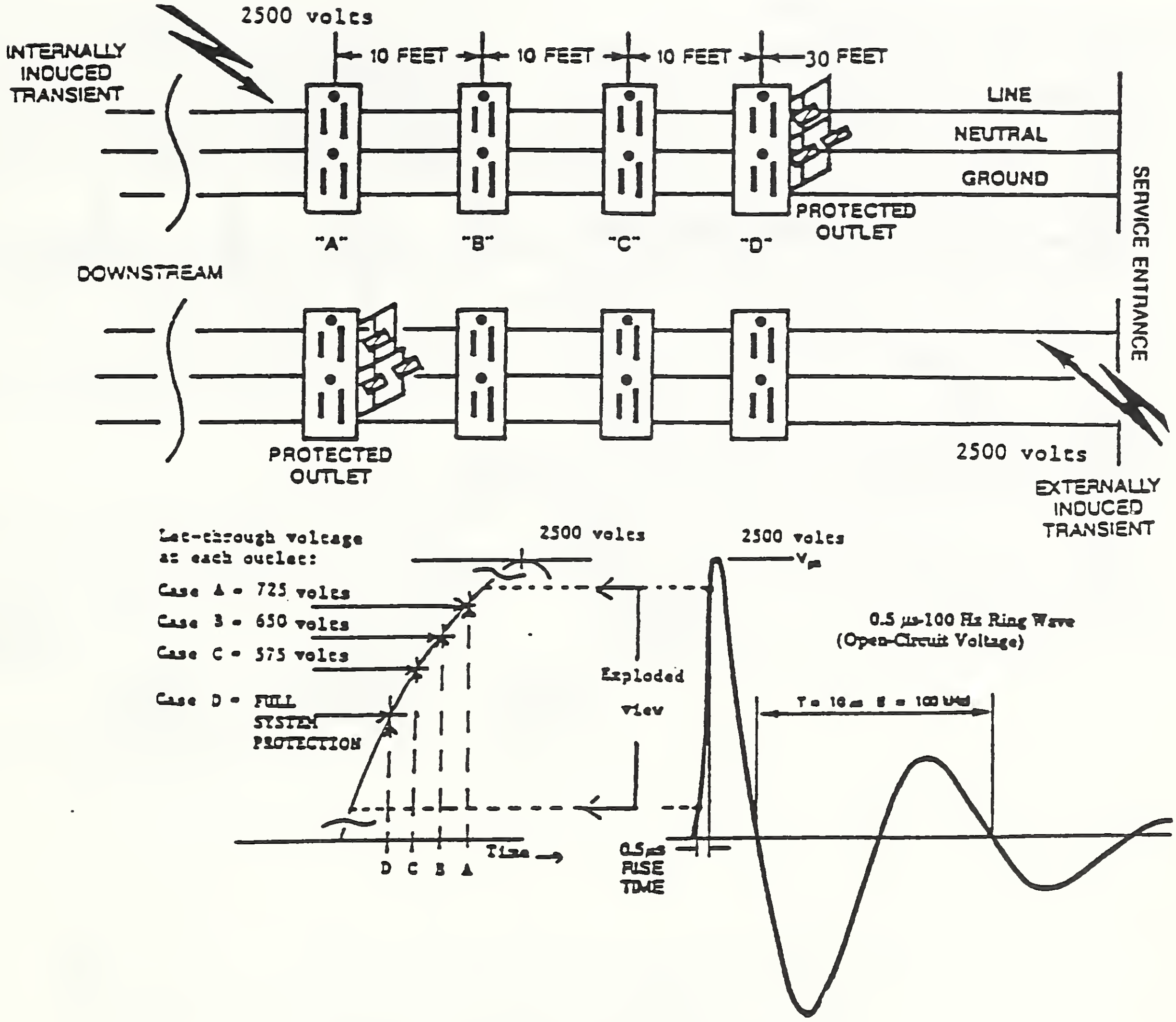


Figure 8 (b)

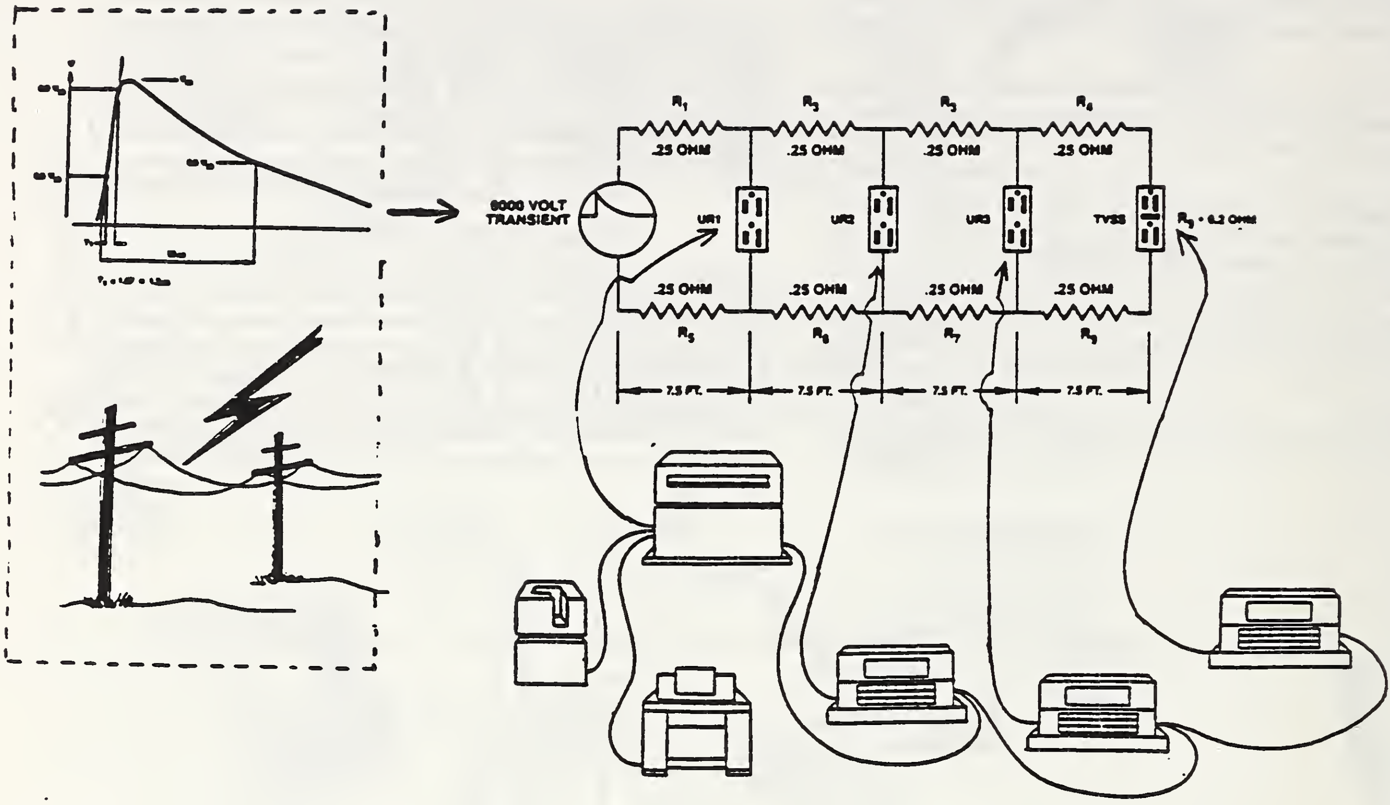
Simplified illustration of the effect of propagation delay on let-through voltage in long branch circuit (ignoring the effect of ohmic impedance between outlets).

Assumptions:

- In a vacuum, the speed of light is approximately one foot in one nanosecond, or billionth of a second (186,000 miles/second).
- In a solid conductor, the speed of a transient spike is approximately one foot in 1.5 nanoseconds (2/3 speed of light).
- TVSS has response time of 100 nanoseconds (nominal).
- Let-through voltage = $\dfrac{(t_s \times d) + t_T}{t_t} \times V$ = 725 Volts

Where:

t_s = Time for transient to travel one foot (nanoseconds/foot)
d = Distance: wall outlet to source of transient (feet)
t_T = TVSS response time (nanoseconds)
t_t = Transient rise time (microseconds)
V = Peak transient voltage (volts)



DATA (Based on GE/Harris MOV manual Fig. 2-2):

1. TVSS = Transient Voltage Surge Suppressor Receptacle
2. UR = Unprotected Receptacle
3. 30 feet = 2 OHM source impedance (IEEE 587)
4. TVSS suppressed voltage = 545 Volts
5. R_9 on-state resistance = 0.2 OHM
6. R_t = R_{total} = R_{1-9} = 2.2 OHM

UR1 Voltage = $\frac{R_2+R_3+R_4+R_6+R_7+R_8+R_9}{R_t} \cdot 6000$ = 4636 Volts

UR2 Voltage = $\frac{R_3+R_4+R_7+R_8+R_9}{R_t} \cdot 6000$ = 3272 Volts

UR3 Voltage = $\frac{R_4+R_8+R_9}{R_t} \cdot 6000$ = 1909 Volts

TVSS Voltage = FULL SYSTEM PROTECTION

Figure 8 (c)

Effect of let-through voltage from impulse waveform in short branch circuit (simplified line impedance based illustration, D.C. condition only).

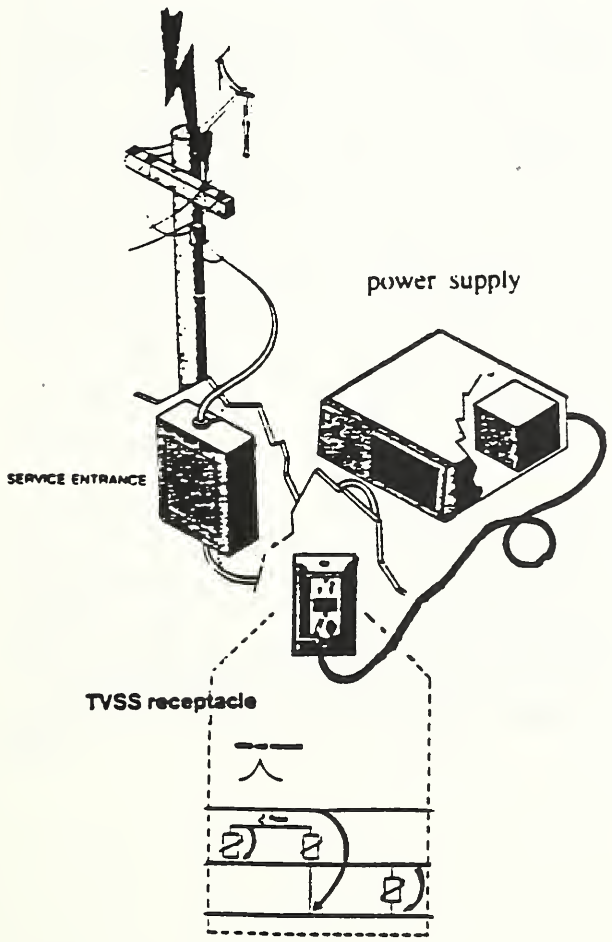
SUMMARY

In non-critical applications most power related disturbances are eliminated with a TVSS wall outlet receptacle localized at the point-of-use between the equipment cordset and the AC power. A decision-tree model suggests effective protection of the TVSS receptacle for microcomputers through maximum UPS protection of a mainframe.

A reliability model of the varistor, the primary component of the TVSS in powerline applications estimates 20 years nominal life.

Until the TVSS became commercially available, an end-user frequently invested in a protection device costing almost as much as the system being protected itself.

TVSS receptacles are replacing regular wall outlets, in extending sensitive equipment performance, reducing contracted maintenance and increasing user productivity. The author recommends the coordination of larger MOV's at the mains and the TVSS with 20 mm 150V varistors at each outlet. Care must be taken with installation practices and design features for full, equal, and symmetrical protection.



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Mr. Basil Dillon-Malone received his BE (Electrical Engineering) Degree from University College Dublin in 1969 and has been Electronics Marketing Manager at Pass & Seymour/Legrand since 1985. Previously he worked with General Electric for 12 years in new product planning, including the metal oxide varistor. He also worked with Sperry (Univac) and was Director of Marketing with Honeywell Optoelectronics. Mr. Dillon-Malone is a member of IEEE and is on the IEEE Surge Protective Devices Low Voltage Sub Committee, serving on several of its working groups. He is a member of the NEMA technical committee (TVSS) since its formation in 1986. He is a delegate to ANSI/IEEE. He is task force chairman of the IEEE working group on AC varistor applications.

REDUCTION OF CLEARANCE IN EQUIPMENT THRU USE OF TRANSIENT OVERVOLTAGE CONTROL WITHIN THE EQUIPMENT

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During the past few years IEC Sub-committee 66E (SC66E) has been working toward completion of IEC Publication 1010-1-1990 (IEC 1010) "Safety requirements for electrical equipment for measurement, control, and laboratory use". The standard, as published in late 1990, has Clearance, and Creepage distance Tables which allow selection of spacings to harmonize with the operating conditions described in IEC publication 664-1980 (IEC 664) "Insulation co-ordination within low-voltage systems including clearances and creepage distances for equipment". The spacing tables in IEC 1010 follow the normal practice which assumes reasonably worse case conditions for the equipment. It has been known that reduced clearances could provide equivalent protection under some conditions; however, a method to define these conditions for a standard has not been available. SC66E has now accepted two methods of reducing clearance below those given in the tables and these will be included in the First Amendment to IEC 1010 which is in process of publication as this paper is prepared. The first method utilizes homogeneous field construction and provides acceptance of reduced clearance on the basis of a voltage test. Most applications for homogeneous field construction are in high voltage secondary circuits. The second method, which will be described in this paper, allows reduced clearance under controlled transient overvoltage conditions in which the overvoltage control or limiting means is verified by a 1.2x50uSec impulse test.

The tables for clearance in IEC 1010 were calculated to stand-off the 1.2x50uSec Impulse Withstand Voltage for the Phase to Earth Voltages as given in Table 2. A Typical table of clearances and corresponding Peak impulse levels is shown in Table 1 and was taken from IEC 1010, Table D4, Basic insulation, Pollution Degree 2, Installation (Overvoltage) Category II. These clearances follow Line 2 of Figure 1 which shows peak impulse withstand voltage versus distance (clearance). The withstand lines of Figure 1 give a small margin below breakdown voltage for the conditions of Altitude 2000 meters, Temperature up to 40°C, and slightly pre-ionized air generated by ultra violet light used during the breakdown voltage tests from which Figure 1 was derived. Table 3 lists clearance values from Figure 1. Column D1 gives clearance values from Line 2 and column D2 gives clearance values from Line 3. D2 is calculated using 1.25 times the peak voltage for margin.

An examination of Figure 1 shows that a given peak voltage will intersect three lines giving clearance (distance) values which can each stand off the voltage depending on the shape of the electrodes and the wave shape of the voltage. For example, the clearance for 2500Vpk can be seen as 0.59mm for Line 1 Case B, 1.5mm for Line 2 Case A 1.2x50uS impulse, and 2.2mm for Line 3 Case A 50/60 Hz Peak Sinusoidal Voltage. Safety standards such as IEC 1010 give Tables of clearance based on Case A inhomogeneous field construction.

Working Voltage rms or dc V	Clearance Distance mm	Peak Impulse Voltage 1.2x50uSec
50	0.2	500
100	0.2	800
150	0.5	1500
300	1.5	2500
600	3.0	4000
1000	5.5	6000

Table 1
Clearance for Basic Insulation, Overvoltage Category II
Pollution Degree 2

<u>Reduction of clearance below Table values</u>

The method described below for reducing clearance by limiting, that is clamping, the maximum level of transient impulse overvoltage thru means within the equipment provides equivalent protection to clearance at table values. For example, a 300V circuit of overvoltage category II, must withstand a 2500V impulse and have a clearance of 1.5mm according to Table 1. If, however, the impulse is clamped at a lower level, the clearance can be reduced and still withstand both the impulse and the working voltage.

Consider for the example, that a metal oxide varistor (MOV) is used to clamp the impulse overvoltage. A surge test must then be done to measure the clamping level from which a new reduced clearance can be determined. SC66E has accepted a test in which the impulse from a 1.2x50uSec surge generator, at the open circuit peak voltage of the impulse called for in Table 1, is applied to the clamping circuit. The resulting clamped level of the impulse is measured. Considering appropriate tolerances, this clamped level forms the basis of a new reduced clearance. Two factors of the test remain, first, impedance of the generator and second, the ratio of peak working voltage to peak clamped impulse overvoltage.

The surge generator is specified for the test as follows.

- Open circuit Voltage Waveform: 1.2x50uSec impulse
- Peak open circuit impulse voltage (no load): according to Table 2
- Short circuit waveform: 8x20uSec current impulse
- Generator Impedance = $\dfrac{\text{Peak open circuit voltage}}{\text{Peak short circuit current}}$

Overvoltage category III circuits:	2 Ohms
Overvoltage category II circuits:	12 Ohms
Overvoltage category I circuits:	30 Ohms

Voltage Phase to earth	Preferred series of impulse withstand voltages for overvoltage categories I to III impulse 1.2x50uSec V		
V	I	II	III
50	330	500	800
100	500	800	1500
150	800	1500	2500
300	1500	2500	4000
600	2500	4000	6000
1000	4000	6000	8000

Table 2 Refer: IEC 664-1980
Impulse Withstand Voltages IEC 1010-1-1990

This method of clamping the impulse overvoltage applies generally to low voltage circuits up to 1000V, and somewhat above, in which clearance must be selected to stand-off expected impulse or surge levels that are considerably greater than the peak working voltage. For example, the 300Vrms (424Vpk) circuit mentioned in the example calls for a clearance to meet a 2500Vpk impulse. Clamping of the impulse overvoltage well above 424Vpk but under 2500Vpk allows considerable room for clearance reduction.
Note also in Figure 1, that the limit for clamping, in which the overvoltage could be clamped to a level only slightly above the peak working voltage, could shift the required clearance from Line 2, a distance related to impulse, to line 3, a distance related to peak 50/60Hz or dc voltage. An interpolation to specify clearances between Lines 2 and 3 based on the ratio of peak working Voltage (Uw) to peak circuit voltage (Umax) which equals (Uw/Umax) is given in Figure 2 below. In practice two clearances must be calculated for the clamped impulse level, first the minimum clearance (D1) from Figure 1 Line 2 and then the maximum clearance (D2) from Line 3. These clearances have been tabulated in Table 3 and include a margin for the working voltage clearance. A final clearance for the clamped overvoltage can be calculated within the range of clearances given in Table 3 using the procedure steps given below.

Design Steps for Reduced Clearance with Values from the Example

The following steps were used to calculate a reduced clearance in a practical example in which 900V Metal Oxide Varistors were used to clamp impulse overvoltage in the measuring circuits of a data scanner.

Rating of the circuits: 300Vac or 424Vdc, Overvoltage Category II

Clearance from Table for Basic insulation from Table 1: 1.5mm

Impulse overvoltage from Table 1 2500vpk

Surge Generator impulse, see Fig.3 1.2x50uS 2500Vpk 12 Ohms impedance

Clamping level as measured, see Figure 4 (include tolerance) 1770Vpk

Clearance range , Table 3 D1 0.75mm D2 1.79mm

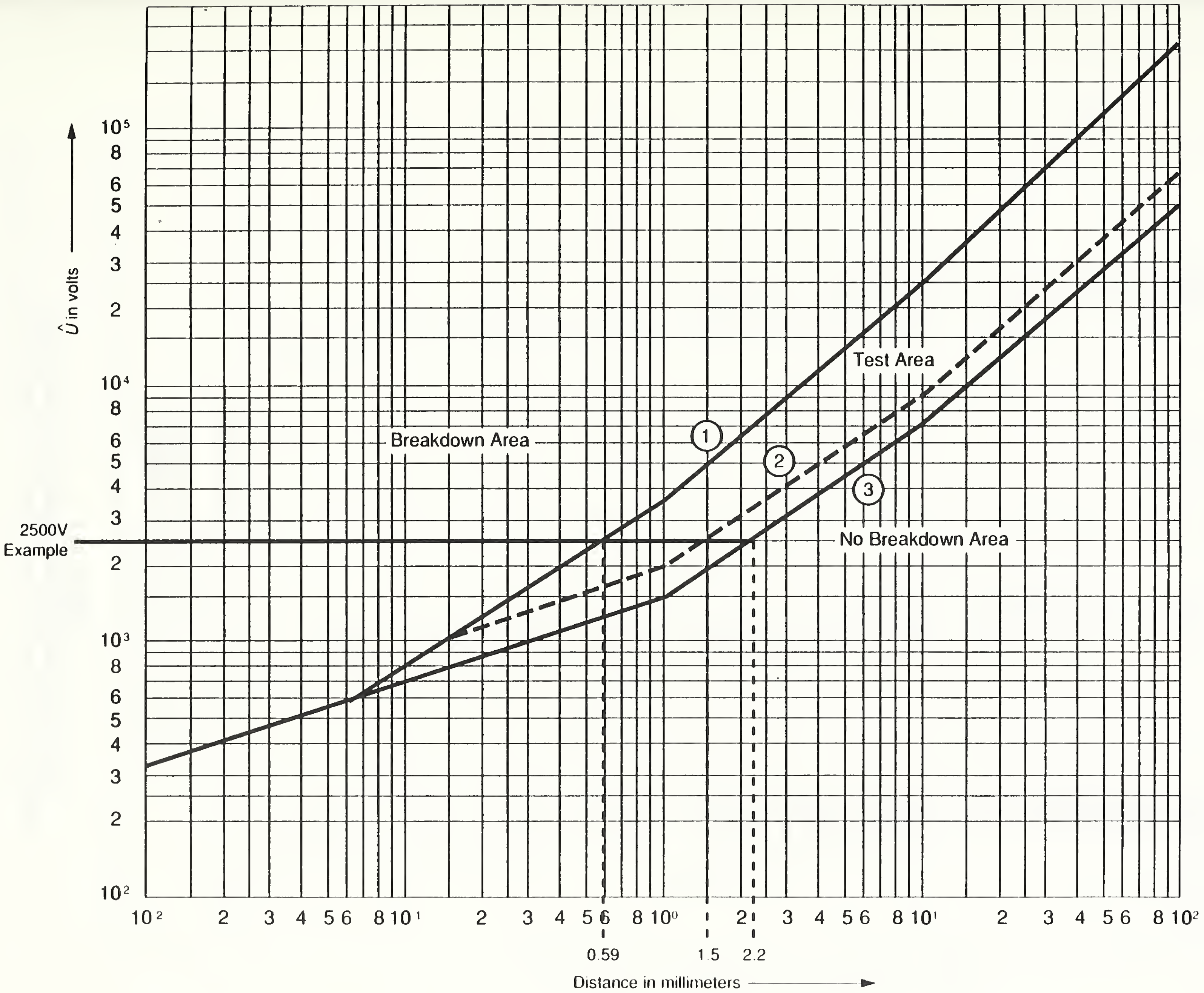
Ratio $\hat{U}w/\hat{U}max$ (include tolerances) 1.1x424Vpk / 1770Vpk = 0.264

Factor from Figure 2 F = 0.08

Calculate reduced clearance = D1 + F (D2 - D1) = 0.83mm

Results of Calculation for reduced clearance

Installation of a 900V MOV in this example clamped the 2500Vpk impulse to 1660Vpk. Dynamic impedance of the MOV accounts for the rise from 900V to 1660Vpk. For tolerance and convenience, the 1770Vpk clearance range values from Table 3 were used to calculate a clearance reduced from 1.5mm to 0.83mm. Performance of the circuit to both working voltage and transient overvoltage with the MOV and reduced clearance of 0.83mm remains the same as the circuit with 1.5mm clearance without an MOV to clamp the impulse. Recorded waveforms of the open circuit impulse and the impulse when clamped by the MOV are shown in Figures 3 and 4. The current thru the MOV due to the impulse is shown in Figure 5. Figure 6 shows the 8x20uSec impulse measured to verify the impulse generator impedance. The impedance was calculated to be 11.5 Ohms, which is appropriate for a 12 Ohm generator requirement.



Case A
Inhomogeneous Field Construction - Sharp pointed electrode spaced from a flat plane

Case B
Homogeneous Field Construction - Two rounded electrodes

① Case B
$\hat{U}$ 1.2/50 and $\hat{U}$pk 50/60 Hz

② Case A
$\hat{U}$ 1.2/50

③ Case A
$\hat{U}$pk 50/60 Hz

Reference:
From IEC 664-1980

NOTE: 50/60 Hz withstand voltage lines are labled incorrectly as Vrms in IEC 664-1980 and should be Vpk as shown here.

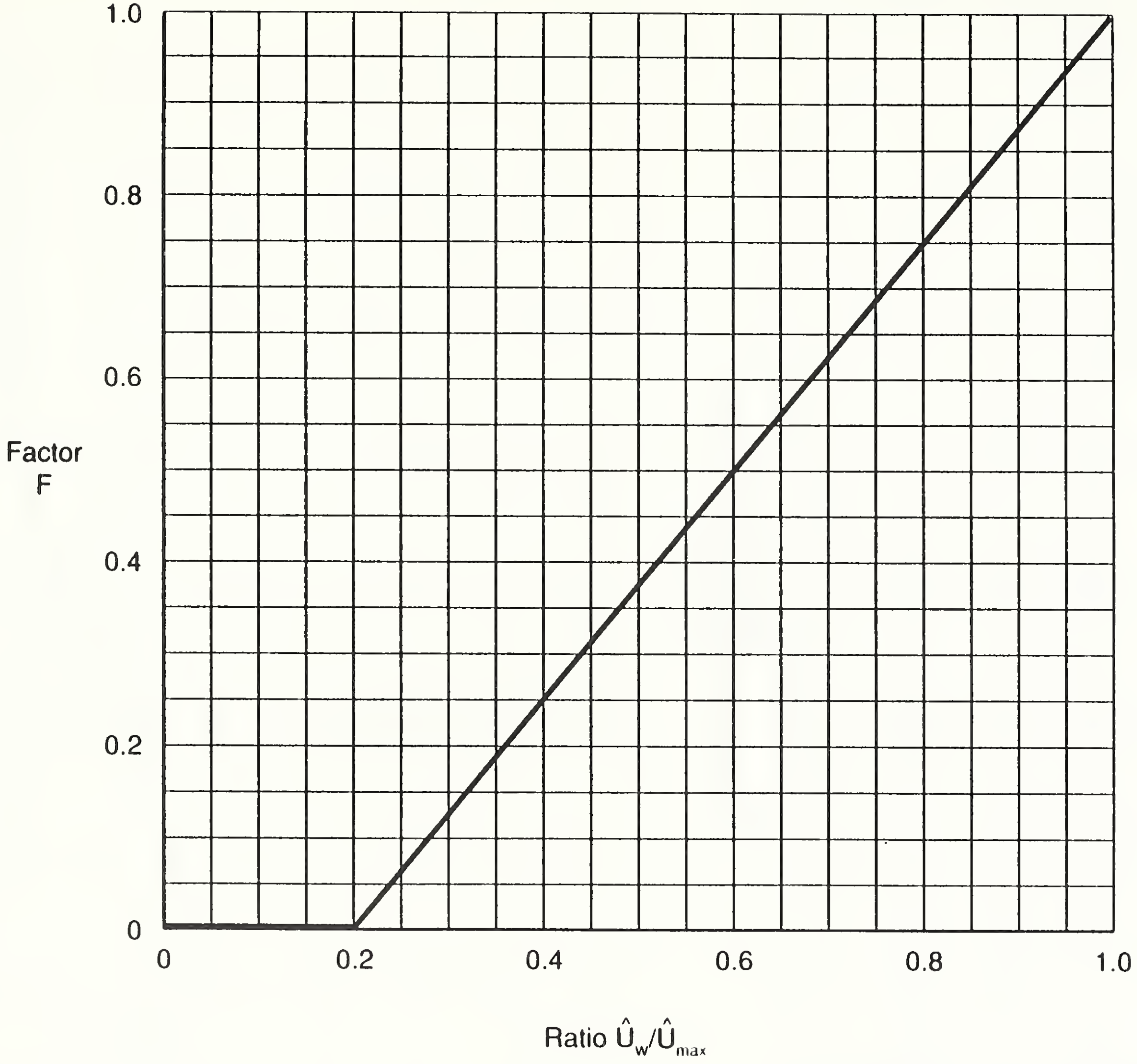
Withstand Voltage for an Altitude of 2,000 m Above Sea Level
Figure 1

	CLEARANCE in mm	
Ûmax in V	When Ûmax is mainly impulse: D1	When Ûmax is working voltage with no impulse: D2
14.1 to 226	.01	.01
283	.01	.013
330	.01	.020
354	.013	.025
453	.027	.052
500	.036	.071
566	.052	.103
707	.081	.202
800	.099	.293
891	.12	.41
1130	.19	.83
1410	.38	1.27
1500	.453	1.40
1770	.75	1.79
2260	1.3	2.58
2500	1.5	3.0
2830	1.7	3.61
3540	2.4	5.04
4000	2.9	6.05
4530	3.5	7.29
5660	4.9	10.1
6000	5.4	10.8
7070	6.9	13.1
8000	8.3	15.2
8910	9.7	17.2
11300	12.9	22.8
14100	16.7	29.5
17700	22.0	38.5
22600	29.0	51.2
28300	38.0	66.7
35400	49.0	86.7
45300	66.0	116
56600	85.0	150
70700	110	195
89100	145	255

NOTE - Linear interpolation is permitted

0.01 mm for POLLUTION DEGREE 1
0.20 mm for POLLUTION DEGREE 2

TABLE 3
Range of Clearance Related to Maximum
Voltage for Basic Insulation or Supplementary Insulation

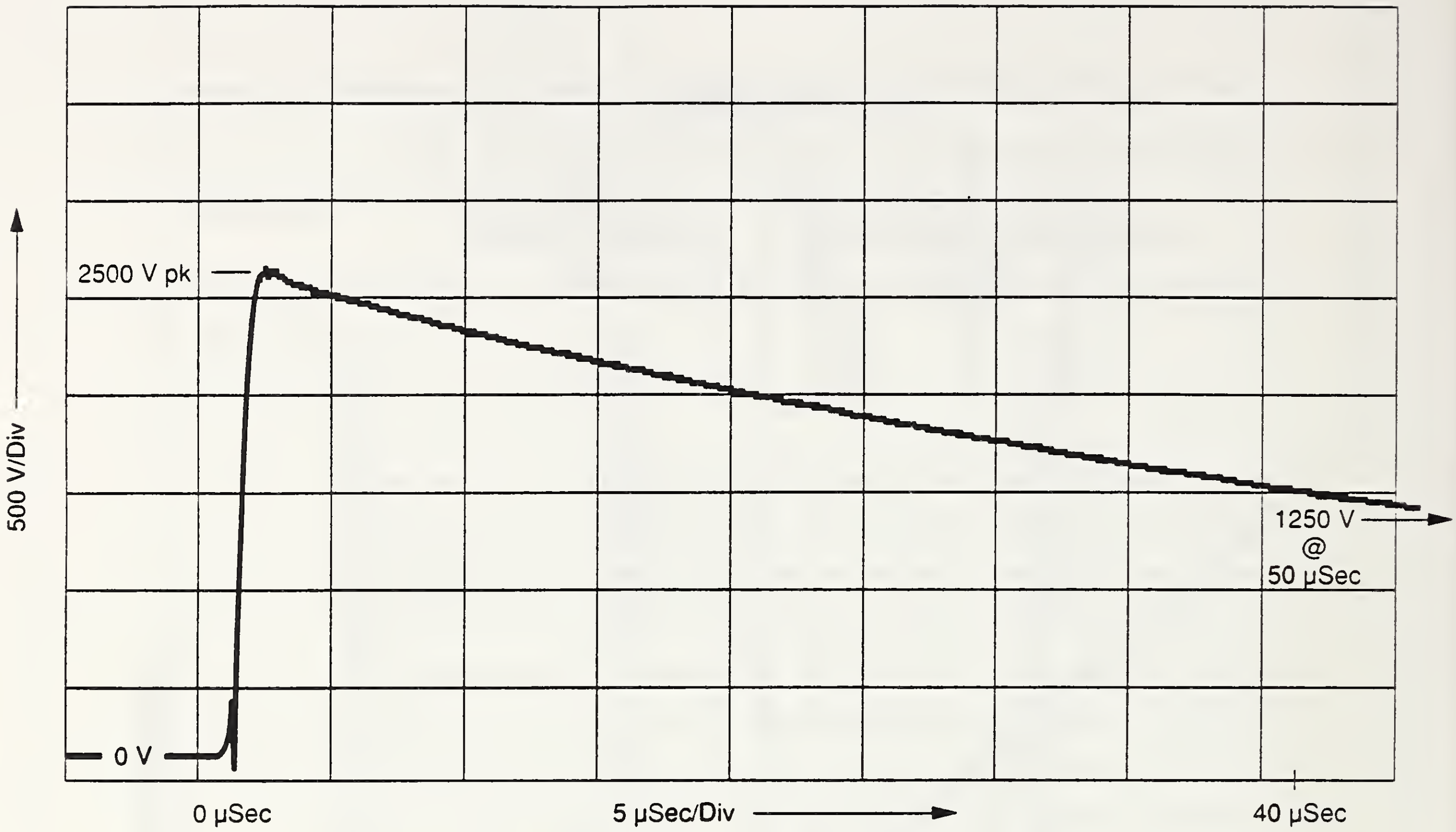


$F = 0$
where $\hat{U}_w/\hat{U}_{max} \le 0.2$

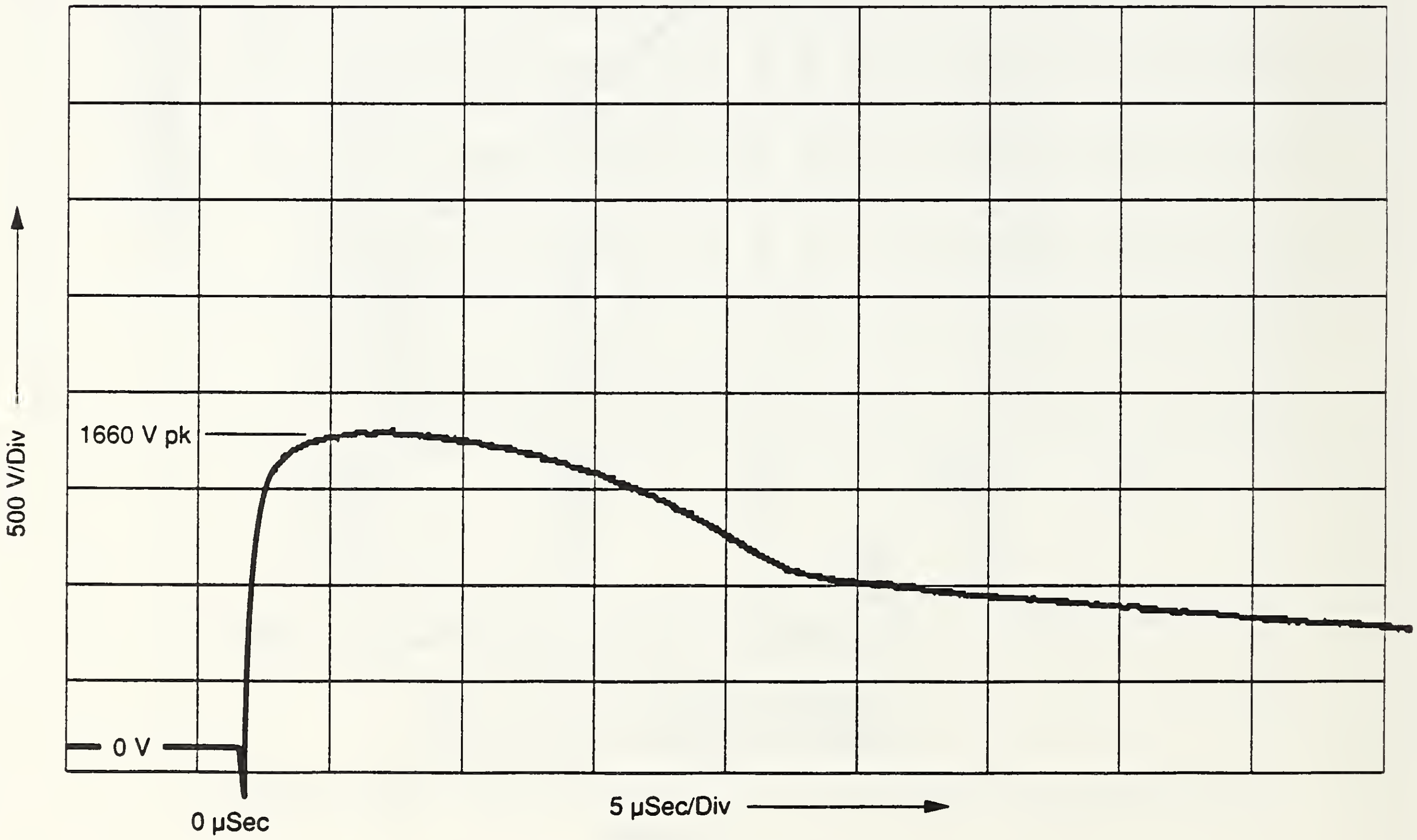
$$F = 1.25 \frac{\hat{U}_w}{\hat{U}_{max}} - 0.25$$

where
$0.2 < \hat{U}_w/\hat{U}_{max} < 1$

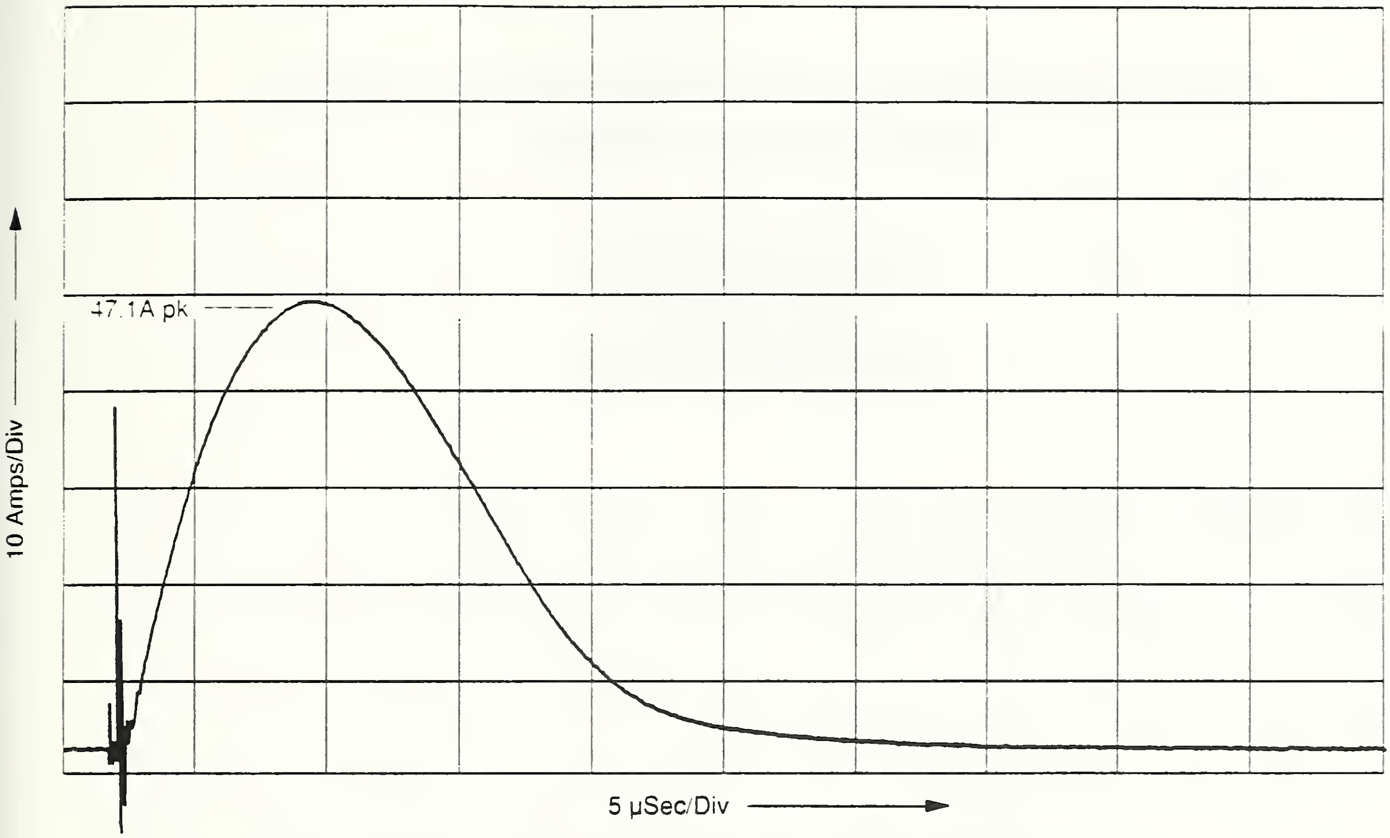
Interpolation Factor For CLEARANCE
Figure 2



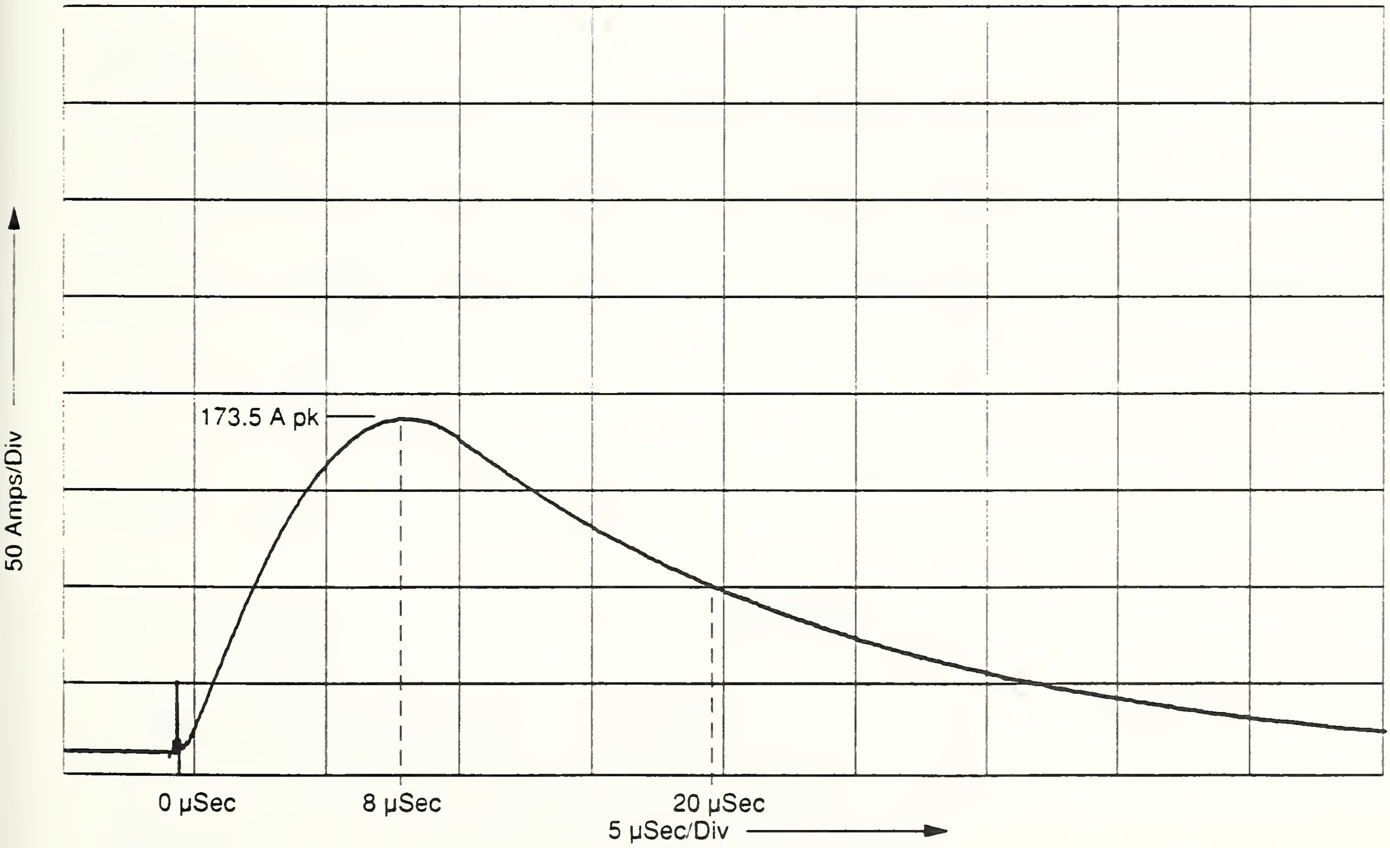
Impulse Voltage, Open Circuit
Figure 3



Impulse Clamped by 900 V Mov
Figure 4



Current Thru 900V MOV During Clamped Impulse of Fig. 2
Figure 5



8x20μSec Current Waveform, Calibration Check with Short Circuit of 2000V pk Impulse to Verify Generator Impedence
Figure 6

RESIDENTIAL SERVICE ENTRANCE SURGE SUPPRESSION DEVICE TESTING & CONSIDERATIONS

by

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Abstract

In an effort to elevate the level of power quality to residential customers, the Georgia Power Company has decided to include service entrance surge suppression as an option for improving power quality in troubled areas. The Research Center and Power Quality departments worked together to investigate an approach for this option. Several tests were deemed necessary before any device would be acceptable for residential use. Mechanical and electrical tests were devised to assure the company of desired performance. Specifications for testing such a device were drawn up with reference to existing standards and laboratory testing. Since service entrance surge suppression devices are fairly new, the Research Center evaluated them using worst case speculation testing, comparison tests, modified industry tests, and existing engineering data. Of particular concern was an "end-of-life" test. This test was devised to determine the response to power follow current when a surge suppressor element failed in service. This paper will present the testing performed and suggested requirements by the Research Center for residential service entrance surge suppression devices.

Introduction

Residential surge suppression is now a part of the Georgia Power Company's efforts to improve customer service. It was determined that a combination of indoor surge suppression and a service entrance surge device would greatly benefit those customers with sensitive electronic equipment. The service entrance device would minimize electrical surges entering the residence from the secondary side of the transformer while the indoor devices located at the sensitive electronic equipment would minimize any transients induced on the interior wiring from nearby lightning strikes. Residential indoor surge suppression devices are prolific. Much testing has already been devoted to these devices and it was felt that the proper selection of these devices could be performed by simple engineering evaluation of the available data. On the other hand, service entrance surge suppression devices are relatively new on the market and should be evaluated carefully to assure proper performance, as historical operating information is not readily available.

The Research Center was asked to review existing standards, evaluate lightning data, and consider previous laboratory tests. Several mechanical and electrical tests were deemed necessary to address the concerns for a device used on residential service entrances. Grounding methods were also discussed with the Meter Department, which would be responsible for installation of the devices. Several surge suppression devices were evaluated. However, one aspect came up which had not been considered before. Only one manufacturer has a patent on the plug-in meter extender type surge suppression device, which is the easiest to retrofit at a residence.

Evaluation

Viewpoint

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

Concerns/Considerations

The electrical characteristics of a surge suppression device are usually the first, and sometimes, the only properties ever considered when choosing these devices. These are important properties, but do not address the physical and mechanical properties which are a necessity for long term service in a real world installation.

Physical characteristics of a residential service entrance surge suppressor should include some indication of suppressor condition, easy installation (including method of grounding), environmental resistance, and safety. Several devices evaluated had neon type indicator lamps. All lamps have a finite lifetime. In most cases, this is less than three years. The surge suppression devices of interest will have a mean time before failure much greater than ten years. Therefore, the use of indicator lamps is unacceptable. 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 up to question. One manufacturer added a clear Lexan® window to the bottom of the meter base extender which housed the surge suppression devices. During testing, when the protective fuses blew, the clear Lexan® window properly clouded over. This gave a noticeable indication of fuse operation and surge protector condition.

Ease of installation was a primary concern. Therefore, meter base extenders with built-in surge suppression devices were chosen as the easiest for the company to retrofit a residential service. These devices 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 Meter Department rejected any idea of modifying the meter box to accept any of the surge suppression devices which 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 also rejected. Where surges entering the residence from the electric service are concerned, better surge suppression is achieved by devices located at the service entrance versus the power distribution panel. The longer leads and paths required for a distribution panel installation reduce the effectiveness of such an installation. However, there may be a trade-off here, since the service entrance device will see larger surges; but the internal house wiring between the meter and power distribution panel will be protected from possible flashover and fire.

Resistance to the environment should be considered. Susceptibility to moisture ingress should be evaluated. Some devices were epoxy encapsulated, o-ring sealed, or covered with a dry tar-like substance. Resistance to ultraviolet radiation is a necessity. Presently, the Research Center has not tested for ultraviolet resistance and has relied on the manufacturer's testing data. Also, corrosion resistance is an obvious test which is necessary. Future evaluation testing at the Research Center should include a "salt-fog" test which will determine a device's water tightness and corrosion resistance. The flammability of any device should be investigated before installation in the field. Flammability testing (self-ignition point) is beyond the capabilities of the Research Center, and for now, the manufacturer's testing data will have to suffice.

There are several mechanical properties of a plug-in residential service entrance surge suppression device which 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. Impact tests using a drop-weight tester were conducted to evaluate the impact resistance of different meter base extender housings available. Thermal resistance of the housings was evaluated using a hot air oven. If the meter base extender jaws can not maintain a low contact resistance with the meter blades, then extensive damage may occur. A current load cycle submersion test was performed to evaluate the different meter jaws which were available.

To evaluate the electrical characteristics of these surge devices, the Research Center performed four varieties of tests. These were: 1) varistor voltage, 2) surge withstand, 3) temporary overvoltage, and 4) "end-of-life failure mode".

All devices evaluated contained metal oxide varistors as the surge suppression elements. Therefore, varistor voltage measurements were made on all units tested. This measurement allows characterization of the voltage class of varistor used in each design. Also, it can indicate to some extent the degradation of a device after testing.

Surge withstand testing was of great concern for this application. Therefore, IEEE Std. 587-1980, "IEEE Guide for Surge Voltages in Low-Voltage AC Power Circuits" and ANSI/IEEE C62.11-1987, "IEEE Standard for Metal-Oxide Surge Arresters for AC Power Circuits" were consulted. The ANSI/IEEE C62.11 standard indicates that secondary arresters should have a discharge voltage test at currents of 1500A and 5000A of an 8 x 20μs wave and a discharge current withstand test of 10kA of a 4 x 10μs wave. IEEE Std. 587 indicates that outdoor secondary equipment may encounter surges of 10kV - 20kV. Also, this standard states that for outdoor equipment the unidirectional impulse is more appropriately used for testing (ie. 1.2 x 50μs voltage and 8 x 20μs current waves). Accordingly, outdoor secondary current amplitudes may exceed 10kA. Table 1, category B (major feeders, short branch circuits, and distribution panels), in IEEE Std. 587, states the indoor environment can include 3kA medium amplitudes and 40 to 80 Joules of energy. This standard also mentions that secondary arresters with 10kA ratings have been applied successfully for many years in location category C (outside and service entrance). Finally, it says that one must consider the cumulative energy deposition of multiple lightning strokes.

Two types of surge withstand tests were performed. The first consisted of the application of an 8 x 20μs current wave with increasing amplitude until device failure. The second test was a multiple surge withstand test. In this test, up to 100 surges from a cable fault locator (thumper) were applied at six second intervals to the surge suppressor.

Because of neutral and/or connector corrosion problems in the past, which cause voltage swings on the residential 120V legs, the temporary overvoltage (TOV) characteristic of the device was of importance. Therefore, temporary overvoltage measurements were made and defined at a point just below where thermal runaway occurred. Although possible voltage swings due to neutral and/or connector corrosion vary in each case, the devices with the highest TOV are always desired.

The question came up of what happens to a plug-in residential service entrance surge suppressor when it fails in service with the fault current available from a distribution transformer. An "end-of-life failure mode" test was devised to answer this question. 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 surge suppressor 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 occurs in the field, then the high side transformer fuse will have to clear the fault. Not only will the residence lose service power, but, because of the long fuse curve of the high side fuse, the residence may sustain extensive damage at the service entrance location.

Tests/Results

Ultraviolet Resistance

Presently, the Research Center has not performed an ultraviolet resistance test. However, this should be required in the future. The device selected for use has passed ASTM G53-84 for ultraviolet stability according to the manufacturer. Future testing should require the compound to withstand one thousand hours of exposure according to ASTM G53 in a QUV Accelerated Weathering Tester.

Salt-Fog Exposure

Presently, a corrosion resistance test has not been performed by the Research Center. However, a salt-fog exposure test should be required in the future. The device selected for use has passed ASTM B117 for salt and spray according to the manufacturer. Future testing should require the device to withstand five hundred to one thousand hours of exposure in a salt-fog chamber according to ASTM B117.

Flammability

Any evaluation should require a flammability test, either a vertical flame or a self-ignition point test. The Research Center can perform a vertical flame test, but does not have the equipment necessary for a self-ignition test. The self-ignition test is a more precise test and preferable. The device selected for use has been tested by the manufacturer per ASTM D1929 and exhibited a self ignition temperature of 1076°F.

Impact Resistance

Standards referred to for test techniques and impact force were ASTM D2444, "Impact Resistance of Thermoplastic Pipe and Fittings by Means of a Tup (Falling Weight)" and ANSI/NEMA Std. TC 8-1978, "Extra-Strength PVC Plastic Utilities Duct for Underground Installation". Two different types of meter extender housings were evaluated. One type was constructed of fiberglass materials while the other was constructed of thermoplastic materials.

A drop weight tester with a 20 pound weight (tup) and a type B (two inch radius) nose was used. The weight was dropped from a distance of one foot. If no damage occurred, the drop height was increased in one foot increments and the test was performed again. The results are shown in Table 1.

Table 1

Sample	Material	Drop Height	Comments
A	Fiberglass	1 ft.	Section of housing broken off
B	Fiberglass	1 ft.	Crushed and deformed section of housing
C	Thermoplastic	1 ft.	No damage
		2 ft.	No damage to housing; metal tabs bent
		3 ft.	No damage to housing; additional bending of tabs
		4 ft.	No damage to housing; additional bending of tabs

The energy delivered to the sample at impact is determined by multiplying the weight of the tup (20 pounds) times the drop height. The thermoplastic housing could withstand at least four times more impact force than the fiberglass housings.

Thermal Withstand

Two fiberglass and one thermoplastic meter extender housings were placed in an air oven for two hours at each temperature of 60°, 80°, 100°, and 125°C. At the end of each two hour period, the devices were examined and flexed by hand. All of the housings held up to the elevated temperature exposures without showing signs of deformation or melting.

UL 414, Section 15, Heating

The jaw and blade assembly of the meter extender selected for use has reportedly passed UL 414 Section 15 for 200A service. This is a good thermal test and the Research Center should verify the results in the future.

Current Cycle Submersion

In the current cycle submersion test, the jaw and blade assembly samples are inserted into meter base assemblies with double jaws. Meter blade shorting bars are then inserted into the sample jaws. Then all the assemblies are connected in a series loop. A computer controlled ac constant current supply is used to drive current through the loop. The samples are subjected to fifty 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 is submerged in 4°C water. At the end of the current-off period, the loop is raised from the water and the current applied for the next cycle. The temperature of the jaws is 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 are used to evaluate the performance of each jaw.

Three different designs of jaw and blade assemblies were tested. Current levels of 200A and then 240A were used to evaluate the jaw and blade assemblies since 200A service is the largest application of interest. One of the three designs failed the 200A test. When subjected to the 240A test, the same design that failed earlier, began burning some of the nearby insulation. The other two designs of jaw and blade assemblies passed the 200A and 240A tests reasonably.

Varistor Voltage Measurement

This parameter was measured in accordance with General Electric's definition of varistor voltage. A dc voltage source was attached to each metal oxide varistor and the voltage raised until a leakage current of 1mA was reached. This point was recorded as the varistor voltage. Some of the initial varistor voltages from several devices are given in Table 2. By referring to varistor data tables one can tell that manufacturers could be using anywhere from 130V to 150V, and up to 175V class metal oxide varistors. One device even has a redundant 250V class metal oxide varistor connected from line-to-line.

Table 2

Varistor Voltage Measurements

Sample	V_{NOM} @ 1mAdc	Comments
A	253.0	New; line-to-neutral
B	248.5	New; line-to-neutral
C	254.8	New; line-to-neutral
D	245.3	New; line-to-neutral
E	242.7	New; line-to-neutral
F	252.9	New; line-to-neutral
G	216.0	New; line-to-neutral
H	216.0	New; line-to-neutral
I	211.0	New; line-to-neutral
J	215.0	New; line-to-neutral
K	209.0	New; line-to-neutral
L	384.0	New; line-to-line

Temporary Overvoltage (TOV)

Surge suppressors connected from line-to-neutral would be subjected to temporary overvoltages with magnitudes dependant on many variables if a neutral connection was corroded or broken. This is commonly known as a floating neutral. In order to determine how much temporary overvoltage the service entrance surge suppressors could withstand, an ac voltage was applied with increasing steps. The point at which thermal runaway occurred was recorded. The voltage step below which thermal runaway occurred was considered the TOV point, provided that the device demonstrated thermal stability for five minutes and constant current draw. The device selected for use had the highest measured TOV of any tested, which was 200Vac. This corresponds to a 67% TOV or 1.67 per unit. At 210Vac, this device experienced thermal runaway and punctured the varistor disc.

Surge Withstand

Surge withstand testing was performed on four different manufacturers' plug-in meter extender type residential service entrance surge suppressors. An 8 x 20μs current surge was applied with increasing steps to each device until failure. A cool-down to near ambient temperature was allowed between successive surges. Tables 3, 4, 5, and 6 give some of these results. From the data acquired from this surge testing, one must evaluate carefully the available devices and decide which will fulfill the desired requirements. 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. When this occurred, the device was considered to have failed. This was necessary because the power follow current available at the service entrance would probably destroy the device. Available power follow currents at residential service entrances greater than 4,000A are not unusual.

Table 3

Sample W

Charge Voltage	Energy*	Current	V_{clamp}	Comments
1.3kV	34J	10kA	613V	
2.3kV	106J	17kA	730V	
4.5kV	405J	23kA	840V	
6.2kV	769J	29kA	910V	
7.1kV	1008J	36kA	1120V	
8.0kV	1280J	42kA	1260V	
8.9kV	1584J	49kA	1470V	
9.8kV	1921J	56kA	1680V	Fuse link blew; movs still intact

* Note: $\frac{1}{2}CV^2$

Table 4

Sample X

Charge Voltage	Energy*	Current	V_{clamp}	Comments
1.3kV	34J	8.4kA	560V	
2.3kV	106J	16kA	840V	
4.5kV	405J	22kA	980V	
6.2kV	769J	28kA	1190V	Internal arcing

Table 5

Sample Y

Charge Voltage	Energy*	Current	V_{clamp}	Comments
1.3kV	34J	9kA	595V	
2.3kV	106J	16kA	770V	
4.5kV	405J	23kA	963V	
6.2kV	769J	28kA	1020V	Internal arcing

Table 6

Sample Z

Charge Voltage	Energy*	Current	V_{clamp}	Comments
1.3kV	34J	9.8kA	403V	
2.3kV	106J	16.5kA	665V	Fuse link blew; internal arcing

* Note: $\frac{1}{2}CV^2$

Multiple Surge Test

Multiple surge testing was performed using a Biddle cable fault locator (thumper). Two of the thumper's three capacitors were removed, leaving 4μF in the bank. The charge voltage was set to 10kV. This provided 200J per surge. The procedure was to surge (thump) each suppressor section individually. Surges were first applied ten times with a thirty second delay between thumps. Varistor voltage was measured, then another forty thumps applied with a six second delay between thumps. Varistor voltage was measured again, and then fifty more thumps applied with a six second delay between thumps. After this application of one hundred total thumps, a final varistor voltage measurement was made. During the multiple surge test, voltage waveshapes of the varistor clamping voltage were monitored. This was performed using a Tektronics 7633 oscilloscope with a Tektronics P6015 40kV probe. Some of these results are given in Table 7.

Table 7

Multiple Surge Test

Sample	Initial V_{NOM}	After 100 Surges	Percent increase
M (L1 - gnd)	216V	226V	4.6
M (L2 - gnd)	216V	227V	5.1
M (N - gnd)	211V	221V	4.7
N (L1 - gnd)	243V	254V	4.5
N (L2 - gnd)	241V	248V	2.9
O (L1 - gnd)	253V	260V	2.8
O (L2 - gnd)	253V	260V	2.8

Sample M was supplied by one manufacturer while samples N and O were from another. Sample M had an initial overshoot of 1500V during the first 100ns and then settled down to 1250V. The initial overshoot is probably due to leads on the varistor and the printed circuit board traces. Pulse width was approximately 20µs. Samples N and O have no radial or axial leads per se, but are connected by a spring type bus bar arrangement. Therefore, there was no overshoot of the voltage waveshape on these two samples, just a 1500V peak. The pulse width was also approximately 20µs. The thumper rise time is on the order of 100ns, which admittedly is much faster than the standard lightning voltage waveform. However, since this is a comparative test, the results are still useful.

For comparison and a matter of interest, since some of the plug-in service entrance surge suppression devices contained 20mm mov discs of the 150V class, a G.E. V150LA20A mov was surge tested in the same manner. This G.E. mov is only rated for 55J (10 x 1000µs current surge). In less than twenty-nine thumps the mov case split open with internal arcing. The mov clamping voltage was monitored with the same equipment as before. The failure of the mov was not noticed at first because the waveshape did not change after failure as expected. The failed mov maintained the same voltage clamping waveshape as an operational mov. The final varistor voltage measurement proved that the mov failed in the shorted mode as expected. Because this was the same type mov used in some of the devices tested, there is some concern over their survivability if used on a residential service entrance.

End-of-Life Failure Mode

A means of disconnecting a failed surge suppression element is required due to the high fault currents (power follow) available at a service entrance. When this means is provided, special fusing is usually the answer. Of the four manufacturers' devices evaluated, only two had integral fuses. The device selected for use on the Georgia Power system was the highest energy device of the four and contained custom fuse elements. This manufacturer, in addressing the question of end-of-life failure mode testing, provided two different design approaches to quenching the failure arc. The failure arc of concern here consists of the power follow current which passes through the ruptured mov disc. This generates hot ionized gasses which can initiate line-to-neutral/ground arcing. When this occurs, catastrophic failure of the meter base is expected. Therefore, an end-of-life failure mode test was performed on four devices, two of each type from the accepted manufacturer. Another failure arc to consider occurs when a circuit trace or internal wiring sparks over during a surge with the accompanying power follow current. Surge testing with increasing amplitude while under ac bias with high fault current available will address this case.

This test circuit was fed by a 167kVA overhead distribution transformer with a 120/240V low side. This transformer fed directly to a load distribution center with an 800A main breaker. Wired from the main bus was a 200A fused disconnect equipped with two 200NLN slow blow fuses. A 200A meter box was then wired to the fused disconnect. Initially. the left side metal oxide varistor of each sample device was punctured by temporary overvoltage with a lightly fused, high impedance power supply. For testing, the sample device was then mounted in the meter socket and the 800A main breaker was used to energize the test sample.

Metering of the fault current was performed using a 2000/5A current transformer, a 10A/100mV current shunt, and a Honeywell digital oscillograph. To view the fault mechanism, a Panasonic Camcorder was used. This allowed a frame by frame study of the test.

A 150A circuit breaker in the power distribution panel had first been used in the test circuit between the 800A main breaker and the 200A disconnect. This caused the first two (one of each design) sample devices' fuses not to blow, by limiting the available fault current and tripping before the fuses. After eliminating the 150A circuit breaker from the circuit, the final two (one of each design) sample devices' fuses cleared the fault in one cycle (60 Hertz base). The available fault current for this test configuration was $2800A_{rms}$.

Conclusions

There are many viewpoints and considerations when evaluating surge suppressors, particularly, those intended for use on a residential service entrance. Physical, mechanical, and electrical aspects must be considered. If any one of these aforementioned aspects breaks down, then the residential surge protection program is compromised. Safety margins and product in-service life must be considered. Therefore, conservative specifications are advisable. The testing program suggested is as follows:

1. Ultraviolet resistance - ASTM G53 - 1000 hours
2. Corrosion resistance via salt-fog chamber - ASTM B117 - 500 to 1000 hours
3. Flammability (self-ignition) - ASTM D1929
4. Impact resistance - as described and referenced ≥ 80 lb-ft
5. Thermal withstand - as described ≥ 125°C for 2 hours
6. UL 414 Section 15 Heating for a 200A service
7. Current cycle submersion - 50 cycles at 240A
8. Varistor voltage measurement (evaluation data)
9. Temporary overvoltage measurement (evaluation data)
10. Surge withstand - 8 x 20μs current to failure (evaluation data) - with ac bias?
11. Multiple surge withstand - 100 surges at 6 second intervals; ≥ 10kV and ≥ 200J; this one is still up for discussion - with ac bias?
12. End-of-life failure mode - puncture mov first, then apply full voltage with at least 2000A of available fault current - integral fuse must clear before line-to-neutral/ground arcing starts

Because of the possibility of service entrance surges cresting upwards of 20kV (IEEE Std. 587), the multiple surge withstand charge voltage may be raised. A better multiple surge withstand test would include ac bias on the device under test. However, this is a more cumbersome and expensive test to set up and perform.

The end-of-life failure mode test was devised by the Research Center with the safety of the customer in mind. Finding the answer to the question of what happens when the surge suppressor finally fails was considered a necessity. Previous testing of residential service entrance surge suppressors has provided at least one example of a "flame-out" of just such a device.

The device finally chosen for use on the Georgia Power system stands up impressively to all the above testing requirements. Any suggestions for further testing or modifications to the above tests are certainly welcome.

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Testing Varistors Against the VDE 0160 Standard

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Abstract — *High-energy surge tests have been performed on metal-oxide varistors of a type in common use, according to a proposed IEC standard derived from German Standard VDE 0160. The surge generator used for the test was a prototype commercial device developed especially to deliver the 100/1300 μs waveform specified by VDE Standard 0160. Depending on the position of the varistor within its manufacturing tolerance band, failure or degradation can occur, validating the concern that this test requirement may be too severe for universal application.*

INTRODUCTION

Concerns over the occurrence of high-energy surges associated with current-limiting fuse operation (Meissen, 1983 [1]) have led the German standards organization (VDE) to specify a high-energy surge test to be applied to electronic equipment installed in industrial environments (VDE 0160, 1988 [2]). Essentially, the test requires discharging into the ac line interface of the equipment under test (EUT) a capacitor of such capacity that the specified waveform is generated, initially charged at a voltage suitable for producing a peak of 2.3 times the power-system sine-wave peak (Figure 1). Technical Committee 77 of the IEC has included this test in its menu of surge immunity tests (TC77B/WG3, 1990 [3]), without limiting the scope of application to industrial environments intended by the Meissen paper. Thus, this test is likely to become a general requirement imposed on commercial and consumer equipment, unless its implications are recognized. In the absence of a readily available surge generator, computer modeling of the test had previously been performed (Fenimore & Martzloff, 1990 [4], 1991 [5]). The findings of these simulations have shown that typical varistors, of which many millions have been installed and continue to operate satisfactorily, cannot survive the proposed IEC/VDE test because excessive energy would be deposited in these varistors during the surge. The recent availability of a prototype surge generator made it possible to subject typical varistors to the VDE/IEC surge, as reported in this paper.

TESTING VARISTORS WITH HIGH-ENERGY SURGES

Schaffner*, a manufacturer of surge generators, has now developed a prototype that can produce the VDE 0160 surge; in response to an invitation to try out this prototype, an informal work session was conducted at the Schaffner facility to subject typical varistors to the VDE 0160 surge. The generator includes the specified capacitor, up to 6000 μF, the necessary dc supply to charge the capacitor, a 220-V ac supply (for European environments), and suitable means to decouple the test specimen circuit from the laboratory ac system. Details of the circuits are still proprietary, and only the output of the generator is described in this paper. A chronological recitation of the work session would require first a discussion of the various considerations and conditions of the test. Recognizing the natural curiosity of the readers, let it be stated here that one varistor was destroyed during the test, and the other (barely) survived, consistent with the predictions of the computer modeling. Having thus given away the outcome, let us now proceed with the detailed recitation of these considerations and conditions.

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* *As a policy, the National Institute of Standards and Technology disclaims any implied endorsement of a commercial product when identifying such products for the sole purpose of adequately describing the equipment used in the experiment. In this particular case, the prototype generator used in the tests was the only one known to be available. Furthermore, there is no certainty that Schaffner will offer a commercial product based on this prototype.*

Voltage across the test specimen and current delivered by the surge generator were recorded with the instrumentation available at the Schaffner engineering demonstration facility. The software package included in the digital storage oscilloscope did not have the capability of computing the power ($i \times v$) dissipated in the varistor and integrating it into total energy deposited. Manual integration of the recorded traces was performed after the tests. This computation yields results of sufficient magnitude (that is, large overstress of the varistor) to make precise computing unnecessary in evaluating the outcome of the test.

The test specimens (EUT) were 20-mm diameter varistors, consisting of two 130-V rms rated devices connected in series, a good approximation of the practice of applying 250-V rated varistors in the 220-V equipment used in Europe (Martzloff and Leedy, 1989 [6]). The nominal voltage, V_{nom}, of each varistor (voltage measured with 0.5 mA or 1 mA dc injected in the varistor) was determined before the test for each device. One varistor pair (referred to as EUT #1) had a nominal voltage of 392.6 V, the other pair (EUT #2), 399.5 V. The nominal voltage for a 250-V rms varistor is 390 V, the minimum 354 V, and the maximum 429 V (Harris Manual, 1990 [7]). Thus, EUT #1 is situated at 1% above the nominal value of a 250-V rated varistor, while EUT #2 is at 2.5% above the nominal value.

To test the varistors under the worst case condition (that is, the varistor at 10% below nominal, thus drawing energy from the generator for a longer portion of the surge waveform), the test voltage should be raised above the voltage specified for nominal test conditions. To place the varistor under conditions equivalent to those prevailing for a -10% specimen, a varistor at some tolerance level must be subjected to the same current as that occurring for a -10% varistor at the nominal test voltage. With the nominal VDE 0160 test voltage of 2.3 times the 220-V peak (714 V), the available EUT varistor specimen can be tested in a manner equivalent to a -10% tolerance varistor by raising the test voltage.

For EUT #1 which is 1% above the V_{nom} of a 250-V rated varistor, the test voltage should be 10% higher than the nominal 714-V peak, plus 1%, that is, 792 V. For EUT #2, 2.5% above the V_{nom}, the test voltage should be 12.5% higher, 803 V. This increased test voltage will place the varistor at the correct value of current on its I-V characteristic, but raises the power dissipated in the varistor by the same percentage. Thus, the energy deposition in varistors other than -10% tested under the artificially raised test voltage received 11% or 12.5% more energy than what a varistor at -10% would have received. However, considering the energy levels observed in the tests reported below (about 200% of rated levels, this 11-12.5% excess does not affect the conclusions. The significant parameter to be observed is the current level, and that correct level was indeed achieved by raising the test voltage.

The VDE 0160 document states that the *specified surge test voltage should be maintained* across the terminals of the EUT, rather than the usual method of having a preset open-circuit voltage, and then connect the EUT *without changing the generator setting* (the so-called 'let-it-rip' mode [5], and (ANSI/IEEE C62.41-1987, [8]). Meissen confirmed this interpretation of the document [9], so that the charging voltage of the generator capacitor was increased toward obtaining the specified voltage with the EUT connected, using an expendable EUT varistor during preliminary tests. However, the prototype generator output voltage, with maximum charging voltage and with varistor connected, could only be raised to 774 volts (Figure 2) instead of the 792 V or 803 V necessary to place the #1 and #2 varistors in the -10% tolerance situation. Thus, EUT #1 was actually tested in a condition corresponding to 774/792 = 98% of the worst case level, and EUT #2 at 774/803 = 96% of the worst case level. In other words, EUT #1 was tested as if it were at a -8% tolerance level, and EUT #2 at a -6% tolerance level with respect to a 0% tolerance on their V_{nom}.

The manufacturer's specifications [7] show a 70-J single-pulse energy rating for the 130-V varistor, or 140 J for two in series. Figure 3, from Ref [5], shows the predicted energy deposition as a function of the varistor position in its tolerance band, for the test condition where the voltage is maintained across the EUT by readjusting the surge generator charging voltage.

The VDE 0160 document shows an elementary circuit diagram (Figure 4) with a maximum of 5 m of leads between the input port of the test specimen and the point of injection of the surge. Accordingly, the test circuit set up by Schaffner included approximately 5 m of leads "suitable for a 16 A load" between the varistor and the output of the generator. Thus, the impedance presented by the test specimen to the applied VDE 0160 surge includes a resistance that will reduce the stress of the varistor; however, this reduction is not readily recognized by the simple mention in the figure of a 5-m maximum lead length, and the cross-section of the conductors is not specified. Operators can interpret the test procedure in a way producing maximum stress (a short lead of large cross section) or a minimum stress (maximum of 5 m of leads with small cross section).

In accordance with the interpretation of the Figure 4 diagram, the voltage measured and shown in Figure 2 is the total of the voltage developed across the varistor and the lead drop. To evaluate the implications of this interpretation, the next test was performed, without changing the generator setting (at its maximum available voltage), with the voltage measurement made at the varistor terminals (Figure 5). Note the 700-V peak in this test, or a 74-V difference (10%) from the value recorded in Figure 2. In the modeling of References [4] and [5], the effect of this 5-m test lead had not been included, so that the conclusions of the modeling are more pessimistic than the consequences of a test condition with a lead length included. Thus, the varistor would be under 10% less voltage stress (keep in mind the nonlinear relationship between voltage and current) than the model prediction, and possibly could survive.

THE DEATH OF A VARISTOR

According to a subsequent amendment to the VDE 0160 test specification, the maximum* capacitor value and the duration of the surges may be reduced to 300 μs for equipment installed in circuits protected by fuses of less than 35 A continuous rating. This reduction will provide significant relief to varistors included in non-industrial environments. However, the IEC document [3] does not include that reduction. The test sequence for EUT #1 included two surges with this reduced stress (Figure 6), followed by surges with the full 6000 μF capacitance and full 1300 μs duration, at the maximum available generator voltage, as shown in Figure 2. Before and after each surge, the varistor V_{nom} was recorded to track any shift in characteristics, comparing it to the maximum shift of 10% allowed in the manufacturer's specifications.

The test sequence and results for EUT #1 (a specimen in the -8% tolerance position), starting with no prior surges applied, were the following:

Shot 1:	718 V crest, 400 μs duration, V_{nom} shift of 1% (Figure 6)
Shot 2:	768 V crest, 1100 μs duration, V_{nom} shift of 1%
Shot 3:	774 V crest, 1400 μs duration, V_{nom} shift of 1% (Figure 2)
Shot 4:	Repeat, same settings as shot 3 (voltage measured at varistor, Figure 5), Varistor (a) of pair punctured Varistor (b) of pair externally intact, but $V_{nom} = 0$ (short circuit) Energy deposited in the varistor; approximately 300 J (215% of rating)

The same test sequence was then applied to EUT #2, that is, first two shots at reduced stress, and then full stress for shot 3 and four additional shots. The V_{nom} shift grew from 1% after the first shot to 6% after the last shot, as measured after cooling down following the test. By the time the author had returned to the United States (20 days later), the shift in V_{nom}, determined by more systematic measurement at NIST, was reduced to 4%. The difference between the 6% immediately after the test and the 4% after 20 days may be the effect of a slow recovery of the material, or a difference in the precision of the measurements, or both.

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* *The surge duration is the specified parameter in the VDE 0160 document, therefore the required value of the capacitor is dependent upon the impedance of the EUT.*

Notwithstanding the shift in V_{nom}, no apparent external damage was visible, except for some darkening of the red epoxy coating. Thus, while EUT #2 did survive a test corresponding to a -6% tolerance position, the onset of permanent change leading to failure was observed.

DISCUSSION OF THE RESULTS

From the simulation predictions, it was expected that the varistors would be destroyed by the test, even though the (late) realization of the stress reduction provided by the lead length does somewhat change the situation. In other words, the 10% loss of voltage caused by the leads places the varistors used in these tests at respectively +2% and +4% in the tolerance band, a condition that the prediction describes as marginal survival. The joule rating specified by the manufacturer tends to be conservative, so that it may take more than 140 J to destroy a varistor. Furthermore, a larger population of test specimens may produce a distribution of more failure as well as more survivals as only two test points can only provide an indication, not a certainty. However, the conclusion is clear, that varistors of common use in commercial and consumer equipment would be in severe jeopardy if the full 100/1300 μs surge were applied, even with the mitigating effect of the 5-m lead length. Discussing the test results with Meissen, we agreed on the following conclusions:

1. There is no disagreement that the basic phenomenon of fuse blowing can lead to the high-energy surges described by Meissen in the heavy industrial environment (circuits with fuses above 35 A).

2. The prediction of varistor failure through modeling is consistent with the tests; the mitigating effect of the allowable EUT lead reduces the forecast of widespread failures, but varistors in the lower tolerance bands are still at risk.

3. The amendments to VDE 0160 providing for reduced maximum capacitance values (see the footnote on page 3) and reduced duration make the test more realistic. Further evaluation of these reduced stress levels would show appropriate limits of application.

4. However, this stress reduction has not yet been acknowledged by the IEC proposals (Figure 1, showing only one value of 1.3 ms is excerpted from the IEC document, not the amended VDE 0160 where the alternate duration of 0.3 ms is shown). This paper is therefore submitted to the engineering community at large as a recommendation of limiting the full duration of a 1300 μs surge and its high energy to the industrial environment for which it was first proposed.

5. The concept of readjusting the surge generator charging voltage to maintain a specified *test voltage* across the specimen is different from the usual practice of maintaining a fixed open-circuit voltage for the generator. However, it may be compared to the practice of readjusting the surge generator used for surge arrester tests at a specified *test current* level. As long as the implications of the procedure are recognized, either method may be suitable, if uniformly interpreted.

6. In its present form, the VDE 0160 document leaves open the possibility of different interpretations by different operators. Should the principle of a high-energy test be adopted by the IEC, more detailed specifications need to be developed and agreed upon by interested parties.

ACKNOWLEDGEMENTS

This successful work session was made possible through the cooperation of T. Hilger and M. Ryser of Schaffner. W. Meissen made the long journey from Erlangen, Germany to Luterbach, Switzerland to participate in the test, and reviewed the manuscript of this paper. The simulation predictions of References [4] and [5] were developed by C. Fenimore. All these contributions toward a better understanding of the VDE 0160 test implications are gratefully acknowledged.

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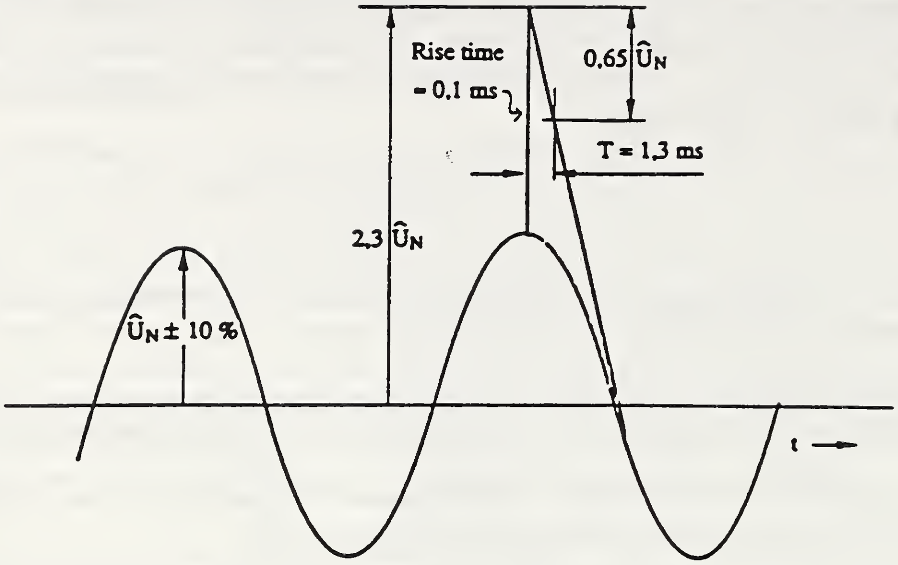

Figure 1. High-energy waveform specification (From Ref. [3])

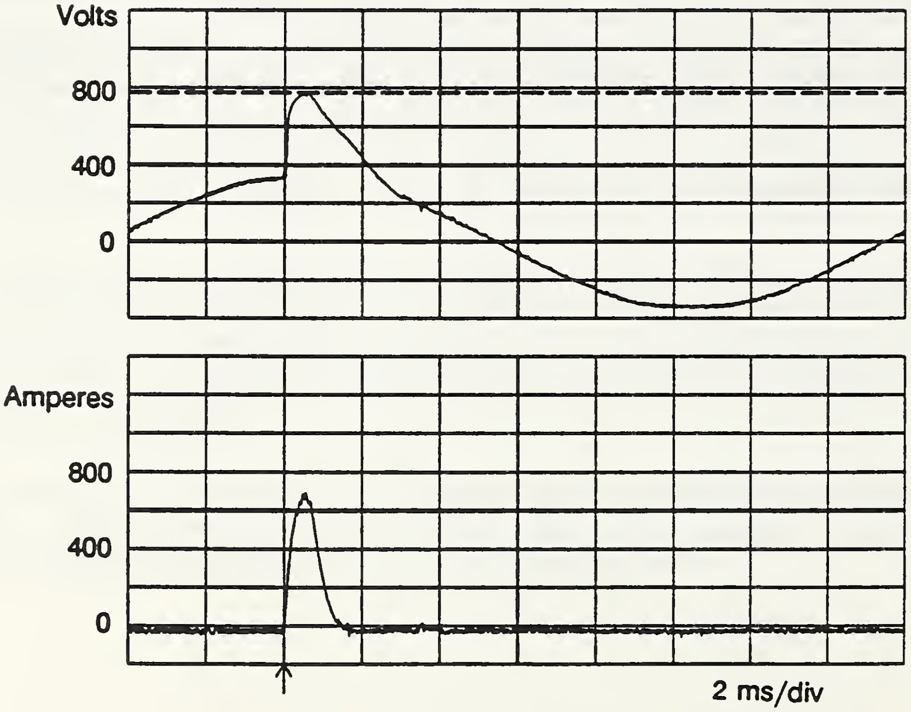

Figure 2. Voltage across and current through EUT #1

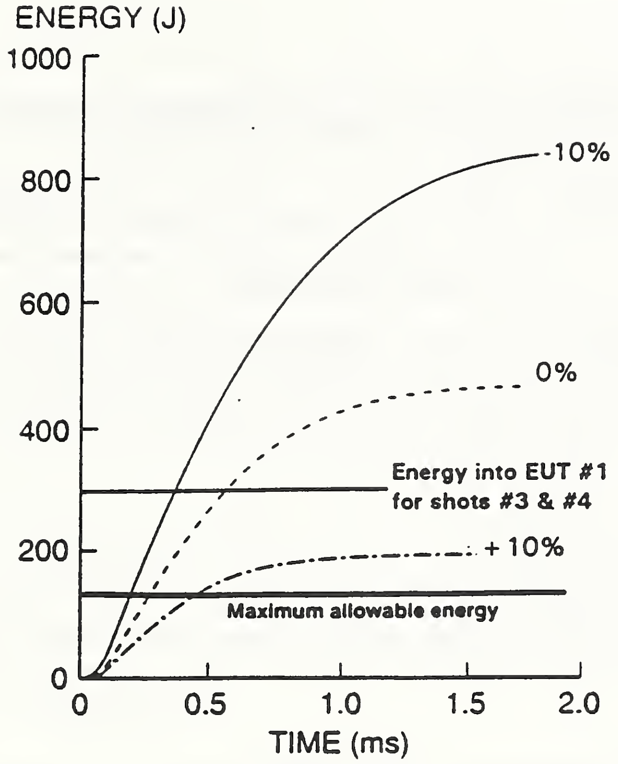

Figure 3.
Energy deposited in varistor as a function of tolerance of device compared to nominal value (From Ref. [5])

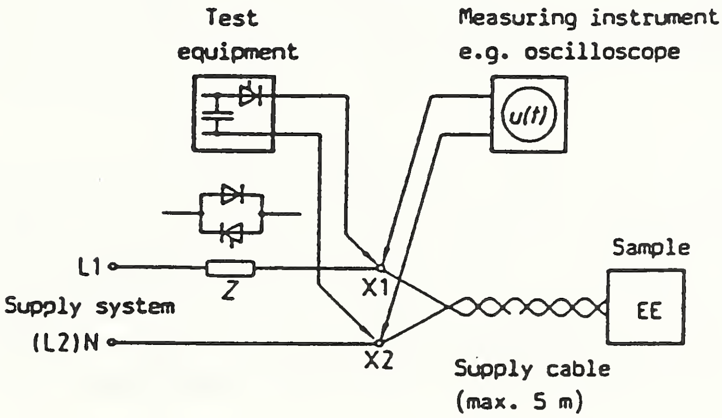

Figure 4. Elementary test circuit diagram (From Ref. [2])

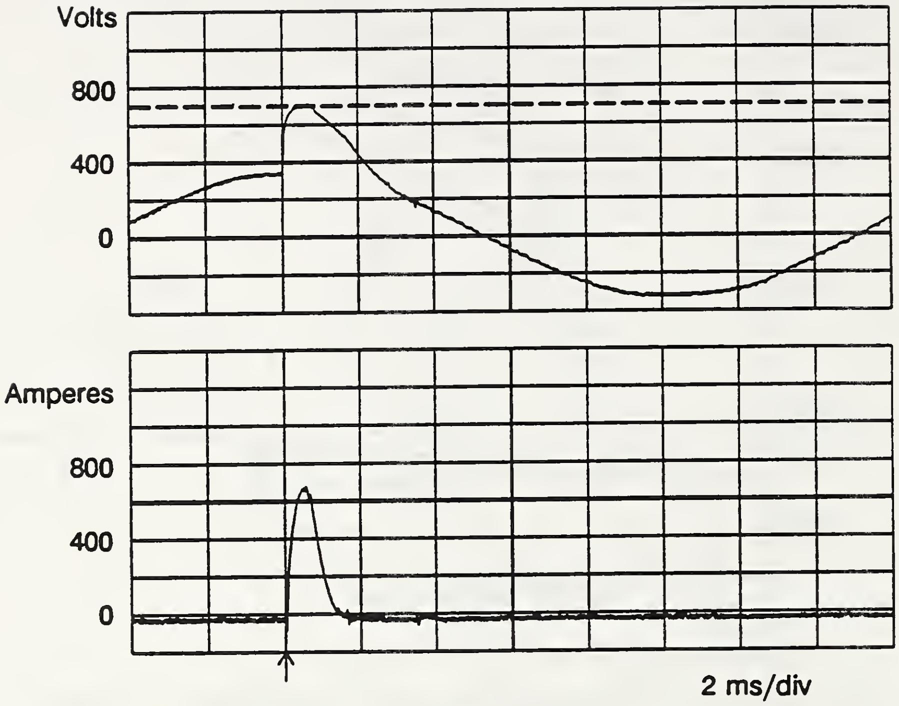

Figure 5. Voltage across and current through varistor only

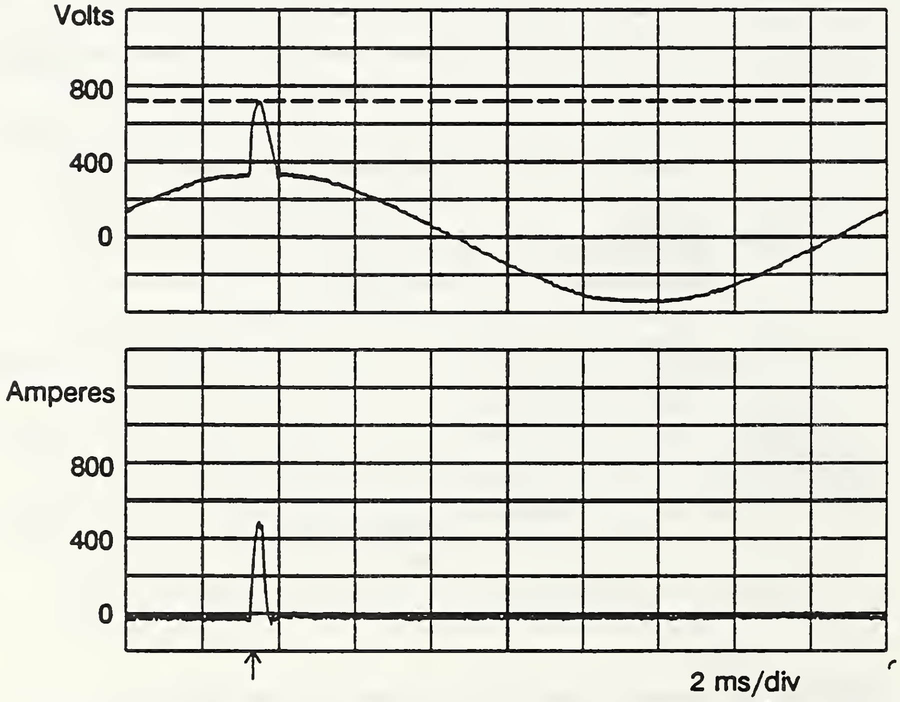

Figure 6. Voltage across and current through varistor with reduced stress

SUPPRESSION VOLTAGE RATINGS ON UL LISTED TRANSIENT VOLTAGE SURGE SUPPRESSORS (TVSS)

Robert Davidson
Underwriters Laboratories Inc.

INTRODUCTION

Some manufacturers and purchasers of UL Listed Transient Voltage Surge Suppressors (TVSS) have expressed concern to UL about certain types of advertising claims that have been made with respect to the suppression voltage ratings marked on UL Listed TVSS.

Examples are claims that the minimum 330 volt suppression rating in UL's Standard for Transient Voltage Surge Suppressors, UL 1449, is "the best UL rating" or that 330 volts affords "the most protection possible", or that "the lower the suppression rating the better the TVSS product (or protection it provides)".

The purpose of this brief paper is to clarify the meaning and limitations of the suppression voltage ratings that are marked on UL Listed TVSS products in association with the UL Listing Mark.

UL 1449 SUPPRESSION VOLTAGE RATINGS

The suppression voltage ratings marked on UL Listed TVSS products are the result of testing conducted in accordance with UL's Standard for Transient Voltage Surge Suppressors, UL 1449. Manufacturers of Listed TVSS and others should keep the following in mind when referencing UL in their advertising material, or when reading advertising material that references UL:

Testing conducted in accordance with UL 1449 is intended to provide confirmation that a TVSS suppresses transient voltages. The sole purpose of the marked suppression rating, determined in accordance with UL 1449, is to provide independent information on the "output" response of a TVSS when subjected to a specific set of "input" surge conditions. This information may be useful when used as part of a comprehensive assessment of the adequacy of surge protection.

Given the above stated purpose, the following should be noted:

1. UL does not support claims that a given TVSS will necessarily protect a specific piece of equipment, nor does it support claims that lower suppression voltage ratings obtained under the specific test conditions of UL 1449 will necessarily mean "better protection" for connected equipment.

2. When UL tests TVSS for Listing under UL 1449, the possible effects of the TVSS on specific connected equipment or on the ac power system are not investigated.

3. UL does not support claims that TVSS are "good", "better", or "best" on the basis of the suppression voltage ratings obtained under UL 1449, nor does it support claims that all TVSS with the same marked suppression rating will necessarily provide the same level of protection for all connected equipment.

The above is reflected, in part, in UL's Guide for Transient Voltage Surge Suppressors (Guide XUHT) which includes the following statement:

"The effect of the suppressor on connected loads, the effect of the suppressor on harmonic distortion of the supply voltage and the adequacy of the suppression level to protect connected equipment from damage from transient voltage surges has not been evaluated"

As previously stated, the suppression voltage rating associated with the UL Listing Mark is intended to provide information on how a TVSS responds to a specific set of surge conditions.

The surge waveforms presently used in UL 1449 are impulse "combination waves" of 6 Kv, 1.2/50 us open circuit voltage and 8/20 us short circuit current (with peak current values depending upon the product type and test). These waveforms are based in part on ANSI/IEEE C62.41- 1980 (IEEE Guide for Surge Voltages in Low-Voltage AC Power Circuits), and are intended to apply to TVSS connected in circuits on the load side of the service disconnect, such as in appliance branch circuits.

The surge waveforms presently used by UL are only one of a number of possible characterizations of the surge environment. Other possible characterizations include 100 kHz and 5 kHz ringwaves, 10/1000 us ("long") waves, and bursts of fast rising transients (called electrical fast transients, or EFT's). Reference should be made to ANSI/IEEE C62.41-1991, Recommended Practice On Surge Voltages In Low-Voltage AC Power Circuits, for a more comprehensive description of these and other possible characterizations of the surge environment. UL is considering incorporating additional waveforms in its Standard UL 1449.

The suppression voltage ratings found in Table 37.1 of UL 1449 were based in part on Table 1 ("Preferred series of values of impulse withstand voltage based on a controlled overvoltage situation") of IEC Publication 664 -1980 (Insulation Co-ordination Within Low-Voltage Systems Including Clearances and Creepage Distances for Equipment), which addresses the co-ordination of insulation, creepages and clearances in equipment. They are not necessarily related to the peak voltages and waveforms that may cause disruption of the operation of electronic equipment (i.e. "equipment upset").

The lowest rating of 330 volts presently found in UL 1449 is based on the lowest "preferred value" of impulse withstand voltage found in Table 1 of IEC 664 - 1980. Although 330 volts is presently the lowest suppression voltage rating indicated in UL 1449, UL does not support any claims that a 330 volt rated TVSS means the "best possible protection", particularly with regard to possible disruption of the operation of electronic data processing equipment due to transient voltages.

SELECTING A TVSS

Depending upon the intended application, the proper selection of a TVSS to protect specific connected equipment may require knowledge of a number of factors that include, but are not necessarily limited to, the following:

1. The nature of likely incoming surges. This may require on site monitoring of the surge environment, coupled with knowledge of (a) the location of the TVSS and connected equipment in the ac power system and (b) the degree to which overvoltages may or may not be controlled elsewhere in the ac power system (i.e., protection coordination).

2. The vulnerability or susceptibility of particular equipment to an incoming surge. This information, which is design dependent, must be obtained from the equipment manufacturer.

Since the above and other factors are outside the present scope of UL 1449, the UL 1449 suppression voltage ratings may not, by themselves, be sufficient to completely determine the adequacy of protection in all applications. The ratings do, however, allow comparison of TVSS responses to a specific set of surge conditions.

CONCLUSION

The suppression voltage ratings marked on UL Listed TVSS provide the purchaser with independently generated information on how a TVSS performs when subjected to a specified impulse surge. On the other hand, the ability of a TVSS to protect connected equipment from both upset and damage may depend on a number of factors including knowledge of the specific surge environment and knowledge of both the susceptibility and vulnerability of the particular equipment.

To the extent that the above mentioned factors are known, the suppression voltage ratings on UL Listed TVSS can contribute useful information to an overall assessment of the adequacy of surge protection. When these factors are not known, claims that one TVSS provides better protection than another, solely on the basis of the UL 1449 suppression voltage rating, may be misleading.

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Utility Compatibility (UC)
Performance Criteria for End-use Equipment

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Abstract - Electrical incompatibility between the utility and specific end-user loads is an escalating problem as more sophisticated microelectronic loads are connected to the power system. As the loads become more sophisticated, they also become more vulnerable to traditional dynamic electrical environments such as surge and fault events. At the same time that loads are becoming increasingly sensitive, the growth of new non-linear loads and related harmonic current is diminishing the quality of the power system voltage. A new criteria is needed to facilitate coordination of the realities of the power system environment with the needs of the electronic loads. This paper describes a family of performance criteria documents for applying specific classes of end-use equipment, including power conditioning equipment. The concept of a Utility Compatibility (UC) label is also introduced. It is based on carefully developed criteria that considers both the electrical power source environment and end-use application requirements.

1. Introduction

Electrical and electronic equipment is purchased and connected by the utility customer in a free market. Some regulations may exist on the performance of the equipment, but the issue of compatibility usually is not part of the consumer concern until problems arise. Preventive measures would be welcomed by all parties but when driven by only natural forces it is a slow process at best. Individual users generally cannot, on their own, effect large-scale changes in load equipment design. Load equipment manufacturers typically do not have the knowledge base or the incentive to research power supply compatibility issues, redesign equipment and market new features to their customers. Competitive economic pressures drive the equipment manufacturers to select components and configurations aimed at delivering a given service at minimum cost. Therefore, equipment may not operate properly over the whole range of electrical environments that can be expected in user power systems. Many architectural and engineering firms who specify power systems and equipment understand the potential utility/load incompatibilities, but do not have the means or the planning horizon to effect special configuration of the facility power supply or specification of increased load immunity.

The concept of matching the customer load and utility source is not new. It has been going on ever since the first power delivery system. However, rapid advances in micro- and power-electronic equipment has created some new and yet unresolved compatibility problems. The major factor is not that these new loads are damaged. Generally damage prevention or survivability has received careful consideration by the manufacturer. The more common problem is that users typically apply the micro-electronic equipment in support of some larger process where simple upset of the equipment may be a serious upset of the entire process. The severity of the problem ranges from an irritating blinking clock to a mass of torn fibers and tons of wasted material in a spinning mill process.

The growing complexity and scope of this problem warrants a more standardized approach to bring about compatibility. The concept of electromagnetic compatibility (EMC) developed by the communications community provides a useful model. With more sensitive loads, and in some cases new electrical environments conducted in the power system, the power engineering community has begun to apply the EMC concepts of the communications community.

Early in this evolution Fisher and Martzloff articulated the need for a clear approach toward achieving compatibility between the transient withstand capability of devices and the transients to which these devices are exposed in low voltage power systems. They called it "transient control levels" [1]. Since then, a number of useful standards have evolved in the IEEE [2], [3], [4], with several more in the works, e.g. [5], [6].

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The aim of most of these standards is to define the EMC environment and provide guidelines or recommended practice on how to deal with it.

The Europeans, through IEC and CENELEC, have taken the concept of EMC in the power network much further. They are defining environments, e.g. [7], providing measurements methods, e.g. [8], [9], developing test procedures, e.g. [10], [11], setting limits on equipment producing disturbances, e.g. [12], and setting basic and specific equipment immunity level standards, e.g. [13], [14]. In this paper, a similar approach is presented for the U.S. electric utility industry.

2. Methods for Improving Utility Compatibility

The common practice has been to improve utility compatibility by installing special "power conditioning" equipment between the load and the power source. Thus a multibillion dollar power conditioning equipment industry has developed over the last twenty years. Power conditioning is sometimes the appropriate solution, but frequently a more cost - effective solution may be modification of the electric power system or the load equipment.

Figure 1 depicts the idea of two-way compatibility and illustrates that all components of the power supply, wiring and load equipment are involved. Often modifying a single component will solve one power quality incompatibility while creating another. In the long run, a more systematic and industry-backed approach is preferred.

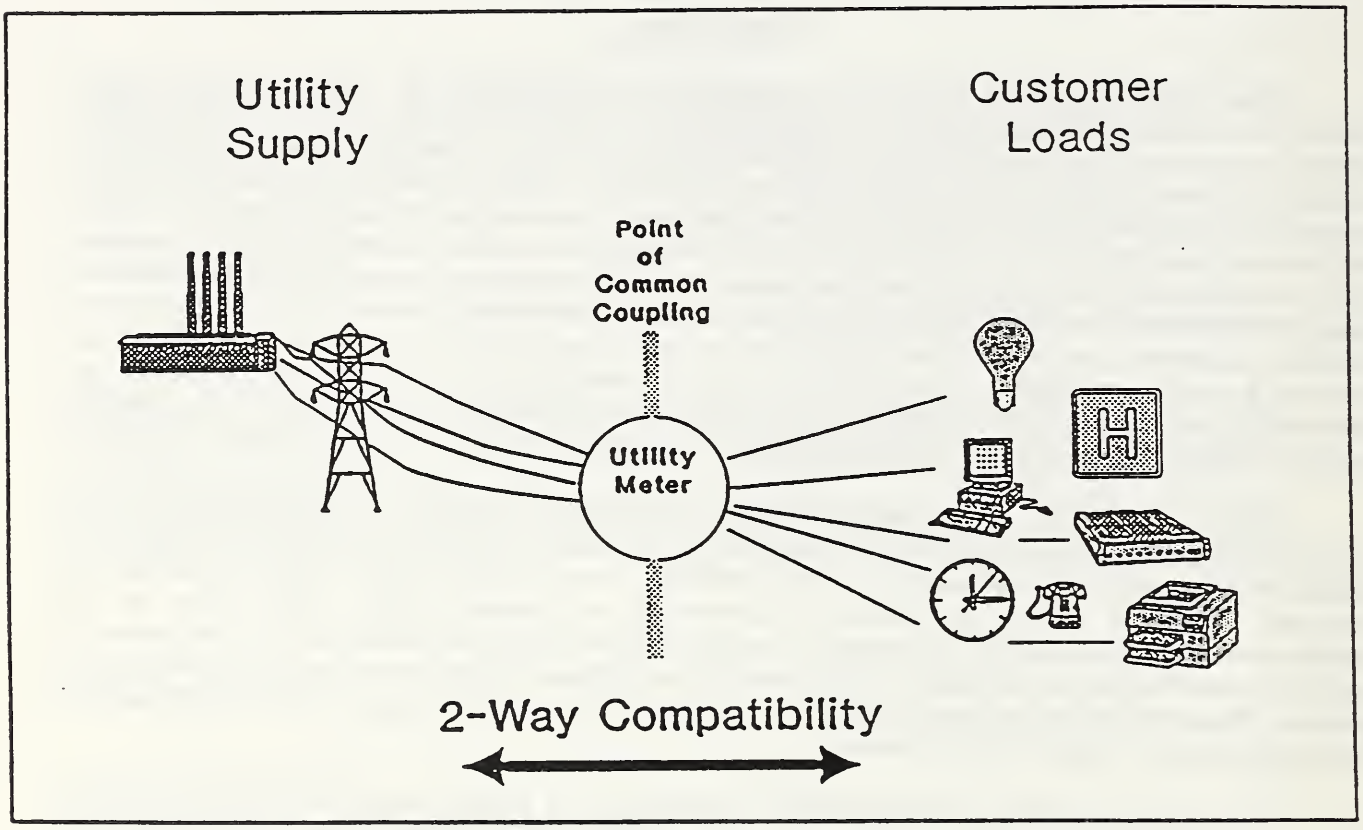

Figure L Achieving Utility Compatibility Requires Addressing Issues That Transcend the Utility Meter

To achieve this, a high level of coordination and planning, as well as a detailed technical understanding of the interactions is needed. It may be argued that only the electric utility industry has the incentives, the means and the patience to tackle this challenge with the required long range view point. Thus, the electric utilities are presented with the opportunity and challenge of taking a leading role in addressing system compatibility issues in the joint interest of the utility and the customer.

3. Today's Vision for Tomorrow's Solution: Utility Compatibility Testing and Labeling

Under the leadership of the **Electric Power Research Institute** (EPRI), the US utility industry has begun a strategic program initiative to address load and power supply incompatibility issues. Although only in its formative stage, work aimed at defining and conducting utility compatibility tests, developing manufacturer cooperation, and proposing performance criteria has begun. This work will address utility compatibility issues at the point of end-use load connection.

The program consists of collecting data from formal field studies, from controlled laboratory measurements, and from direct interaction with equipment manufacturers. This data will provide a knowledge base upon which the utilities can propose a Utility Compatibility (UC) performance criteria for specific classes of end-use equipment. If adopted by standards setting bodies, a "UC" label that indicates a preferred level of performance and reliability may become commonplace. Even a "UC" index could be adopted which would provide a simplified figure of merit. The figure would identify the likelihood that connecting a piece of electrical equipment to a specified utility power supply environment will result in no detrimental impacts to the utility system, other equipment in the customers facility, or to the specific equipment in question. Selected definitions of "UC" terms are provided in Table 1.

Table 1. What is Utility Compatibility? *

UTILITY COMPATIBILITY	The ability of a device, equipment or system, generally a load, to function satisfactorily with respect to its power supply electrical environment without introducing intolerable electrical disturbances to anything in that environment.
ENVIRONMENT	The totality of power supply electrical phenomena existing at a given location. In general, this totality is time-dependent and its description may require a statistical approach. It is very important not to confuse the environment with the location itself.
LOCATION CLASS	A set of locations having a common property related to the types and density of electrical and electronic equipment in use, including installation conditions and external influences. (residential, commercial, industrial or utility power systems, for example).
COMPATIBILITY LEVEL	The specified steady state or dynamic electrical disturbance level in the power supply at which an acceptable, high probability of power supply and load compatibility should exist.
DISTURBANCE LEVEL	The level of a given steady state or dynamic electrical power supply disturbance, measured in a specified way.
DISTURBANCE	Any power supply electrical phenomena, steady state or dynamic, that may degrade the performance of a device, equipment or system connected in that system.
SUSCEPTIBILITY	The inability of a device, equipment or system to perform without degradation in the presence of a power supply electrical disturbance.
IMMUNITY	The ability of a device, equipment or system to perform without degradation in the presence of a power system disturbance.
IMMUNITY LEVEL	The maximum level of a given power supply disturbance, incident in a specified way on a particular device, equipment or system, for which no degradation of operation occurs.

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* Adapted from *Classification of Electromagnetic Environments*, International Electrotechnical Commission (IEC), Technical Committee 77, Working Group 6, Draft 5, January 1991.

Applying the "UC" concept benefits both the utilities and their customers. Customers will be able to install electrical appliances and other equipment with a high degree of confidence that power disturbances will not disrupt their operations or life-styles. Utilities will experience improved operation in their supply systems insofar as the reduced prevalence and impact of both utility and customer system originated power disturbances. So far, support from the manufacturing community has also been excellent. It has included recommendations for specific performance criteria and requests for testing of specific products.

4. Approach

A primary objective has been to develop a uniform and effective approach to achieve compatibility. This approach has been to first define the environment and then conduct appropriate tests to evaluate equipment performance. For example, a digital clock used in the typical residential setting is expected to experience the electrical environment depicted in Table 2.

Table 2. Utility Compatibility of a Residential Digital Alarm Clock

Line Conditions	Expected Range or Frequency (Conditions are site-dependent)
Steady-State	
A. Voltage Regulation Limits	87% to 106% of nominal voltage
B. Voltage Harmonic Distortion	1% to 10% THD
C. Conducted EMI (noise)	Highly variable
D. Frequency Regulation Limits	59.8 Hz to 60.2 Hz
Intermittent	
A. Momentary Undervoltage during Power System Fault (cycles)	2 to 20 per month (severity varies)
B. Short-term Loss of Voltage during Reclosure Operation (seconds)	0.5 to 5 per month (duration varies)
C. Outage (seconds to minutes)	0 to 12 per year
D. Voltage Phase Shift (due to short-term change in VAR loading	Daily to Seldom (severity varies)
E. Voltage Surge or Impulse (due to lightning or switching events)	Daily to Seldom (severity varies)
F. Electrostatic Discharge [ESD] (from nearby object)	Highly variable

The same clock used in a typical commercial or industrial setting might experience a completely different electrical environment. Therefore, the environment must first be clearly defined before appropriate tests can be selected.

Once the equipment's operational environment has been defined, utility compatibility test procedures must be devised to appropriately evaluate whether the equipment can perform satisfactorily within the prescribed electrical environment. Existing Standards and other appropriate references are consulted to ensure uniform testing methods are used. Tables 3 and 4 show appropriate tests and related standards or references for various power line conditions.

Using the knowledge and experience gained through prior equipment testing and field experience, "Utility Compatibility" (UC) performance criteria can begin to be written for specific equipment operating in a specific environment. Different UC criteria will be required for each class of equipment and for each operational environment (e.g. residential, commercial, and industrial.) Power conditioning and utility system equipment are also considered. Utility compatibility of specific equipment will depend upon the creation of a UC criteria. Typical examples of performance criteria for utility compatibility include:

UC - 110: *"Surge-Protective Devices used in Low - Voltage AC Power Systems"*

UC - 120: *"Local Ground Windows used in Facility Power and Communications Systems"*

UC - 410: *"High-Frequency Fluorescent Ballasts used in Indoor Lighting Systems"*

UC - 920: *"Dry-Type Service Transformers used in Commercial and Industrial Facilities (k-factor rating)"*

Table 3. Utility Compatibility Testing for Varying Steady-State Conditions

VARYING STEADY-STATE CONDITIONS	ASSOCIATED STEADY-STATE TESTS	TEST PROCEDURE STANDARD OR REFERENCE
Changes in power system cause voltage and frequency variations or phase voltage imbalance	V1. Undervoltage Limits V2. Undervoltage Limits V3. Frequency Limits V4. Phase Voltage Unbalance Limits	ANSI Std C37.106 ANSI Std C84.1 NFPA 70 [15] IEEE Std 141 IEEE Std 241
Harmonic currents and voltages, voltage notching, and flicker caused by non-linear loads	V5. Harmonics V6. Voltage Notching V7. Voltage Flicker	IEEE Std 141 IEEE Std 241 IEEE Std 519
System losses, voltage drop, low utilization voltage, increased operating costs	V8. Reactive Power Demand	IEEE Std 141 IEEE Std 519
Temperature variations due to equipment condition or design, loading, or electrical environment	V9. Temperature Limits and Cycling	ANSI/IEEE Std 1 ANSI/IEEE Std 3 IEEE Std 112 IEEE Std 119
Swings in voltage as the load changes, availability of fault current, and potential for resonance	V10. Source Impedance Limits	IEEE Std 141 ANSI/IEEE Std 399
Electromagnetic Interference may either radiate through space or conduct through the power system into sensitive electronic equipment	V11. Conducted and radiated Electromagnetic Interference (EMI)	IEEE Std 139 FCC Part 15 [16] MilStd 461C [17] MilStd 462 [18] Mil-Hdbk-241 [19]

Table 4. Utility Compatibility Testing for Intermittent Conditions

INTERMITTENT CONDITIONS	ASSOCIATED DYNAMIC TESTS	TEST PROCEDURE STANDARD OR REFERENCE
Lightning and Load Switching events produce unknown surge exposure environments, creating the requirement for determining the surge withstand capability of specific exposed equipment.	D1. Surge Withstand Capability	ANSI/IEEE Std C37.90.1 ANSI/IEEE Std C62.41 ANSI/IEEE Std C62.45 IEC Std 801-4
Line voltage sags for several cycles may result during power system faults and when heavy loads are switched on, effecting voltage-sensitive electronic equipment on the line.	D2. Sag	ANSI/IEEE Std C37 IEEE Std 141
Line voltage may increase from 1½ to 2 times nominal for several cycles during power system faults or other equipment malfunctions.	D3. Swell	ANSI/IEEE Std C37
In power distribution systems, switching of heavy loads on an inductive feeder can create phase shifts of the delivered voltage and upset phase-sensitive equipment.	D4. Phase Shifts	ANSI/IEEE Std C37
Equipment will shutdown and require restart following outages exceeding the equipment's ride-through capability.	D5. Momentary Outages	ANSI/IEEE Std 242
Static discharges up to 15 kV may be introduced from a person's body, or between metal objects, resulting in malfunction or damage to sensitive circuits in the vicinity of the discharge.	D6. Electrostatic Discharge (ESD)	ANSI/IEEE Std C62.47 IEC Std 801-2

Conclusion

The electromagnetic compatibility of utility electric power supply networks and the customer loads they serve is receiving increasing attention world-wide. In the U.S., EPRI has taken the lead to bring together the interested parties and the technical resources to accelerate the process of achieving better compatibility. A key element is the development of Utility Compatibility (UC) performance criteria that apply to the power quality performance of specific end-use equipment. With these criteria and other available power quality standards and procedures, equipment testing can be accomplished with useful results provided to manufacturers and end users.

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THE NETWORK PROTECTION DILEMMA

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Morrisville, NC

ABSTRACT

This paper attempts to resolve some misconceptions in the electronic industry relative to conducted electrical disturbances, EMI suppressors, and electronic equipment networks. It shows how an unsystematic approach to resolving electrical disturbance problems in electronic networks can lead to problems in circuits that seem far removed from the original problem. The paper outlines a more systematic approach to hardening the network to typical electrical disturbances. Finally, it illustrates several methods that are commonly used to protect and/or isolate network communication circuitry from the affects of powerline disturbances.

THE NETWORK PROTECTION DILEMMA

In the last year or so, there has been a rash of articles written about the protection of electronic equipment networks from electrical disturbances. Many of these articles contain incomplete and/or incorrect information and are spreading unnecessary fear in the minds of network users.

These articles are being written primarily by members of the power disturbance mitigation products industry, who are using them to justify one type of mitigation device technology over another. The most common claim being made in a majority of these articles is the fact that many power disturbance mitigation products, (EMI suppressors), are not protecting electronic equipment networks from electrical disturbances, but instead they are placing these networks in an area of greater risk of disruption and damage from electrical disturbances. The articles typically go on to discuss a unique type of disturbance mitigation technology which does not produce the above effect when incorporated into such a network environment.

This paper will attempt to enlighten the network user with a more complete and understandable analysis of the unique properties of networks and the special care that needs to be taken when trying to protect these sensitive systems from potentially damaging and/or disruptive electrical disturbances.

Figure 1 shows a block diagram of a simple two terminal network. It can be seen from the diagram that although both computer terminals are powered from the same breaker panel, that the distance from this breaker panel to each of the two computer terminals is not the same. Note as well, the distance, (5m in this particular configuration), between the two computer terminals. As can be seen in figure 1, both computer terminals are fitted with EMI suppressors between their dc power supply connection and the AC wall outlet.

Finally, notice the communication network used, (as shown by the two conductors between the Transmit/Receive, TX/RX, circuits of one computer terminal to the TX/RX circuits of the other computer terminal), to interface one terminal with the other. In this system we will assume a coaxial cable interface where a centre positive signal conductor is surrounded by a signal reference shield. Figure 1 shows how this outer shield or braid is often either directly or capacitively coupled to AC ground at each end of its length within each computer terminal. Other types of communication networks commonly used are RJ11/RJ45, RS232, RS423, and IEEE488 configurations. In these systems, one or more conductors are typically used as a signal reference and often these references are directly or capacitively coupled to AC ground just as the coaxial cable system above.

In the network of figure 1, 60Hz power is delivered to each computer terminal via a three conductor, (line, neutral, and ground), 120 Vrms system. This power distribution system is not ideal, with each conductor having both distributed resistance and inductance along their length and each pair of conductors having a certain amount of distributed shunt capacitance

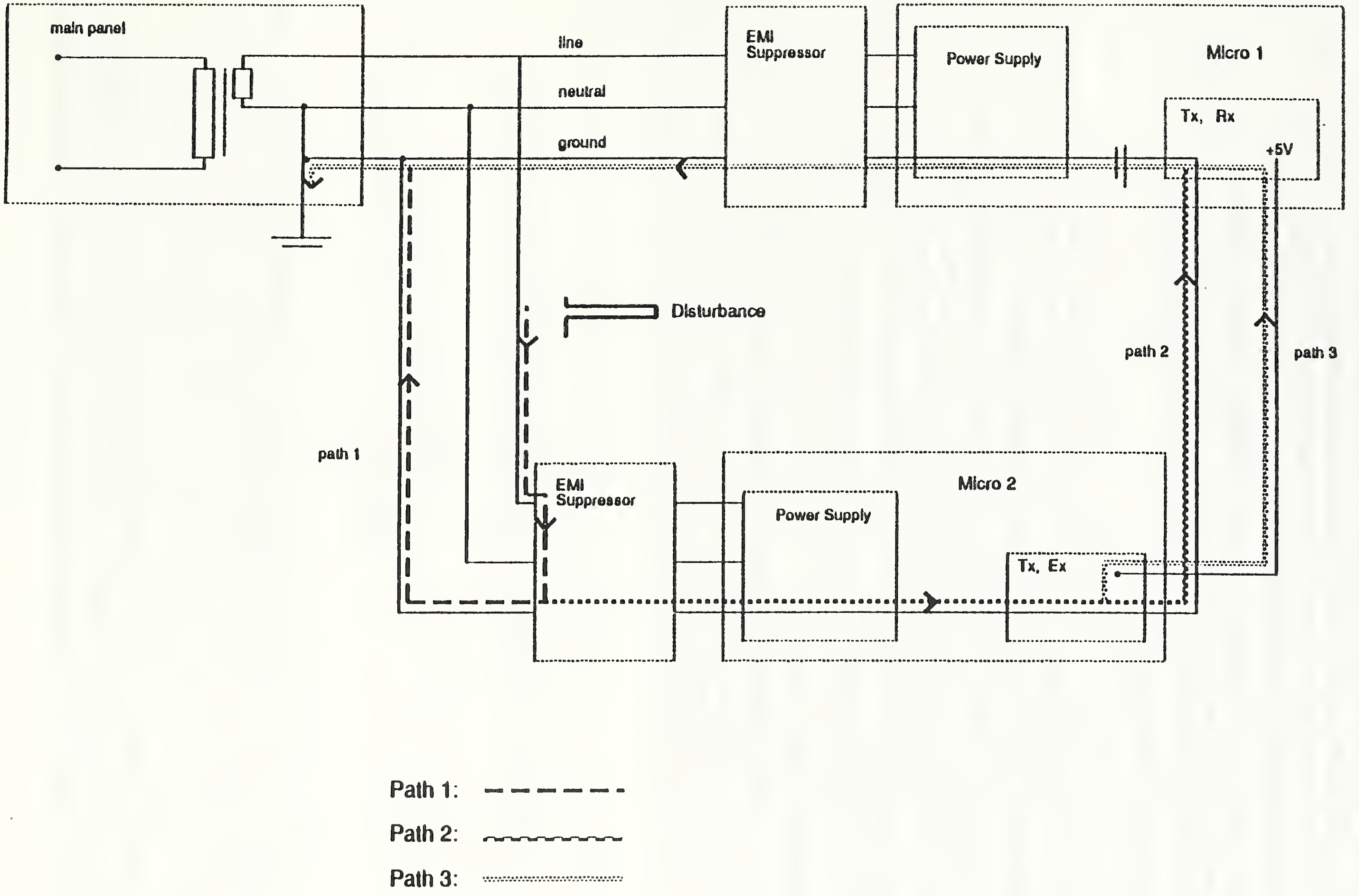
main panel
line
neutral
ground
EMI Suppressor
Power Supply
Micro 1
Tx, Rx
+5V
Disturbance
path 1
path 2
path 3
EMI Suppressor
Power Supply
Micro 2
Tx, Ex
Path 1:
Path 2:
Path 3:

FIGURE 1

between the pair. This results in a equivalent circuit model as shown in figure 2. These distributed impedances, primarily the distributed conductor resistance, produce power losses in response to steady state load demands by each of the network computer terminals of figure 1. Because of the distributed conductor inductance, the series impedance increases with increasing frequency while the distributed capacitance causes the shunt impedance to drop with increasing frequency. These two effects bandwidth limit the power distribution system to a frequency of about 30 MHz. Although this affect appears to be insignificant, with a power signal frequency of only 60 Hz, it will be shown to be very significant in terms of network performance under the influence of electrical disturbances such as transient overvoltages.

Let us now look at the effect of this nonideal power distribution system on the operation of our computer network of figure 1. For the sake of simplicity, let us assume a line to ground power disturbance, (note that a neutral to ground disturbance will produce a result similar to this line to ground disturbance), has occurred and is propagating towards computer terminal #2 in figure 1. Let us also assume, for simplicity, that the disturbance is "entirely absorbed" by the EMI suppressor protecting terminal #2. Regardless of the type of EMI suppressor used, (LC filter based, MOV or TVS diode suppressor based, hybrid filter based, or transformer based), surge current along the ground conductor, as shown by path 1, will be produced as a result of suppressing this common mode disturbance. With the nonidealities of the power distribution system and the generally high frequency characteristics of the common mode disturbance, a significant amount of ground impedance will appear between the EMI suppressor protecting computer terminal 2 and the earth ground connection at the breaker panel. Because of this, some of the return surge current will take alternate paths back to the breaker panel, (source of the disturbance). A second path for this relatively high frequency surge current is through the signal reference conductor of the communication network. This is illustrated by path 2 in figure 1. Assuming there are no sensitive components in this path, this situation by itself is not a threat to the operation of the network.

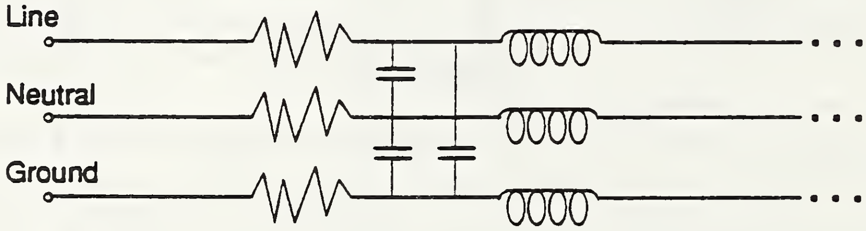

FIGURE 2

This is not the only other path for return surge current, however, and a third example is illustrated by path 3 in figure 1. Path 3 represents a potentially disruptive/damaging route for surge current as this current travels through sensitive TX/RX circuitry of each computer terminal. Remember that electrical current travels the path of least impedance so that the amount of current taking path 3 depends on the relative impedances of the available current paths at the frequencies of this particular electrical disturbance. Since the sum of the surge currents in all available return current paths is equal to the surge current propagating down the line conductor towards the EMI suppressor protecting computer terminal 2, then the amount of current taking path 3 is also a function of the severity, "amplitude", of the power disturbance itself. Whether or not disruption or damage occurs to either or both of the communication circuits of computer terminal 1 and/or 2 depends on other factors such as the sensitivity of the TX/RX circuits themselves, as well as the frequency content and duration of the surge current of path 3. In general, however, the greater the amplitude of this surge current, the greater is the chance of equipment damage and/or disruption.

From the above description, it is evident that there is a chance that network disruption and/ or damage may occur even though both terminals are fitted with EMI suppressors as protection against potentially disruptive/damaging powerline disturbances. It is this fact that is misunderstood and incorrectly interpreted by many recent power disturbance articles. In fact, many articles are claiming that it is the EMI suppressor that is causing the network disruption and damage. While some articles claim that EMI suppressors should not be employed in network applications, others are claiming that these suppressors should not attempt to suppress common mode disturbances, (line to ground or neutral to ground), as this creates the AC ground surge currents that can be potentially disruptive/damaging to other AC ground referenced network circuitry. Still other articles suggest that one particular type of EMI suppressor technology should be used in network applications and all others should be avoided. Some of these statements are misleading and avoid the overall electrical disturbance problem with respect to electronic equipment networks.

Let's overcome some of these misconceptions with the facts:

1) all types of AC powerline EMI suppressors that provide common mode attenuation produce surge currents in the AC mains ground conductor.

2) many networks have sensitive circuits, such as the TX/RX circuitry of computer terminals 1 and 2, figure 1, referenced to AC ground; either directly or capacitively coupled.

3) the above two facts can cause common mode powerline disturbances to affect other seemingly unrelated network circuits.

4) using EMI suppressors that do not attenuate AC mains disturbances in the common modes leave the computer terminal dc power supplies open to possible disruption or damage from these common mode events.

5) by not using an AC mains EMI suppressor or by using one that does not provide common mode suppression, the dc power supply is left open to "common mode" damage, often in the form of a short, which will produce AC mains ground surge current.

6) the above ground surge current can have the same disruptive/ damaging effects on AC mains ground referenced EMI sensitive network circuits as explained previously.

The EMI problem in most systems stems from the fact that most attempts at network EMI immunity are made after installation. The system is installed, problems occur, and a very unsystematic approach is taken to try to solve the particular EMI compatibility problem. This trial and error approach may produce an acceptable solution but usually at the expense of much time and customer dissatisfaction. The more logical approach involves selecting compatible EMI suppressor technology for all susceptible network circuits before installation. If at all possible, EMI tests should be made in the lab to confirm immunity levels and then when all is acceptable, network installation should be made "properly" by a trained installer. These measures can pay dividends in the long run.

Examples of this systems approach are illustrated in the following paragraphs. Figure 3 shows the same two terminal network with systems protection. As can be seen, each terminal is fitted with an equipment compatible multimode EMI suppressor at the AC mains input connection. This hardens the dc power supply and associated circuitry to potentially damaging powerline disturbances. This by itself, is not the complete solution, however, as a large AC mains ground impedance at disturbance frequencies can produce alternate surge current return paths through other AC mains ground referenced network circuitry. Many approaches may be taken to solve this problem and Figure 3 illustrates the use of communication network EMI suppressors at each computer terminal port. These suppressors provide an alternate surge current return path, path 4, as illustrated in the diagram. Correctly designed, this dramatically reduces the surge current of path 3, through sensitive TX/RX circuitry and significantly reduces the chance of damage/disruption to these circuits. Designed correctly, this network is now immune to most conducted EMI disturbances occurring on the AC mains or communication network. More sophisticated networks may utilize several communication networks and each needs to be evaluated in terms of conducted EMI compatibility.

While this represents one systematic approach to the electronic network conducted EMI compatibility problem, other approaches may be taken instead or in addition to this approach. Opto-isolators are often employed in such communication networks to semi-isolate the system from the influence of the AC mains. Fiber optics may be used for this communication system to similarly isolate it from outside EMI disturbance sources. In sophisticated systems, an approach that is often recommended is to isolate the communication network from the AC mains ground by using a signal reference grid, usually installed

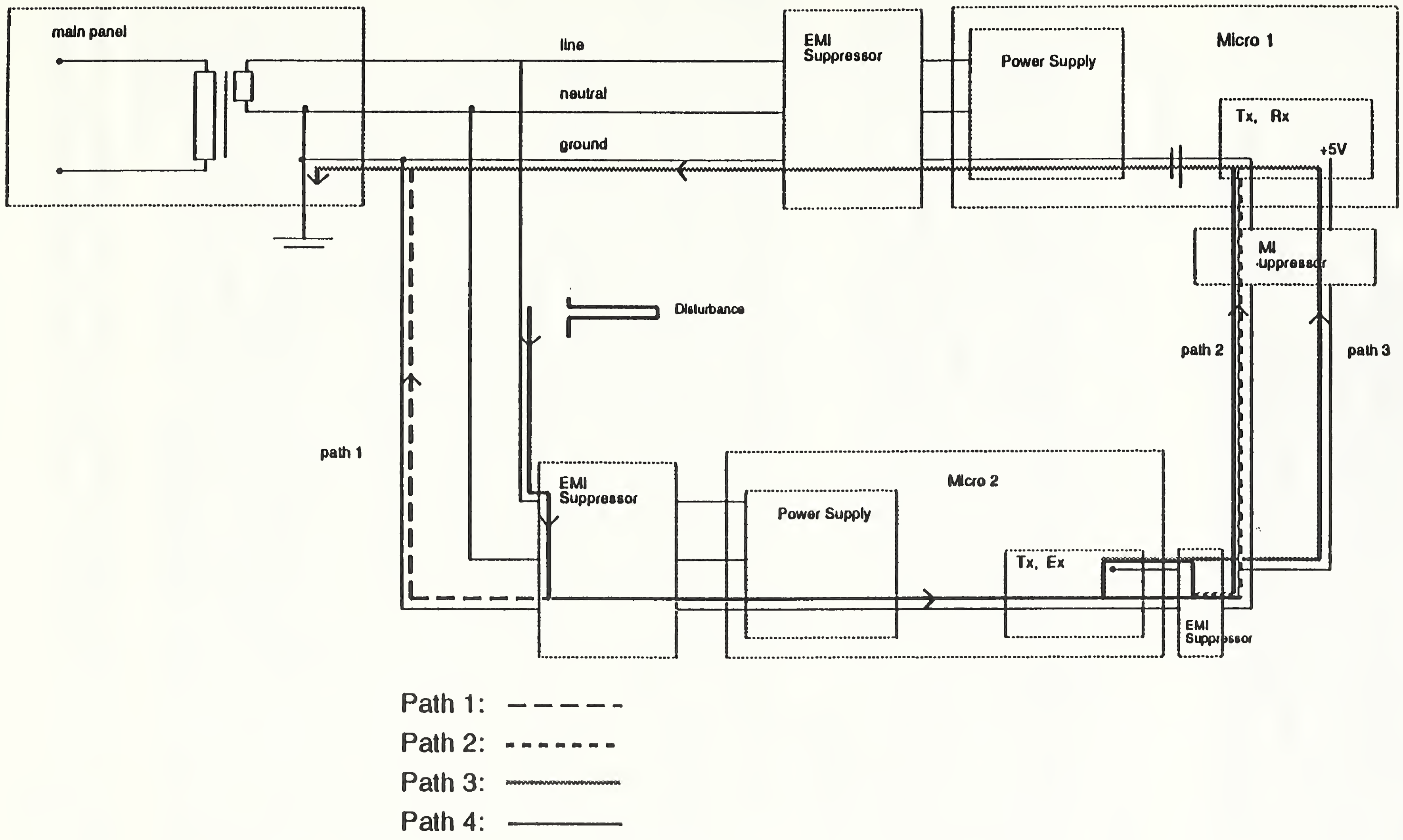
main panel
line
neutral
ground
EMI Suppressor
Power Supply
Micro 1
Tx, Rx
+5V
MI ·uppressor
Disturbance
path 1
path 2
path 3
EMI Suppressor
Micro 2
Power Supply
Tx, Ex
EMI Suppressor
Path 1: – – – – –
Path 2: - - - - - - -
Path 3:
Path 4:

FIGURE 3

under the facility floor, (see pages 23 to 45 of the Ontario Hydro "Power Quality Reference Guide"). In this system, electronic equipment communication circuits are referenced with very short lead lengths to a low impedance, wide bandwidth signal reference grid. This grid is isolated from the AC mains ground system except where it is connected in one place at the panel board, thereby providing a "ground window." With such a low impedance reference, the entire system signal reference will "float" on approximately the same electrical potential and most EMI disturbance problems will be eliminated.

SUMMARY

Electronic equipment networks require special attention in terms of protection from conducted electrical disturbances such as Electro-Magnetic Interference. Applying powerline EMI suppressors to each network terminal after installation of the system may not be the solution to the conducted EMI compatibility problem. As explained in the article, multimode EMI suppressors that harden terminal dc power supplies to electrical disturbances can introduce high frequency surge currents into the AC mains ground system. This can have an effect on seemingly unrelated circuits such as the TX/RX circuitry of each computer terminal of the network.

Many recent articles, related to this problem, have contained incomplete and/or incorrect information that has complicated the issue for the network user. Contrary to many of these articles, the answer to this Network Protection Dilemma is not a mysterious, new powerline EMI suppressor that reduces potentially disruptive/damaging electrical disturbances without producing surge currents in the AC mains ground conductor. The answer is also not an EMI suppressor for the AC mains that does not suppress in all propagation modes as this leaves the dc power supply open to damage from common mode AC mains disturbances. Failure of the dc power supply in this instance can produce the same surge currents in the ground conductor that may also affect other ground referenced circuits. In most cases, EMI compatibility problems arise in sophisticated electronic networks because the problem is not addressed until after the network is installed and disruption or damage occurs.

The answer to the special problem of making Electronic networks compatible to "typical conducted EMI disturbances" is to address the problem before installation. The network should be examined as a whole and all possible paths of conducted EMI disturbances should be considered. Equipment compatible EMI suppressors should be selected and, if at all possible, EMI testing should be performed to confirm the effectiveness of the protection system chosen. In addition to the above, especially sensitive communication systems should be isolated from AC mains disturbances through the use fibre optic links, opto isolators, or electrical signal reference grids.

Each of the above methods add additional costs to the price of the network, but in many installations they can pay for themselves in as little as a few months by reducing service costs to the system.

THE EFFECTS OF INSTALLATION PRACTICE ON THE PERFORMANCE OF TRANSIENT VOLTAGE SURGE SUPPRESORS

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1. INTRODUCTION

Packaged surge protection devices are generally installed on low voltage AC systems to provide a controlled transient environment, as opposed to an uncontrolled environment relying upon the unpredictable sparkover of some clearance within the distribution system.

The objective of effective surge protection devices or systems is to control transient overvoltages to a level below the vulnerability to damage and, in many cases, the susceptibility to interference of electronic equipment.

The achievement of this objective is dependent on the characteristics of the protection device, the length and configuration of connecting leads used, fusing and the coordination of protection devices.

The effects of differing installation techniques are investigated and, where possible, the optimum solution is proposed.

2. TRANSIENT SAFETY MARGINS

In order to establish the protection of electronic loads two concepts can be adopted from work on aircraft protection (10).

These concern the process of achieving an adequate safety margin between the maximum level that transients are allowed to attain, that is the Transient Control Level (TCL) and the maximum transient withstand of the load or equipment (ETDL - Equipment Transient Design Level).

As we know from various surveys and standards (2, 3, 4, 5) transients in an uncontrolled environment can attain amplitudes as high as 6000V. Commonly, a disparity exists between the transient control level and the transient withstand of the electronic equipment. The purpose of transient voltage surge suppression is to bridge this gap with a reasonable Transient Safety Margin.

2.1 Assessment

In assessing the efficacy of any device claiming to offer transient protection, the concept of Transient Safety Margins is extremely useful.

Clearly, the residual transient overvoltage appearing across a protection device - the surge remnant, should be kept to a level not harmful to electronic loads.

2.2 Surge Remnant

Surge remnant is the maximum residual transient voltage appearing across a protection device during (and after) the application of a specified test in transient waveform (6, 7).

For a given surge threat, the surge remnant or residual transient voltage is dependent on both the characteristics of the surge protection device and the manner in which the device is installed.

3. CONNECTION TO THE POWER BOARD

Transient voltage surge suppressors, designed for installation at power panels are generally connnected in a shunt configuration across the supply to be protected. To ensure that specified performance (control of transients) is achieved and achieved safely, two key aspects must be observed:

- Length and configuration of connecting leads (performance related)
- Overcurrent protection and size of connecting leads (safety and performance related)

3.1 Connecting Leads

The measured residual transient voltage of a surge protection device has been shown to be influenced by the length and configuration of the cables from the protective device to the power panel.

The transient voltage appearing across a protected power panel is dictated by the following equation:

$$v(t) = i(t)R_c + L_c \frac{di(t)}{dt} + vp(t)$$

Where R_c = Total resistance of connecting cables

L_c = Total inductance of connecting cables

$vp(t)$ = Voltage across terminals of surge protection components

Generally the cross-sectional area of connecting cables required for safe connection to a power board ensures that R_c is low, contributing several volts per kiloampere of current discharged. However, the impulsive nature of the current flowing ensures that the effects of inductance will dominate.

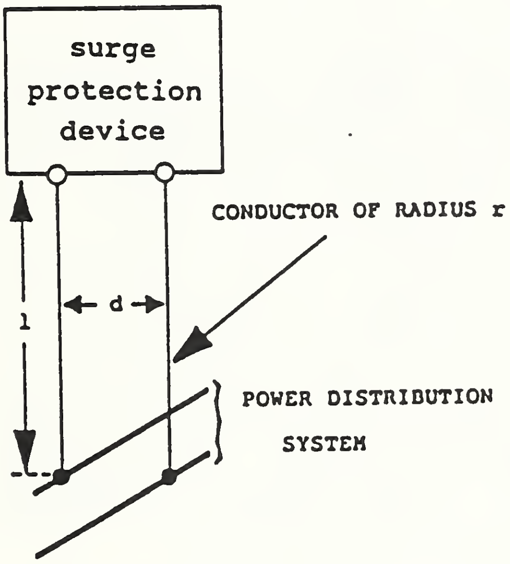

Fig. 1
Inductance loop formed by a pair of connecting cables from a surge protection device to a power distribution panel

The loop inductance of the connecting cables is dependent on the conductor's length, diameter and spacing and is dictated by the following equation:

$$L = \frac{\mu_0}{\pi}\left\{\ln\left(\frac{d - r}{r}\right) + \frac{1}{4}\right\}$$

Where L = inductance per meter of cable

r = cable radius

d = separation measured between centers of cables

μ_0 = permeability of free space

The "1/4" term is due to internal flux within each conductor. At high frequencies skin effect predominates and this term tends to zero. For the purposes of the following calculations, the term is included.

Table 1 and 2 below show variation in inductance and hence voltage drop with cable cross-sectional area and cable spacing ("d").

CABLE CROSS SECTIONAL AREA	INTER CABLE SPACING "d"	INDUCTANCE Per Metre	VOLT DROP Per Metre Per kA
1 mm^2	3.2mm	0.617µH	77.1V
10 mm^2	5.6mm	0.404µH	50.5V
100 mm^2	14.3mm	0.271µH	33.9V

Table 1 shows inductance per meter and voltage drop per meter per kilo ampere of 8/20 µs current for a loop of tightly bound cables, The distance between the cable centers "d" is as small as as practical, allowing approximately for 1 mm of insulation on each cable.

CABLE CROSS SECTIONAL AREA	INTER CABLE SPACING "d"	INDUCTANCE Per Metre	VOLT DROP Per Metre Per kA
1 mm	50mm	1.89μH	236V
10 mm^2	50mm	1.42μH	177V
100 mm^2	50mm	0.925μH	116V

Table 2 shows the same cable loop with centers spaced at 50mm representing loose unbound cables.

The inductive voltage drop is calculated for a current impulse of 1kA (8/20μs), flowing through a total loop cable length of 1 meter.

To summarize, connecting cables introduce series impedance (predominantly inductance) between the power panel and the protection device. The resulting increase in residual transient voltage, across the power panel when surge currents flow, can be minimized by controlling the loop inductance.

- Inductance of a cable loop can be minimized by binding cables together as closely as possible.
- Inductance is directly proportional to cable length. Keep cables short.
- Increasing the cable cross-sectional area has little effect on inductance.

4. USE OF FUSES

Surge protective devices do not normally carry mains current; indeed at mains voltage they represent a very high impedance. Why then should fusing of these devices be necessary ?

Over current protection is necessary on two safety grounds;

- To protect against excess fault current due to the short circuit failure mode of transient protection components.
- To prevent damage to the connecting cable due either to failure of transient protection components or a fault, for instance, across the terminals of the device.

4.1 Response of Fuses to Surge Currents

Users and manufacturers of surge protection devices must be aware that series fuses can operate when surge currents of short duration are flowing.

In suppressing a lightning induced overvoltage, surge protection devices discharge current. This surge current must flow through the series fuse without causing it to operate - otherwise fuse operation will disconnect the protection from the circuit when it is most needed.

A fuse will operate when the rated pre-arcing I^2t value for the fuse is exceeded. Some calculation and experiments necessary since fuse manufacturers generally quote pre-arcing I^2t for values of t greater than 10 ms. Lightning induced surge currents, for example, are of a shorter duration.

To ensure that a given fuse will not operate when discharging surge currents, the following must hold true:

$$\int_0^{\infty} [I(t)]^2 .dt < \text{Rated fuse pre-arcing } I^2t$$

$I(t)$ = Surge current as a function of time.

Experiments are required to determine just how much lower the I^2t value of the surge current has to be below the pre-arcing I^2t of the fuse, to prevent fuse operation.

4.5 I^2t Value of a Lightning Current

Consider the well known 8/20us waveform. Normalized, this surge current waveform can be approximately represented as:

$$I_n = Ae^{-\alpha t} \sin wt$$

Total I^2t can be derived as

$$A^2 (e^{-\alpha t} \sin wt)^2 \; dt$$

Integrating, we find

$$I^2t = A^2 . \frac{w^2}{4\alpha(\alpha^2 + w^2)}$$

Where for 8/20μs waveform

$$A = 1.728$$
$$w = 114.4 \times 10^3$$
$$\alpha = 45.45 \times 10^3$$

Therefore, for a given 8/20 us discharge current of peak magnitude I, I^2t is given by:

$$I^2t = A^2I^2 \cdot \frac{w^2}{4\alpha(\alpha^2 + w^2)}$$

substituting values of A, w,

$$I^2t = 14.18 \times 10^{-6} (I)^2$$

4.3 Evaluation of Fuses

The usefulness of pre-arcing I^2t figures for fuses can be evaluated and guidelines proposed.

For the purpose of the experiment, general purpose high rupture capacity fuses were considered, conforming to BS88 Part 2. Fuses, with ratings between 10 and 63A were surged with an 8/20 s impulse current whose calculated I^2t was close to the pre-arcing I^2t value of the fuse.

With an 8/20μs current waveform 90% of the I^2t is deposited in the first 25μs. It was, therefore, assumed that, if fuse operation occurred after 25μs, the I^2t of the impulse waveform was approximately equal to the I^2t rating of the fuse. Results were ignored if fuse operation occurred significantly before 25us.

4.3.1 Results

As expected, quite a spread of results were obtained. Based on rated pre-arcing I^2t, some "new" fuses passed peak currents 18% higher than predicted, others operated at currents 10% lower than expected.

A degradation in fuse characteristics was noticeable, even after a single impulse whose I^2t is close to the pre-arcing I^2t of the fuse. A degraded fuse (having successfully passed one impulse at predicted peak) could operate at currents 19% lower than the expected value.

The reasons for the variance of experimental results with calculated values are:

a) Pre-arcing I^2t values for fuses quoted by manufacturers generally have a tolerance of +-10%.

b) The 'actual' pre-arcing I^2t for a 8/20µs current waveform will differ from manufacturers' quoted figures due to the shorter duration of the impulse.

c) Experimental errors.

It is reasonable to assume that a fuse will safely pass an 8/20µs current impulse, 30% lower than that predicted by pre-arcing I^2t of the fuse.

The importance of fuse operation as a limiting factor on surge protection device performance is significant.

The following table indicates maximum safe discharge current for, a range of common European fuses.

FUSE RATING (A)	PRE-ARCING I^2t RANGE (x 1000 A^2S)	PEAK DISCHARGE CURRENT (8/20µs) (x 1000 A)
32	0.83 - 2.10	5.3 - 8.5
63	5.20 - 11.5	13.4 - 19.9
100	17.0 - 28.0	24.2 - 31.1
200	105 - 125	60.2 - 65.7
500	846 - 1220	171 - 205

Table 3 Relationship between fuse rating, pre-arcing I^2t values and peak discharge current (8/20µs) capability.

The results in Table 3 were conducted on European fuses, values for North American fuses will vary. However, the general principles hold true.

PROTECTION COORDINATION

In general, a low voltage power distribution system is split into a high number of branches feeding numerous secondary panels. A knowledge of the interaction between surge protection devices installed on LV AC circuits is important if protection devices are to be coordinated. The uncoordinated application of surge protection may lead to the following problems:

- High magnitude surge currents are encouraged to flow in inner-building wiring.
- Spark-over of clearances of wiring devices, with the possibility of power-follow-on.
- The corruption or physical damage of data/comm ports, due to surge currents flowing in AC grounding conductors.
- The corruption or physical damage of data/comm ports due to coupling between LV AC circuits and data/comm wiring.

The occurrance of the above problems can be mitigated by the coordination of surge protection devices such that surge current is not encouraged to flow within the building.

To highlight the potential problems of coordination, two simple experiments were performed.

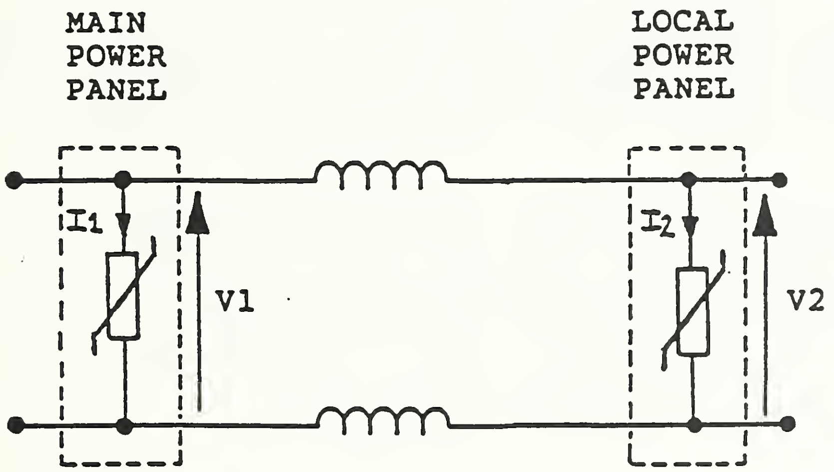

Fig. 2
Test Circuit

Test Circuits

The test circuit in Fig. 2, consists of two 32m 150V Varistors separated by 12 feet of building wiring. For ease of analysis the Varistors were matched at 1 mA and 1kA 8/20us.

Two surge generators were used, one capable of providing 4kA 8/20 µs into a short circuit; the second producing 100A 10/310µs. The distribution of currents in the test circuit is shown in Table 4.

Generator Short Circuit Current	I_1(A)	I_2(A)	I_1/I_2
4kA (8/20µs)	3760	460	8.1
100A (10/310µs)	46.5	37.5	1.2

Table 4 Distribution of currents in test circuits

Discussion

The limited tests conducted here clearly show that the coordination of devices, with similar characteristics, separated by a relatively short length of building wiring, is highly dependent on current waveforms.

Building wiring has distributed resistance, inductance and capacitance. In this experiment, neither capacitance nor resistance determine the division of current. It is the inductance of building wiring that modifies the waveshape of I_2.

The greater the length of building wiring between two surge protection devices, the greater the inductive effect. The coordination of surge protective devices, with short duration current pulses (e.g., 20µs) is dictated by the inductance of the building wiring. The coordination of surge protective devices, with longer duration current pulses (e.g., 10/310µs), may be dictated more by the characteristics of the protection devices than the inductance of wiring.

CONCLUSION

Correctly specified, correctly installed, transient voltage surge suppression can significantly reduce the incidence of disruption and damage of electronic equipment due to transient surge voltages.

The objective in specifying protection is to ensure that transient overvoltages are controlled to a level below the Equipment Transient Design Level, achieving a reasonable safety margin.

In practice, this objective can only be achieved if the performance of the surge protection device is not compromised by poor installation practice and inappropriate device coordination.

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No-Nonsense Computer Surge Protection: Wrong Choices Can *Cause* Failures

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Introduction

Modern desktop computers use complex, sophisticated, and very delicate, microprocessor circuits hardly dreamed of only a decade ago. The explosive proliferation of extremely fast "plug-in" computers with powerful user-friendly software has brought huge computing capability to virtually every office in America today, and to many homes.

The combination of faster computers at lower prices has spawned huge growth in sophisticated and critical applications, with users becoming increasingly, some say even dangerously, dependent on their computers.

Despite its incredibly low cost, today's plug-in computer is a highly sophisticated instrument, and its faster speeds and more densely packed circuits have made it more vulnerable than its predecessors to powerline surges. In response, computer owners have accepted the notion that they need surge protectors, whether or not they understand how such protectors work. As LAN Magazine says (December 1990), "Surge protectors are widely used, but poorly understood".[1] The lack of understanding by most consumers combined with the absence of objective and relevant comparison criteria, have inspired an active, energetic industry of surge suppressor manufacturers, with products of widely varying effectiveness.[2]

What Are Surges?

Surges are packets of unusable energy, like shock waves, propagating through the powerline. Their high voltage potential, up to 6000 volts in 110 volt power systems, makes them dangerous to delicate electronic components in their way as they search for paths to ground. Although they contain little total energy, their intensity can seriously damage and disrupt electronics, while being generally harmless to ordinary electric power equipment like heaters, motors and refrigerators.

Surges are picked up by the powerline from magnetic fields such as lightning, and from events on the powerline such as power factor correction, load shedding, and faults. They propagate like shock waves or tidal waves, not harming the powerline itself, but posing serious dangers to electronic loads in which they expend their energy as they flow to ground.

How Do Surge Protectors Work?

Ordinary surge protectors simply divert surges from the hot line (the only source of external surges, since the neutral and ground circuits are grounded at every service entrance) to the neutral and ground wires, where they are assumed to flow harmlessly to earth, the ultimate surge sink. These surge suppressors use metal oxide varistors (MOVs) and/or other similar shunt components which sense the high voltage of a surge, and quickly change state from an open (non-conducting) circuit, to a very low impedance short circuit for the duration of the surge. When the surge voltage disappears, the MOV returns to an open circuit, much like a pressure relief valve closes. In this way, the protector diverts mainly the surge energy and not significant amounts of powerline energy, because of the short duration of the surge, unless the MOV has degraded in its normal wearout process to the point where it "clamps" on the powerline. When that happens, the MOV explodes and fails, leaving the surge protector unable to provide any protection.[3]

An explanation of this performance vs. service life trade-off with MOVs, and an appeal to the industry to minimize the risk of premature failures, was presented by Martzloff and Leedy in their paper "Selecting Varistor Clamping Voltage: Lower Is Not Better!"[4] In it, the authors urge protector makers to avoid the race to provide "better" protection, at the expense of protector service life, since MOVs degrade in service and have caught fire.[5] Vernon L. Chi, Director of the Microelectronic Systems Laboratory at University of North Carolina at Chapel Hill says "The singular virtue of the shunt type protection device is that it's inexpensive."[6] The process of diverting unwanted surge energy to ground in a conventional surge protector is shown schematically in Figure 1.

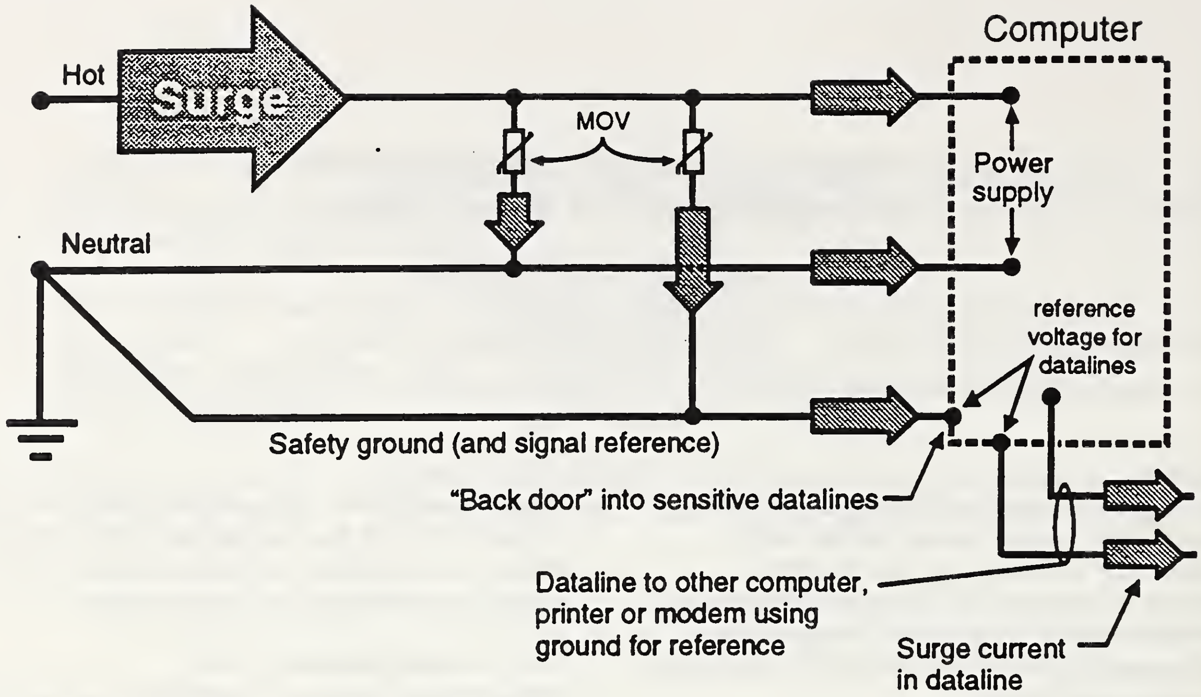


Figure 1. Ordinary Shunt Surge Suppressor

Cost of Computer Failure

As users become more dependent upon their computers, the cost of failure often means lost productivity, lost data, and disaster recovery, and generally far exceeds the simple cost of hardware repair. The New York Times reported in September 1989 that the average Fortune 1000 company incurred losses of $3.48 million from Local Area Network failures, which occurred an average of 23.6 times per year, for an average of 4.9 hours duration.[7] Of this total cost of computer failure, hardware repair was only a minor component. Those who doubt the cost and disruption caused by computer failure need only ask someone who has experienced one.

Networks and Modems Bring New Problems

Computers interconnected by datalines present a whole new problem because network (and modem) datalines use the powerline ground circuit for signal voltage reference. When a conventional surge protector diverts a surge to ground, the surge directly enters the datalines through the ground reference. As Martzloff explained in "Protecting computer systems against power transients"(IEEE SPECTRUM, April 1990), this causes high surge voltages to appear across datalines between computers, and dangerous surge currents to flow in these datalines.[8] Data Communications reported in December 1990 that "Most experts now agree that TVSSs [Transient Voltage Surge Suppressors] based on conventional diversion designs should not be used for networked equipment."[9] LAN TIMES commented in May 1990 "Surge protectors may contribute to LAN crashes by diverting surge pulses to ground thereby contaminating the reference used by data cabling."[10]

This problem was first discovered by a team of National Institute of Standards and Technology (NIST) researchers led by Martzloff in 1988. After they had performed some surge experiments on the powerlines in an industrial building, office workers reported damage to the data ports of their printers. On reflection, Martzloff concluded that the computer's shunt suppression circuitry had diverted the powerline surge to ground and created a surge current in the printer dataline, which damaged the printer data ports.[11]

What Protection Do Computers Need?

Because of secondary problems created by surges after they have been diverted, conventional unfiltered shunt surge suppression is unsatisfactory for plug-in computers. The laws of conservation of energy must prevail, and until this energy reaches earth, it poses a danger to electronic loads in its path. Adequate point-of-use protection for increasingly complex computer configurations requires that the surge energy be captured and released safely at a controlled rate, rather than simply be diverted to wreak its havoc elsewhere. A reliable surge suppressor would provide the following protection:

- keep let-through voltage under 250 volts
- preserve the integrity of the ground circuit as a clean reference for datalines
- provide noise filtering and attenuate the fast rise times of all surges, to prevent stray surge coupling into computer circuitry
- intercept all surge frequencies, including high frequency surges generated inside buildings, due to current interruption on branch circuits
- not use components that degrade in service.

The Ideal Surge Protector

The ideal computer surge protector would interrupt the power for the short duration, e.g. 50 microseconds, of the surge, then reconnect the circuit, as shown in Figure 2. Unfortunately, no switch exists today that can respond this fast, so this effect must be simulated by a circuit.

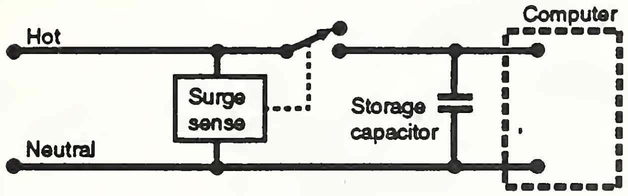


Figure 2. Ideal Surge Protector

A Practical Solution

A circuit solution which provides a high impedance to the surge while presenting a low impedance to the power wave is embodied in the patented new Surge Eliminator from Zero Surge. This unique protector employs a floating surge clamp which rides on the peak of the AC powerline wave and immediately captures any surge which exceeds the AC power wave envelope. Noise filtering within the dynamic range of the AC power wave (± 180 volts) slows the surge slew rate enough to enable the floating clamp to intercept the surge within 2 volts of the powerline peak, and successive stages of energy storage capacitance are brought into the circuit by sensing circuits measuring slew rate and surge amplitude. The stored energy is then released slowly to the neutral circuit, without disturbing the critical reference ground. The action of this dynamic clamp is shown in Figure 3 and the resultant surge energy paths in Figure 4.

This comprehensive energy storage circuit, which uses no wear parts, meets all the requirements for effective, non-degrading protection for modern plug-in computers. The circuit acts like a tennis net or a bucket with a hole in it, capturing the sudden rush of surge energy then slowly releasing it harmlessly to the neutral conductor. The circuit clears itself quickly enough to suppress repeated 6000 volt surges of unlimited current at the known 30-50 millisecond interval between multiple lightning strikes and so cannot be overloaded by the most severe natural phenomena.

Conclusion

Dependable surge protection is an important factor in computer reliability. Buyers of commercial surge protectors need to be informed of the technology employed in the various surge protectors they are considering. Particularly they need to know if the proposed surge protection technology is compatible and not in conflict with their application, as most surge suppressors are in conflict with modems and networks. The growing use of plug-in computers in critical

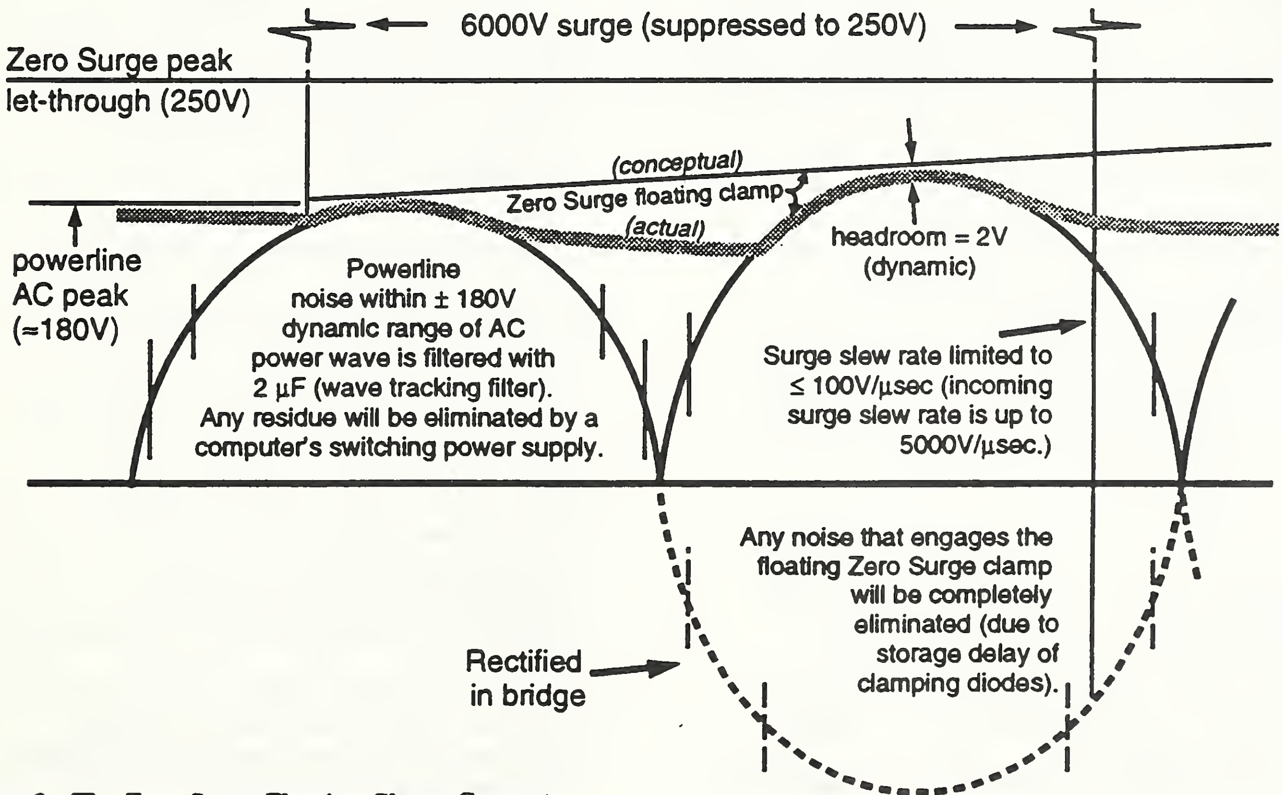
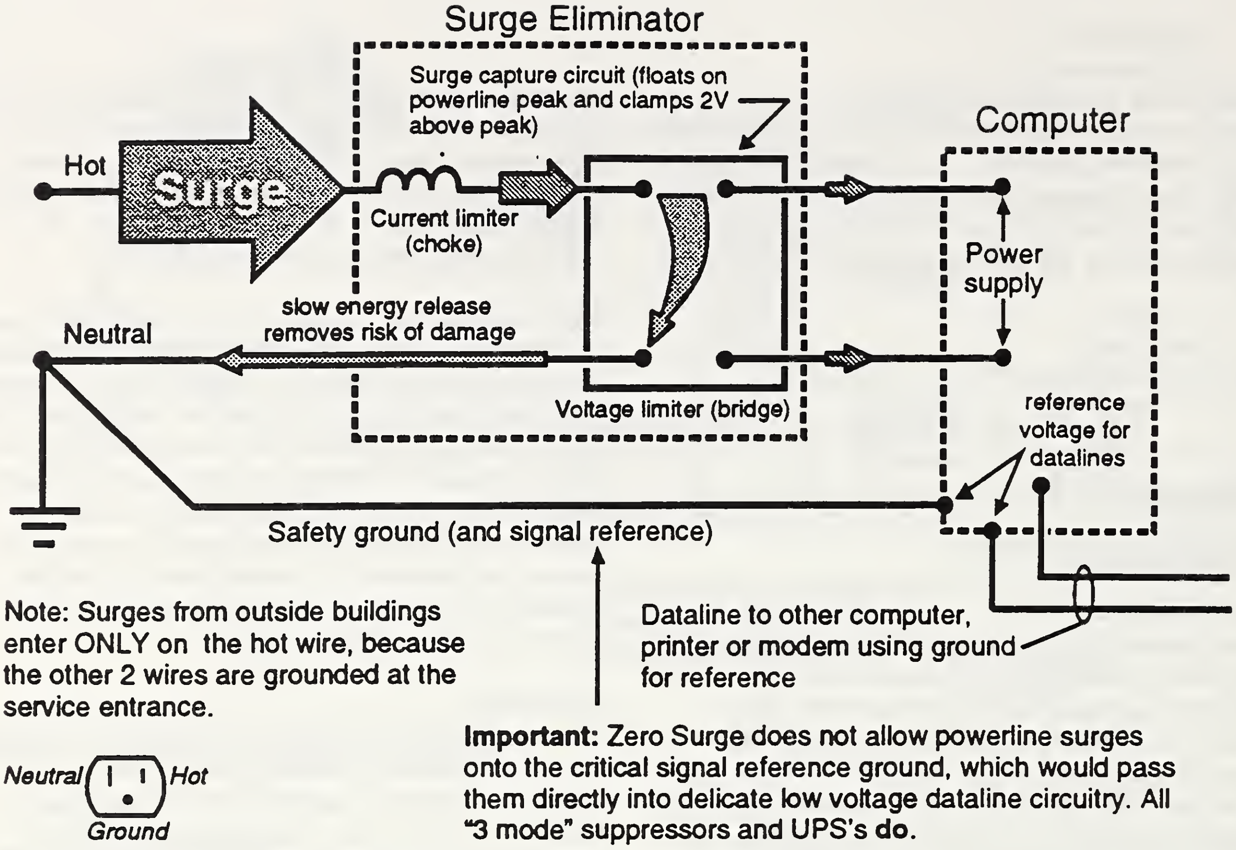


Figure 3. The Zero Surge Floating Clamp Concept



Note: Surges from outside buildings enter ONLY on the hot wire, because the other 2 wires are grounded at the service entrance.

Important: Zero Surge does not allow powerline surges onto the critical signal reference ground, which would pass them directly into delicate low voltage dataline circuitry. All "3 mode" suppressors and UPS's **do**.

Figure 4. Zero Surge Energy Flow System. Incoming surge energy is restricted by current limiter, then energy which gets through limiter flows into voltage limiting bridge, which presents far lower impedance path to surge than does computer. Like a river reaching an island, where the majority of the water flows past in the widest and deepest channel, so the majority of the surge energy flows where the impedance is lower, into the bridge, from which it is then slowly and harmlessly released to the neutral conductor.

applications, and the importance of effective, reliable surge protection to keep them operating, demands that consumers be honestly informed of the real characteristics of their surge protector, through industry standard performance tests like those for other products. Underwriters Laboratories deserves credit for the first objective performance test in their 1449 standard, but UL should not be responsible to establish and maintain useful performance standards in the fast-changing and controversial world of plug-in computers. Hopefully this NIST Forum will lead to some appropriate consumer guidelines, but until reliable standards and specifications are in place, consumers will be left to "buyer beware" in the jungle of computer power protection suppliers promoting various devices of varying effectiveness.

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GROUND MODE CONVERSION OF TRANSIENTS ON LOW-VOLTAGE AC POWER CIRCUITS

by

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Introduction

Mode-conversion of transients flowing on ac power circuits is a generally recognized phenomenon [1,2]. It means that transient currents and voltages appearing between two conductors may be transferred to other conductors. The transfer may occur through mutual inductive or capacitive line coupling, through connected loads, or through power-conditioning devices.

Of greatest concern to users of computer equipment are transient voltages occurring between ground reference points within a building. Many types of data communication line connected between computers are connected to equipment chassis. The chassis in turn uses the grounding conductor of the ac power circuit as its ground reference. Transient currents flowing in building wiring can produce momentary differences in voltage between these ground-reference points. Disruption or damage can result when these voltages are impressed on the data lines and their associated transceiver chips [3].

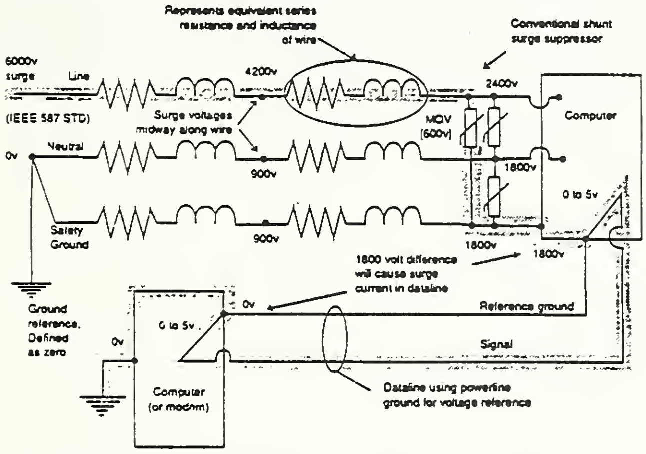

Figure 1. Ground-mode conversion resulting from service-entrance transients.

This paper examines the conversion of transient overvoltages applied between line and neutral conductors to the grounding conductor of a three-wire 120 V ac power system. Experimental data are presented showing the effects of the connection of surge suppressors, filters and isolation transformers at various points on the power system.

The data show that transient voltages can exceed 1 kV between grounds in a building when surges occur. The measurements also show that ground-mode conversion cannot be eliminated by the application of any single power-conditioning device. However, these differential voltages can be minimized by applying surge suppressors at the service entrance and branch distribution panels. This strategy reduces the flow of surge current in the branch circuit wiring, thereby reducing coupled voltages. Surge protection of data lines is shown to be necessary in most cases, in addition to all-mode ac power protection.

Experimental Study

The experimental study was carried out on a 100-foot branch circuit consisting of Romex 12/2 NM-B. This standard building-wiring cable has two insulated and one bare #12 copper conductors. Two separate tests were carried out. In the first, transients were injected between both the line and neutral and ground conductors of the branch circuit at the service entrance. In the second, transients were injected between line and neutral conductors at a distribution panel. In both tests, the voltage between the ground conductor at the end of the 100-foot branch circuit (where a computer might be attached) and a reference building ground were measured using a digital storage oscilloscope.

The differences in the ground-mode voltages when various surge protective devices were applied at the load were then compared.

The tested surge protective devices at the point-of-use were as follows:

1. No device.
2. A single 130-volt rated 20 mm mov connected line to neutral.
3. A commercial surge suppressor, having three 130-volt movs connected line to neutral, line to ground and neutral to ground.
4. A commercial filter suppressor, having six movs providing normal and common-mode protection and a broadband normal-mode low-pass filter.
5. A commercial filter-suppressor having a broadband normal-mode low-pass filter and no common-mode protection.
6. A commercial isolation transformer having low-pass filtration and neutral to ground bonding.

The surge suppressor applied at the service entrance and the distribution panel was a parallel combination of a 40mm 250-volt mov and a 4 μF capacitor.

Service-Entrance Surges

The first measurements were carried out with surges applied at a simulated service-entrance. At this point, neutral and ground conductors were bonded, in accordance with standard U.S. practice. Category B3 Ringwave (6 kV, 500 A, 100 kHz: ANSI C62.41-1991) test surges were applied between line and neutral-ground. The surge protective devices listed above were then applied at the end of the 100-foot branch circuit. The line to neutral let-through voltages were measured there, as well as the mode-conversion voltage between suppressor and building grounds (Figure 2).

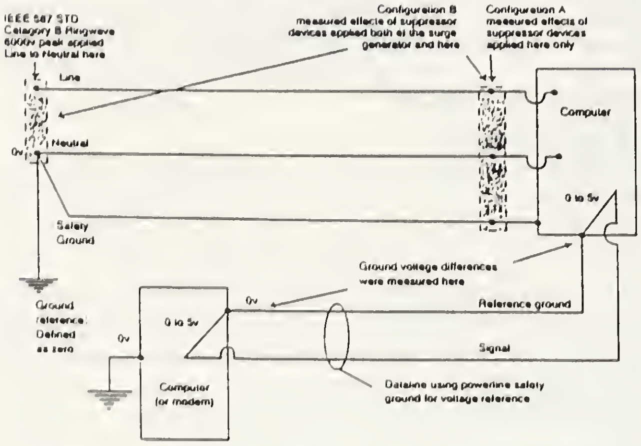

Figure 2. Experimental set-up, service-entrance transients.

The measured peak transient voltages for the two modes are shown in Table 1. A typical ground-mode conversion voltage waveshape is shown in Figure 3.

Protector	Peak Surge Voltage	
	L/N	G/G
1) No Device	>6,000	520
2) L/N MOV	334	768
3) 3 MOVS	345	1,780
4) Filter/suppressor	60	1,440
5) L/N filter	84	712*
6) Isolation Xformer	24	848

* Shown in Figure 3.

Table 1. Results of service-entrance surge test, protector only.

It is clear that the three devices giving best line-to neutral protection are those offering filtration, as might be expected for oscillatory transients. The largest ground-mode conversion voltages occur with the devices provided with common-mode protection. This is not unexpected, since the test surges are applied between line and both neutral and ground conductors. However, the differential ground transient peak voltage is greater than 500 volts in the absence of any protective device, and over 700 volts when any protective device is applied. These voltages are much larger than the withstand of all directly-connected data lines and approach the breakdown voltage of isolation transformers used in modems and LAN systems.

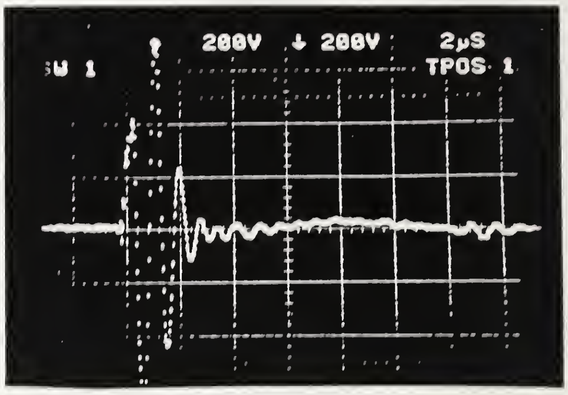

Figure 3. Typical differential ground-mode transient waveshape.

A second set of measurements was then made with a surge suppressor applied at the service entrance. This surge suppressor comprises essentially a 150-volt 40 mm mov in parallel with a 4 μF capacitor. The transients for the two modes were then measured again with the various point-of-use protectors, and the results are shown in Table 2.

Protector	Peak Surge Voltage	
	L/N	G/G
1) No Device	352	200
2) L/N MOV	256	184
3) 3 MOVS	312	192
4) Filter/suppressor	<10	184
5) L/N filter	24	192
6) Isolation Xformer	<10	188

Table 2. Results of service-entrance surge test, protector plus service-entrance suppressor.

Again, best normal-mode protection is provided by the three filter devices. Mode-conversion differential ground voltages are significantly reduced, with typical values below 200 volts. No significant differences were noted between the ground voltages of the various protection devices. However, levels were still much higher than the withstand of directly-connected communication media.

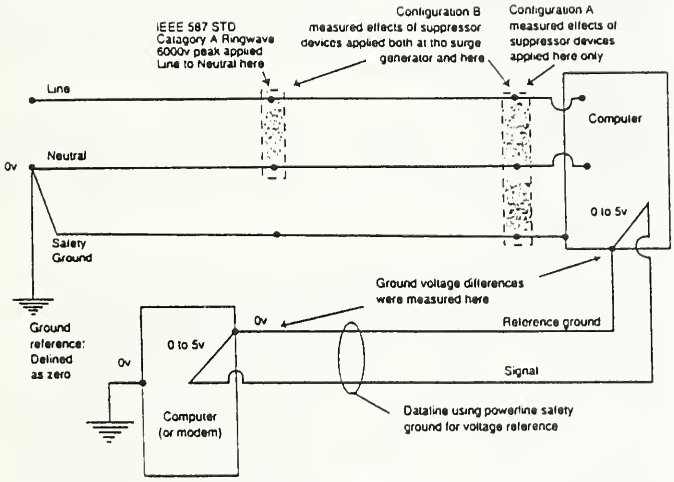

Figure 4. Experimental set-up, branch panel transients.

Internal System Surges

The second surge test was done by applying Category A3 Ringwave (6 kV, 200 A, 100 kHz: ANSI C62.41-1991) test waves between line and neutral conductors at the beginning of the branch circuit (Figure 4). Line and neutral conductors were bonded at the service entrance only, approximately 150 feet ahead of the branch service. This test simulates the effects of transients entering the system from internal disturbances, such as motor switching. It is a fairly realistic simulation of the majority of surges experienced under normal circumstances in commercial buildings.

Like the previous set of measurements, the first configuration used surge protective devices only at the load, at the end of the 100-foot branch service. Again, line to neutral let-through and differential ground voltages were measured. The results of these measurements are shown in Table 3.

Protector	Peak Surge Voltage	
	L/N	G/G
1) No Device	>6,000	152
2) L/N MOV	344	158
3) 3 MOVS	352	216
4) Filter/suppressor	<10	176
5) L/N filter	32	1,180
6) Isolation Xformer	<10	248

Table 3. Results of branch-panel surge test, protector only.

The best normal-mode protection was provided by the three products offering filtration, as in the previous tests. Ground-mode conversion was much lower in this test, as might be expected with no direct connection of the generator to ground. However, measured differential ground voltages exceeded 150 volts in all cases. One product, the line-to-neutral filter, gave significantly more mode-conversion than the others with over 1,100 volts. The isolation transformer was the second worst at ground-mode conversion.

The measurements were then repeated with a second configuration with the panel-mount suppressor described above connected line to neutral at the surge generator (Figure 4).

Protector	Peak Surge Voltage	
	L/N	G/G
1) No Device	242	128
2) L/N MOV	180	142
3) 3 MOVS	224	180
4) Filter/suppressor	<10	178
5) L/N filter	<10	208
6) Isolation Xformer	<10	180

Table 4. Results of branch-panel surge test, protector plus branch-panel suppressor.

The provision of this panel-mount suppressor was observed to have similar beneficial effects in reducing mode-conversion observed previously. Although there was not as much improvement as in the case of service-entrance surges, the ground voltages were generally reduced to below 200 volts.

Discussion of Results

The most significant result of this study is that the differential ground voltages which arise from ground-mode conversion when transients flow in the line to neutral conductors cannot be eliminated by the application of any filter, transformer or surge protective device at the load.

Removal of line to ground and neutral to ground protection elements not only has no beneficial effect on the reduction of ground-mode voltages, but exposes the connected equipment to potentially damaging common-mode surges. This is particularly significant since several products are being marketed which make specific claims to offer this benefit.

The reason for this is that most ground-mode conversion takes place because of coupling between conductors in the wiring. This coupling takes the form of capacitance and mutual inductance between the wires (Figure 5) and not through common-mode protective elements.

The most effective means of reducing these differential ground voltages is to reduce the flow of transient current in the branch circuit wiring by applying surge suppressors at the service entrance or distribution panel. This reduces the magnitude of surge currents and voltages flowing in the branch circuit wiring, and hence induced ground-mode voltages.

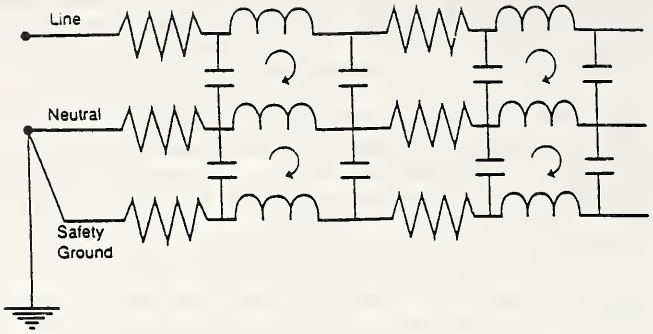

Figure 5. Mode-conversion coupling through capacitance and mutual inductance.

Protection of data lines

The experimental data presented above also show that measures are necessary to protect data lines and connected equipment from ground-mode transient overvoltages. Directly-connected data lines, such as RS-232, are susceptible to transient voltages in the range between 10 to 50 volts. Thus, even with comprehensive service entrance, distribution panel and point-of-use surge suppressors on the ac service, ground-mode voltages will be too high.

Application of surge suppressors capable of clamping transients to below 50 volts will be needed on both ends of such a data line. The experimental results presented here suggest that even relatively short lines (tens of feet) may require protection. This is consistent with observations of damage to computers via data lines, which has been observed to occur within a building, and even within the same room.

Data communications devices and media designed for long-distance transmission, such as modems and LAN terminal units, generally connect to the data line through an isolation transformer. Such transformers have transient withstand capabilities from about 500 volts up to about 3,000 volts [4]. These devices have reasonable immunity against most internally-generated ground-mode transients. Where ac power services are provided with service entrance and branch-panel suppressors, such devices should have sufficient withstand for most ground-mode transients.

However, ac circuits with insufficient surge protection could allow the generation of differential ground-voltages high enough to break down this isolation transformer. In this event, surge currents and voltages would be transferred directly to the terminal equipment and communications interface circuitry and perhaps also to the mother board of the computer.

Thus, severe common-mode transients should be reduced to a voltage lower than the withstand voltage of the isolation transformer. This can be accomplished by grounding the shield of a coaxial line to the chassis of the terminal unit or computer, either directly or through a suppressor. This grounding should be done at each piece of equipment.

Twisted-pair lines supporting a balanced communications medium (such as 10Base-T) should have balanced protection to equipment ground or chassis from each pair of conductors.

In all cases, the intent is to reduce the data line voltage with respect to the equipment chassis. Connecting shields and suppressors to equipment chassis is the most effective way of achieving this. Ungrounded shields or protective devices will be ineffectual, as will be suppressors connected to remote grounds, such as driven rods. However, even where protection against damage is achieved by the application of suitable data-line suppressors, the operation of a suppressor may corrupt data.

Complete immunity against ground-mode transient currents and voltages can only be achieved by using a non-conducting medium, such as fiber-optic cable or radio communications.

Conclusions

1. Large differential ground-mode voltages are induced when transients occur in other modes.

2. These voltages arise mainly through capacitive and inductive coupling in the wiring.

3. Ground-mode voltages cannot be mitigated by the application of any surge suppressor, filter or isolation transformer at the point-of-use alone.

4. Removal of common-mode protective elements is not beneficial in minimizing these voltages.

5. The best strategy for minimizing ground-mode voltages is to apply surge suppressors at the service entrance and distribution panels.

6. Data lines must be either protected against transients or have sufficient inherent immunity through isolation or use of a non-conducting medium.

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Diverting Surges to Ground:
Expectations versus Reality

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Preamble — A misconception is sometimes encountered, that surges can be eliminated by sending them on a one-way trip to "ground" in a manner similar to leftovers that disappear in the kitchen sink disposall, never to be seen again. Unfortunately, electricity travels on closed loops, and no amount of "grounding" - be it dedicated, isolated, separated, or otherwise - can dispose of unwanted electrons. Sending them down the drain of a grounding conductor makes them reappear in a microsecond about 200 meters away on some other conductor. The cycle for the waste through the environment takes longer, giving the illusion of disposal (at least as seen from the point of view of the kitchen sink - from the global point of view, one should take a different view, but that is another story). This paper presents a brief review of some of the fallacies, with illustrative measurement results, and proposes two approaches for remedy, rather than counterproductive grounding practices based on misconceptions.

SURGE PROTECTION SCHEMES

The usual method of providing surge protection involves diverting the surge current into some low-impedance path, so that the voltage drop resulting from the flow of the surge current through the diverter will produce only a small fraction of the voltage that would appear if no diversion were provided. This diversion can be performed by devices acting as a "crowbar" or as a "clamp." Another method of providing surge suppression involves attempting to block propagation of the surge, for instance with a low-pass filter. This method, however, would not succeed with the filter alone because the typical surge is originating from a current source so that an attempt to prevent the current flow would mean a very high voltage across the filter input components. As a second stage, a filter will work if another means is provided for diverting the surge before it reaches the filter (Figure 1). This approach is sometimes implemented in a single packaged device; another possible implementation is the "cascade" arrangement [1], [2], [3], [4] where a high-energy surge arrester is provided at the service entrance of the building to effect diversion of the surge before it would enter the building and propagate down the branch circuits.

A surge having the capability of delivering substantial currents and propagating down the branch circuits will result in large voltages at the end of the branch. Depending upon the relative values of the time for the surge to travel the length of the branch, and the duration of the surge, the propagation can be described in terms of traveling waves (surges shorter than the travel time) or in terms of a circuit analysis with lumped L, R, and C components (surges longer than the travel time) [5]. In the absence of a diverter at the service entrance, users can protect their connected equipment by installing a readily available plug-in protective device at the end of the branch circuit, that will divert the surge from the line conductor to the neutral conductor or to the equipment grounding conductor, or both.

Figure 2 shows the configuration of the conductors of a branch circuit extending from the service entrance panel to a receptacle at the end of the branch: L and N are the two current-carrying conductors, EG is the equipment grounding conductor, and LG is the "local ground" which can be building steel, piping, ducts, or the equipment grounding conductor of another outlet connected to another branch circuit. In Figure 2a, a plug-in surge suppressor is connected between line and neutral; in Figure 2b, a generic-type filter is plugged in the receptacle. Both types of devices at the end of the branch circuit will effectively limit the surge voltage between the line and neutral conductors, the two conductors feeding the power input components of the (sensitive) equipment. However, the surge current ‘returning to ground’ in the neutral conductor N will produce an inductive voltage drop along this conductor. With respect to the equipment grounding conductor EG at that point, a voltage will appear that can be magnified by the traveling wave effect of the branch circuit for the short inductive spike in the neutral conductor [6]. If the surge-protective device arrangement involves a path by way of the equipment grounding conductor (most electronic equipment, even if not provided with a built-in surge protector, have an EMI filter containing capacitors connected line-to-ground), then a voltage will be developed between the end of the equipment grounding conductor EG and other local grounded points at the potential of LG.

When a system is made of several pieces of equipment that are powered from such separate branch circuits, their respective chassis which are connected to their own equipment grounding conductors will be at different potentials at the instant a surge occurs on one branch circuit, but not the other. A data transmission link between the elements of the system typically has its reference connected to the equipment chassis. Thus, the data link becomes involved in attempts to equalize the potential between the two chassis, and may fail in the process. This scenario is well recognized [7]. Thus, protecting the power port of the equipment transfers the problem to the data port: the surge did not disappear!

CLAMPING OR FILTERING PROTECTION

In an attempt to overcome this problem, an alternate approach has been proposed whereby the protection would be obtained by a filter action rather than a diverter action. The expectation is that the filtering action would not involve the flow of current in the surge return path that was found to be the cause of the data link problem. However, even the filter, in order to provide the necessary closed-loop path for the surge current, has to accept the surge current at the rate which is imposed by the surge source. On the output side of the filter, the let-through voltage may well be very low, but on the input side, current will flow. If this filter is installed at the end of a branch circuit, the same effects of developing potential differences among grounded elements should be expected in the final analysis, a disappointing result in view of the hoped-for elimination of the data link problem.

The situation is illustrated by a series of simple laboratory experiments where a 30-meter length of three-conductor wire was used to simulate a branch circuit. Surges were injected at one end, and the effects of connecting surge-protective devices at the other end were observed by measuring the voltages between several combinations among the neutral conductor, the equipment grounding conductor, and the local building ground. Figure 3 shows a 0.5 μs - 100 kHz Ring Wave [8] with 3-kV peak applied at the origin of the branch circuit (Figure 3a) and the 4.2-kV surge arriving at the other end (Figure 3b).

Note that the first peak of the surge is higher at the end than at the origin, illustrating the enhancement of the traveling wave arriving at the open end of the transmission line. Figures 4 and 5 show the effects, desirable and undesirable, of connecting a clamp-type device at the end of the branch in an attempt to limit the line-to-neutral surge voltage.

Figure 4a shows the desired effect, that is, clamping of the Ring Wave at about 400 V between line and neutral conductors (L-N). Figure 4b shows the classic side-effect, a spike of 1300 V between the neutral conductor and the equipment grounding conductor (N-EG), occurring during the fast rise of the Ring Wave. Figure 5a shows the voltage between the neutral conductor and the local ground (N-LG), still a 1300-V spike. Figure 5b shows the voltage between the equipment grounding conductor and the local ground (EG-LG). The voltage of Figure 5b is a burst of 80-V oscillations that could be damaging to a data link connecting two pieces of equipment, each with its own signal reference but separated by this difference of potential.

With a filter-type device installed at the end of the branch, the voltages shown in Figure 6 and Figure 7 were observed. Figure 6a shows the voltage between the neutral conductor and the local ground (N-LG), a 1100-V spike similar to that produced by the clamp in Figure 5a. Figure 6b shows the voltage between equipment grounding conductor and the local ground (EG-LG), with a brief oscillation and peak of about 500 V, significantly higher than the 80-V burst of Figure 5b. Figure 7 shows a simultaneous recording of the initial part of the surge event: current in the line conductor, upstream from the filter (upper trace), and line-neutral voltage (L-N) at the output of the filter (lower trace), which is essentially free from significant overvoltage. Note in Figure 7 the 70-A peak current in the line conductor, with a rise time of 400 ns (about 170 A/μs) which has to be returned by way of the neutral. Figure 8, in a similar manner for the case of a clamp, shows the 120-A peak current in the line conductor, with a rise time of 700 ns (probably by happenstance, also about 170 A/μs). Thus, both approaches involve a return current path with substantial rates of current change, which are at the root of the ground differential side-effect.

Two possible methods (and perhaps more, still to be developed) can overcome the problem. The first is to avoid the problem altogether by not allowing large surges to enter the building. This desirable situation can be obtained by providing a suitable surge arrester at the service entrance. While earlier proposals to recommend or even to mandate such installation by means of the National Electrical Code have not been accepted by the Code Panels, growing recognition of the benefits may eventually lead to a more general application of this method. Of course, proper coordination, as discussed in Refs [2]-[4] will have to be implemented. With the high-current surges effectively diverted before they enter the building, there is still room for an effective application of surge-protective devices at inside receptacles, to deal with the (low-energy) surges generated within the building by normal and abnormal operation of the array of diverse equipment installed in the building.

The second approach, available to users who do not have the opportunity or means to install an arrester at the service entrance, is to provide a combined surge protection that covers both the power port and the communication port of the equipment to be protected. Dubbed ‘local ground window’ [9], this approach consists in routing both the power cord and the communication line (telephone, cable TV, RS232 link) through a single ‘window’, with any protective device on either line diverting any surge through the same path.

Thus, regardless of the length of that path, both ports are kept at the same potential, correcting the root problem of potential differences. These local ground windows are now becoming available from many sources; however, no generic standards have yet been developed to evaluate their effectiveness. The electric utility industry is attempting to develop 'performance criteria' that will help in the process. The author invites comments and inquiries on the development of these criteria, an objective of this Open Forum.

CONCLUSIONS

1. Effective protection against surges unavoidably requires diversion of the surge through a closed-loop path, which can involve two or more branch circuit conductors if the surge-protective device is installed at the end of a branch circuit.

2. While the main function of the device, limiting overvoltages between line and neutral, is accomplished, the return path for the surge current will produce differences of potential among the conductive parts at the end of the branch circuit, differences that can be damaging to certain components of connected equipment.

3. A more effective protection scheme is to divert the surges at the service entrance, rather than allow them to flow in the branch circuits. This cascading of a device at the service entrance and one at the end of branch circuit (the latter still necessary for protection against internally-generated surges) needs appropriate coordination.

4. Users who do not have control over their facility to the extent of providing a service entrance arrester may obtain relief and avoid side effects by applying a combined 'local ground window' to both the power port and communication port of their equipment.

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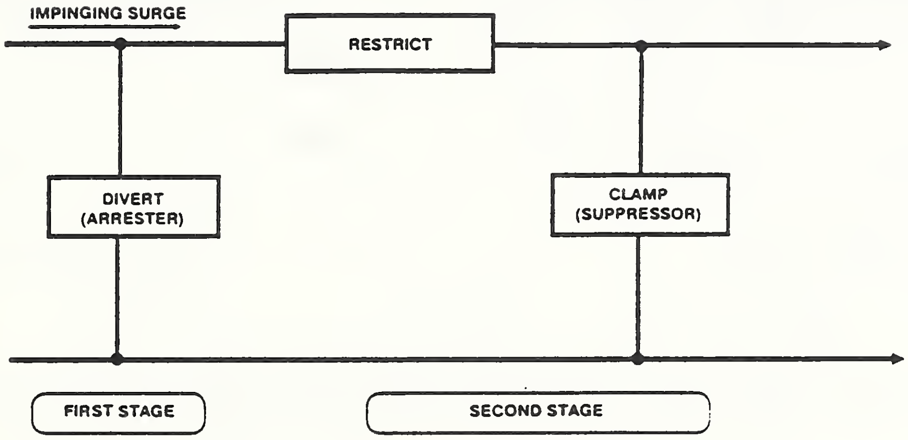
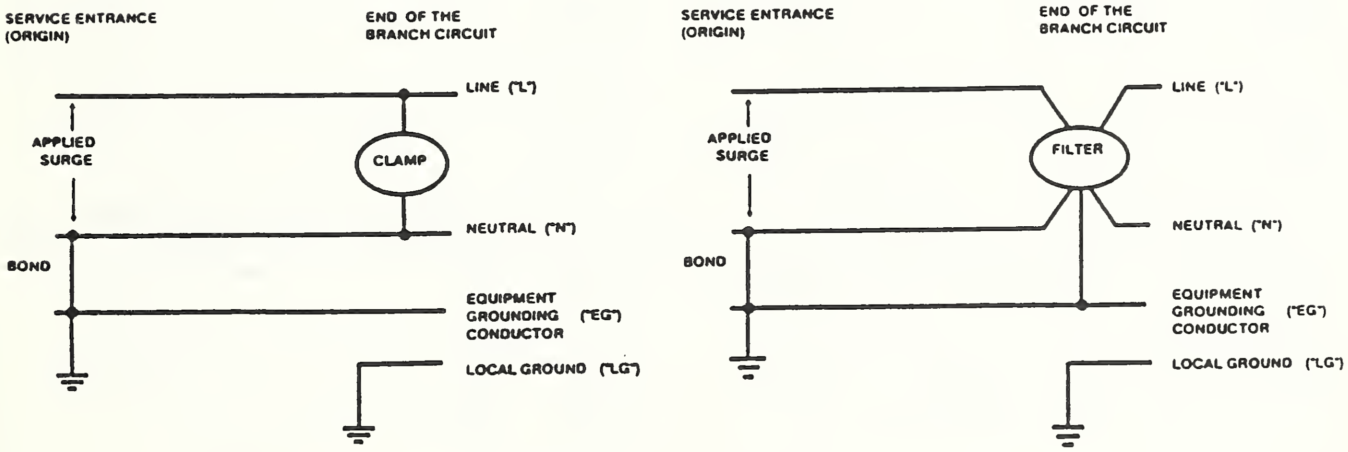


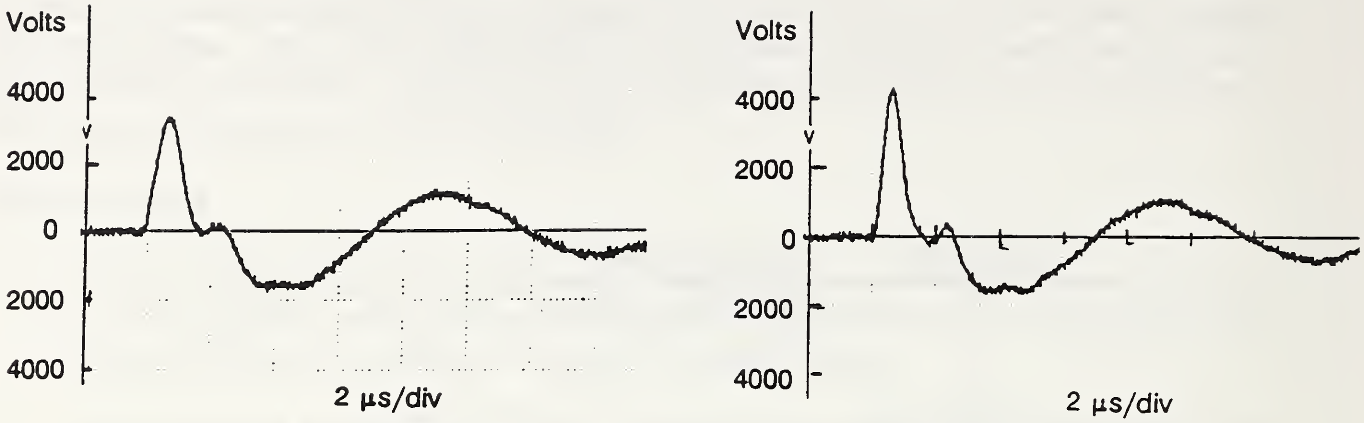
Figure 1
Basic approach for two-stage protection schemes



(a) Clamp-type suppressor

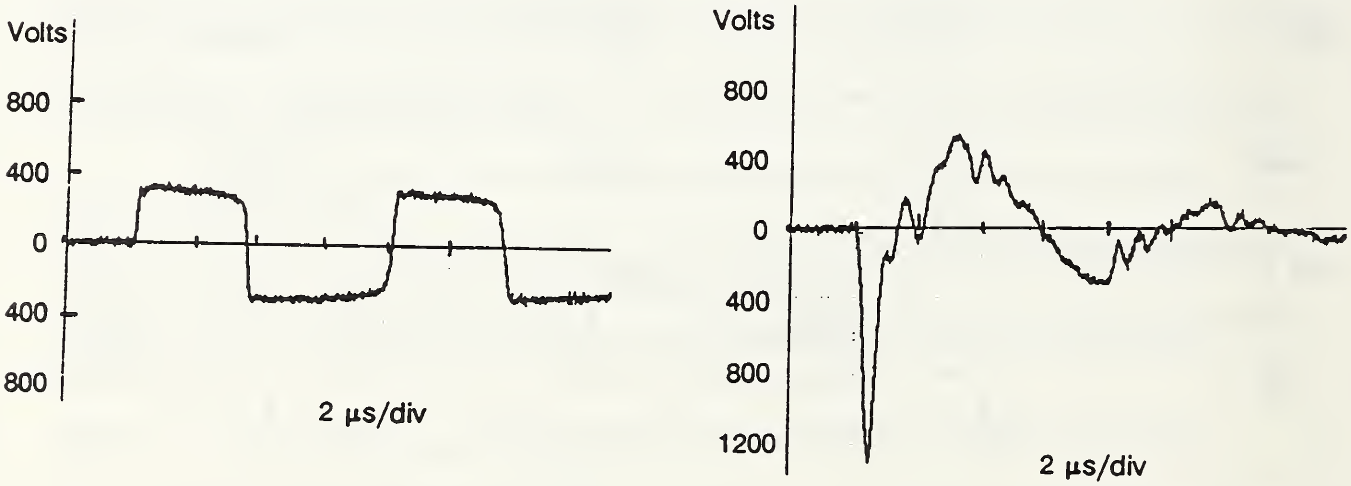
(b) Filter-type suppressor

Figure 2
Configuration of branch circuit conductors and suppressors



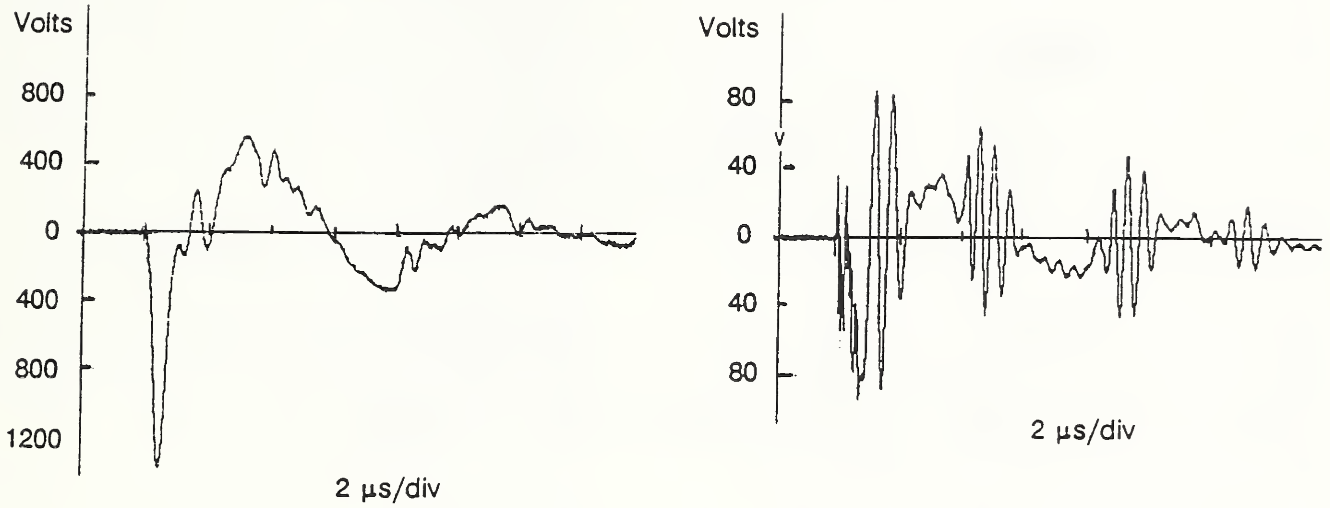
(a) At origin (b) At end of branch

Figure 3
Voltages at origin and at end of 30-m branch circuit,
with a 3-kV Ring Wave applied between the line and neutral conductors



(a) L-N Voltage (b) N-EG Voltage

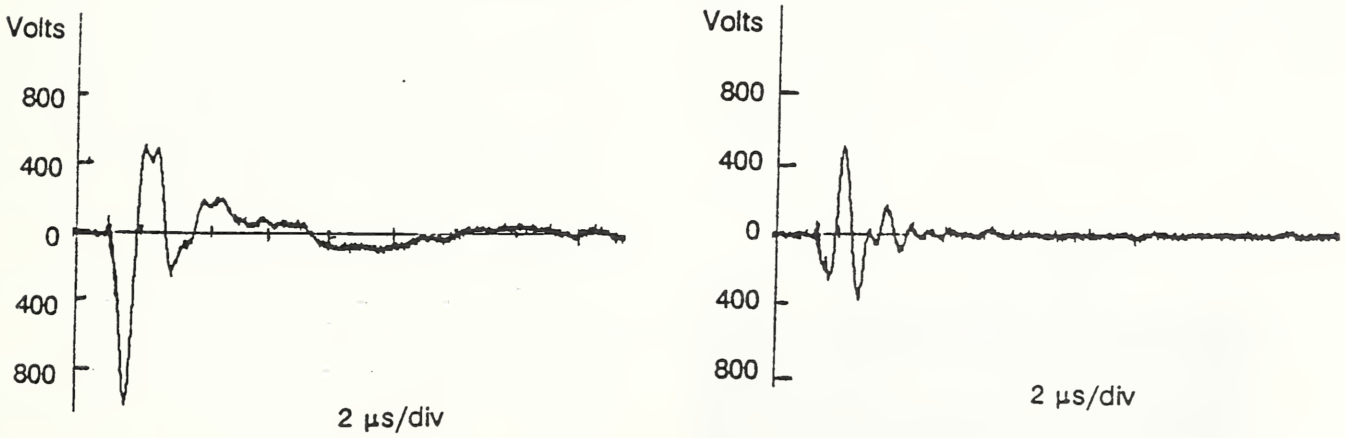
Figure 4
Voltages between line and neutral conductors (L-N)
and between neutral and equipment grounding conductors (N-EG)
at end of branch, with single varistor connected between line and neutral conductors



(a) N-LG

(b) EG-LG

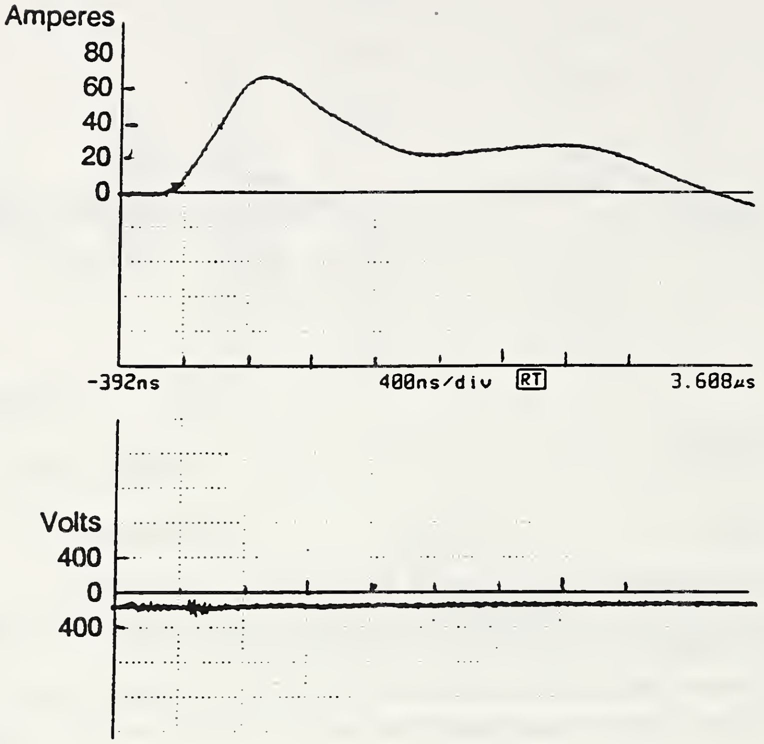
Figure 5
Voltages between neutral and local ground (N-LG)
and between equipment grounding conductor and local ground (EG-LG)
at end of branch, with single varistor connected between line and neutral conductors



(a) N-LG

(b) EG-LG

Figure 6
Voltages between neutral and local ground (N-LG)
and between equipment grounding conductor and local ground (EG-LG)
at end of branch, with filter-type suppressor connected at end of branch



(a) Line current

(b) Output voltage

Figure 7
Current in line conductor upstream of filter
and voltage output of the filter (synchronous traces)
with filter-type suppressor connected at end of 30-m branch

Figure 8
Current in line conductor upstream of varistor,
with varistor connected between line and neutral at end of 30-m branch

COORDINATION OF METAL OXIDE VARISTORS IN LOW-VOLTAGE AC POWER CIRCUITS

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Abstract

This paper reports on a theoretical and experimental study on the coordination of metal oxide varistors on an indoor low-voltage power system. The system studied was a 120-volt three-wire power line, equipped with phase, neutral and ground conductors. Metal-oxide varistors were applied at three points on the system. These were at the service entrance, at a distribution panel and at the load. Total line length studied was 30 meters (100 feet), with the distribution panel being located at the central point.

When unidirectional surges typical of lightning were applied at the service entrance, both experimental and theoretical studies showed similar results. Namely, removal of protection at either load or distribution panel resulted in unacceptably large oscillatory voltages. Best load protection was achieved with movs in all three locations. Distribution of surge current between movs in the three locations was shown to be good for both low and high surge currents. Coordination of protective levels was shown to be achieved, even with long surge waves typical of lightning.

Experimental Study

Experimental Set-up

For the experimental study two 15 meter (50 foot) lengths of #12 AWG Romex cable were set up. At the "service entrance" end, neutral and ground conductors were bonded and a single 40 mm metal-oxide varistor (mov), rated at 250 V rms, was connected between line and neutral- ground. At the end of the first length of cable, three 20 mm movs rated 150 V rms were connected to protect the distribution panel, one between each pair of wires. The second 15-meter length of line was connected to the first at this point. Three 20 mm movs rated 130 V rms were then connected at the end of the second length of line, to protect the load. A Velonex model 587 was used to apply the ANSI C62.41-1991 Category B3 standard Combination Wave surge (6 kV 1.2x50 µs open-circuit voltage, 3 kA 8x20 µs short-circuit current [1]) at the "service entrance" (Figure 1). Voltages at the various nodes were measured using a pair of matched Tektronix high-voltage probes and a 100 MHz storage oscilloscope, in accordance with ANSI C62.45. Mov currents were measured using a wide-bandwidth Pearson current transformer and a second similar storage oscilloscope.

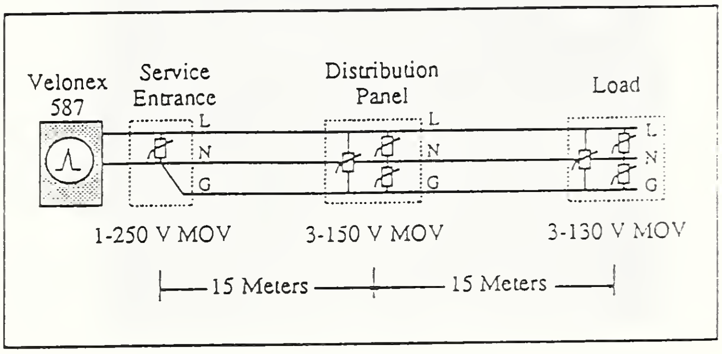

Figure 1: Experimental set-up.

Test Configurations

Three configurations of movs were used with the above set-up:

1) Load movs disconnected.

2) Distribution panel movs disconnected.

3) Movs at all three points.

For each configuration, the line to neutral transient voltage was measured at the service entrance, at the distribution panel, and at the load. The current flowing in the service entrance mov and the line to neutral movs was also measured.

Experimental Results

1) The transient voltages measured with the single service entrance mov and three distribution panel movs are shown in Figure 2 and 3.

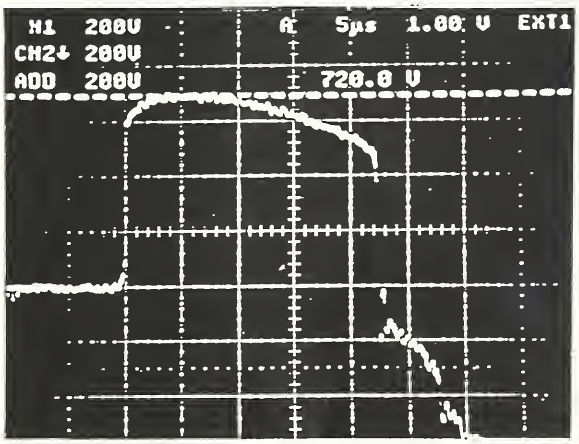

Figure 2. Voltage at service entrance.

Figure 2 shows the almost rectangular wave typical of mov response to unidirectional impulse currents. Peak voltage was 720 V.

The waveshape at the distribution panel was similar to the service entrance, with a peak value of 486 V.

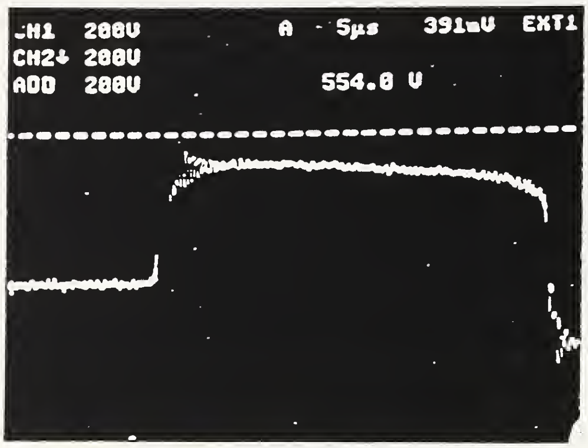

Figure 3. Voltage at load.

Figure 3 shows that the voltage at the load has a high-frequency oscillatory component, with a peak voltage of 554 V. This is due to the transient response of the 15 m length of unterminated power line.

The currents flowing in the service entrance mov and load line to neutral mov are shown in Figures 4 and 5 respectively.

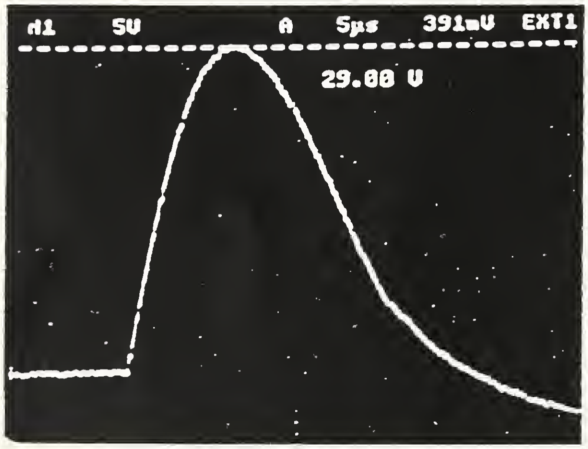

Figure 4. Total Input Surge Current.

The input current has the characteristic 8x20 µs waveshape, with a little negative overshoot due to the backfilter response. Peak current was 2.90 kA.

The distribution panel mov current reached a peak of 232 amps with a time-to-peak of 24 microseconds.

This measurement alone shows that the impedance of the 15 m of line forces virtually all of the surge current and energy through the service entrance mov. This occurs despite the very much lower clamping voltage of the distribution panel mov.

Figure 5. Panel line/neutral mov current.

2) The transient voltages measured with the single service entrance mov and three load movs showed similar characteristics. The service entrance voltage and current were identical to the previous measurement. The voltage at the load showed the normal mov response, with a peak voltage of 326 V. The voltage at the distribution panel showed a high-frequency oscillation superimposed on the mov response. Peak voltage at this point was 600 V. Load line-to-neutral mov current was 170 amps, with a time-to-peak of 28 µs.

3) The transient measurements made with movs at all three locations showed no unexpected results. Voltages at all three locations had the characteristic rectangular mov response, with peak voltages of 720 V, 416 V and 310 V respectively (Figure 7).

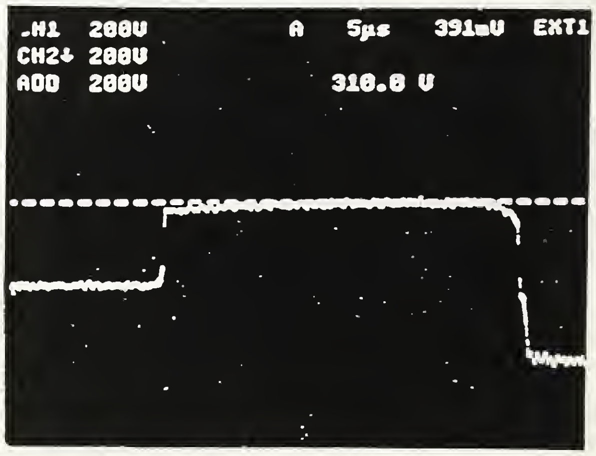

Figure 7. Voltage at load.

The total surge input current remained at 2.90 kA. The distribution panel mov current was 165 amps (Figure 8), the load mov current 95 amps.

These data show that the transient current distributes itself between the movs at the three locations. In all cases, most surge current flows in the service entrance mov, despite its relatively high clamping voltage.

Distribution of current in the panel and load movs is also good, with lowest current flowing at the load.

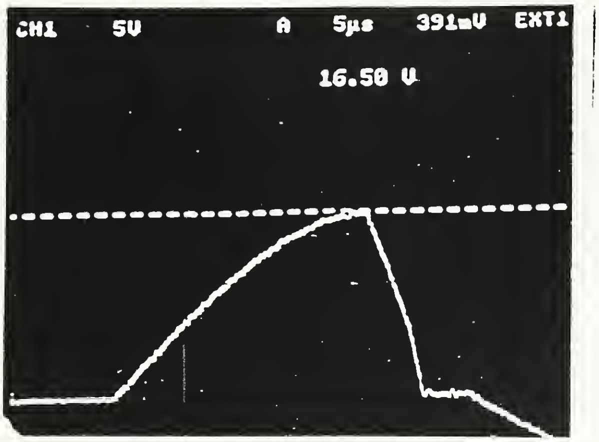

Figure 8. Panel line/neutral mov current.

Theoretical Study

Introduction

The purpose of the theoretical study was first to duplicate the results of the experimental study in order to validate the models used. The second purpose was to calculate the energy deposited in the various movs, which cannot easily be measured. Finally, the study was done to simulate the effects of lightning transient currents and waveshapes more representative of the real world.

Theoretical Models

Transient analyses were carried out using a spice-based program [2] on an IBM-compatible personal computer. Metal-oxide varistors were represented as time-invariant non-linear resistors. Mov characteristics used were based on laboratory measurements. This mov model does not take account of the time and temperature characteristics of real movs, but has been shown accurate to within 5% [3].

The power line was modeled by distributed capacitance, inductance and resistance (Figure 9). The values used were obtained from laboratory measurements on the Romex cable used for the experimental study.

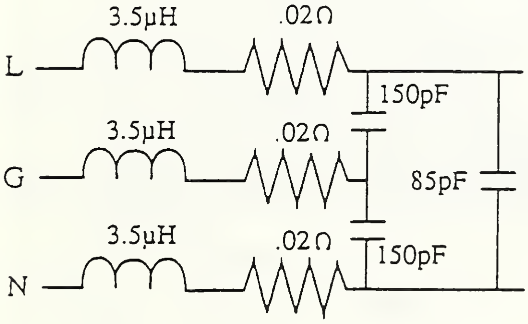

Figure 9. Power line model.

Two waveforms were used in the study. The first was the ANSI C62.41-1991 Combination wave used in the experimental study. The combination wave was used at two levels, both Category B3 (6 kV / 3 kA) and Category C3 (20 kV / 10 kA).

The second transient waveform used was a 10 kA 8x100 µs current wave, more typical of lightning than the usual 8x 20us wave [4].

Results of Theoretical Study

ANSI C62.41 Combination Wave

The first study was carried out with a single 40 mm mov rated at 250 V rms at the service entrance and three 20 mm movs rated at 150 V rms at the distribution panel. This is equivalent to the experimental study configuration 1.

The voltage waveform at the load and the panel line-to neutral mov current predicted by the simulation for a category B3 6 kV / 3 kA combination wave are shown in Figure 9.

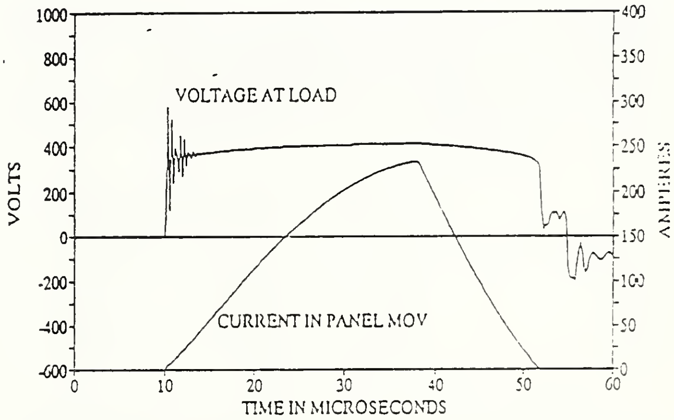

Figure 9. Simulated load voltage and panel line-neutral mov current, 3 kA 8x20 µs short-circuit current.

The voltage waveshape should be compared with that in Figure 3, and the current with that in Figure 5. It can be seen that both waveshape and amplitude are in excellent agreement with the measured values.

A simulation with the panel movs removed and those at the load added showed a very similar result to the experimental study, configuration 2.

Since these simulations validated the models used, it was considered that other input currents and waveforms could be used with confidence.

For the remainder of the study, three 20 mm movs rated at 130 V rms were added at the load. The third simulation repeated that of the first, with the addition of these movs, and should be compared with experimental test configuration 3. The distribution of currents predicted by the simulation in the service entrance, distribution panel and load movs is shown in Figure 10.

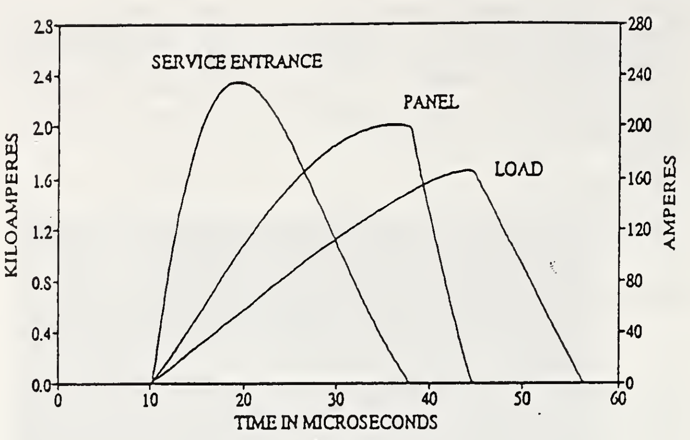

Figure 10. Currents in line-neutral movs at all three locations, 3 kA 8x 20 μs short-circuit current.

Note that the service entrance current scale is ten times the scale used for the other locations.

The predicted currents in the panel and load movs are somewhat higher than the values measured in the experimental study.
The peak voltage, mov current and energy from this simulation are summarized in the following table:

	Voltage	Current	Energy
Entrance	720 V	2.4 kA	26 J
Panel	397 V	200 A	1.7 J
Load	289 V	166 A	1.3 J

The energy deposited in the movs represents a very small fraction of their capabilities.

The next simulation also used the combination wave, but at 20 kV / 10 kA (Category C3). The currents predicted in the service entrance, and line-to-neutral movs at the panel and load are shown in Figure 11.

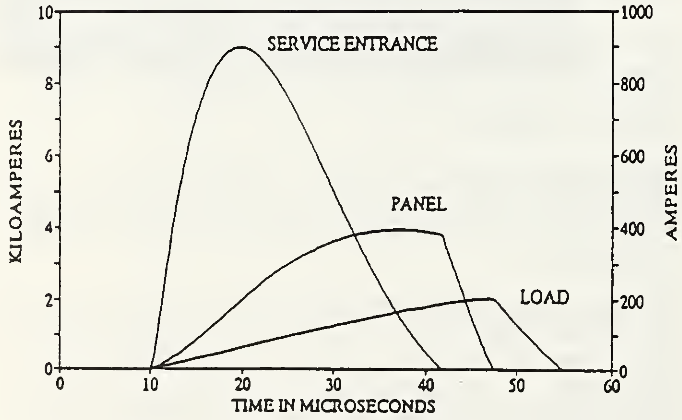

Figure 11. Currents in line-neutral movs at all three locations, 10 kA 8x 20 μs short-circuit current.

This simulation showed very interesting results. The current in the service entrance mov rose over 3.5 times, and the energy deposited in it by over 5 times. However, the panel mov current only doubled, and the load mov current increased only slightly.

The predicted distribution of voltage, mov current and energy is again shown in the following table:

	Voltage	Current	Energy
Entrance	940 V	9.0 kA	140 J
Panel	416 V	393 A	3.9 J
Load	292 V	204 A	1.6 J

The new ANSI C62.41 Category C3 test wave clearly does not represent a severe test for a service entrance suppressor. The impedance of the wiring in a typical building also provides for good coordination with suppressors at distribution panels and at loads.

<u>8x100 μs Lightning Wave</u>

The simulation was finally carried out with all three sets of movs in place with a 10 kA, 8x100 μs wave, typical of lightning [4].

The current waveforms predicted for the service entrance mov and the two other line-to-neutral movs are shown in Figure 12. Note again that the service entrance current scale is ten times higher than that used for the other two.

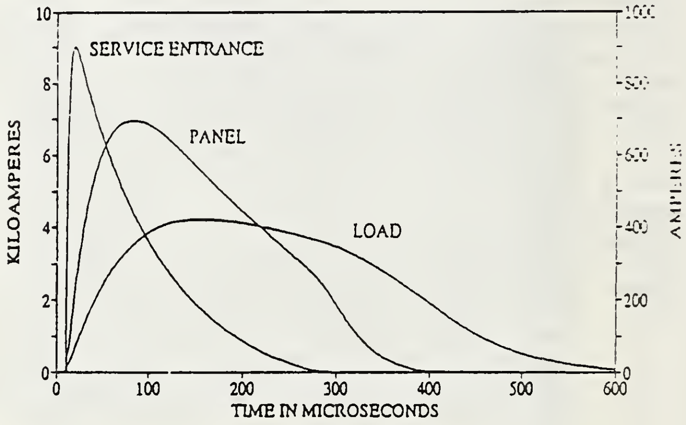

Figure 12. Currents in line-neutral movs at all three locations, 10 kA 8x100 μs short-circuit current.

The predicted distribution of voltage, mov current and energy is again shown in the following table:

	Voltage	Current	Energy
Entrance	950 V	9.03 kA	630 J
Panel	439 V	697 A	61 J
Load	307 V	423 A	43 J

As might be expected for an input current of longer duration, the currents flowing in the building wiring increase compared to the 8x20 μs test current. Nevertheless, protective levels at the panel and load are within 20 volts of the previously calculated levels. However, energy deposition in all movs increases markedly, and becomes a significant fraction of their one-time rating in all cases.

Surprisingly, a good distribution of current is still achieved between movs at the three locations, with the bulk of the current and energy still being handled by the service entrance mov. Excellent coordination of protective levels is also achieved.

The currents flowing in the building wiring and movs have much longer wavefronts and wavetails than the normally-used 8x20 us wave, and approach the 10x1000 us wave commonly used for testing of telephone and communications suppressors. This 10x1000 us test wave is now included in the new ANSI C62.41 as an alternate wave. The results of this paper suggest that it would be a suitable waveform for testing equipment and suppressors in buildings exposed to lightning surges impinging from outside.

Conclusions

The following conclusions may be reached regarding the protection of loads connected to low-voltage ac power systems inside buildings when subjected to external transients:

1) A service-entrance arrester or suppressor diverts the majority of surge current away from the building wiring.

2) The best protection is always obtained when suppressors are located on internal wiring at both distribution panels and at the load.

3) The lowest-rated mov does not have to be located at the service entrance, but can be effective when applied at the load.

4) Testing with the new ANSI C62.41 Category C3 combination wave gives results in reasonable agreement with those expected from more realistic lightning waves. However, the energy deposited in movs by this wave is much lower than expected from lightning.

5) Surge current waveshapes inside buildings have longer risetimes and wavetails than standard test waves. The 10x1000 us wave is the closest standard wave to those measured or predicted.

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Overview of the Revision of IEC Publication 664 and 664A

Insulation Coordination for Equipment Within Low-Voltage Systems

Part 1: Basic Principles and Requirement

SC28A only addresses insulation coordination, i.e. not upset (susceptibility). However, by necessity, SC28A is involved in subjects associated with transient overvoltages. It was important early in the work of SC28A to establish standardized overvoltage levels corresponding to the electrical distribution system voltages and overvoltage categories (see Table I). Overvoltage categories were initially termed installation categories but the use of the word installation was not acceptable to TC64.

Some of the overvoltage information and especially the concept of insulation coordination was new to the standards community. Eventually other IEC committees became interested and started to contribute to this work including TC64, TC42/WG9, and a new subcommittee SC37A. Although the revision of Publication 664 helps to clarify some of the original work and includes additional detail that was marked "under consideration", a few issues remain to be resolved. One critical issue is that of INTERFACES which will be addressed in this presentation.

C. R. Luebke June 14, 1991

What is Insulation Coordination?

Insulation coordination implies the selection of the electric insulation characteristics of the equipment is made with regard to its application and in relation to its environment. Insulation coordination can only be achieved if the design of the equipment is based on the stresses that are anticipated to occur in the installation. A major type of stress is that due to transient overvoltages.

When an insulation system is coordinated, the insulation should have a voltage breakdown level that is higher than that of the associated overvoltage [surge] protective device or higher than the transient overvoltages that are statistically predicted to occur at the location in an installation. And the equipment shall not generate switching overvoltages greater than the rated impulse voltage i.e. as declared by the manufacturer or marked on the nameplate.

The performance criteria can be verified using an impulse test generator or a method that produces an equivalent transient overvoltage stress. The results to be obtained are simply stated:

> When a peak voltage according to the desired insulation coordination is applied, no flash-over or breakdown shall occur.

It is important to point out that this test is not the traditional one minute dielectric test. And it is not a test for damage (vulnerability) or upset (susceptibility) per se.

HISTORY

R. C. Mierendorf chaired SC28A since its formation in 1974. Bob enthusiastically promoted the philosophy of insulation coordination until his retirement in 1990. Several original members of the subcommittee are still active in SC28A, for example Milt Cox of Underwriters Laboratories. UL Standard 840 incorporates insulation coordination concepts of IEC Publication 664 and 664A.

SC28A was assigned the role of a safety pilot function by the IEC Advisory Committee on Safety (ACOS) as noted in IEC Guide 104. The original Publication 664 in 1980 dealt only with clearances. Dimensioning of clearances is based upon fundamental research in the field of breakdown voltage between electrodes in air. Therefore, this information has only been edited for the revision and not materially altered. This is understandable since the basic laws of physics have not changed [at least not in the Northern Hemisphere]. Although this document was identified as a report, a report is a recognized safety publication per IEC Guide 104.

This report was followed in 1981 by Publication 664A as the first supplement to provide fundamental information for dimensioning of creepage distances. It was based in part on empirical data and also on an extensive German/American research project. The research project is also the basis for future work on the pollution section of the standard.

Amendment 1 on Dielectric Tests was published in 1989 and has been incorporated into the revision. A second Amendment on Requirements for Dimensioning Basic, Double, and Reinforced Insulation Based Upon Performance Criteria will also be included in the revision without first being released as a separate publication.

The subject of solid insulation was assigned to a new Working Group 2. The Committee Draft Standard developed by WG2 was recently voted affirmatively by national committees. Thus after editing, it will be included in the Part 1 Revision of Pub. 664.

It is anticipated that the revision will be published by IEC Central Office by the end of 1991 together with Part 3: Use of coatings to achieve insulation coordination of printed board assemblies.

TRANSIENT OVERVOLTAGES

Transient overvoltages can be caused by external events such as lightning or utility network switching or generated within the installation from operation of equipment. Insulation coordination with respect to transient overvoltages is based on controlled overvoltage conditions. The revision now gives equal importance to two kinds of control:

Protective control: The condition within an electrical system wherein specific overvoltage attenuating means can be expected to limit the prospective transient overvoltages to a defined level.

Inherent control: The condition within an electrical system wherein the characteristics of the system can be expected to limit the prospective transient overvoltages to a defined level.

Inherent control is based either on experience from measurements of overvoltages in typical systems or selection of overvoltage values from probabilistic analysis. The risk associated with Inherent Control may be greater than for Protective Control because of more variables. This is especially the case, if one must take into account the switching overvoltages produced by adjacent equipment, now or in the future.

Insulation coordination uses a preferred series of values of rated impulse voltage: 330v, 500v, 800v, 1500v ,2500v, 4000v, 6000v, 8000v, 12000v.

Initial protective control was based on the surge arrester performance as given in IEC Publication 99-1: Lightning Arresters written by TC37 and released in 1970. These devices consist of a spark gap in series with a non-linear resistor which have relatively high discharge voltage levels. More recent technology in surge protective devices has led to the need for new performance standards and the formation of SC37A. This has also led to the need for guidance in the coordination of surge protective devices when there is more than one located in the same installation or associated equipment. In fact this is a critical issue as it bears directly on the concept of interfaces for overvoltage categories.

The concept of insulation coordination is based upon controlled overvoltage categories to allow standardized impulse withstand values as given in Table I.

As a side issue, a clearance may be considered a renewable insulation. Under some circumstances a properly dimensioned clearance could be used to flashover at a level lower than the breakdown level of the solid insulation and thus serve as a overvoltage attenuating means. This assumes of course that there is no harmful power-follow current.

TRANSIENT OVERVOLTAGES (continued)

Karl Lerstrup of Denmark made many significant contributions to the early work of SC28A. The following idea is fundamental to insulation coordination:

"It is the duty of the manufacturer to indicate what insulation level [rated impulse voltage] the equipment satisfies, but it is the duty of the user to decide where to use that particular piece of equipment. The user is the only one who can make this decision, but only if the manufacturer has told him what the equipment is good for.

Concerning the implementation of this insulation coordination, the first step must be the decision of the individual technical committees on the proper insulation level [rated impulse voltage] for the equipment under their jurisdiction. The second decision will be that of the manufacturer.

However, the most important requirement is still the mandatory marking of the equipment, making it possible for the user to benefit from proper coordination."

Remember that this implies that no overvoltage in excess of this value can be generated by the equipment itself. Or stated another way, this means that overvoltages of that magnitude might be generated and that as a consequence, the equipment could be unsuitable for use in a lower overvoltage category. Or it may necessitate consideration of suppression means suitable for the lower overvoltage category.

INTERFACES

The interface concept was introduced by SC28A in Publication 664 as a written description of four installation categories (now termed overvoltage categories) and a stair-step example was illustrated. The stair-step example was of a residence for a specific electrical distribution system and voltages. This example caused difficulty for those who tried to relate the categories to a different application or tried to assign fixed distances to each step. It later became apparent that the subject was more complex because of the need to coordinate overvoltage protective devices. This resulted first in a working group paper, 28A(Las Vegas)09, updated December 1984 and later was released for national comment as 28A(Secretariat)30. Mr. Martzloff was a key contributor to the work during this time period. Unfortunately this document was not acted upon for some time because of other committee work.

Eventually the subject surfaced again because of an overlap with the work of TC64. A joint meeting was held in Munich in 1986 where Mr. Martzloff was enlisted to participate and explain the assumptions that were made in the 28A(Secretariat)30 document. As a result of that meeting and ensuing discussions, the document was reworked and released again as 28A(Secretariat)47, November 1987.

Again there were objections to the document, so the task was given to TC64 to have the experts in WG3 address the subject. After considerable delays, an ad hoc committee of TC64/WG3 with experts from other committees was formed to investigate the subject of interfaces. The committee, chaired by Mr. Start of the United Kingdom, generated a paper which was included in the Forum handout as IEC TC64/WG3(Secretary)138A. SC28A commends the committee for its contribution, especially the information on the the energy distribution in a multiple overvoltage protection application. However, the document needs more work to provide guidance to technical committees. Therefore, SC28A has again overtaken responsibility for this document.

There was also a companion document, 28A(Secretariat)48, Nov. 1987, Draft-Application Guide to Clause 8: Dielectric Tests of Publication 664; Considerations for dielectric withstand testing using the 1.2x50 impulse for testing equipment. This document was contributed by Mr. Walter Hart based upon his work in SC66E. Some of the work on testing was overtaken by TC42/WG9, High Voltage Test Techniques for Low Voltage Equipment. Several members of other committees including SC28A participate in this work.

FUTURE WORK

Future work will include:

Part 2: Concise Requirements for technical committees

Mr. John Humphries, a member of SC28A, will chair a special working group in TC61, Safety of Household and Similar Appliances, to develop the insulation coordination requirements for this type of equipment.

Part 4: Application Guide

1. Interfaces - developed jointly with other committees
2. Pollution - quantifying micro-environmental categories and coordinating with the macro-environmental categories based upon TC75 documents
3. Effects of higher frequencies on insulation - up to 1 MHz

Harmonization of definitions and terminology

CONCLUSION

The following statement was written by Dr. A. G. Day of the United Kingdom. Dr. Day was an early member of SC28A and later chaired the new Working Group 2 that generated the initial Committee Draft standard on Solid Insulation.

At first sight IEC SC28A was set the impossible task of devising a scheme of insulation coordination applicable to everything from computers to industrial traction drives. Early appreciation that only guidance could be produced made the target achievable. Over and over again it has been stated that IEC 664 and IEC 664A are intended to guide IEC Technical Committees and their national counterparts towards a better use of insulation, from both technical and economic standpoints. ....

Throughout the preparation of these documents it has been accepted that individual technical committees may have special knowledge of their equipment and its mode of use which will justify their selection of insulation distances both greater and less than those set out in IEC 664 and IEC 664A.

The objectives of the documents will have been achieved if committees take into account the many factors shown to influence the best use of insulation.

System Supply Voltages based on Publication 38	Voltages phase-to-earth derived from rated system voltages up to and including V r.m.s. and d.c.	Rated impulse voltages in volts for equipment Overvoltage Category			
	Reference Voltage	I	II	III	IV
	50	330	500	800	1 500
	100	500	800	1 500	2 500
120-240	150	800	1 500	2 500	4 000
230/400 277/480	300	1 500	2 500	4 000	6 000
400/690	600	2 500	4 000	6 000	8 000
1000	1000	4 000	6 000	8 000	12 000

Performance Criteria for Cascading Surge Protective Devices*

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Abstract - Cascaded surge protective devices in a low-voltage power system interact each other under surge conditions. Coordination of cascaded devices may be achieved by manipulating the device voltage clamping level and energy handling capability. However, a cascade condition may be effective for a certain surge source and the distance between devices but not effective for other cases. To develop the performance criteria for cascaded devices, all possible environments need to be taken into account. This paper uses the voltage clamping level of cascaded devices, their separation distance, and the surge waveform as parameters to study the energy deposited in the devices. All assumed cases were studied using computer simulation with necessary experimental verification. Results show reasonable agreement between simulation and experiment. A total of 72 case study results provide standard writers and application engineers with quantification information for the development of improved cascade coordination.

1. Introduction

In a low-voltage ac power system, the coordination of surge protection devices requires the high energy-handling capability device to absorb the largest part of the total surge energy. This high energy device is typically installed at the service entrance and will be called 'arrester' in this paper. A low energy-handling capability device is then installed at the downstream to protective sensitive equipment and will be called 'suppressor'. The arrester design can be a gap+varistor, a single large-size metal-oxide varistor (MOV), or paralleled small-size MOVs, and the suppressor is typically designed with small-size MOV(s). This paper assumes: (1) MOVs are used in both arresters and suppressors and (2) the arrester can absorb more energy than the suppressor.

Some utilities want to ensure survival of the arrester under loss of neutral condition, which requires twice voltage rating for the arrester. The downstream suppressors were selected with a low voltage level, driven by the perception that sensitive equipment requires a low protective level [1]. "High-Low" cascade scheme has been proposed to install a high-voltage device at the service entrance to absorb most of the surge energy and a small low-voltage device near the sensitive equipment to prevent possible over-voltage failures [2]. The

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scheme can work if there is a sufficient series impedance (mostly inductance) between the arrester and the suppressor, because the inductive drop in the series impedance is high enough to ensure that the major part of the surge energy is absorbed by the arrester, relieving the suppressor from the heavy duty [3]. However, during the tail of the surge, the inductive drop is negative and thus the suppressor with lower voltage, not the arrester, will divert the current. The ascending portion of a relatively steep 8/20 μs wave may be sufficient to develop an inductive drop between the arrester and the suppressor. For a surge like 10/1000 μs Impulse Wave proposed in C62.41-1991 [4], the tail contains most of the energy, and its drooping during negative slope of the waveform develops a higher voltage at the downstream device. The low voltage suppressor now absorbs most of the surge energy: the low bidder gets the contract. An alternate approach has been proposed - "Low-High" where the high energy-handling arrester clamping voltage is lower than that of the suppressor [5,6]. Thus, a disagreement has emerged among the recommendations for a coordinated cascade scheme.

In this paper, mathematical models for three voltage-level surge protective devices were developed. The device models were used for computer simulation to study all possible nine cascade schemes of three devices with four distances and two waveforms. A total of 72 cases were simulated using a 25-MHz personal computer. Some simulation cases were proved by laboratory experiment with satisfactory agreements. The results set the limits of a valid cascade coordination, and serve as input to the surge protector application guides now under development.

2. MOV Circuit Modeling

The current-voltage (I-V) characteristic of a Metal Oxide Varistor (MOV) has long been represented by an exponential equation, i. e., $I = k V^{\alpha}$ [7]. This equation is only applicable in a certain voltage (current) range in which the I-V characteristic presents a linear relationship in a log-log plot. When the voltage exceeds this "linear region," the current increment rate starts dropping. A modified I-V characteristic is proposed here as expressed in (1).

$$I = k V^{\alpha} e^{-(V - Vo)(\lambda - \zeta (V - Vo))} \qquad (1)$$

The parameters in (1) can be obtained from a minimum-error-norm curve fitting technique [8] using manufacturer's data book [7] or experimental results. The parameters k and α can be obtained from fitting the data in the linear log-log region. The exponential term is added to cover the voltages higher than a threshold voltage Vo and can be obtained from fitting the I-V characteristics in the higher current (voltage) region. Using (1), the MOV circuit model can be simply represented by a voltage-dependent current source.

Model parameters in (1) can be obtained from the manufacturer's data book and verified by experimental results. The parameter α is typically a function of the MOV voltage rating. The threshold voltage V_o and coefficients λ and ζ are functions of the voltage rating and the size. Table 1 lists curve fitting results for the equivalent circuit parameters of three MOVs.

Table 1: Curve fitting results for circuit modeling of three MOVs.

MOV number	k	α	λ	ζ	V_o
V130LA20A	4.0×10^{-74}	30	0.051	8×10^{-6}	320
V150LA20A	3.9×10^{-89}	35	0.053	4×10^{-6}	370
V250LA40A	5.7×10^{-110}	40	0.04	4×10^{-6}	570

The MOV number actually reflects the device voltage rating and the size. For V130LA20A, the continuous operating voltage rating is 130 V (rms). The other two devices are 150 V (rms) and 250 V (rms) respectively. All three devices have a 20-mm diameter. Figure 1 shows fitted curves for the three devices.

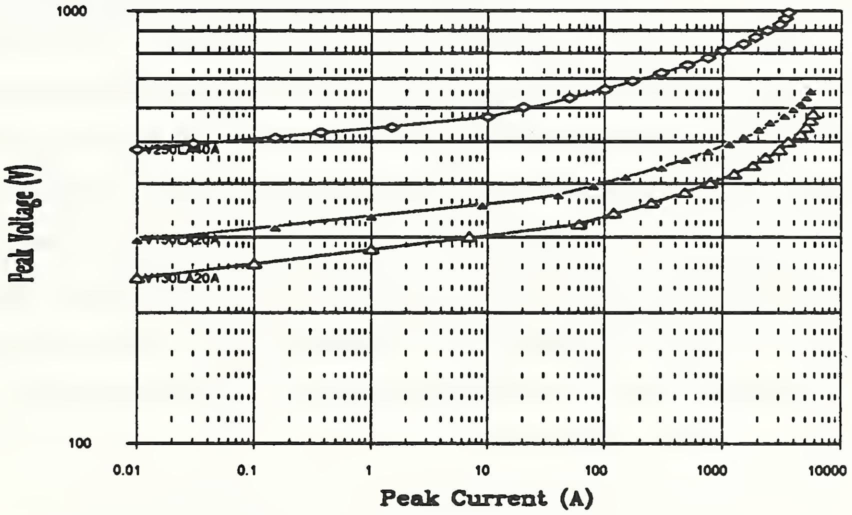


Figure 1: MOV characteristics obtained from modeling results.

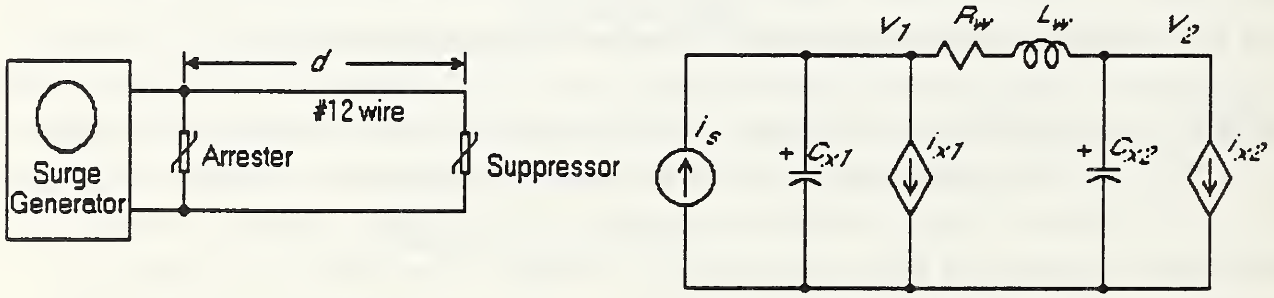
In Figure 1 the marked dots are the data directly obtained from the manufacturer's data book [7], while the three solid lines were calculated from (1) using the parameters listed in Table 1. It should be noted that each individual MOV may have slightly different I-V characteristics even with the same model number. In Figure 1, the data show the maximum voltage level which is 10% higher than the nominal voltage level. A typical off-the-shelf device has a tolerance within ±10% of the nominal voltage level, which means a lowest-level device could have an I-V characteristic 20% lower than the data book characteristics. In fact, the two closely rated cascading devices (130 V and 150 V) could in some extreme cases become inverted in the sequence, "Low-High" becoming in reality "High-Low," as 130 x 1.1 = 143 and 150 x 0.9 = 135. Furthermore, the results show that for the 250-150 combination, the difference is so large that a low 250 combined with a high 150 would not make an appreciable difference. Thus, the following simulations were performed for all three devices at their nominal values. From the maximum voltage tolerance parameters listed in Table 1, the parameters for the nominal (0 tolerance) I-V characteristics were derived, as listed in Table 2.

Table 2: Parameters for nominal I-V characteristics of three MOVs.

MOV number	k	α	λ	ζ	V_o
V130LA20A	$9.4\text{x}10^{-66}$	27	0.046	$0.8\text{x}10^{-6}$	285
V150LA20A	$4.8\text{x}10^{-79}$	31.5	0.053	$1.6\text{x}10^{-6}$	340
V250LA40A	$1.7\text{x}10^{-97}$	36	0.044	$1.6\text{x}10^{-6}$	520

3. Simulation of Cascaded Surge Protection Devices in a Low-Voltage System

In a two-stage cascade surge protection system, the arrester is placed near the surge source (the service entrance for premises wiring) and the varistor is placed near the load. Figure 2(a) shows a typical two-stage cascade surge protection system. The arrester and the varistor are separated by a distance *d* which depends on the specific installation. In the following simulation study, four different *d* values are considered. They are: 5 m, 10 m, 20 m, and 40 m. The #12 wire is a typical size for the premises wiring and is used for the following simulation and experiment study. Based on an impedance meter measurement, the resistance of #12 wire is 0.00104 Ω/m, and the inductance is 1 μH/m (per two parallel wires). For high frequency waves, the inductive drop is more dominant [9]. The complete simulation diagram consists of a surge source, two voltage-dependent current sources, and a line impedance between the two current sources as shown in Figure 2(b).



(a) Circuit diagram

(b) Simulation diagram

Figure 2: A two-stage cascade surge protection system.

For the three selected device voltage levels, there is a total of nine possible cascade combinations as shown in Table 3. Two standard waves from Ref. [4] were chosen to cover different frequency responses. These are: 1.2/50 μs - 8/20 μs Combination Wave and

10/1000 μs Impulse Wave. For the sake of brevity, these two waveforms will be called "Combo Wave" and "Long Wave." For four distances, two voltage waves, and nine cascade combinations, a total of 72 cases were studied in the simulation, about 140 hours of machine time on a 25-MHz personal computer.

Table 3: Nine possible cascade combinations for three devices.

Arrester	Suppressor
250 V	250 V
	150 V
	130 V
150 V	250 V
	150 V
	130 V
130 V	250 V
	150 V
	130 V

3.1 Simulation Results With the Combination Wave

Because of the back filter effect, a waveform generator might not couple a true standard wave to the test circuit. Figure 3 shows the standard 8/20 μs current and the coupled current waves where curve A is the standard 8/20 μs current, and curve B is the actual coupled wave with a small negative swing. For the standard 8/20 μs Wave, the current is always positive, and the clamping voltage is always positive. When applying curve B as the surge source, the negative current portion will cause a negative clamping voltage. This has been observed in the experiment. In order to reflect the experimental results, the following simulation will use curve B as the Combo Wave source.

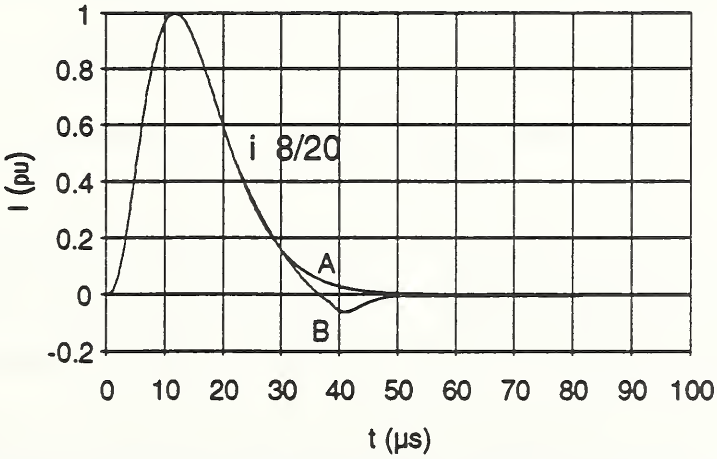


Figure 3: A standard 8/20 μs short-circuit wave and a possible negative swing caused by the filtering circuit.

Consider a 250 V-130 V, 10-m apart cascade. The simulation results of the currents flowing in the two devices are shown in Figure 4 where I_t is the total current injected into the cascade by the surge source of the model, I_1 is the arrester current, and I_2 is the suppressor current. Figure 5 shows device clamping voltages with V_1 and V_2 representing arrester and suppressor voltage respectively.

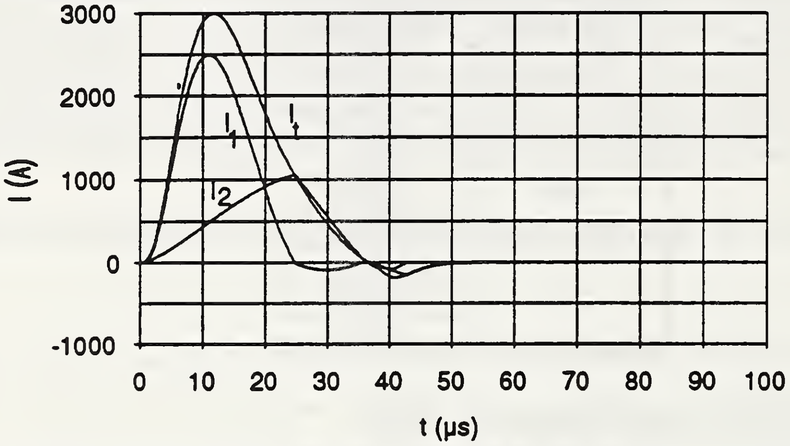


Figure 4: Simulated Combo Wave current responses for the 250 V - 130V, 10-m apart cascaded devices.

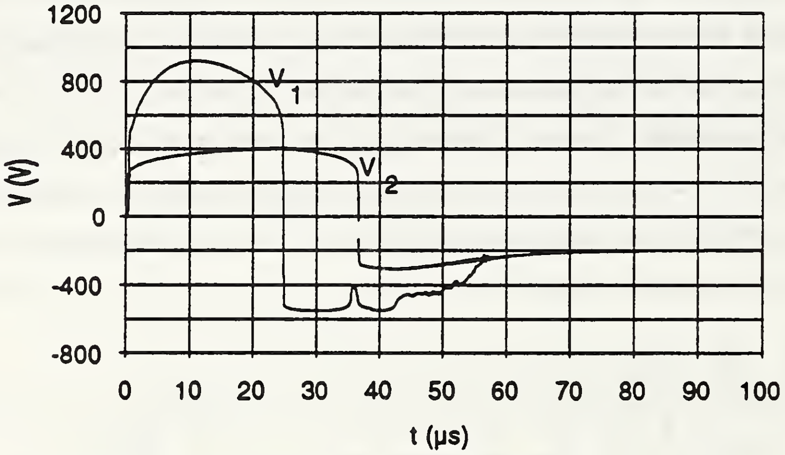


Figure 5: Simulated Combo Wave voltage responses for the 250 V - 130V, 10-m apart cascaded devices.

Figure 6 shows instantaneous powers with P_1 and P_2 representing arrester and suppressor power respectively. By integrating the instantaneous power over the entire simulation period (100 µs), the energy deposition values in the arrester and the suppressor were calculated as 29.7 J and 8.6 J respectively.

Before proceeding with further simulations, the simulation results of the 250-130, 10-m cascade were verified by an experiment. With the experimental setup of Figure 2 and 250 V and 130 V rated devices in cascade, the experimental results for the arrester and suppressor are shown in Figure 7.

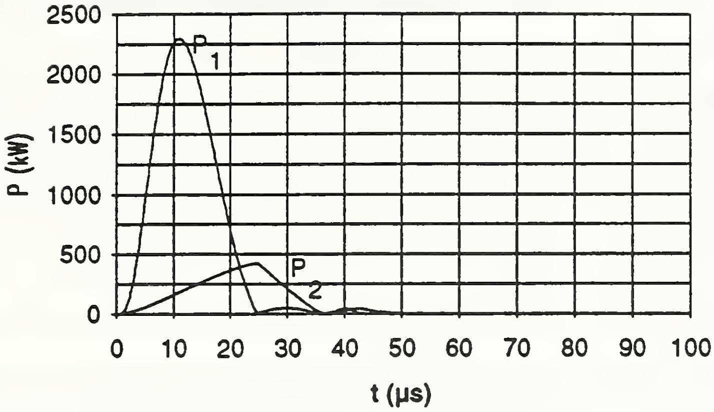
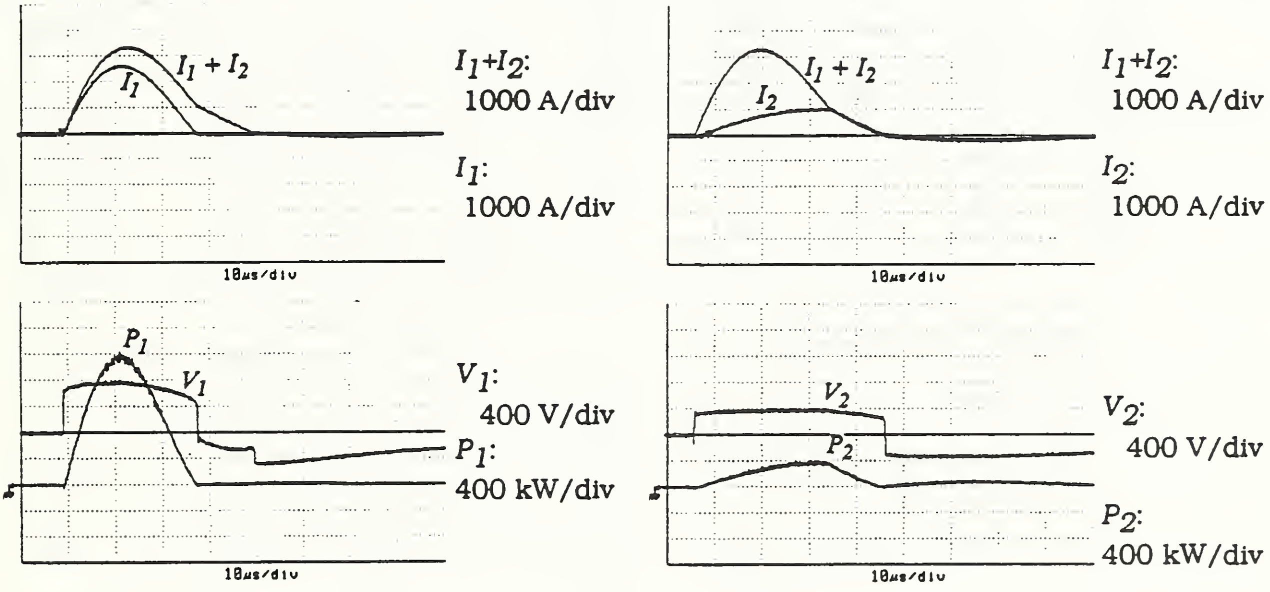


Figure 6: Simulated Combo Wave power responses for the 250 V - 130V, 10-m apart cascaded devices.



(a) arrester

(b) suppressor

Figure 7: Experimental results for the 250 V-130 V, 10-m apart cascade condition.

Because the surge generator generates non-standard waveforms, the waveforms obtained from the experiment are not exactly the same as the simulated waveforms. However, the power distribution between the two devices shows good agreement between simulation and experiment. For the same 250-130, 10-m cascade case but slightly higher peak surge current (3.3 kA instead of 3 kA in simulation), the experimental result shows 33.8 J and 11.1 J energy depositions in the arrester and the suppressor respectively. Prorating the simulation results from Figure 6 to 3.3 kA would yield 32.7 J and 9.5 J, respectively, a reasonable agreement.

Table 4 lists Combo Wave simulation results of the energy deposition in the arrester and the suppressor for all the combinations of different High-Low and Low-High cascade conditions. For the High-Low configuration, the energy deposition in the suppressor increases when the distance decreases. This result explains how the High-Low configuration can achieve a good coordination under the Combo Wave provided that there is a sufficient distance between the two devices, as stated in Ref. [3].

Table 4: Energy deposition in the cascaded devices with a 3-kA Combo Wave as the surge source.

Clamping voltage of device (V)		Distance separating devices and energy deposited in each device (J)							
		5 m		10 m		20 m		40 m	
Arrester	Suppressor	Arrester	Suppressor	Arrester	Suppressor	Arrester	Suppressor	Arrester	Suppressor
250	250	75.9	27.3	83.5	19.9	89.5	14.4	91.7	9.69
	150	22.2	12.0	29.9	8.52	35.9	5.40	39.80	3.30
	130	21.3	11.9	29.7	8.6	35.3	5.2	40.1	3.3
150	250	24.3	0.005	24.3	0.006	24.3	0.007	24.3	0.008
	150	21.2	4.65	23.1	3.06	24.4	1.93	25.5	0.88
	130	19.84	5.16	22.16	3.05	24.05	1.86	25.02	1.08
130	250	22.9	0.003	22.9	0.003	22.9	0.004	22.9	0.004
	150	20.2	1.72	20.8	1.18	21.30	0.76	21.1	0.44
	130	18.6	2.92	19.4	1.71	20.3	1.03	20.9	0.70

Consider the High-Low configuration with a 250-V device as the arrester. When the distance between two devices is reduced, the energy deposition tends to increase in the suppressor and decrease in the arrester. This decrease occurs because the line inductance does not provide enough voltage drop (L di/dt), and the low clamping voltage of the suppressor reduces the voltage across the arrester, and thus reduces the energy deposition level. The total energy deposition in the two devices also varies with the distance for the High-Low configuration. In Table 1, the total energy deposition for the 250-250 combination is near constant at 103 J for different distances. However, for 250-150 and 250-130 combinations, the total energy deposition decreases when the distance is reduced, because the suppressor tends to lower the voltage across the arrester.

For Low-High configurations such as 150-250 and 130-250 cases, the high voltage suppressor receives almost zero energy. The use of the suppressor is near redundant in this case, except for its application to mitigate internally generated surges. With closely rated devices (130-150), the 150-V suppressor also receives much less energy than the 130-V arrester.

For equally rated configurations like 250-250, 150-150, and 130-130, the arrester always receives higher energy because the line impedance reduces the voltage across the suppressor.

3.2 Simulation Results with the 10/1000 µs Impulse Wave

Compared to the Combo Wave, the Long Wave has a slower and longer drooping tail that contains most of the surge energy. During the long tail period, the inductive voltage drop between the arrester and the suppressor is low due to low L di/dt, and the voltage across the arrester is reduced by the suppressor even with long distance between the two devices. This makes the High-Low configuration not coordinated as the high voltage arrester will not absorb any impinging energy, but the suppressor does. Figures 8, 9 and 10 show the simulated Long Wave current, voltage, and power responses for the arrester and the suppressor under a High-Low (250-130) configuration for a 220-A peak surge current.

The high-voltage arrester clamps the voltage during the impulse rising period and draws a small amount of the current pulse, I_1, which is almost invisible in the computer-generated plot of Figure 8. The power absorbed by the arrester, P_1, is also a small pulse that appears at the rising period as shown in Figure 10. The low-voltage suppressor absorbs all the impinging energy in this High-Low configuration, defeating the intended coordination with the Combo Wave.

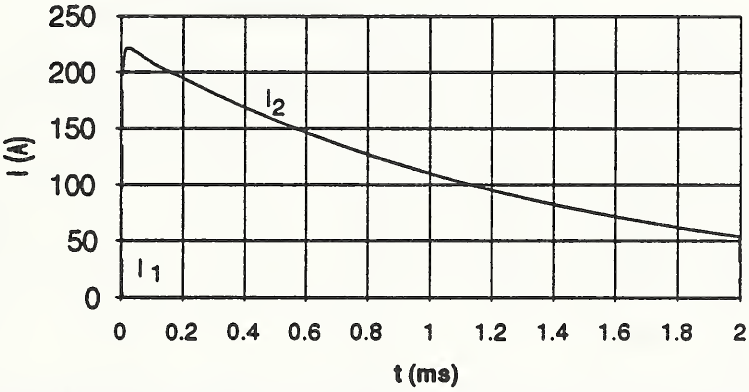


Figure 8: Simulated Long Wave current responses for the 250 V - 130 V, 10-m apart cascaded devices.

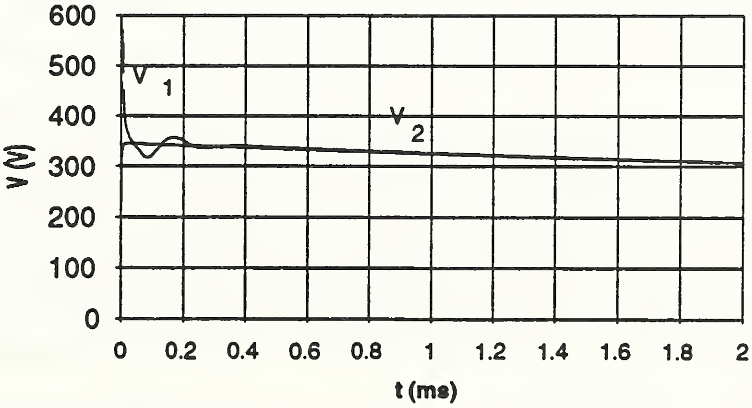


Figure 9: Simulated Long Wave voltage responses for the 250 V - 130 V, 10-m apart cascaded devices.

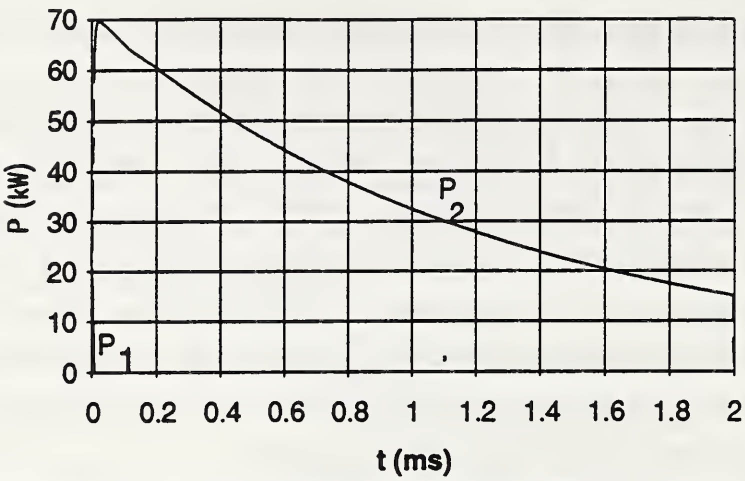


Figure 10: Simulated Long Wave power responses for the 250 V - 130 V, 10-m apart cascaded devices.

Table 5 lists the simulated energy deposition in the cascaded devices for different High-Low and Low-High combinations and for different distances.

Table 5: Energy deposition in the cascaded devices with a 220-A peak Long Wave surge source.

Clamping voltage of device (V)		Distance separating devices and energy deposited in each device (J)							
		5 m		10 m		20 m		40 m	
Arrester	Suppressor	Arrester	Suppressor	Arrester	Suppressor	Arrester	Suppressor	Arrester	Suppressor
250	250	73.63	72.76	74.10	72.31	75.06	71.38	76.28	70.13
	150	0.031	92.15	0.208	92.031	0.690	91.70	1.768	91.00
	130	0.011	79.23	0.125	79.16	0.518	78.94	1.424	78.42
150	250	92.17	0.0013	92.17	0.0020	92.17	0.0024	92.74	0.0027
	150	44.03	42.79	44.69	42.15	45.96	40.91	47.32	39.12
	130	7.92	70.67	8.86	69.76	10.72	67.97	14.28	64.58
130	250	79.2	0.0006	79.2	0.0008	79.2	0.0010	79.2	0.0012
	150	66.98	11.12	71.72	6.82	71.87	6.67	72.21	6.36
	130	38.03	36.74	38.70	36.09	39.98	34.84	42.28	32.62

It can be seen from Table 5 that the low-voltage surge protector always absorbs higher energy than the higher voltage surge protector because the voltage across the high-voltage device is clamped to the same level as that of the low-voltage device, and the energy is diverted to the low-energy device. Unlike the Combo Wave, the coordination for the slow Long Wave can only be achieved by Low-High or equally rated devices (250-250, 150-150, and 130-130). Note that with two devices of equal nominal value, it is possible that the relative tolerance might in fact produce a High-Low situation, which would not achieve good coordination: for instance, a 150-130 combination resulting from tolerance shifts imposes a 70-J duty to the suppressor, in the case of 5-m separation.

4. Experimental Results

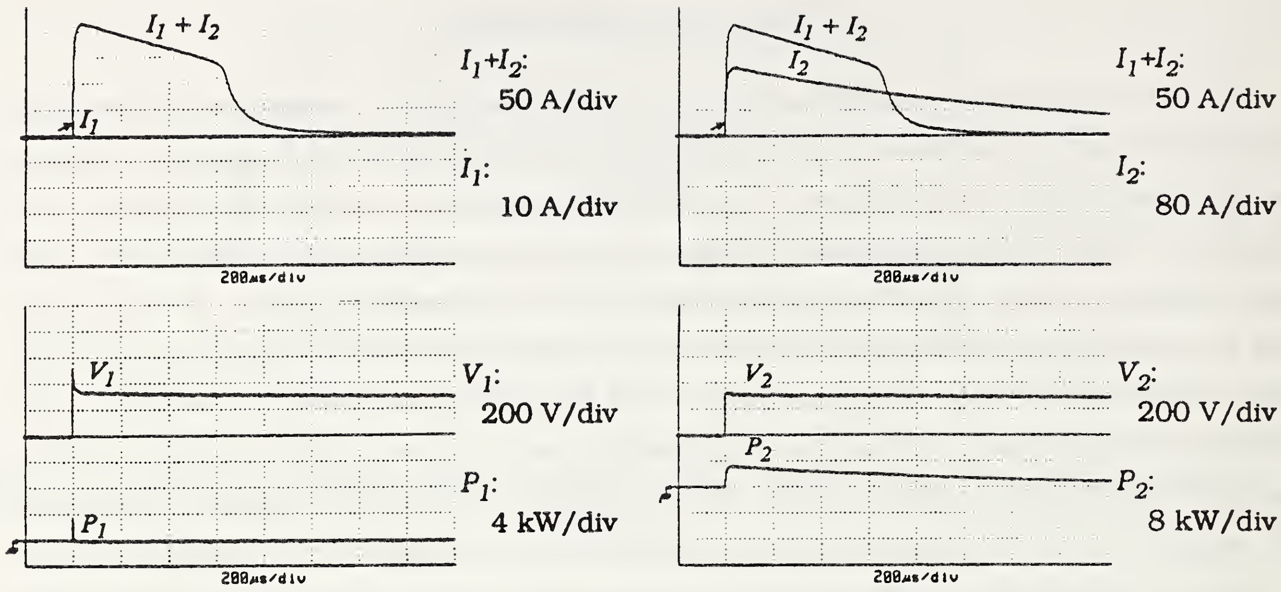
In order to verify the validity of the simulation, a series of experiments have been conducted using the two waves for different High-Low and Low-High combinations, especially for the Long Wave which has not been used for cascaded coordination studies in the literature. Table 6 lists experimental results using the two waveforms for 250V-130V, 10-m apart cascaded devices. Note that peak currents do not occur simultaneously. A * sign shows that low-voltage suppressor absorbs almost all the energy under the 10/1000 μs Long Wave. The experimental results, in general, agree with the simulation results especially for the Combo Wave which has well matched surge sources and a limited surge period (the tail does not extend over the integration period). For the Long Wave, the total integration period and the surge source are not matched between simulation and experiment, and thus the numbers in Table 7 have higher deviation from the simulation results. However, the proportion between the arrester and the suppressor energies agrees well between simulation and experiment, which explains that the simulation can be effectively used for the coordination analysis.

Table6: Experimental results using different waveforms for 250 V-130 V, 10-m apart cascaded devices.

Applied Wave	Arrester			Suppressor		
	V_{pk}(V)	I_{pk}(A)	W (J)	V_{pk}(V)	I_{pk}(A)	W (J)
Combo 3 kA pk	790	2600	33.8	400	1000	11.1
Long 220 A pk	450	6	0.05	320	220	64.4*

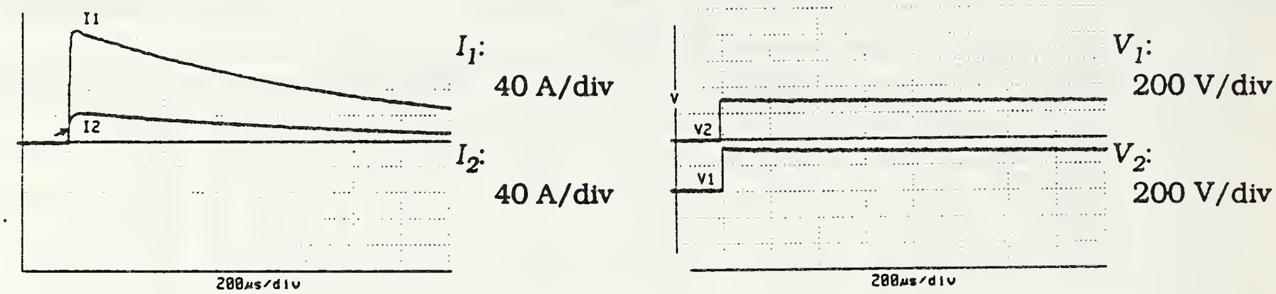
The experimental verification of the Combo Wave for the simulation can be seen from Figure 7. For the Long Wave experimental current, voltage, and power waveforms are shown in Figures 11, and 12. The measurement of the coupled Long Wave, I_1+I_2, shows a saturation on the small CT (5,000 A peak and 65 A rms rated). However, the currents flowing through the surge protection devices, I_1 and I_2, were measured by a large CT (20,000 A peak and 325 A rated) and were not saturated.

The experimental Long Wave response for a Low-High configuration is shown in Figure 12 where I_1 and I_2 are the currents flowing in the 130-V arrester and the 150-V suppressor respectively. This figure shows an example of good coordination by Low-High, where most of the surge energy is absorbed by the low-voltage arrester. The arrester voltage, V_1, is almost the same as the suppressor voltage V_2 with a slight difference at the beginning of the surge.



(a) arrester (b) suppressor

Figure 11: Experimental results for the 250V -130 V, 10-m apart cascade with the Long Wave.



(a) current (b) voltage

Figure 12: Experimental results for the 130 V - 150 V, 10-m apart cascade with the Long Wave.

5. Discussion and Conclusion

In order to receive more acceptance on the performance criteria for cascaded surge protective devices, all possible surge sources and cascade combinations need to be considered. Significant parameters in achieving successful coordination involve three factors: the relative clamping voltage of the arrester and the suppressor, their separation distance, and the waveform of the impinging surge. With study of a total of 72 cascade combinations using different parameters, this paper initiates a broader view of cascade coordination and a need for further consensus on real-life environments which involve the magnitude and waveshape of the high energy impinging surges from utility lines, probability and severity of neutral losing condition, surge energy from the switch-mode power conversion equipment, size of conductors, and the distance between surge protection devices.

The basic coordination idea is to have a high energy-handling capability device absorb most of the impinging energy from the surge source. The small device, typically installed near the sensitive equipment, simply performs voltage clamping with little energy absorption. The benefit from this coordinated approach is to allow a single device at the service entrance to perform the high-energy duty, while several smaller devices within the premises can perform local suppression. This arrangement avoids the flow of large surge currents in the branch circuits of the installation, a situation known to produce undesirable side effects [10]. Coordination of cascaded devices can be achieved under various combinations of parameters, but some combinations will result in having a suppressor with low energy-handling capability called upon to divert the largest part of the surge energy. This uncoordinated situation can create adverse side effects when high current surges occur.

In C62.41-1991 defined waves, the two highest energy waves are used in this paper. These are: the Combo Wave which contains relatively high-frequency components and the Long Wave which contains relatively low-frequency components and a long drooping tail. A line inductance can build a substantial voltage drop between two cascaded devices under the Combo Wave but not the Long Wave. Especially, the long drooping tail can develop a negative voltage drop which diverts most energy to the low-voltage downstream devices. For two relatively low-energy C62.41-1991 ring waves, featuring high and low frequencies (100 kHz and 5 kHz), the cascade coordinations are also expected to see different requirement: High-Low versus Low-High. The ring wave responses of cascaded devices, however, need further study for more evidence.

Although the MOV model described in this paper successfully predicts the I-V characteristics and surge responses especially the energy sharing of the cascaded devices, more analytical studies are needed to reduce the deviation between simulation and experiment. These include:

- MOV stray inductance and capacitance if more accurate waveshape matching is necessary.
- Consensus of MOV characteristics for the same voltage level and size of the device but different manufacturers.
- Modeling of gap-type surge protection devices which would cause different surge responses when used as the arrester to replace MOVs.
- Well-defined impinging surge sources including voltage and current waveforms and the coupled source impedance network.

Acknowledgment

The author wishes to thank Dr. William M. Smith of EPRI for supporting this project. The author is also grateful to Michael Maher and Renae Brooks of Potomac Electric Power Electric Power Company (Pepco) and Tom Key of PEAC for their encouragement in this project. Technical help from François Martzloff of NIST made this paper possible.

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Appendix A

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Appendix B
Interest of Participants

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Biography and Interest in Forum. Vladi Basch has an MSEE from Polytech Institute of Bucharest and an MBA from Farleigh Dickinson University. After spending 6 years with Dranetz he joined BEST Power about 18 months ago as product manager. He is a member of NEMA-UPS Committee, IEEE P1100, and has a constant interest in all issues of Power Quality. At the Forum, he presented the paper on Power Quality Comparison written by D.S. Dorr.

Richard Bentinger
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Biography. Graduated in 1959. Worked with military projects until 1989. Specialist on EMC at Ericsson Radar electronics 1984-89. Joined Ericsson Telecom in 1989 and is responsible for questions related to lightning and AC power faults. Ericsson delegate at CCITT Com 5 and a member of the Swedish Electrical Commission, a counterpart to IEC TC 37A and TC 77. Main work today is specifications and test procedures on system as well as on components.

Interest in Forum. I hope that an open forum like this may influence the national and international standardization bodies to harmonize to a common worldwide accepted standard on overvoltage protection.

Richard Billingsley
ESP, Electronic Systems Protection, Inc.
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Biography. An EE Graduate of the University of Calgary, Richard Billingsley has been involved in the Power Disturbance Mitigation Product Industry since 1985. Unsatisfied with many of the products in this industry, Rich set out on his own to develop EMI Suppressors compatible with today's sensitive electronic equipment. Rich has been with ESP (Electronic Systems Protection, Inc.) since it was founded in 1988. He designed and developed ESP's full line of power and data line EMI filter/suppressors, for which patents are pending.

Interest in Forum. Forums such as this are critical for sharing and publishing new ideas and research. This information educates everyone associated with this industry and can be used to establish and update industry safety and performance standards. If the North American Electronics Industry is to stay competitive in the world marketplace, we must maintain up to date industry standards from which state of the art products can be ensured. I thus hope to leave the forum with an understanding of the latest research and ideas in the Surge Protection Industry. I hope that my input unravels some of the mysteries and misconceptions of the application of surge protection products in the electronic equipment network environment.

Anthony Bird
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Biography. Anthony O. Bird received a 1st class BSc (Hons) degree in Electrical and Electronic Engineering from the University of Nottingham, England. He has recently taken over as Director of Engineering at Atlantic Scientific Corporation, Melbourne, Florida. Prior to this, he has been actively involved in the field of surge protection for five years in England and is a member of a British Standards committee looking at the protection of electronics against lightning.

Interest in Forum. The coordination of correctly specified, correctly installed within a building is of great interest. The subject of SPD coordination requires careful consideration by both the user and the manufacturer of surge-protective devices.

Renae Brooks
Pepco
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Interest in Forum. Ms. Brooks is conducting a residential TVSS evaluation program for the Potomac Electric Power Company (Pepco).

A "Whole House" TVSS device is mounted between the electric meter and the meter socket to guard against incoming power disturbances. The TV cable and modem communications line is also protected by using MOV based surge protectors within the house at the appliance. A "strawman" test specification is under development. This specification will provide minimum TVSS performance requirements. Specs for the internal devices will also be developed. Some consideration is being given to the interaction of the internal and meter mounted devices in terms of appropriate relative clamping voltages. Opinions as to specific requirement waveforms and voltage and amperage levels will be solicited. Rough drafts of the specs will be available to interested parties.

Mel Clark
General Semiconductor Industries Inc.
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Biography. O. Melville Clark has been associated with the semiconductor industry for more than thirty five years having worked in research and development, process engineering and applications engineering. He developed seven patented products and invented the sloped junction surface technology used for enhancing breakdown voltage for fast recovery rectifiers and silicon controlled rectifiers. He has published numerous articles on transient suppression devices and application methods and has a B.A. and M.A. in Physical Science from Arizona State University.

Interest in Forum. Areas of interest encompass transient voltage phenomenon, including a detailed description of the sources and characteristics. Of specific concern are those areas involving transient suppression device technologies and their use in mitigating a broad range of threats from electrostatic discharge to direct lightning hits with focus on realistic designs, specifications, applications and expectations of suppressor devices and suppressor assemblies.

Richard L. Cohen
Panamax
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Biography. Richard L. Cohen is the Vice President of Engineering for Panamax, a company in San Rafael that manufactures surge suppression devices for residential and office use. He was previously the Manager of Protector Development for AT&T Bell Laboratories. Before that he spent many years as a research physicist and materials scientist at Bell Laboratories. He is a Member of the IEEE, and a Fellow of the American Physical Society and the AAAS.

Interest in Forum.
1. What is the surge/overvoltage environment?
2. What is the spectrum of equipment vulnerability?
3. What can be done to encourage manufacturers to make their equipment more rugged?
4. What can be done to make consumers (residential and business) more aware of surge protection issues and remediation?

Martin Corbett
Harris Semiconductor
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Biography. I obtained my degree in Mechanical Engineering from Carlow College, Ireland. I have held various positions in the manufacturing of metal oxide varistors (MOV's), including those of process, quality and reliability engineer at the Harris facility in Ireland. More recently, I have worked in the U.S. in the areas of product and applications engineering for transient suppression products. I have two publications on transient protection to my credit.

Interest in Forum. I work in the applications group of Harris semiconductor specializing in transient surge protection. The majority of my time consists of dealing with customer queries. Invariably these discussions begin with an education of the customer as to what an MOV is and how it works. I feel that there is a lack of "simple and understandable" information pertaining to this subject. If such information were made available under the auspices of a recognized control body (eg. ANSI or IEEE) it would be beneficial to all. There is also a lot of misinformation regarding the operating characteristics of MOV's in terms of speed of response, paralleling and degradation. These issue's need to be addressed in a factual and clinical matter.

Robert Davidson
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Biography. Mr. Davidson is an Associate Managing Engineer at the Melville, N.Y. office of Underwriters Laboratories Inc.. He is a registered Professional Engineer in the state of New York, and has 22 years experience in the field of product evaluation and testing.

Interest in Forum. Underwriters Laboratories Inc. has been asked to indicate its position regarding certain types of potentially misleading advertising claims that have been made with respect to the suppression voltage ratings marked on UL Listed TVSS. The purpose of this brief paper is to address these concerns in general and to solicit further questions and comments on the subject.

Basil Dillon-Malone
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Biography. Mr. Basil Dillon-Malone received his BE (Electrical Engineering) Degree from University College Dublin in 1969 and has been Electronics Marketing Manager at Pass & Seymour/Legrand since 1985. He worked with General Electric for 12 years in new product planning, including the metal oxide varistor. He is a member of the IEEE Surge Protective Devices Low Voltage Subcommittee, serving on several of its working groups. He is a member of the NEMA Technical Committee (TVSS) since its formation in 1986. He is a delegate to ANSI/IEEE and the USNC For the IEC SC37A. He is task force chairman of the IEEE working group on AC varistor applications. He has presented power quality papers to the Association for the Advancement of Medical Instrumentation, the Canadian Electricity Forum and the 9th International EMC Symposium, and the 1991 EMC Zürich Symposium.

Interest in Forum. The metal oxide varistor has been a most misunderstood protective component within the equipment user community. Frequently, computer trade articles comment that all MOV's either degrade catastrophically after one large spike, or have a maximum life expectancy of two years! The industry has a responsibility to address such unqualified statements which contradict actual field failure reports, Arrhenius Life-modelling and IEEE papers on MOV estimated lifetimes.

There are a number of purported design reasons for failure of the assembled MOV or failure of equipment using MOV's. These include 1) documented reports on 130 volts MOV's failing under powerline "swell" conditions, 2) the lack of MOV installation in all three wiring modes vulnerable to transients, 3) the use of smaller than 20 mm MOV's in powerline applications, 4) inappropriate MOV sizing for coordination between the service entrance and the branch circuit, 5) the false assumption that protection at one wall outlet offers full downstream/upstream protection to other sensitive equipment against random transients occurring anywhere on an electrical circuit, 6) poor design coordination of hybrid components with/without MOV's (such as avalanche diodes before the high energy stage; gas tubes without a remnant quenching stage) 7) poor manufacturing techniques, 8) failure of non-protected data port while power port only protected.

The debate continues on a) service/branch coordination, b) hybrid component coordination, c) "Lower is/is not better", d) confusion on diagnostic/monitoring mechanisms (either not user-friendly or non-existent), e) "fail-open, fail-short, fail-safe", f) neutral-ground mode considerations, g) "noise" versus high voltage transients, and finally h) who/what constitutes "performance".

Richard L. Diller
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Biography. Mr. Diller founded Advanced Electronics Systems, Inc. in 1974 as a manufacturer of Transient Voltage Surge Suppressors. He is currently CEO and President of the firm that has developed the StediWatt line of Power Quality Products which are marketed throughout the electrical, computer and telecom industries. The products range from a series of panel protectors, plug-in protectors and dataline protectors to a series of Back-up Power Systems for DOS and UNIX Based Computer Systems.

Interest in Forum. Having 20 plus years of direct experience in the power industry, I wish to maintain current awareness of the mainstream technology. I'm also encouraged to find a forum where there can be dialogue among industry peers to minimize the current confusion of end users as well as specifying engineers regarding product application and selection. Since we are faced with national and local power shortages and the resulting costs of overloads, blackouts and downtime, we must collectively pursue solutions. Today's electronic world demands power integrity to feed the pipelines of industry and commerce. Where controversy remains, more evidence dispels it! Let's bring credibility and lasting solutions to our growing industry. I am anticipating a mutually profitable caucus.

Curtis A. Domsch
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Biography. Received BSEE from Iowa State University and BA Mathematics from Briarcliff College. Joined Atlantic Scientific Engineering in 1987. As Senior Design Manager, he has designed a wide range of transient suppressors for AC and Data Communications Applications. He is a member of IEEE (SPD), NEMA (5VS) and Underwriters Laboratories IAG.

Interest in Forum. The main interest is transient suppressions system coordination and keeping current with the transient suppression industry.

M. Frank Erwin
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Biography. Mr. Erwin has 29 years of experience in electrical engineering and design. Degrees include AAS and BS in EE, licensed in New York and Maine. He is a member of the IEEE and the NY Society of Professional Engineers. His work experience includes utility engineering an power plant design, as well as four years as a field engineer. Mr. Erwin presently owns a consulting service focused on the resolution or Power Quality related problems.

Interest in Forum. The act of inviting such a number of divergent viewpoints in one room for two days was a very good first step. It is obvious that the industry is in need of legitimacy and systematization. I look forward to the next meeting.

Gary Goedde
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Biography. Gary L. Goedde received his BS degree in Electrical Engineering Technology at the Milwaukee School of Engineering in 1980. He has been with Cooper Power Systems, Franksville, WI, since 1969. His experience has been in semiconductor devices and insulating materials evaluations. He has been involved in the development of ceramic-bonded varistors, high strength electrical porcelain and has been responsible for projects that include mechanical, electrical, and ultrasonic testing. He is currently the project leader of an extensive capacitor fuse study project and is involved in electrical distribution system testing for devising improved protection techniques. Gary has co-adhered four publications and has five U.S. patents. He is a registered professional engineer in Wisconsin.

Interest in Forum. As a result of high failure rates in distribution transformers, Cooper Power Systems sought to reduce these failure rates by applying secondary protection to distribution transformers. The application of secondary arresters far exceeded expectations in reducing failure rates. This phenomena led to full scale lightning surge tests of distribution transformers and secondary systems. In performing these tests, protective devices were applied at various locations in the secondary system. The need to upgrade energy capacities of protective devices in secondary systems is recommended by Cooper Power Systems, to provide coordinated system protection. This can be accomplished by higher energy devices and three mode protection. Cooper Power System's exposure to low voltage standards and application guides has led to concerns over re-fusing protective devices. Refusing failed protective devices may require safety precautions.

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Biography. Walter F. Hart P.E. was born in Portland, Oregon, USA on February 21, 1929. He has been a Registered Professional Engineer in Washington State since 1965. He studied Electrical Engineering at Oregon State College and Seattle University and holds a BSGS from City University of Seattle. He is a member of IEEE and ISA. He joined the John Fluke Mfg. Co., Inc. in 1965 and worked on instrument design until becoming Product Safety Administrator in 1977, the position he still holds.

Interest in Forum. His interest in surge protection has grown from design efforts to protect Measuring Circuits and Supply Mains in equipment. For the past 15 years he has been active in safety standards development for Test and Measuring Equipment in the USA, Canada, and the IEC.

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Biography. Raymond C. (Ray) Hill, P.E. received his Bachelor of Electrical Engineering Technology degree, with honors, from Southern Technical Institute, Marietta, Georgia, in 1973. He received his Professional Engineer license for Georgia in 1983. Mr. Hill has worked for Western Electric in Sandy Springs, Georgia, Florida Power and Light in System Protection in Sarasota, Florida, and Georgia Power. He spent his first five years with Georgia Power working in System Protection and Substation Test. For the last twelve years he has been at the Georgia Power Research Center in Forest Park, Georgia. At the Research Center, he was responsible for high voltage and high current testing of various equipment, components, and accessories for the electric utility industry. Presently, Mr. Hill is a Sr. Research Engineer assigned to the Project Section of the Research Center, where he works as a Project Engineer and electrical consultant. He has taught in the High Voltage Testing Techniques course sponsored by Georgia Power and Georgia Tech, and in the Cable and Accessory Failure Analysis course sponsored by Georgia Power and Power Technologies, Inc. Mr. Hill has been specializing in high voltage and fault current testing, corona detection, electromagnetic compatibility, and surge protection for a number of years.

Interest in Forum. The Georgia Power Research Center, being involved with high voltage and high current testing, has always been active in surge suppression applications for instruments, sensors, data acquisition equipment and computers. Also, for several years now, the subject of Power Quality for its customers has been of concern to Georgia Power. One avenue of investigation involves surge protection of residential service on the secondary side of the distribution transformer at the service entrance. Recently, Georgia Power has started a program to evaluate surge suppression devices for this use.

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Biography. Mr. Wilhelm Kapp received his BSEE degree from the University of California, Santa Barbara, in 1965. After graduation he started to work for Joslyn Electronic Systems Corporation in Goleta, CA where, at present, he is manager of the Engineering Design Group. He has been actively involved in the design, testing, and application of surge-protective devices for power and communication circuits for the last 26 years. He is a member of IEEE and serves on several working groups of the IEEE Surge-Protective Devices Low Voltage Subcommittee. He is also a member of the NEMA Technical Committee on Transient Voltage Surge Suppressors.

Interest in Forum. Mr. Kapp believes that open discussions among qualified participants concerning issues of surge protection and power quality will help to advance the technology of surge-protective devices. Of particular interest to him are realistic and verifiable specifications, vulnerability of electronic equipment, new development in surge protector components, coordination of SPDs, proper connection of hard-wired SPDs, proper paralleling and fusing of MOVs, and world-wide standards on surge-protective devices.

has been actively involved in the design, testing, manufacture and application of surge protective devices for both the power and the communication fields for the last 26 years. He offers his extensive experience to the participants of the forum and hopes to receive challenges and stimuli to promote further growth and progress in the important field of electrical surge protection.

Thomas S. Key
Power Electronics Applications Center
10521 Research Dr., Ste. 400
Knoxville, TN 37932
Tel. 615 675-9505 - Fax 615 675-9530

Biography. Tom Key is currently Manager of Power Quality at the PEAC, where he is responsible for power quality research, development and testing. He joined PEAC in 1989. PEAC was created by Electric Power Research Institute (EPRI) in 1986 to encourage the effective application of power electronics for more efficient use and better control of electric energy. During the ten years before joining PEAC, Mr. Key managed electrical power system design and power electronic system applications for renewable sources of energy at Sandia National Laboratory in Albuquerque.

Interest in Forum. While at Sandia Lab he initiated the development of recommended practices for power systems design and performance criteria that define "Utility Compatibility" of grid-connected photo voltaic power systems. At PEAC he is developing criteria and testing customer loads to determine where utility compatibility can be improved. The first major test project for EPRI will address TVSS used in premises wiring.

Suang Khuwatsamrit
Reliance Electric Co.
Collins Ind. Blvd.
Athens, GA 30613

Biography. Suang Khuwatsamrit was born in Bangkok, Thailand. He graduated from Chulalongkorn University in Bangkok with a B.Eng.(EE) degree in 1976. He got his MS(EE) and Ph.D(EE) degrees from the University of Missouri-Columbia in 1979 and 1983 respectively. He joined Reliance Electric Company in Athens, Georgia in 1983 and has been working in both AC and DC Drive development. He is a member of IEEE and is a registered Professional Engineer in the state of Georgia.

Interest in Forum. His research interest is in the field of drive technologies which include PWM technique, high power semiconductor devices and power electronics. He is also interested in Power Quality problems concerning drive applications.

Jih-Sheng Lai
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Biography. Jih-Sheng (Jason) Lai is a native of Taiwan. He received his M.S. and Ph.D in electrical engineering from the University of Tennessee, Knoxville, in 1985 and 1989, respectively. From 1980 to 1983, he was the Electrical Engineering Department Chairman of Ming-Chi Institute of Technology, Taipei, Taiwan, where he initiated a power electronic program and received a grant from the school and the National Science Council to study aboard. In 1986, he was a staff member of the University of Tennessee teaching control systems and energy conversion courses. In 1989, he joined the EPRI Power Electronics Applications Center as a senior power electronics engineer. His main research interests are power electronics modeling and simulation, circuit design, and microcomputer applications. Dr. Lai has 1 awarded patent and 2 pending patents and more than 20 articles published in the fields of control systems, power systems, and power electronics.

Interest in Forum. The author started working on the surge protection applications from 1990. He developed an improved surge protection circuit for Frymaster triac protection, a MOV mathematical circuit model for computer simulation on cascaded surge protection devices, and a utility compatibility document (UC110) for performance criteria of low-voltage ac power system surge protection devices. He is currently in charge of a service entrance surge protection device test project for PEPCO. He likes to continue research on coordinating cascaded surge protection devices.

Wendell H. Laidley
Zero Surge Inc.
103 Claremont Road
Bernardsville, NJ 07924
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Biography. Wendell H. Laidley is President of Zero Surge Inc., which he co-founded in 1989. He holds an engineering degree from McGill University and an MBA from the University of Western Ontario. His career has included Systems Engineering at IBM, management consulting at Booz, Allen & Hamilton, President of Laidley Development Group Ltd., and President of Isomedix prior to founding Zero Surge.

Interest in Forum. My primary interest is in the development of relevant and objective evaluation criteria which consumers may rely on to guide surge protection purchasing decisions. I consider some specifications currently quoted by surge suppressor manufacturers to be confusing and potentially misleading, with dimensions like nanoseconds, even picoseconds, and megawatts. Consumers should not need technical training to evaluate and differentiate surge protectors. I think the industry should initiate meaningful performance standards and self-regulation to avoid consumer dissatisfaction and the form of public investigation that resulted in a CBS 60 Minutes report some years ago, into "energy saving" surge protectors.

Geoffrey Lindes
Delmarva Power
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Biography. Geoffrey H. Lindes received a Bachelor of Science in Electrical-Electronics Engineering Technology from Spring Garden College, Philadelphia, PA in 1980. Since 1980 he has held several positions in the operating areas of Delmarva Power. He is currently a Project Engineer in the utility's power quality program. He was a start-up engineer for Indian River Unit 4, a 400 MW coal-fired power plant located in Millsboro, DE. He was responsible for the plant's boiler-turbine-generator control systems and electric power distribution system. He has extensive hardware maintenance experience having installed and maintained SCADA equipment in both the Electric System Operations and Natural Gas System Operations areas. He was the responsible engineer for capital projects in Delmarva's Liquified Natural Gas and Propane-air peakshaving plants.

Interest in Forum. An understanding of surge protectors and their applications and limitations is essential for making recommendations, evaluations and for failure analysis. Surge protectors exist as discrete packages. They are integrated into various equipments and they are applied at the system level by electric utilities. How are they coordinated? What are the installation considerations?

Charles R. Luebke
Square D Company
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Biography. Charles Luebke is the Director of International Standards at Square D Company. He received his B.S. degree from the University of Wisconsin in electrical engineering in 1956 cum laude. Mr. Luebke is a registered professional engineer in the State of Wisconsin and is a member of the following professional organizations: Senior member of Institute of Electrical and Electronics Engineers (IEEE); Senior member of Instrument Society of America (ISA); Member of the International Association of Electrical Inspectors (IAEI); Member of the Product Safety Technical Committee of the IEEE EMC Society

Since 1985, Mr. Luebke has been primarily responsible for the worldwide standards activities for the Square D Company. In this position he is active in many national and international organizations: United States National Committee for IEC (USNC/IEC); National Electrical Manufacturers Association (NEMA); International Electrotechnical Committee (IEC); IEEE Surge Protective Devices Committee of the Power Engineering Society.

Interest in Forum. SC28A collaborates with other IEC committees and other organizations that have an interest in overvoltage protection and related subjects, e.g. TC81, TC77, TC65, TC64, TC42, SC37A, SC17B. A review of the documentation (including standards) from various sources shows significant differences in dealing with the subject. There is a need for uniform terminology and identification of the overvoltage environment. Performance requirements and test methods can then be established for standards. Joint Working Groups and Ad Hoc Task Forces have been formed to address some of these differences. The Forum on Surge Protection Application provides an opportunity to identify these differences and separate fact from opinion.

A. Michael Maher
Pepco (Retired)
c/o Renae Brooks

Biography. Mr. Maher received his BS in Physics from Tulane University. He has completed graduate work at George Washington University (Engineering Management) and at the University of Maryland (Theoretical Physics). He has directed the Potomac Electric Power Company Customer Use R&D program since 1980. Previously, he was Senior Scientist with the US Department of Commerce, Office of Energy Programs. He also headed a major testing laboratory, General Testing Laboratories. Mr. Maher was chairman of the ASTM Committee on Laboratory Criteria ((E-36) and was chairman of the EPRI Committee on Power Electronics and Controls. He has served on other EPRI committees and working groups, including the Residential/Commercial Task Force and the Customer Systems Division Committee.

Interest in Forum. Mr. Maher is conducting a residential TVSS evaluation program for the Potomac Electric Power Company (Pepco).

A "Whole House" TVSS device is mounted between the electric meter and the meter socket to guard against incoming power disturbances. The TV cable and modem communications line is also protected by using MOV based surge protectors within the house at the appliance. A "strawman" test specification is under development. This specification will provide minimum TVSS performance requirements. Specs for the internal devices will also be developed. Some consideration is being given to the interaction of the internal and meter mounted devices in terms of appropriate relative clamping voltages. Opinions as to specific requirement waveforms and voltage and amperage levels will be solicited. Rough drafts of the specs will be available to interested parties.

François D. Martzloff
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Biography. François Martzloff was born in France where he completed his undergraduate training, and came to the United States in the fifties to continue his graduate studies. In 1985, he joined the staff of the National Bureau of Standards (NBS), to expand NBS activities in the field of Conducted Electromagnetic Interference, with more recent emphasis on Power Quality and Surge Protection issues. Prior to joining NBS (recently renamed the National Institute of Standards and Technology), his long career at General Electric included high voltage fuses and bushings development, power electronics, transient measurements, surge protection of electronics, applications of varistors, and electromagnetic interference protection.

Interest in Forum. His interests include metrology power disturbances, contributing to the work of several IEEE committees, in particular the revision of a Guide on Surge Voltages into a Recommended Practice, and the updating of a Guide on Surge Testing. He is serving as vice chairman of the IEEE Standards Coordinating Committee on Power Quality. In the IEC, he is serving as Secretary of WG6 of TC77 on Electromagnetic Compatibility. He is a member of the Underwriters Laboratories Industry Advisory Group (1449). He has published many papers, articles, or reports, and is contributing to technology transfer in the arena of surge protection by lectures and tutorials at the University of Wisconsin, University of Minnesota, IEEE workshops, and is a participant in the EPRI/PEAC Power Quality Testing Network.

Bruno W. Paszek
General Electric
381 Upper Broadway
Ft. Edward, NY 12828
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Biography. Bruno Paszek was born in Poland. He graduated from Union College, Schenectady, NY, with a degree in Electrical Engineering. Since 1968 he has held several positions in Engineering of Capacitor and Power Protection Operations of GE. Prior to joining Arrester Engineering in 1988, he was Senior Design and Production Engineer for small industrial capacitors. Presently as a Marketing Support Engineer, he is involved in development and design of surge protectors and has engineering responsibility for production of surge protective 'devices and secondary arresters.

Interest in Forum. His interests are design application of surge protective devices for ac and dc circuitry.

Andy Reck
Whirlpool Corp.
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Biography. Andrew C. Reck is a project engineer with Whirlpool Corporation and has been involved in electronic appliance controls development for the past 5 years. Before joining Whirlpool, spent several years designing Switch Mode power supplies for aircraft controls at Hamilton Standard Avionics Division during which time he received a patent for a solid state current limiting device. Andy has a Bachelors in Electrical Engineering (1984) from Western Michigan University, a member of IEEE EMC and Power Electronics societies and is co-author of a paper on computing modeling of Triacs to be presented at EPE '91(European Power Electronics Conference in Florence, Italy).

Interest in Forum. Andy is considered the resident EMI expert on appliance emissions at Whirlpool and is a member of an ANSI C63 Subcommittee (1-11.1) addressing emissions from appliances. He has expanded his area of interest to include appliance control susceptibility to AC line transients and ESD, and is currently working with Sears and Roebuck to develop susceptibility tests for Fast transient Burst, AC line dropout and Sag/Swell for the next generation of appliance controls.

Harry Ruther
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Biography. Harry E. Ruther received his B.S. degree in electrical engineering from the University of Arizona in 1957 and an M.B.A. from the University of Chicago in 1961. He is a registered professional engineer in the state of Illinois. He has worked on various consumer, commercial, and military research projects. He has been a member of the technical staff of the Sears Laboratories for the last 25 years on consumer electronic products.

Interest in Forum. One of his specialties and interests is all ESD and AC line problems and their effect upon products.

G. Keith Sames
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Biography. Mr. Sames is a graduate of Penn State University and is a Registered Professional Engineer in the state of Pennsylvania. He has worked for Pennsylvania Power and Light Company (PP&L) since 1971. Mr. Sames has experience in distribution facilities design, nuclear cost management, residential marketing, and is currently a member of the Industrial/Commercial marketing group at PP&L corporate offices.

Interest in Forum. PP&L is currently expanding efforts in the area of Power Quality toward developing a company-wide program that addresses all aspects of quality of service. Power Quality consultants must be aware of available equipment and the associated advantages/disadvantages. Mr. Sames attended this forum to obtain information regarding surge suppression devices that can be incorporated into PP&L Power Quality program.

Stanley Schoonover
SCS Enterprises
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Biography. Mr. Schoonover is Founder and President of the SCS Group, Inc., located at Waynesboro, PA, 17268, a consulting firm in the field of Industrial and Commercial Power Integrity. His broad experience in the machine tool industry with V/F Drives (Converters), CNC Controls and especially with the evolution of Programmable Controllers has familiarized him with many applications of power solutions. He has worked extensively with the early stages of surge suppression, power conditioning, and uninterruptible power systems. Mr. Schoonover is considered a leading authority in current power quality technology. He has pioneered in electromechanical design of the first numerically controlled (NC) turret lathe and has since designed and patented 7 major machine tool industry projects. He was awarded the "Charles Thornton Advanced Technology Award" by Litton Industries. He is also registered in the National Inventors Hall of Fame.

Interest in Forum. Having developed and designed numerous power protection products, I am interested in the current issues of power quality technology. To participate in a forum with industry peers will enlighten all who will bring their experience together. I support this opportunity to learn.

Hans Steinhoff
Joslyn Electronic Systems
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Biography. Hans J. Steinhoff was born in Germany; he received his Bachelor of Science in electrical engineering from the University of California at Santa Barbara in 1965. He has been with Joslyn Electronic Systems in Goleta, California, since 1964, where he designed test equipment, lightning arresters for aircraft HF radios, and surge protection devices for AC and DC circuits as a project engineer. Since early 1990 he has been a senior applications engineer. He is a member of the IEEE and has been active in several working groups of the Surge Protective Devices Committee.

Interest in Forum. Mr. Steinhoff is interested in the design and application of surge protective devices for AC power systems up to 600 volts and communications and signalling circuits. He has a strong concern for truth in advertising as it relates to these devices. He believes the customer and the industry is best served by manufacturers who make only claims that can be readily verified by all concerned.

Michael Stringfellow
EFI Electronics Corp.
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Biography. Dr. Stringfellow received his B.S. Honors Degree in Physics from the University of London and his PhD degree in Atmospheric Electricity from the University of Durham, England. Since he came to the United States in 1985, he has specialized in the field of protection of low-voltage circuits and equipment from transient overvoltages. He joined EFI Electronics Corporation in 1988, where he is now Director of Research and Applications Engineering. He has written over fifty scientific and engineering papers on the subjects of lightning, lightning protection and overvoltages. His papers have been published in such journals as Nature, Transactions of IEEE, Proceedings of IEE, Transactions of SAIEE and New Scientist. Dr. Stringfellow is an active participant in several national and international committees, including the IEEE Surge Protective Devices Committee, the International Electrotechnical Commission Low-Voltage Surge Suppressor Section. He is a registered Professional Engineer in the State of Georgia.

Interest in Forum. EFI Electronics is interested in participating in any interchange of ideas which will lead to a better understanding of power quality issues. This interchange is necessary for the improvement and development of power-conditioning products needed for a rapidly changing technological environment.

David Vannoy
Delmarva Power
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Biography. David B. Vannoy received his Bachelor of Electrical Engineering and Master of Electrical Engineering degrees at the University of Delaware in 1965 and 1967 respectively. He was a digital design and development engineer at the USAF Armament Development and Test Center, from 1968-1972. Since 1972 he has held several positions in the engineering and operating departments at Delmarva Power. He is currently a Senior Engineer responsible for the utility's power quality program. He was a member of the EPRI Power Electronics and Controls Working Group, and currently serves on the IEEE IAS Emerald Book Working Group, the IEEE Working Group on Monitoring Electrical Quality, and the EPRI Power Quality Steering Committee.

Interest in Forum. The implementation of an electric power quality program necessitates both evaluation and recommendations regarding proper application of surge protection devices both on the utility power system and on customer premises. An understanding of the state-of-the-art of surge protection is required in order to be able to provide effective assistance to customers. Insights gained from field experience may provide input as to customer needs.

Appendix C
Expectations of Participants

At the opening of the Forum, the participants were asked to state their major concern on surge protection, for which they expected to find useful information during the Forum. The original list was obtained by going around the room; the list below has been organized into broad categories, with similar topics merged into a single line entry. Asterisks preceding the entry indicate that the topic was cited by several participants (** for two, *** for three ...). It is interesting to compare this list with the topics presented by the authors - developed independently by each author - and with the Action Wish List (Appendix D) - indicating the wishes for further action or information, also organized in the same broad categories.

Education

***** Develop guidelines for SPD application
*** Separate but reconcile real world and theory
Educate consumer
Educate commercial user
Include surge protection in EE college curriculum

Avoid Specmanship

***** Get it right!
** Debunk response time claims

Liaison

Promote cooperation among Utilities, Manufacturers, and Users
Actions by utilities to provide end-user protection
Update on UL standards status

Systems Engineering

**** Coordinate cascaded SPDs
Effect of repetitive spikes on MOVs and other SPDs
Fusing of SPDs
Hardwire correctly (lead dress)
Contamination from adjacent loads ('bad neighbors')
Contamination of ground reference
Neutral grounding practices
Reconcile lifetime of protected product and lifetime of protection
Performance of SPDs in data networks
Compatibility with other equipment in system
IEC Overvoltage categories
Effects of swells on MOV life

Appendix D

Action Wish List

At the conclusion of the Forum, the participants were asked to state their top priority wish for action, based on the discussion that took place for two days. To avoid wishes beyond the possibility of implementation, each of the wishes was associated with an organization or individual that might be in a position to act on the wish, as indicated in the right hand column below. The original list was obtained by going around the room; the list below has been organized into broad categories. In conclusion to this Forum, at least the last of the wishes listed below has come true - herewith; other wishes will come true if the participants continue their involvement and contributions to the shared pool of experience.

Topic	Organization or individual for possible action
Education	
Education of users by non-utility	Tech Magazines IEEE/SPD Academia
Education in layman's terms	Tech Magazines
What can users expect from utilities	PEAC (Key)
Education on U.S. Power Systems	All of us
Educate OEM and others with feedback	NEMA
Avoid Specmanship	
Realistic surge specifications	SCC22, SC28A
Discourage meaningless claims	NEMA
Make 4 statements: - MOV life vs. Neon pilot life - Response time < 1 ns irrelevant - UL 1449 is safety, not performance - More than a filter is necessary at end of branch	NEMA

Liaison

Liaison with NEMA	NIST (Martzloff)
Liaison with ISA	SCC22
Obtain information from CBEMA et al.	EPRI-PEAC (Key)
Participate in International Lightning Conference	Cohen
Enhance interface with IEC	SCC22
Strengthen liaison with UL	SCC22
Organize Forum II	NIST (Martzloff)
Liaison/emulate ESD/OSD structure	Clark, Martzloff
Obtain draft of NEMA standard	Dillon-Malone

Systems Engineering

Develop Simulations	Lai
Develop performance and compatibility criteria	ASTM (Maher)
Coordinate with primary SPD's	IEEE SPDC
Reasonable inherent immunity for equipment	NEMA, CBEMA
Get A&E's in the act	BICSI
Change communications medium to non-metallic	SCC22
Protect for all modes of coupling	NEMA, UL
Coordination of cascades	IEEE SPDC
Applications for protection of signal lines	IEEE SPDC

Data Bases

Establish repository of standards (periodic issue)	NIST (Martzloff)
More information on C62.41 Cat C	Hill
Publish Forum Proceedings	NIST (Martzloff)