Effects of Temporary Overvoltage on Residential Products

System Compatibility Research Project

Technical Report

Effects of Temporary Overvoltage on Residential Products

System Compatibility Research Project

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EPRI Project Manager
R. Schainker

Electric Power Research Institute • 3412 Hillview Avenue, Palo Alto, California 94304 • PO Box 10412, Palo Alto, California 94303 • USA
800.313.3774 • 650.855.2121 • askepri@epri.com • www.epri.com

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Principal Investigator
D. Nastasi

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PRODUCT DESCRIPTION

Temporary overvoltage can have deleterious effects on electronic equipment. It is possible for the effects to be either immediate, as in the case of stress beyond a component's ability to withstand the voltage, or long-term, such as slow degradation brought on by long-term heating. This report contains results of three complementary areas of research conducted in 2004 concerning effects of temporary overvoltage (TOV) on common residential electrical and electronic devices. Research included a study of the causes of TOV, destructive testing on equipment to evaluate its tolerance to TOV, and a study of failed test specimens that were destroyed during TOV testing. The combined effort has yielded some unique and useful information on the common phenomenon known as *temporary overvoltage.*

Results & Findings

The information in this report gives readers an understanding of temporary overvoltage and the damage that it can cause. Postmortem analysis of failed specimens revealed interesting and practical data that invite further study. For example, the metal-oxide varistor (MOV), which is designed to be the first line of defense against transients, is often the weakest link during TOV events. During lab tests conducted for this report, investigators destroyed several surge suppressors, computers, monitors, and other equipment with temporary overvoltages. In addition to the common household surge protector, new, more innovative surge protectors were tested. Models containing these various innovations were better able to survive TOV conditions.

Laboratory creation of TOV events also revealed that appliances, such as personal computers, with no built-in MOVs were able to survive TOV events better than those appliances that had MOVs installed internally. Even though the MOVs were provided by the PC manufacturer for the commendable function of surge protection, the ratings of the MOVs were selected such that they were more susceptible to TOV than other components of the PC power supply.

Challenges & Objective(s)

This project continues from prior years' research to produce a systematic procedure for performing destructive tests on end-use equipment. The objective of the multi-year project is to develop a set of useful test protocols and to build on the existing knowledgebase of correlation between failed equipment and disturbances that cause failures. Readers will ultimately benefit by being able to recognize failure modes and correlate observed damage to a particular power-system event.

Applications, Values & Use

This report was composed for electric utilities—especially power quality engineers and customer-claims departments—to shed some light on correlating equipment damage with the cause of that damage. Insurance companies, which issue millions of checks to compensate customers for equipment damage attributed to power disturbances, also will benefit from understanding this issue. As this project matures, its results will enable electric utilities and insurance companies to develop a knowledgebase of power-related failure for classes of equipment. Understanding common failure modes among classes of equipment also will enable manufacturers of end-use equipment and mitigation devices to improve surge and TOV-withstand capabilities of equipment. This improvement will result in fewer claims of damaged equipment for electric utilities and insurance companies, as well as reduced inconvenience for end users.

EPRI Perspective

Its vast resource pool has uniquely qualified EPRI to conduct research and testing on consumer products to evaluate their compatibility with the electric utility grid. EPRI can tap into knowledge from a variety of sources to conduct a highly specialized research project on phenomena such as temporary overvoltage and then correlate equipment damage to power disturbances. EPRI's expertise ranges from evaluating the distribution of disturbances across North America to laboratory testing, field investigations, and statistical analysis. Benefiting from this array of experience and resources are electric utilities and insurance companies who must determine whether equipment damage results from power disturbances or some other event, such as the catastrophic failure of an electrical component within the equipment.

Approach

This report contains three main areas of research, each described in detail. The report also provides supporting information or details relating to the main topics. The main topics are

- Common scenarios of TOV (magnitudes, durations, and causes)
- Laboratory creation of TOV events to evaluate equipment susceptibility (including a test protocol and survivability results from specific equipment)
- Postmortem analysis of failed equipment

Keywords

Temporary overvoltage
Swell
Destructive testing
Failure analysis
Surge-protective device (SPD)
Metal-oxide varistor (MOV)

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1 INTRODUCTION

This report fits into a theme of failure analysis that was begun during the research year 2002. The goal was to study destructive power-line phenomena such as lightning-induced surges and temporary overvoltages. Each year, project sponsors choose from a proposed list of destructive events and electrical equipment. Sponsors are also invited to suggest ideas for a particular study within the theme of destructive testing and failure analysis.

Each yearlong project usually includes a description of the laboratory testing to be performed, a test protocol, destructive laboratory tests, and failure analysis. A power quality laboratory is used to create the disturbances in a controlled manner. Testing is performed with the intent to destroy a certain number of electrical appliances. Testing thus reveals not only susceptibility levels but also reveals the weakest components within the appliances upon a postmortem investigation of failed specimens.

In the inaugural project, sponsors indicated a preference for AC power-line surge testing on light industrial equipment, such as programmable logic controllers (PLCs) and small, fractional-horsepower adjustable-speed drives (ASDs). The results are presented in an EPRI report [1]. The following year, the failure-analysis research continued by applying surges to specifically the communication lines between ASDs and PLCs. The results are presented in an EPRI report [2].

The year 2004 marked the third year in the ongoing project. Among the project sponsors, a task force of volunteers was put together for technical review of the test plan and specimen selection. The destructive test changed from surges to temporary overvoltage (TOV), and the test specimens were broadly selected to include more variety of residential, commercial, and light industrial types of equipment. Sponsors expressed their preference to study the effects of TOVs on surge-protective devices (SPDs).

2
CAUSES AND CHARACTERISTICS OF TEMPORARY OVERVOLTAGE

This chapter presents a detailed discussion and technical explanation of the five most common causes of TOVs on the electric power system. Some but not all of these events are generated at the distribution level. Under one common scenario, for example, a TOV is created locally inside a residence.

Two other important topics discussed in this chapter are *magnitudes* and *durations* for each of the five TOV scenarios. These magnitudes and durations feed the testing portion of the project. The test protocol was developed with the intent of evaluating the tolerance of connected loads to replicated TOV events having the magnitudes and durations (not necessarily the correct waveforms) that are discussed in this chapter.

Overvoltages During a Fault

The system grounding configuration determines the overvoltages that can occur during a line-to-ground fault. A single line-to-ground fault shifts the ground potential at the fault location. The severity of this shift in ground reference depends on the grounding configuration (see Figure 2-1). On a solidly grounded system with a good return path to the grounding source, little reference shift occurs. On an ungrounded system, a full offset occurs—the line-to-ground voltage on the unfaulted phases rises to the line-to-line voltage, which is 1.73 per unit. On a multigrounded distribution system with a solidly grounded station transformer, overvoltages above 1.3 per unit are rare.

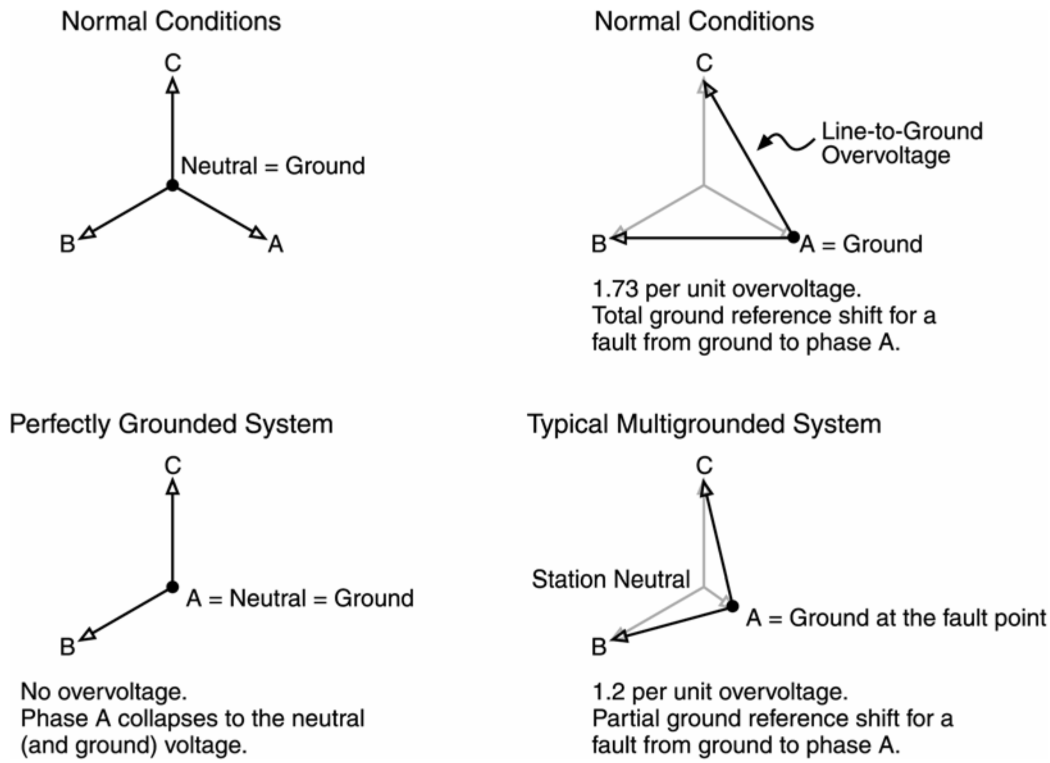


Figure 2-1
Shifts in Ground Potential and Overvoltages Depending on the Grounding Configuration

Two factors relate the overvoltage to the system voltage:

- Coefficient of grounding:
  - $COG = V'_{LN}/V_{LL}$
- Earth fault factor:
  - $EFF = V'_{LN}/V_{LN}$

where

V'_{LN} = maximum line-to-ground voltage on the unfaulted phases during a fault from one or more phases to ground

V_{LN} , V_{LL} = nominal line-to-neutral and line-to-line voltages

A system is "effectively grounded" if the coefficient of grounding is less than or equal to 80% (the earth-fault factor is less than 138%) [3]. This is met approximately with the following conditions:

$X_0/X_1<3$

$R_0/X_1<1$

For a single line-to-ground fault on phase A, the voltages on phases B and C are:

$$V_b = \left(a^2 + \frac{Z_1 - Z_0}{2Z_1 + Z_0 + 3R_F}\right)E \qquad \textbf{Eq. 2-1}$$

$$V_c = \left(a + \frac{Z_1 - Z_0}{2Z_1 + Z_0 + 3R_F}\right)E \qquad \textbf{Eq. 2-2}$$

where

Z_1 = positive-sequence impedance

Z_0 = zero-sequence impedance

$a = 1\angle 120°$

R_F = fault resistance

E = line-to-neutral voltage magnitude prior to the fault

For a double line-to-ground fault, the voltage on the unfaulted phase is:

$$V = \frac{3Z_0 + 6R_F}{Z_1 + 2Z_0 + 6R_F}E \qquad \textbf{Eq. 2-3}$$

In some cases, the double line-to-ground fault causes overvoltages that are slightly higher than the single line-to-ground fault. But because single line-to-ground faults are so much more common, we often design for the single line-to-ground fault. For single line-to-ground faults, the voltage is always worse when the fault impedance is zero (R_F=0). For double line-to-ground faults, it may not always be worse when the fault impedance is zero. Figure 2-2 shows overvoltage charts as a function of X_0/X_1 and R_0/X_1. This includes overvoltages due to single line-to-ground faults and for double line-to-ground faults (assuming that R_F=0).

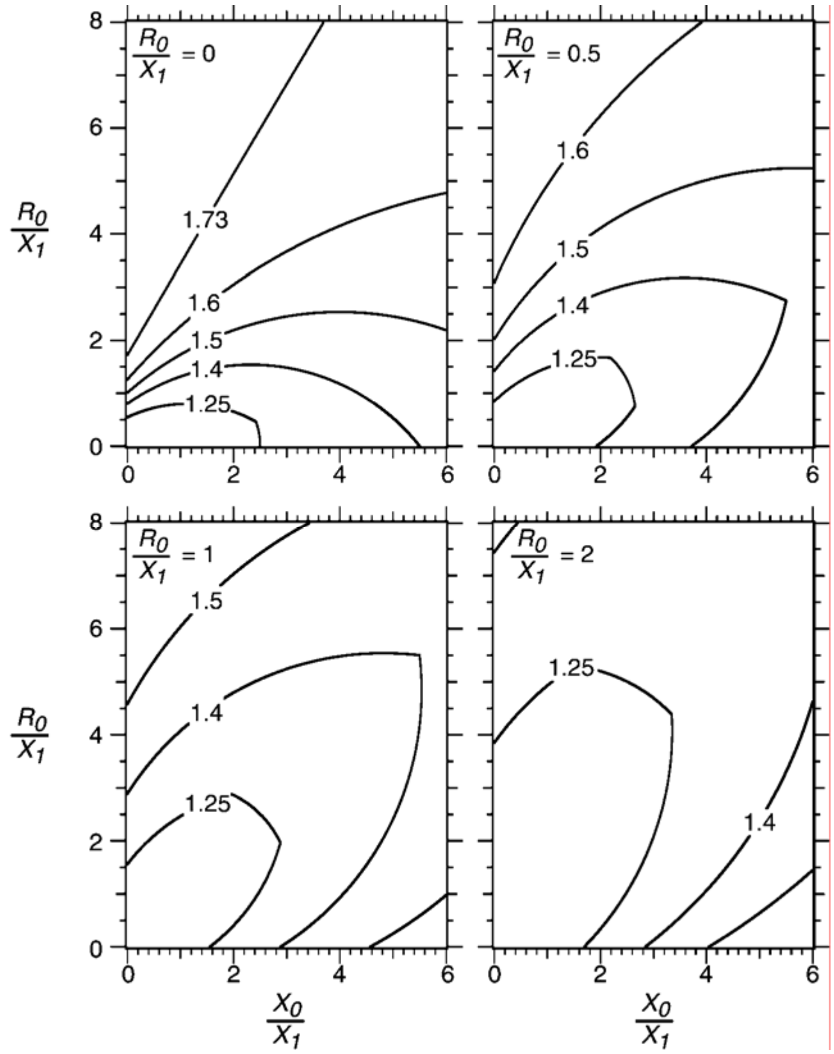


Figure 2-2
Maximum Overvoltages in Per Unit for Line-to-Ground Faults Based on X_0/X_1 and R_0/X_1 (the Contours Mark the Threshold of Voltage)

IEEE suggests the overvoltage multiplier factors for different systems, as shown in Table 2-1 [4]. The multipliers include the neutral shift during line-to-ground faults at a voltage of 105% (the ungrounded system therefore has an overvoltage of 1.73×1.05=1.82).

The higher overvoltage factor of 1.35 for multigrounded systems with metal-oxide arresters was identified as a more conservative factor for four-wire systems because of the reduced saturation of newer transformers and use of metal-oxide arresters (they are always connected, so they are more sensitive to overvoltages than older arresters, which have an isolating gap).

Table 2-1
Overvoltage Factors for Different Grounding Systems

System	Overvoltage factor
Ungrounded system	1.82
Four-wire multigrounded system (spacer cable)	1.5
Three- or four-wire unigrounded system (open wire)	1.4
Four-wire multigrounded system (open wire-gapped arrester)	1.25
Four-wire multigrounded system (open-wire metal-oxide arrester)	1.35

Loss of a Secondary Neutral

Open neutral connections in 120/240-V customer installations can occur and have been reported under several circumstances, including:

- When corrosion of an underground service reaches an acute stage
- When the neutral wire of a separate-conductor service drop is broken by falling branches or icing
- When an intermittent loose connection exists in the service panel

Note that all of the above are "when" clauses—not "if and when"—because all of these circumstances are likely to occur at some point; it is only a matter of probability and frequency of occurrence.

With a broken neutral on a 120/240-V service, the voltage in the residence's neutral conductor can float. The overvoltage is a function of the load imbalance between the two 120-V legs. The leg with lighter loading will have higher voltage, and the leg with heavier loading will have lower voltage. Figure 2-3 shows a diagram of this. The per-unit voltage on V_1 is:

$$V_1 = \frac{Z_1}{Z_1 + Z_2}$$ **Eq. 2-4**

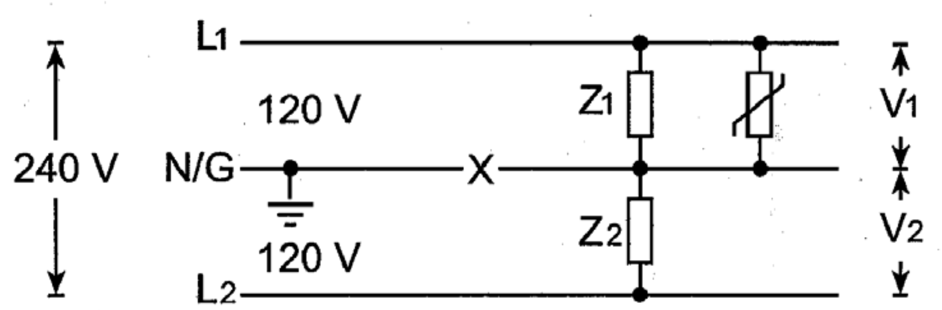


Figure 2-3
Voltage Divider During an Open Neutral

Figure 2-3 is a worst-case drawing where the neutral is not loose but is broken. In the worst case, the voltage on the lightly loaded leg can reach nearly 240 V, or nearly 2 per unit. Under most circumstances, even if the neutral is broken, the earth should form a connection back to the transformer's neutral because the neutral is bonded to ground at the house (not shown in the figure). The earth should form a connection from the earth-to-neutral bond at the house back to the transformer's neutral through the pole ground. But unfortunately, this impedance can be high enough to still cause a significant overvoltage on the leg with lighter loading.

Ferroresonance

Ferroresonance is a special form of series resonance between the magnetizing reactance of a transformer and the system capacitance. A common form of ferroresonance occurs during single phasing of three-phase distribution transformers [5]. This most commonly happens on cable-fed transformers because of the high capacitance of the cables. The transformer connection is also critical for ferroresonance. An ungrounded primary connection (see Figure 2-4) leads to the highest magnitude of ferroresonance. During single phasing (usually when line crews energize or de-energize the transformer with single-phase cutouts at the cable riser pole), a ferroresonant circuit between the cable capacitance and the transformer's magnetizing reactance drives voltages to as high as five per unit on the open legs of the transformer. The voltage waveform is normally distorted and often chaotic (see Figure 2-5).

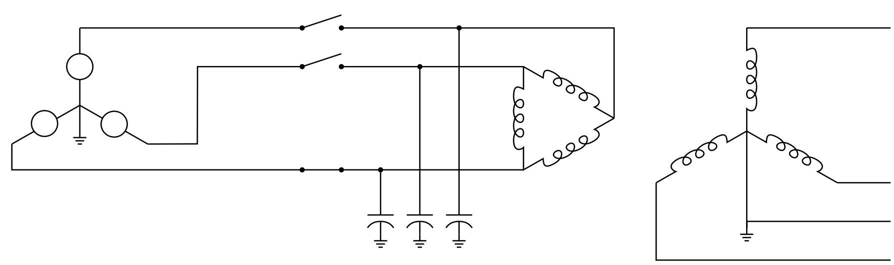


Figure 2-4
Ferroresonant Circuit With a Cable-Fed Transformer With an Ungrounded High-Side Connection

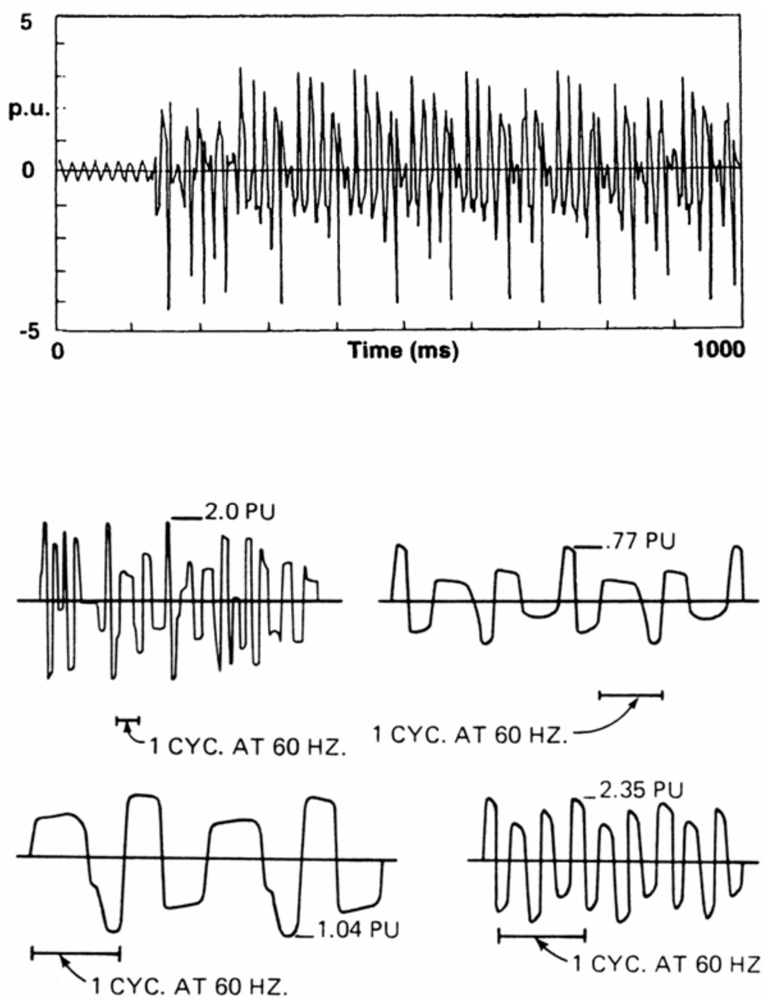


Figure 2-5
Examples of Ferroresonance [6], [7]

Ferroresonance drove utilities to use three-phase transformer connections with a grounded-wye primary, especially on underground systems. The chance of ferroresonance is determined by the capacitance (cable length) and by the core losses and other resistive loads on the transformer [8]. The core losses are an important part of the ferroresonant circuit.

Walling [9] breaks down ferroresonance in a way that highlights several important aspects of this complicated phenomenon. Consider the simplified ferroresonant circuit in Figure 2-6. The transformer magnetizing branch has the core-loss resistance in parallel with a switched inductor. When the transformer is unsaturated, the switched inductance is open, and the only connection between the capacitance and the system is through the core-loss resistance. When the core saturates, the capacitive charge dumps into the system (the switch in Figure 2-6 closes). The voltage overshoots, and as the core comes out of saturation, charge is again trapped on the capacitor (but of opposite polarity). This happens every half cycle (see Figure 2-7 for waveforms). If the core loss is large enough (or the resistive load on the transformer is large enough), the charge on the capacitor drains off before the next half cycle, and ferroresonance does not occur. The transformer core does not stay saturated long during each half cycle, just long enough to release the trapped charge on the capacitor. If the cable susceptance or even just the transformer susceptance is greater than the transformer core loss conductance, then ferroresonant overvoltages may occur.

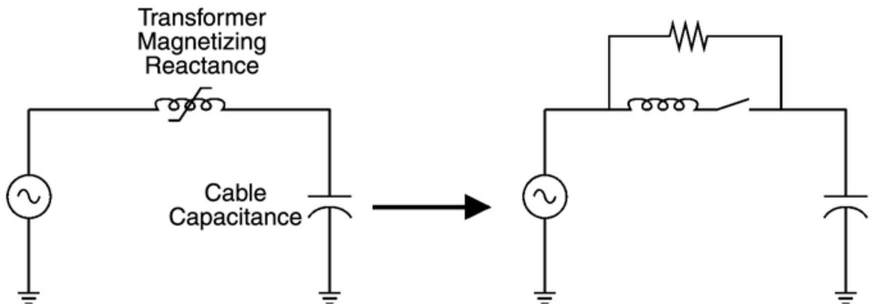
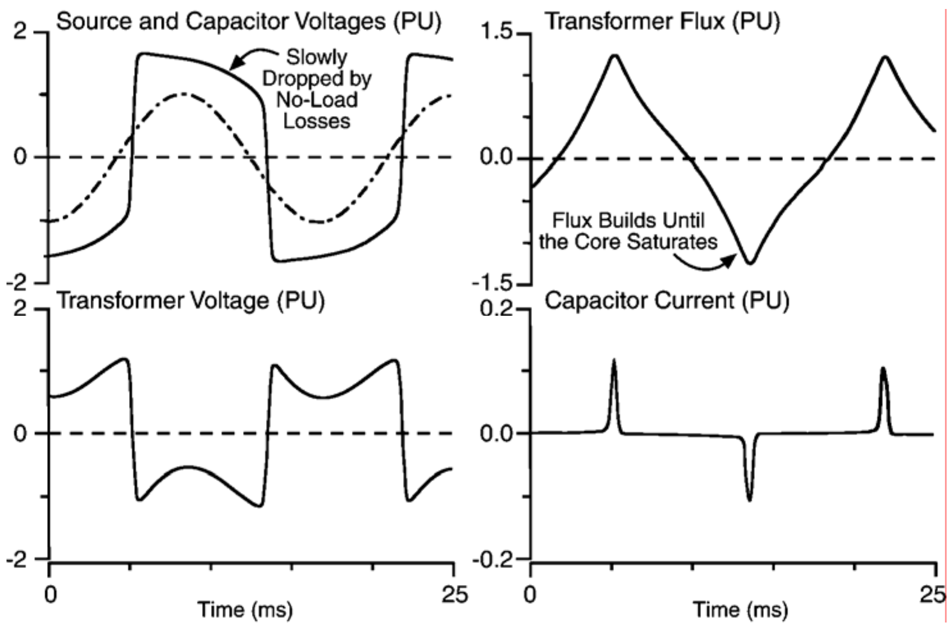


Figure 2-6
Simplified Equivalent Circuit of Ferroresonance on a Transformer With an Ungrounded High-Side Connection



Source: [9]

Figure 2-7
Voltages, Currents, and Transformer Flux During Ferroresonance

In modern silicon-steel distribution transformers, the flux density at rated voltage is typically between 1.3 and 1.6 T. These operating flux densities slightly saturate the core (magnetic steel fully saturates at about 2 T). Because the core is operated near saturation, a small transient (such as switching) is enough to saturate the core. Once started, the ferroresonance self-sustains—the resonance repeatedly saturates the transformer every half cycle.

Table 2-2 shows what types of transformer connections are susceptible to ferroresonance. To avoid ferroresonance on floating-wye/delta transformers, some utilities temporarily ground the wye on the primary side of floating-wye/delta connections during switching operations.

Table 2-2
Transformer Primary Connections Susceptible to Ferroresonance

Susceptible Connections	Not Susceptible
• Floating wye • Delta • Grounded wye with 3-, 4-, or 5-legged core construction • Line-to-line connected single-phase units	• Grounded wye made of three individual units or units of triplex construction • Open wye/open delta • Single-phase units connected line-to-ground

Ferroresonance can occur on transformers with a grounded primary connection if the windings are on a common core, such as the five-legged core transformer (the magnetic coupling between phases completes the ferroresonant circuit [7]). The five-legged core transformer connected as a grounded wye/grounded wye is the most common underground transformer configuration. Ferroresonant overvoltages involving five-legged core transformers normally do not exceed two per unit.

Ferroresonance is a function of the cable capacitance and the transformer no-load losses. The lower the losses relative to the capacitance, the higher the ferroresonant overvoltage can be. For transformer configurations that are susceptible to ferroresonance, ferroresonance can occur approximately when:

$$B_C \geq P_{NL} \qquad \textbf{Eq. 2-5}$$

where

B_C = capacitive-reactive power per phase in vars

P_{NL} = core loss per phase in watts

The capacitive-reactive power on one phase in vars depends on the voltage and the capacitance as:

$$B_C = \frac{V_{kV}^{\ 2}}{3} 2\pi f C \qquad \textbf{Eq. 2-6}$$

where

V_{kV} = rated line-to-line voltage in kV

f = frequency in Hz

C = capacitance from one phase to ground in μF

Normally, ferroresonance occurs without equipment failure if the crew finishes the switching operation in a timely manner. The loud banging, rumbling, and rattling of the transformer during ferroresonance may alarm line crews. Occasionally, ferroresonance is severe enough to damage a transformer—the overvoltage stresses the transformer insulation, and the repeated saturation may cause tank heating as flux leaves the core (although many modes of ferroresonance barely saturate the transformer and do not cause significant tank heating). Surge arresters are the most likely equipment casualty; in attempting to limit the ferroresonant overvoltage, an arrester may absorb more current than it can handle and thermally run away. Gapped silicon-carbide arresters are particularly prone to failure because the gap cannot reseal the repeated sparkovers from a long-duration overvoltage. Gapless metal-oxide arresters are much more resistant to failure from ferroresonance and help hold down the overvoltages. Ferroresonant overvoltages may also damage customer's equipment from high secondary voltages. Small end-use arresters are particularly susceptible to damage.

Ferroresonance is more likely with:

- *Unloaded transformers* – Ferroresonance disappears with load as little as a few percent of the transformer rating.
- *Higher primary voltages* – Shorter cable lengths are required for ferroresonance. Resonance is more likely even without cables, just due to the internal capacitance of the transformer. With higher voltages, the capacitances do not change significantly (cable capacitance increases just slightly because of thicker insulation), but vars are much higher for the same capacitance.
- *Smaller transformers* – Smaller no-load losses.
- *Low-loss transformers* – Smaller no-load losses.

Severe ferroresonance with voltages reaching peaks of 4 or 5 per unit occurs on three-phase transformers with an ungrounded high-voltage winding during single-pole switching. If the transformer is fed by underground cables and crews switch the transformer remotely, ferroresonance is likely.

On overhead circuits, ferroresonance is common with ungrounded primary connections on 25- and 35-kV distribution systems. At these voltages, the internal capacitance of most transformers is enough to ferroresonate. The use of low-loss transformers has caused ferroresonance to appear on overhead 15-kV distribution systems as well. Amorphous core and low-loss silicon-steel core transformers have much lower core losses than previous designs. With less core loss, ferroresonance happens with lower amounts of capacitance. Tests by the Southern California Edison Company on three-phase transformers with ungrounded primary connections found that ferroresonance occurred when the capacitive power per phase exceeded the transformer's no-load losses per phase by the following relationship [10]:

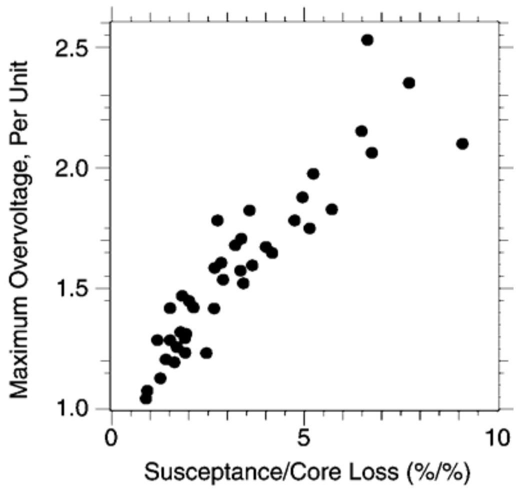
$$B_C \geq 1.27 P_{NL} \quad \textbf{Eq. 2-7}$$

The phase-to-ground capacitance of overhead transformers is primarily due to the capacitance between the primary and secondary windings (the secondary windings are almost at zero potential). A typical 25-kVA transformer has a phase-to-ground capacitance of about 2 nF [6]. For a 7.2-kV line-to-ground voltage, 0.002 μF is 39 vars. So, if the no-load losses are less than 39 vars/1.27 = 30.7 W per phase, the transformer may ferroresonate under single-pole switching.

Normally, ferroresonance occurs on three-phase transformers; but ferroresonance can occur on single-phase transformers if they are connected phase to phase and one of the phases is opened either remotely or at the transformer. Jufer [10] found that small single-phase pad-mounted transformers connected phase to phase ferroresonate when remotely switched with relatively short cables. Their tests of silicon-steel core transformer found that a 25-kVA transformer resonated with 50 feet (15 m) of 1/0 XLPE cable at 12 kV. A 50-kVA transformer resonated with 100 feet of cable, and a 75-kVA unit resonated with 150 feet of the cable. Peak primary voltages reached 3 to 4 per unit. Secondary-side peaks were all under 2 per unit. Longer cables produced slightly higher voltages during ferroresonance. Jufer [10] found that ferroresonance did not occur if the resistive load in watts per phase (including the transformers no-load losses and the resistive load on the secondary) exceeded 1.15 times the capacitive vars per phase ($P_{NL} + P_L > 1.15B_C$). Bohmann et al. [11] describe a feeder where single-phase loads were switched to a phase-to-phase configuration, and the reconfiguration caused a higher-than-normal arrester failure rate that was attributed to ferroresonant conditions on the circuit.

It is widely believed that a grounded-wye primary connection eliminates ferroresonance. This is not true if the three-phase transformer has windings on a common core. The most common underground three-phase distribution transformer has a five-legged wound core. The common core couples the phases. With the center phase energized and the outer phases open, the coupling induces 50% voltage in the outer phases. Any load on the outer two phases is effectively in series with the voltage induced on the center phase. Because the coupling is indirect and because the open phase capacitance is in parallel with a transformer winding to ground, this type of ferroresonance is not as severe as ferroresonance on configurations with an ungrounded primary winding. Overvoltages rarely exceed 2.5 per unit.

Five-legged core ferroresonance also depends on the core losses of the transformer and the phase-to-ground capacitance. If the capacitive vars exceed the resistive load in watts, ferroresonance may occur. Higher capacitances—longer cable lengths—generally cause higher voltages (see Figure 2-8).



Source: Walling et al. [8]

Figure 2-8
Five-Legged Core Ferroresonance as a Function of No-Load Losses and Line-to-Ground Capacitance

Ferroresonance can occur with five-legged core transformers even when switching at the transformer terminals due to the transformer's internal line-to-ground capacitance. On 34.5-kV systems, transformers smaller than 500 kVA may ferroresonate if single-pole switched right at the transformer terminals. Even on 15-kV-class systems, where crews can safely switch all but the smallest five-legged core transformers at the terminals, we should include the transformer's capacitance in any cable-length calculation—the transformer's capacitance is equivalent to several feet (meters) of cable. The capacitance from line-to-ground is mainly due to the capacitance between the small paper-filled layers of the high-voltage winding.

Ferroresonance most commonly happens when switching an unloaded transformer. It also usually happens with manual switching; ferroresonance can occur because a fault clears a single-phase protective device, but it is much less common.

If the fuse is a tap fuse, and several customers are on a section, the transformers will have somewhat different characteristics, which lowers the probability of ferroresonance (and ferroresonance is less likely with larger transformers).

Overvoltages Due to Poor Voltage Regulation

Occasionally, overvoltages occur because of the malfunction or misapplication of utility voltage-regulation equipment. Some scenarios that could cause overvoltages include:

- Regulator installed or set incorrectly
- Malfunctioning voltage regulator
- Capacitor-bank controllers with an incorrect clock setting
- Malfunctioning capacitor-bank controller

If one or more capacitors are on at light load, the capacitors can push the voltage above normal. A malfunctioning regulator can also push the voltages higher.

Another factor that can cause high voltage is sudden loss of load. If a recloser is downstream of a regulator and the recloser trips, the remaining customers may have high voltage until the regulator adjusts its taps to compensate.

Accidental Contact to High-Voltage Circuits

Faults from transmission circuits to distribution circuits are another hazard that can subject distribution equipment and customer equipment to extremely high voltages. Consider the example in Figure 2-9 of a fault from a subtransmission circuit to a distribution circuit. As is the case for primary-to-secondary faults discussed in the previous circuit, overvoltages are not extremely high as long as the distribution circuit stays connected (just like the primary-to-secondary faults discussed in the previous section). But if a distribution interrupter opens the circuit, the voltage on the faulted distribution conductor jumps to the full transmission-line voltage. With voltage at several times normal, something will fail quickly. Such a severe overvoltage is also likely to damage end-use equipment. The distribution interrupter, either a circuit breaker or recloser, may not be able to clear the fault (the recovery voltage is many times normal); it may fail trying.

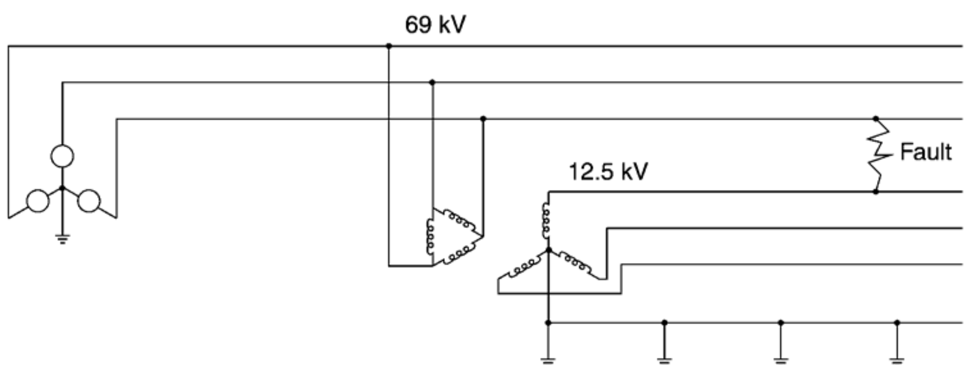


Figure 2-9
Example of a Fault From a Transmission Conductor to a Distribution Conductor

Faults further from the distribution substation cause higher voltages, with the highest voltage at the fault location. Current flowing back towards the circuit causes a voltage rise along the circuit.

While one can use a computer model for an exact analysis (but it is not possible with most standard distribution short-circuit programs), a simplified single-phase analysis (assuming a wye-wye transformer) helps frame the problem. The fault current is approximately:

$$I = \frac{V_S}{\frac{(n-1)}{n} Z_A + \frac{n}{(n-1)} Z_B} \approx \frac{V_S}{Z_A + Z_B} \qquad \textbf{Eq. 2-8}$$

where

n = ratio of the transmission to distribution voltage (n=69/12.5=5.5 in the example)

V_S = rms line-to-ground transmission source voltage (40 kV in the example)

Z_A = loop impedance from the transmission source to the high side of the distribution station

Z_B = loop impedance from the high side at the distribution station out to the fault and back to the distribution low side of the distribution substation

And, the 69-kV impedance often dominates, so the fault current is really determined by Z_A. For the distribution and transmission-line impedances, Z_A and Z_B, you can use one ohm per mile for quick approximations. The worst case is with a small Z_A, a stiff subtransmission system.

The voltage at the fault is:

$$V = I \frac{Z_B}{2} + V_d$$ **Eq. 2-9**

where

V_d = line-to-ground voltage on the distribution circuit at the substation (as a worst case, assume that it is the nominal voltage—it will usually be less because of the sag that pulls down the voltages).

Figure 2-10 shows results from a series of computer simulations on a 12.5-kV circuit for various fault locations and subtransmission source stiffnesses. Results only modestly differ for other configurations: a 69-kV source in the opposite direction, a looped transmission source, a different substation transformer configuration, or different phases faulted. The worst cases are for stiff transmission systems.

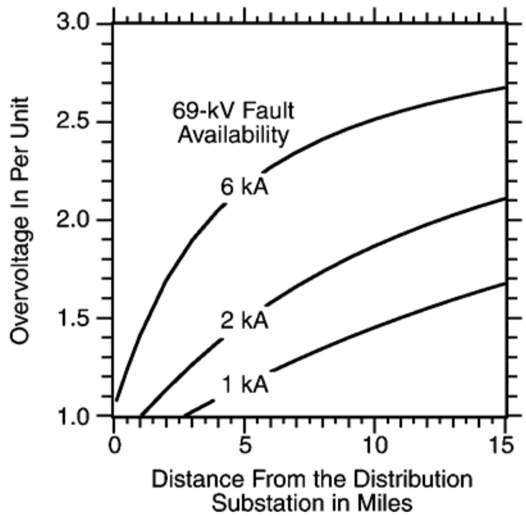


Figure 2-10
Results of Simulations of a Fault From a 69-kV Circuit to a 12.5-kV Circuit (Before the Distribution Substation Breaker Trips)

In this situation, distribution transformers would saturate, and metal-oxide arresters would move into heavy conduction. Transformer saturation distorts the voltage but does not appreciably reduce the peak voltage. Arresters can reduce the peak voltage, but they could still allow quite high voltages to customers. Arresters with an 8.4-kV maximum continuous operating voltage start conducting for power-frequency voltages at about 11 to 12 kV (1.5 to 1.6 times the nominal system line-to-ground voltage). At higher voltages, the arresters will draw more current.

Summary

The main causes of TOV are given below along with typical magnitudes and durations:

- Overvoltages during a fault:
  - Typical magnitudes: 1.2 to 1.3 per unit, worst case: 1.5 per unit
  - Typical durations: 0.1 to 2 seconds, worst case: 10 seconds
- Loss of a secondary neutral:
  - Typical magnitudes: 1.3 to 1.5 per unit, worst case: 2 per unit
  - Typical durations: hours
- Overvoltages due to poor regulation:
  - Typical magnitudes: 1.1 to 1.15 per unit, worst case: 1.2 per unit
  - Typical durations: hours
- Ferroresonance:
  - Typical magnitudes: 1.5 to 2 per unit, worst case: 3 per unit
  - Typical durations: several seconds to minutes

- Contact to high-voltage circuits:
  - Typical magnitudes: unknown, worst case: several per unit
  - Typical durations: 0.1 to 1 second

3
A NATIONWIDE SURVEY OF TOV EVENTS

At the disposal of the project investigators is an existing database of power-line disturbance data taken by EPRI as part of a multi-year nationwide project. Since the project's completion, the data have been queried and polled in many ways and have been used in countless technical reports and presentations in order to illustrate the types of events that occur and the frequency of their occurrence on distribution circuits across the United States.

The project under which the data were taken is called Distribution Power Quality (DPQ) [12]. The project included a monitoring period that began in June of 1993 and lasted through September 1995. It included a set of power-line monitors in about 277 locations across the United States, with the cooperation of 24 host utilities. As the name indicates, these monitors were installed at distribution locations such as just outside the substations, at the middle of distribution feeders, and near the end of distribution feeders.

In the year 2000, EPRI began another nationwide power quality survey, but with additional types of monitoring equipment and at different system locations (primarily distribution locations). This project included about 480 monitors, covering the time period August of 1993 through December of 2002, although the majority of the data covered the time period of April of 2000 through April of 2002. This project is known as Distribution Power Quality II (DPQ II) [13].

The two databases created during these projects can be queried for any events with a given set of magnitude and duration parameters. Of interest in the present TOV project are the events having magnitudes and durations outlined at the end of the previous chapter of this report. Table 3-1 shows the boundaries used in the query for events based on the five most common TOV scenarios.

Table 3-1
Boundaries Chosen for Database Query on TOV Events

Magnitude	Duration	Represented Event
1.2 to 1.3 PU	0.1 to 2 s	Overvoltages during a fault
1.3 to 1.5 PU	60 to 300 s	Loss of a secondary neutral
1.1 to 1.15 PU	>30 min	Overvoltages due to poor regulation
1.5 to 2.0 PU	1 to 180 s	Ferroresonance
2.0 to 5.0 PU	0.1 to 1 s	Contact to high-voltage circuits

Figure 3-1 is a scatter plot of the resulting queries, where the data points represent magnitudes and durations of TOV events that were recorded during the original DPQ project. It is very important to note that the actual causes of these events are unknown. They are shown here only because their magnitude and durations fall into the range considered typical for TOV events described in this report. As a result, no importance should be placed on the number of events within a particular category. For example, ferroresonance is a fairly rare condition but is represented in the scatter plot by a very large number of points.

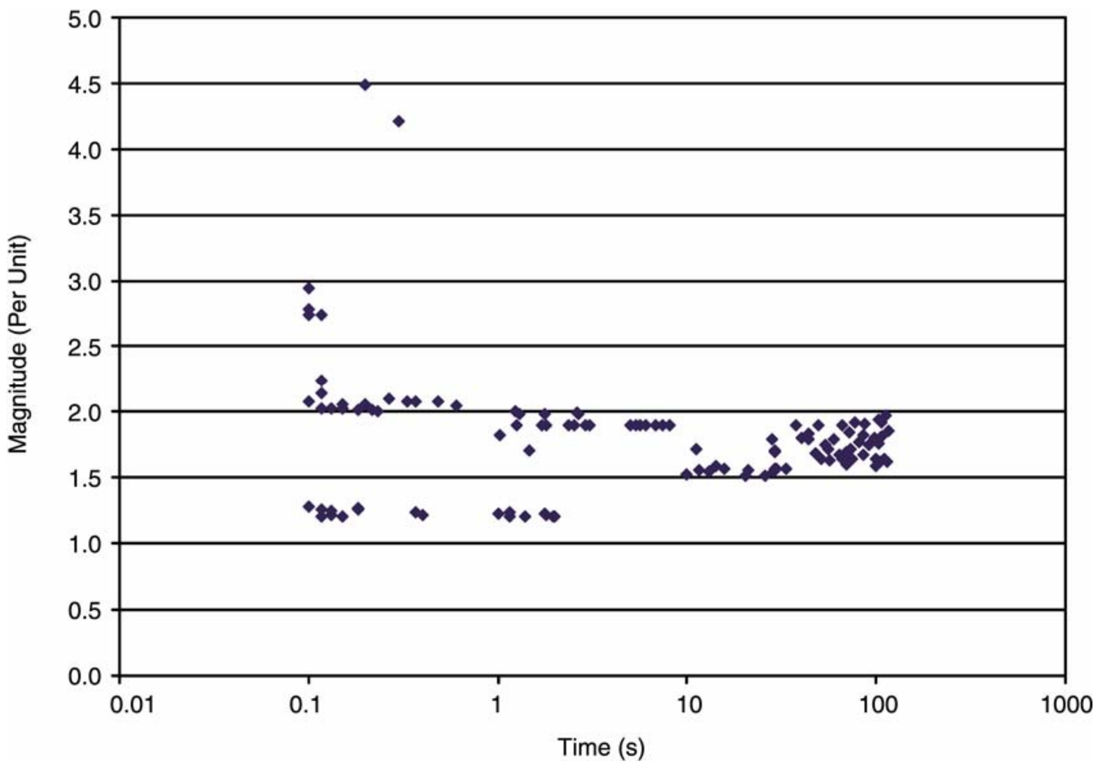


Figure 3-1
Scatter Plot of TOV Events Recorded During the EPRI DPQ Study

Another note worth making is regarding the loss of secondary neutral connection. The power quality monitors were located along the distribution circuit, making it impossible to detect any events actually caused by a loose neutral at a residence. However, our query, for completeness and for general interest, also included the set of parameters that we have set forth as a representation of a "loss of secondary neutral." Coincidentally, there were no events captured in this small window.

The same exercise was repeated for the more recent EPRI survey. Figure 3-2 shows the results of the same queries on the DPQ II data.

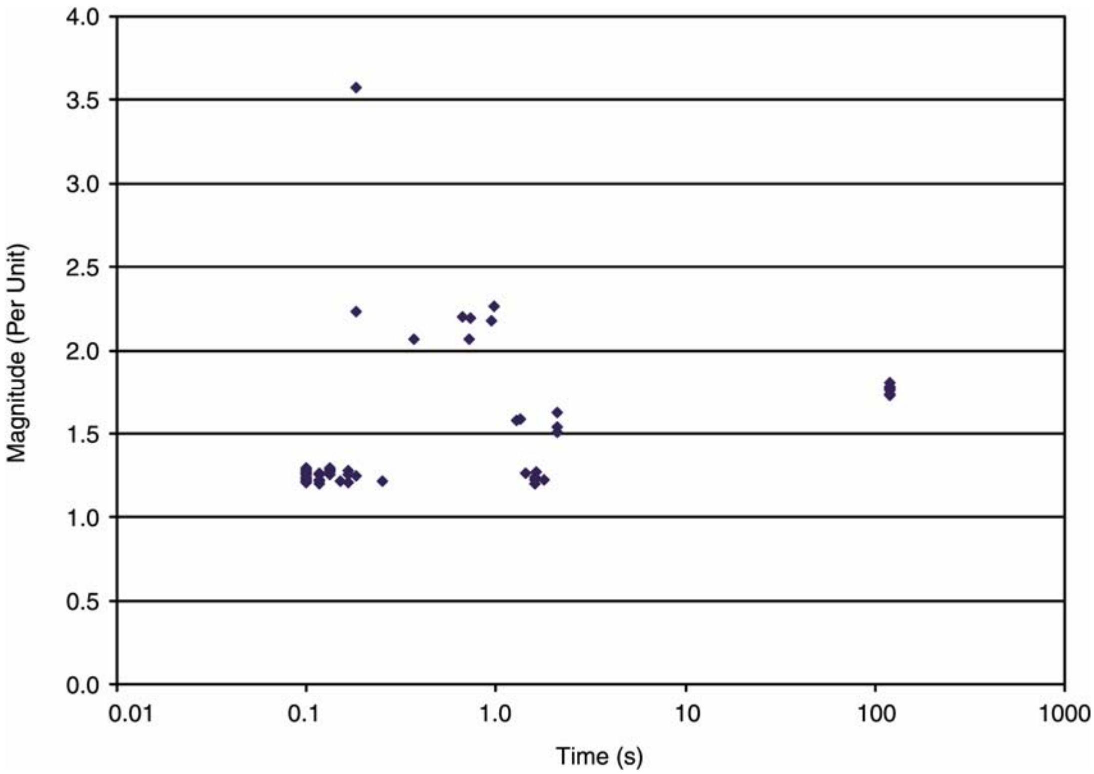


Figure 3-2
Scatter Plot of TOV Events Recorded During the EPRI DPQ-II Study

In Figure 3-3, data points from both EPRI DPQ surveys are combined into one graph. Additionally, bounding rectangles show the relative positions of the five queries. Note that the events due to poor regulation fall outside the graph area because of their long durations. An additional feature of this figure is the upper portion of the ITIC curve shown for reference. The Information Technology Industry Council (ITIC) publishes a well-known curve representing the expected tolerance (no interruption in performance or failures) of computer equipment. It is not intended to be a design criterion for equipment or the AC power system. Only the portion of the curve that fits into the time window is shown.

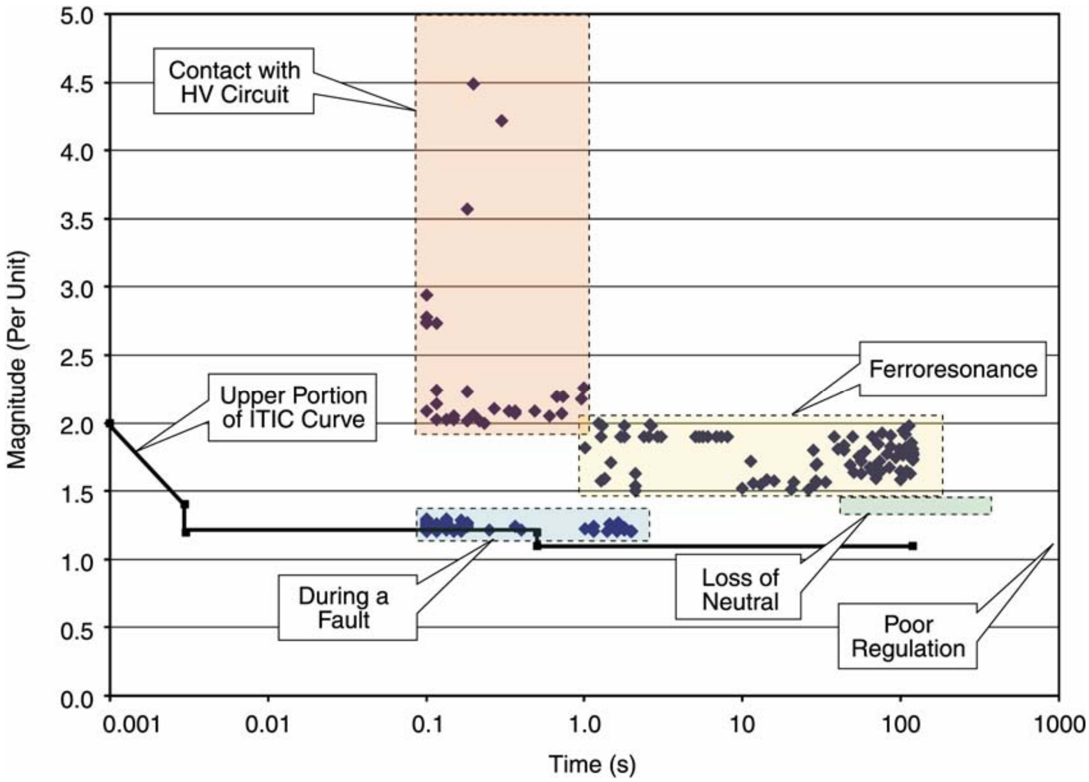


Figure 3-3
TOV Events Grouped by Query Results

4
TEMPORARY OVERVOLTAGE TESTING IN THE LABORATORY

The purpose of the laboratory tests is to evaluate the susceptibility levels of common electronic equipment to temporary overvoltage. The tests are destructive in nature and therefore require multiple specimens of each equipment type.

Two logical test methods are possible: a test-until-failure method and a pass/fail method. Under the test-until-failure scenario, a specimen is presented with a temporary overvoltage of a particular “safe” magnitude and for a specified maximum duration. If it does not fail by the end of that maximum duration, then the voltage is increased by 5% and the test is repeated. This pattern continues until the device eventually fails. The final magnitude and duration are recorded. The problem with this test method is that investigators are not certain that the overvoltage events prior to failure had no effect on the specimen. To eliminate this speculation, a very large number of identical specimens is required. This might not be practical if the equipment type is expensive or complex to set up.

Alternatively, a pass/fail method of testing involves a prescribed set of tests, each having a specific magnitude and duration. One new specimen per test in the sequence is required. In the case of the present project, only five tests were chosen.

The pass/fail method was the chosen test method for this project. Chosen appliances were exposed to five overvoltage conditions.

Appliances Chosen for Testing

With input from project sponsors on the types of equipment that should be exposed to TOV, Table 4-1 shows the specimen types and their quantities that underwent laboratory tests. In the case of inexpensive EUTs, for example, cord-connected surge-protective devices (SPDs), a fresh specimen was used for each of the five tests. Other types, such as PCs and programmable logic controllers (PLCs), were not new, but functional used equipment. Used equipment, being limited in number, was treated on a case-by-case basis. The results are described in detail in the next chapter.

This project was not focused on a comparison of brands or manufacturers. Therefore, names and logos were hidden. Instead, the focus was a comparison of technology types. For example, project sponsors were interested in a comparison MOV-based SPDs to hybrid models with MOV and spark gap. In some cases, the technology was unique and could be identified by those knowledgeable in the industry. However, for consistency, this report identifies samples only by technology type and their assigned identification numbers as described in the following sections.

Table 4-1
Test Specimens

Specimen Name	Description	Quantity
SPD1-1 through SPD1-5	Cord-connected SPD (also known as a surge strip) for residential use, very inexpensive variety, Brand A	5
SPD2-1 through SPD2-5	Cord-connected SPD for residential use, very inexpensive variety, Brand B	5
SPD3-1 through SPD3-5	Premium-grade cord-connected SPD for residential/business use, Brand C	5
SPD4-1 through SPD4-5	Unique, large, single 40-mm MOV component for packaging into an SPD product, industrial use	5
SPD5-1 through SPD5-5	Unique, large, single 80-mm MOV component for packaging into an SPD product, industrial use	5
SPD6	Permanently connected SPD for commercial/industrial use	1
SPD7	Permanently connected SPD for commercial/industrial use	3
PC1 through PC5	Used computer and monitor	5
PLC1	PLC - Brand A	1
PLC2	PLC - Brand B	1
PLC3	PLC - Brand C	1
LB1 through LB5	Incandescent lamp, 60-W, 120-V	5

The magnitudes and durations of the overvoltage conditions were chosen based on the five most common TOV scenarios discussed in Chapter 2. They are repeated for convenience in Table 4-2, where they are arranged in order of increasing voltage magnitude, not necessarily the resulting stress. This table shows the order in which the tests were performed.

Table 4-2
Overvoltage Scenarios in Testing Order

Test Number	Imitated Condition	Magnitude	Duration	Test Setup
1	Poor voltage regulation	1.15 PU (138 V)	6 hr	1
2	During a fault	1.3 PU (156 V)	2 sec	2
3	Loss of a secondary neutral	1.5 PU (180 V)	4 hr	2
4	Ferroresonance	2.0 PU (240 V)	1 min	2
5	Contact to high-voltage circuits	3.0 PU (360 V)	1 sec	2

General Procedures for All Tests

For simplicity in record keeping, investigators acquired five test specimens of the same make and model. Specimens were numbered 1 to 5, and each specimen was identified with a number that represented the test to which the specimen would be subjected.

A sinusoidal voltage was applied during all tests. Some but not all of the actual TOV conditions were expected to have sinusoidal waveforms. It was assumed that an irregular waveform, such as that which might be cause by ferroresonance, could be ignored during these tests. The investigators followed the following procedures:

Equipment under test (EUT), also referred to as specimens in this report, are to be kept in a "warm-up" area, where they will run at nominal voltage for at least two hours before each test. Surviving specimens are returned to the warm-up area after a test for observation. It is possible for a specimen to fail shortly after a TOV stress test. Record the times and dates as specimens move to and from the warm-up area.

Another general procedure for all tests is the observation of conditions before and after a failure. If a specimen contains status LEDs, for example, note the state of those LEDs when the specimen is running at nominal voltage. If a specimen fails, note and record the state of any LEDs, error messages, flashes of light, smoke, sounds, and so on. Mark failed specimens and store them in an appropriate place for later failure analysis. Be careful not to lose any information about failed specimens by careless placement or loose record keeping.

Test Procedures

1. Test 1 is a lengthy test and has a very low magnitude. Using engineering judgment, Test 1 can be performed with multiple specimens in the circuit together. Using Test Setup 1 shown in Figure 4-1, connect all specimens identified with number 1 to the test circuit. Run the group

of specimens at nominal voltage for at least 2 hours to stabilize their temperature. If thermal imaging equipment is available, take a "before" snapshot of each specimen before applying the TOV. Apply the TOV magnitude and duration shown in Table 4-2 for Test 1. If a specimen fails, leave it in the circuit until the end of the tests unless the breaker has tripped. If the breaker has tripped, remove the offending load, reset the breaker, and continue testing for the remainder of the test duration. At the end of the period, but before removing TOV, take an "after" snapshot of each EUT with the thermal-imaging equipment.

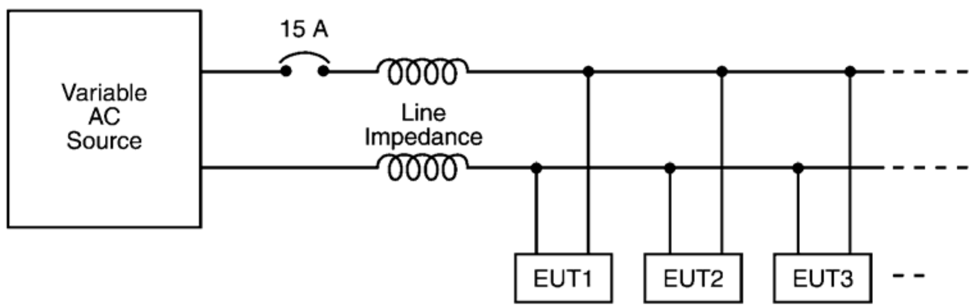


Figure 4-1
Test Setup 1 for Multiple EUTs

At the end of Test 1, without delay, move the specimens to the warm-up area for a 2-hour observation period at nominal voltage. If specimens fail during this period, record observations (including time and date) and remove the offending specimens from the circuit.

2. Test 2 is performed on individual pieces of equipment as shown in Figure 4-2. Apply the magnitude and duration shown in Table 4-2 for Test 2. Record the voltage and current waveforms for the entire event. Return a surviving specimen to the warm-up area for a continued observation period.

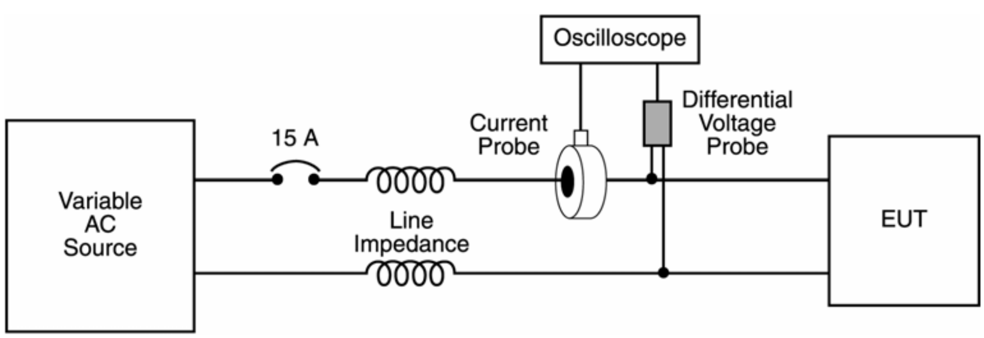


Figure 4-2
Test Setup 2 for a Single EUT

3. From the warm-up area, select the next specimen for Test 3, which is performed on individual pieces of equipment as shown in Test Setup 2 (Figure 4-2). Apply the magnitude and duration shown in Table 4-2 for Test 3. Take a thermal snapshot of the specimen. Apply the TOV and record voltage and current waveforms using an oscilloscope with a time base of approximately 1 s/div. Set the oscilloscope to trigger on line current in order to capture an event in case the specimen fails after the initial sweep. If the specimen fails, remove it from

the circuit and record observations. If the specimen does not fail, take a thermal snapshot at the end of the test period but before removing the overvoltage.

4. From the warm-up area, select the next specimen for Test 4, which is performed on individual pieces of equipment as shown in Figure 4-2. Apply the magnitude and duration shown in Table 4-2 for Test 4. Record the voltage and current waveforms during the entire event.
5. From the warm-up area, select the next specimen for Test 5, which is performed on individual pieces of equipment as shown in Figure 4-2. Apply the magnitude and duration shown in Table 4-2 for Test 5. Record the voltage and current waveforms during the entire event.

Details of EUTs

This section more fully describes the EUTs chosen for laboratory tests. In the case of SPDs (surge-protective devices), not much information exists in the area of temporary overvoltage, so special attention is paid to SPDs in this project. Sponsors also ranked SPDs very high and indicated a preference for the study of several different types of SPDs. For that reason, the project included a range of SPDs from the common surge strip (officially called cord-connected SPD) to the permanently mounted service-entrance type that can be used in commercial or industrial applications.

Cord-Connected SPDs 1, 2, and 3

Within the well-known cord-connected variety of SPD, three models were chosen. Table 4-3 shows details of these three models. SPDs 1 and 2 were purchased at a retail price of approximately $8 each. SPD3 was purchased at a retail price of approximately $35 each. Figure 4-3 shows an example of a cord-connected SPD.

Table 4-3
Details of Cord-Connected SPDs 1, 2, and 3

Sample ID	Figure	Technology	Nominal MOV Voltage	Manufacturer claims
SPD1	4-3 and 4-4	130-V MOVs	195 V (see Note 1)	10 kA 490 joules $25,000 protected equipment guarantee Building wiring fault indicator Catastrophic event protection Fail Safe Mode IEEE let-through rating and UL 1449 compliance Lightning and surge protection Noise filtering Protection working indicator Status indicator LEDs Surge protection TVSS ratings 330 V (L-N) (L-G) (N-G)
SPD2	4-3 and 4-4	130-V MOVs	201 V (see Note 1)	750 joules $25,000 connected equipment warranty TVSS 330 V (L-N) (L-G) (N-G)
SPD3	4-3 and 4-5	multiple MOV paths + inductors and capacitors	231 V 218 V (see Note 2)	140 V RMS clamping 2200 joules/85,000 amps $50,000 ultimate lifetime insurance UL1449 listed - surge suppression (330V let-through), UL1283 listed - EMI protection, UL1363 listed - power tap, CUL approved to Canadian standards Transient suppression voltage 330 V (L-N) (L-G) (N-G)

Note 1 – Measured value at 1 mA DC for an intact MOV taken out of the package.

Note 2 – Complex network of MOVs. Two slightly different values and component markings.

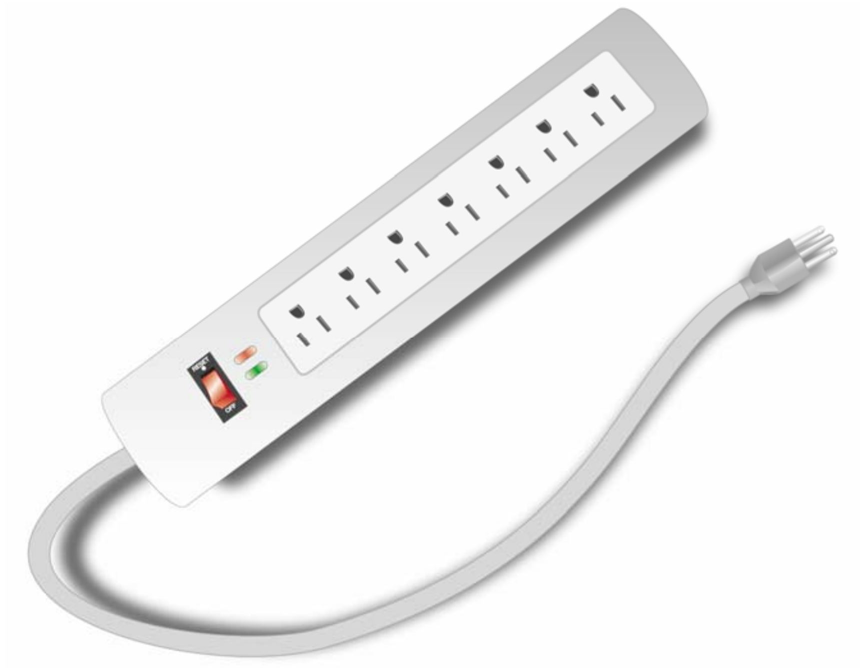


Figure 4-3
Example of a Cord-Connected SPD

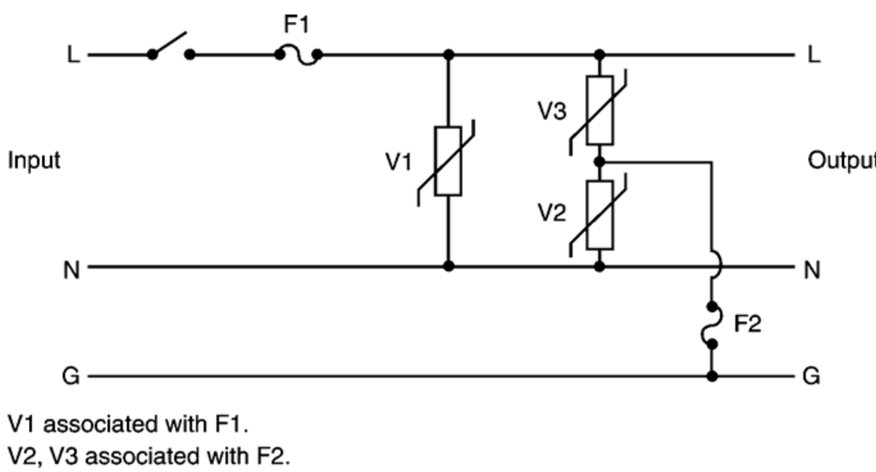


Figure 4-4
Simplified Schematic of SPD1 and SPD2

Note that association of MOVs and fuses simply means that the thermal fuse is physically located on the circuit board so that it has intimate contact with the associated MOV(s). The heat generated by the failing MOV then triggers the heat-responsive fuse to open the circuit. The method of creating intimate contact between the MOVs and fuses varies from manufacturer to manufacturer. Some rely only on proximity of the two components. However, the person or machine responsible for placing the components could unintentionally introduce some variance among products. Others wrap a piece of tape around the MOV and the fuse to help ensure that they are held in contact.

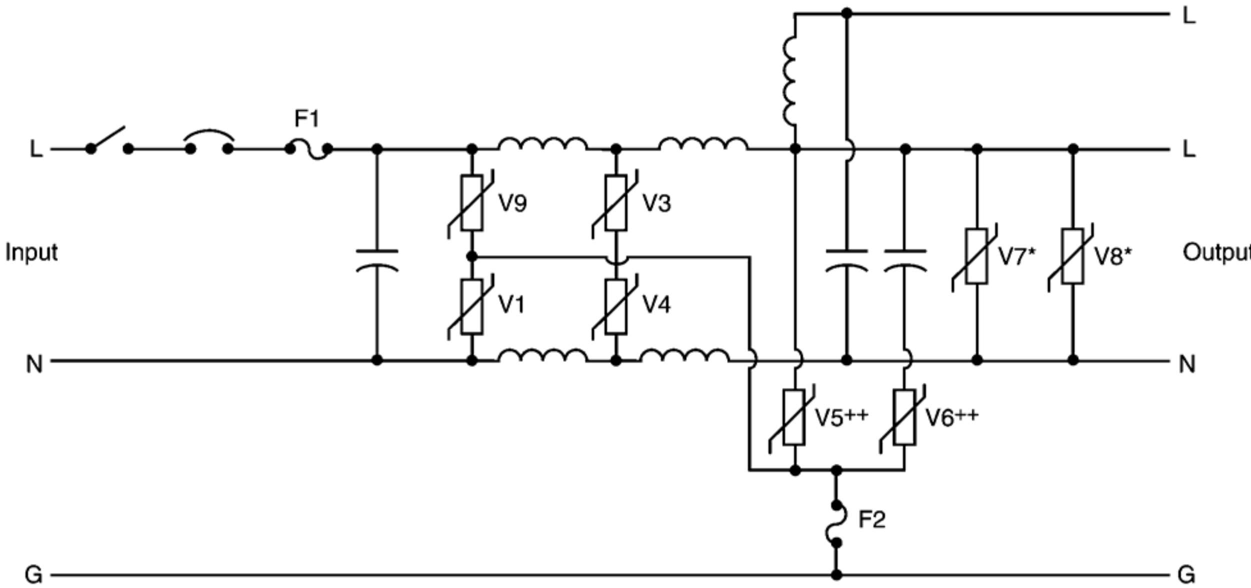


Figure 4-5
Simplified Schematic of SPD3

The astute observer of Figure 4-5 might note that at the output are two terminals labeled L and that these terminals do not represent the same point in the circuit. The two points are connected together internally by an inductor. The output receptacles appear to the end user to be exactly the same point, and no attempt is made by the manufacturer to differentiate them. Therefore, the same philosophy is carried forward to this schematic, which was traced by hand by the investigating engineer.

Permanently Connected SPDs 6 and 7

These SPDs are designed for permanent mounting to a service-entrance panel or a sub-panel. Both are equipped with short pigtails of approximately 12 inches (30.5 cm) for direct connection. Both models were purchased at retail outlets. The price of SPD6 was approximately $500. The price of SPD7 was approximately $100. Details of these models are given in Table 4-4. An example of this type of device is pictured in Figure 4-6.

Table 4-4
Details of Permanently Connected SPDs 6 and 7

Sample ID	Figure	Technology	Nominal MOV Voltage	Manufacturer Claims
SPD6	4-6 and 4-7	Multiple MOV + multiple gas discharge + sine-wave tracking	176 V (see Note 1)	Multiple MOVs with built-in thermal fuses Gas discharge tubes in series with MOVs 100-kA 8/20-μs protection (50 kA per mode) Ideal for sites with poor voltage regulation Thermal protection Over-current fusing UL 1449 Edition 2 listed All modes protected Dual LED status indication per line to monitor the integrity of the internal protection EMI/RFI sine-wave tracking filter Specified in full compliance with NEMA LS1
SPD7	4-6 and 4-8	Multiple MOV + multiple gas discharge	206 V (see Note 1)	Multiple parallel protection circuits Gas discharge tubes in series with MOVs Thermal fusing Catastrophic surge circuit Single-pulse energy dissipation 2700 joules Spike capacity 60 kA (each wire) Line voltage 120/240 1 phase 50/60 Hz Clamping level (TVSS voltage) 400 V Initial clamping level 240 V
Note 1 – Measured value at 1 mA DC for an intact MOV taken out of the package.				

Figure 4-6
Example of a Permanently Connected SPD

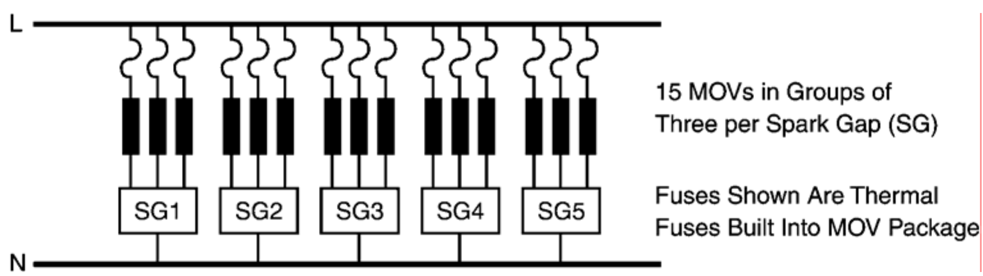


Figure 4-7
Simplified Diagram of the SPD6 Power Circuit (One of Two L-N Circuits Shown)

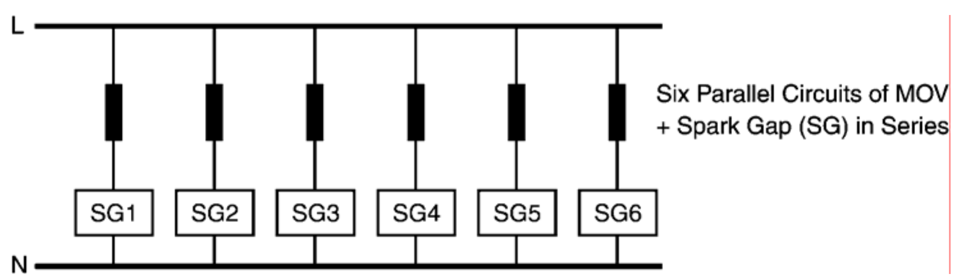


Figure 4-8
Simplified Diagram of the SPD7 Power Circuit (One of Two L-N Circuits Shown)

Component SPDs 4 and 5

The SPD components are not intended for standalone use. They are only the packaged MOV components that are configured for a particular application into an SPD product, which is then installed at the service entrance. These components were donated by the manufacturer for study in this project. Details of these models are given in Table 4-5. Two sizes were tested – 40mm and 80mm.

Table 4-5
Details of Component SPDs 4 and 5

<table>
<tr><th>Sample ID</th><th>Technology</th><th>Nominal MOV Voltage</th><th>Manufacturer Claims</th></tr>
<tr><td>SPD4</td><td>130-V MOV
40-mm dia</td><td>254 V</td><td rowspan="2">Single MOV disc
Heavy aluminum heat sink
Exceptionally high energy-handling capability
100-kA – 8/20 (40 mm)
200-kA – 8/20 (80 mm)
Operation voltage 120 Vrms
MCOV 150 Vrms
Suppressed voltage rating: 400 V (40 mm)
Suppressed voltage rating: 330 V (80 mm)</td></tr>
<tr><td>SPD5</td><td>130-V MOV
80-mm dia</td><td>232 V</td></tr>
<tr><td colspan="4">Notes:

1. Large surge rating capability and TOV immunity are not directly related, so one should not expect that the 80-mm-diameter component would have a greater TOV immunity than the 40-mm-diameter component .

2. TOV immunity depends on the rated maximum operating voltage (MCOV). The higher the MCOV, the less the temperature rise that eventually launched a thermal runaway under TOV conditions.

3. In the case of these components, compared to the classic lead-mounted MOV discs, the large heat-sink design reduces the temperature rise for a given TOV level.</td></tr>
</table>

Other EUTs

Other EUTs included in the tests were desktop personal computers (PCs), programmable logic controllers (PLCs), and 60-W incandescent lamps.

Because of the seemingly infinite number of brands of PCs, because the particular PCs obtained for testing are considered obsolete, and because there is no large technological difference among PC power supplies of this era, no effort was made to maintain information on makes and models. Although the PCs ranged in manufacture dates, all were within the era of the early Pentium microprocessor. All computers were fully functional before testing and were running Microsoft Windows 95 or 98. All PC specimens included used CRT (cathode ray tube) monitors of generally the same era.

Only three PLCs were available for testing, each made by a different manufacturer. All samples appeared to be relatively close to one another in technology and were all purchased new in 2002. None of the manufacturers claimed any special technological advancement that would allow their brand to better withstand power-line disturbances such as a TOV.

Light bulbs were also tested but only to serve as a reality check. The valuable information to be gained is the comparison of their performance—not compared to other brands of light bulbs but compared to other equipment such as SPDs, computers, and PLCs. Five samples of one brand of common-variety incandescent lamps were purchased for these tests.

5

TEST RESULTS SUMMARY

The TOV testing resulted in failures at different levels for different types of equipment. Table 5-1 is a summary of pass/fail results for each device tested. One of the more notable results is the low TOV levels at which the cord-connected SPDs failed, illustrating the fallacy of the market-driven trend toward unnecessarily low "clamping" voltages. These SPDs are the only EUTs to fail during any of the first three tests. They showed to be even more susceptible to TOVs than the incandescent light bulbs.

Incidentally, any failures that occurred as a result of any TOV event lasting one minute or longer did so within the first 5 to 10 seconds of the event. In other words, no failures occurred as a result of a gradual breakdown or heating of a component. One result of this testing is the realization that a study of the long-term effects of TOV on equipment would require a set of tests designed specifically for that purpose.

Table 5-1
Summary of TOV Test Results

Sample Description		Results Summary				
Type	Technology	Test 1	Test 2	Test 3	Test 4	Test 5
		138V 6 hrs	156V 2 sec	180V 4 hrs	240V 1 min	360V 1 sec
SPD - plug strip	130V MOV	ok	ok	fail	fail	fail
SPD - plug strip	130V MOV	ok	ok	fail	fail	fail
SPD - plug strip	multiple 130V MOVs + filtering	ok	ok	fail	fail	fail
SPD - service entrance	single MOV 40 mm	ok	ok	ok	heat, no fail	fail
SPD - service entrance	single MOV 80 mm	ok	ok	ok	heat, no fail	fail
SPD - service entrance	multiple MOV + multiple gas discharge + sine wave tracking	ok	ok	ok	ok	fail
SPD - service entrance	multiple MOV + multiple gas discharge	ok	ok	ok	ok	fail
PLC		ok	ok			fail
PLC		ok		ok		ok
PLC		ok			ok	ok
PC + monitor		ok				
PC + monitor			ok			
PC + monitor				ok		
PC + monitor					fail	
PC + monitor						fail
Incandescent bulb 60W	tungsten	ok	ok	ok	fail	fail

For brevity, not all test results are described in detail, but representative examples are shown. Figure 5-1 shows the voltage and current oscillogram of Test 4 applied to a cord-connected SPD. The top trace is voltage and the bottom trace is current. Notice that the SPD conducted a measurable amount of current as soon as the overvoltage was applied. After only 10 cycles at this level, the MOV was overcome by heat and began to fail short. As the current increased with each cycle, the voltage collapsed proportionately because of the relatively high circuit impedance. After approximately another 5 cycles, the 15-A breaker opened (see Figure 4-2 for the test setup).

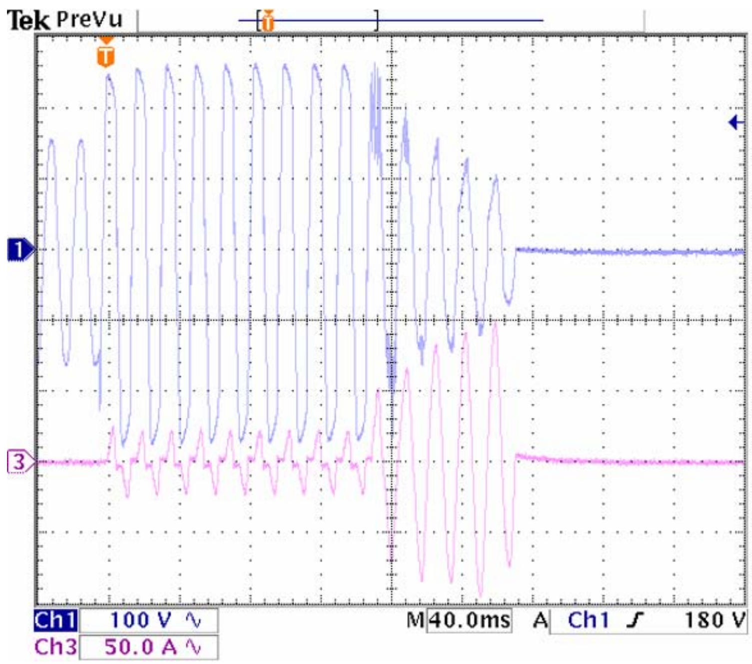


Figure 5-1
Typical Voltage and Current Waveforms of a Cord-Connected SPD During Test 4

Figure 5-2 shows the voltage and current traces for a cord-connected SPD during Test 5. Compared to the waveforms of Figure 5-1, note that this device failed very quickly. Again, the MOV was destroyed by heat when excessive current passed through the MOV. In this case, the MOV failed after only two cycles and tripped the 15-A breaker.

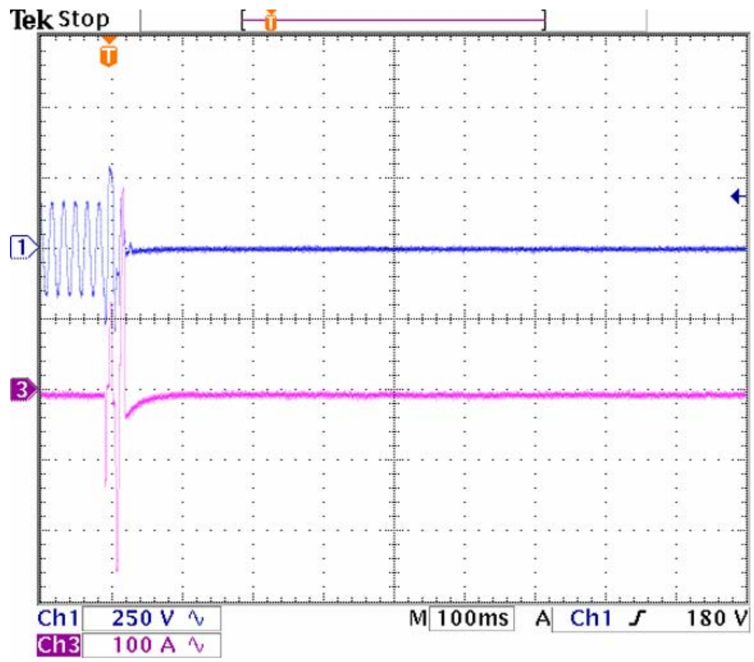


Figure 5-2
Typical Voltage and Current Waveforms of a Cord-Connected SPD During Test 5

Note in Table 5-1 the result of "heat, no fail" for SPD4 and SPD5 during Test 4. This unique response to the TOV events was brought about by the unique construction of these SPDs. During this same test, traditional MOVs were easily overcome by heat when they conducted excessive current (see the previous discussion on the cord-connected SPDs). However, the heat-dissipating design of these two samples gave them the capability to survive the event. Surface temperature was monitored but not recorded during the entire one-minute event. Observers noted the rapid rise of temperature while the TOV was applied. Temperature was still rising until the end of the one-minute test, at which point the highest temperature was recorded as 92.3 degrees C, represented in the thermal image of Figure 5-3 by the white areas. The reflective aluminum surface interfered with the thermal camera's ability to report temperature, but the label on the EUT allowed an accurate measurement of surface temperature. The associated voltage and current oscillograms are shown in Figure 5-4. Note that as soon as the overvoltage ended and nominal voltage was restored, the excessive current ceased. After the specimen cooled to room temperature, a test of nominal varistor voltage was performed. After the investigators compared the result to the one done prior to the TOV test on the specimen, the TOV result was declared "heat, no failure." SPD5, the larger SPD component of the same design, showed nearly identical results.

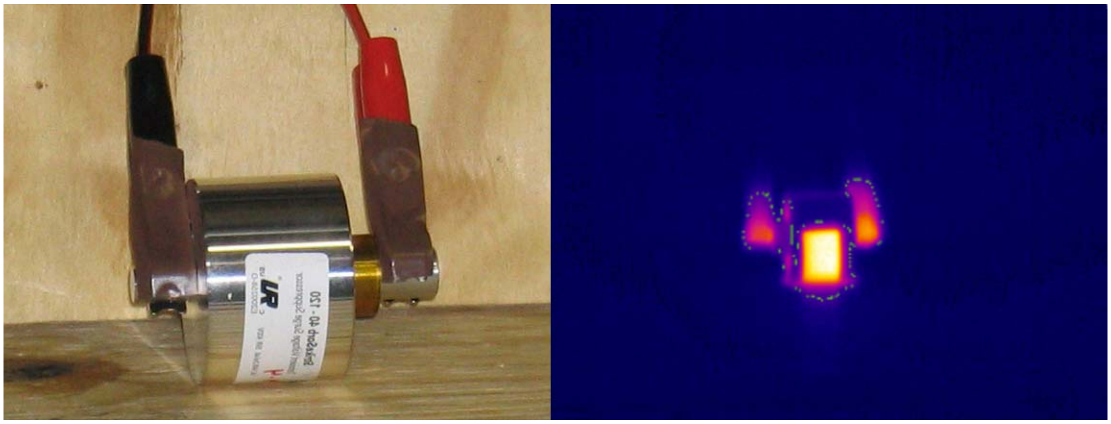


Figure 5-3
Photograph and Thermal Image of SPD4 During Test 4

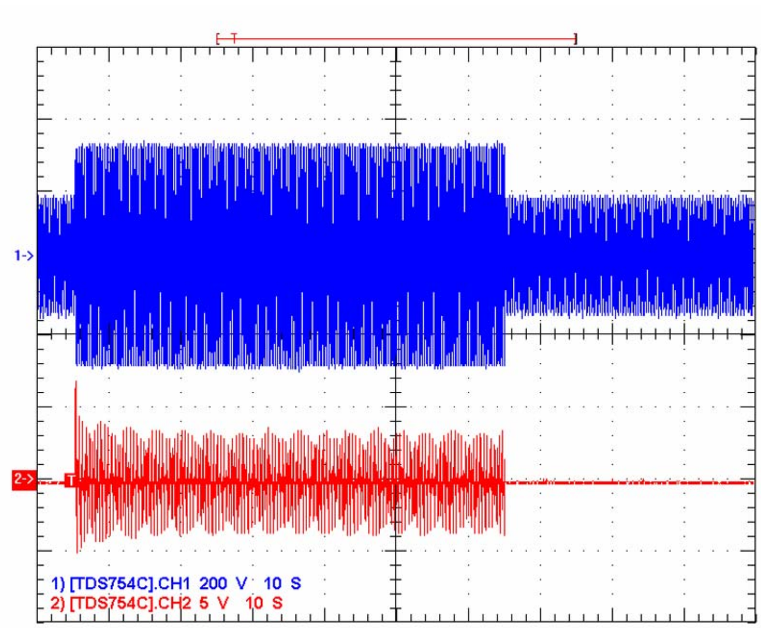


Figure 5-4
Voltage and Current Snapshots of SPD4 during Test 4

The computers and monitors survived the first three tests. The first failure was on Test 4, during which both the computer and monitor failed. A photograph pinpointing the areas of failure is given in Figure 5-5. Test 5 ended similarly, with even less fanfare.

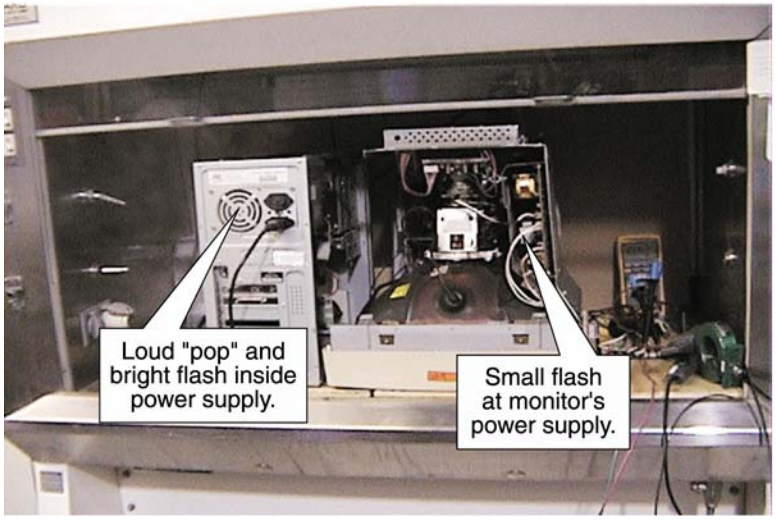


Figure 5-5
Result of Test 4 (240 V for 1 Minute)

More test results are mixed with failure analyses in the next chapter. Much more detail is available on the SPDs because they are not treated merely as loads themselves, but, particularly in the case of cord-connected SPDs, they are designed to protect loads connected to their output terminals.

6
FAILURE ANALYSIS OF SPECIMENS

This chapter offers background and summary information of the test program as well as the detailed postmortem analysis of specimens that failed during TOV tests. The tested equipment is discussed in small groups by category in the following sections.

TOV Effects on Surge-Protective Devices

Among the diverse equipment permanently installed or plug-connected in low-voltage power distribution systems, SPDs have a special position because of the expectation that they perform an effective protective function against surges. However (and unfortunately), because of the common misuse of the word "surge,"[1] some expectations linger that an SPD might also protect equipment against TOVs.[2] The reality is that because of their intended deliberate response to any overvoltage, SPDs are perhaps more likely to be victims rather than protectors when a power distribution system experiences an overvoltage lasting more than microseconds. Therefore, the scope of this project, although limited by available resources, did include some tests on a variety of typical or special SPDs.

Test Specimens and Test Regimen

The specimens selected for the test program included three different categories: two categories classified by UL Std 1449 (the major applicable North American safety standard for low-voltage SPDs—a.k.a. "TVSS"—see Appendix A, Annotated Bibliography) as "Cord Connected" and as "Permanently Connected." A third device, not a packaged SPD but an SPD component, was also included because of its claim of large heat-dissipation capacity, a beneficial side effect of its design aimed at dissipating large depositions of surge energy.

The test regimen applied to the selected SPDs was that defined for the complete program (see Chapter 2, showing five scenarios of increasing stress, representing typical TOV occurrences). In the detailed discussions of results and postmortems, one for each of the three categories of test specimens, the less stressful scenarios that did not produce any noticeable effects are not included.

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[1] IEEE Std 100: "**surge**. A transient wave of current, potential, or power in an electric circuit. *Note:* The use of this term to describe a momentary overvoltage consisting in a mere increase of the mains voltage for several cycles is deprecated. *See also*: swell."

[2] IEEE Std 100: "**temporary overvoltage.** An oscillatory overvoltage, associated with switching or faults … and/or nonlinearities … of relatively long duration, which is undamped or slightly damped."

It must be emphasized that the prime objective of the tests was simply to obtain a description of the behavior of SPDs exposed to real-world TOV occurrences, not to perform exhaustive tests to assess the acceptability of failure modes. There is growing recognition among standards-developing groups that a clear distinction must be made when assessing the results of a stress test: It is permissible to have a device fail, as long as the failure mode is “acceptable” according to some agreed-upon criteria. The difficulty in the industry at this point is to agree on what can be called acceptable in the face of well-documented anecdotes of clearly unacceptable failure modes for some UL-listed SPDs that passed the present standardized tests (see “Black Boxes” in the Appendix A). The results of this project, perhaps augmented by a follow-on program, offer an opportunity to contribute to the improvement of existing SPD standards.

Definitions of Terms Used in Failure Analysis of SPDs

During the failure analysis of SPDs, it became apparent that some descriptive terms were needed to adequately describe the condition of failed MOVs. Of the many components within an EUT that are susceptible to failure by temporary overvoltage, the MOV is capable of disbursing the largest quantity of soot. The term *crispy factor* is introduced as an informal and unscientific term, but one that describes the condition of an MOV by visual inspection. The numeric ranking of crispy factor is shown in Table 6-1.

Table 6-1
Descriptive Terminology Used to Describe Failed MOVs

Crispy Factor	Description	Example
CF3	Large chunks of MOV fall off the circuit board with very little coercion.	Figure 6-1
CF2	MOV flaky over ½ to ¾ of its surface.	Figure 6-2
CF1	MOV has one large hole or split but is still structurally sound.	Figure 2-1
CF0	Not crispy. Structurally sound. Might or might not be covered with soot from nearby MOVs. Appears to be a working MOV.	Figure 6-4

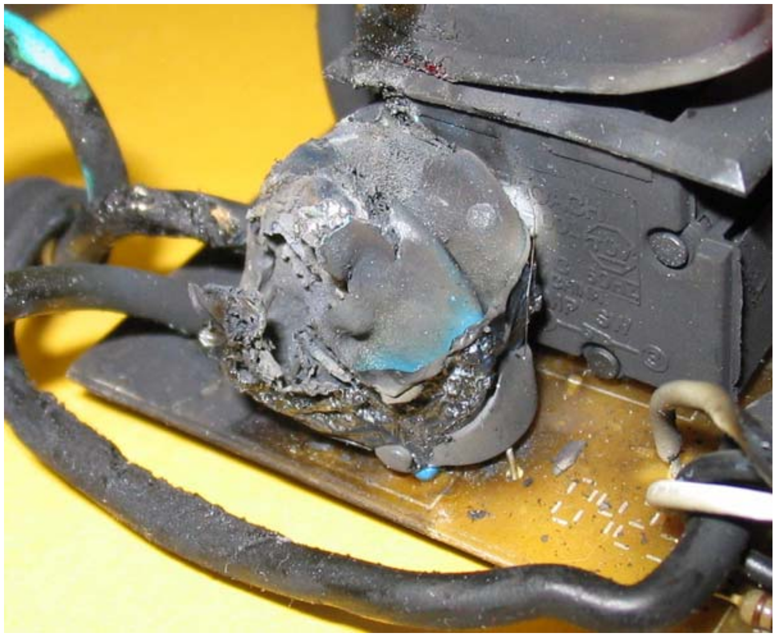

Figure 6-1
Crispy Factor of CF3, Indicating Obliteration

Figure 6-2
Crispy Factor of CF2, Indicating a Flaky Surface and Some Loss of Physical Structure

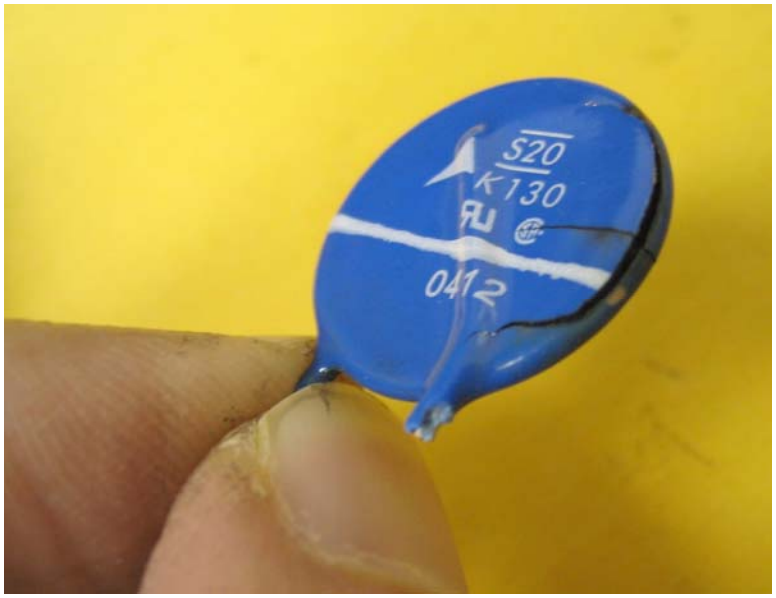

Figure 6-3
Crispy Factor of CF1, Indicating a Single Split or Hole

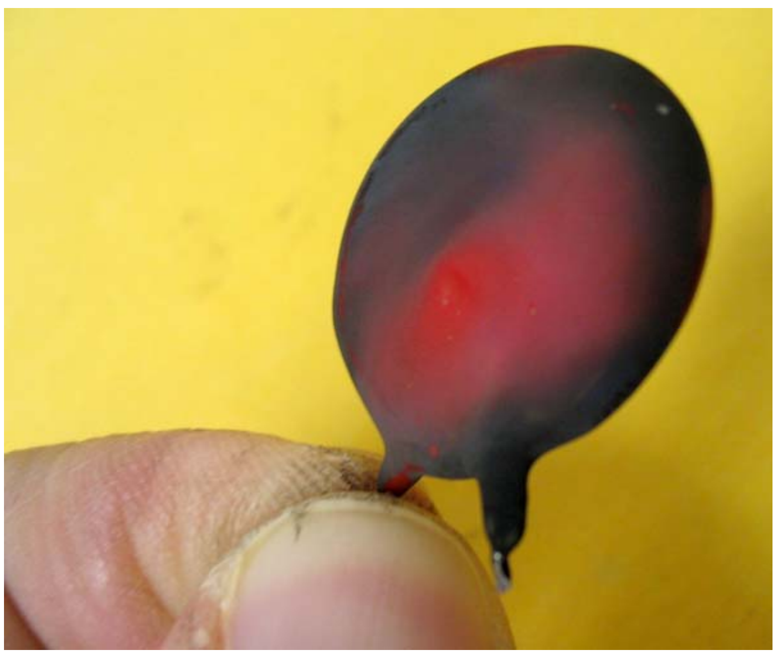

Figure 6-4
Crispy Factor of CF0, Indicating an Intact MOV Even If Covered With Soot From Other MOVs

Effects of TOVs on Cord Connected SPDs

Details of the postmortem analysis of the cord connected SPDs are given in Table 6-2. Each brand offered three modes of protection (line-to-neutral, line-to-ground, and neutral-to-ground). The table gives details of the condition of the MOVs in each of these modes and the condition of the internal fuses. Refer to Figure 4-4 and Figure 4-5for positions of these elements within the circuits.

Table 6-2
Results and Postmortems on Cord-Connected SPDs 1, 2, and 3

Type and Technology		Test 3	Test 4	Test 5
		180 V – 4 Hours	240 V – 1 Minute	360 V – 1 Second
SPD 1 Cord-connected strip	130-V MOV	Fail Load off L-N MOV- CF1, open L-G MOV- CF3, open N-G MOV – CF2, short F1 = open F2 = open	Fail Load still on* L-N MOV CF0, intact L-G MOV CF1, short N-G MOV CF0, intact F1 = intact F2 = open	Fail Load still on* L-N MOV – CF0, intact L-G MOV – CF1, open N-G MOV – CF0, intact F1= intact F2 = open
SPD 2 Cord-connected strip	130-V MOV	Fail Load still on* L-N MOV – CF0, OK L-G MOV – CF3, open N-G MOV- CF3, open F1 = intact F2 = open	Fail Load still on* L-N MOV- CF0, OK L-G MOV- CF2, short N-G MOV- CF2, short F1 = intact F2 = open	Fail Load still on* L-N MOV- CF1, short L-G MOV- CF3, open N-G MOV- CF2, open F1 = intact F2 = open
SPD3 Cord-connected box	multiple MOVs + filtering	Fail Load off L-N MOV7 CF2, short All other MOV- CF0, OK F1 = open F2 = intact	Fail Load off L-N MOV7 CF3, open All other MOV- CF0, OK F1 = open F2 = intact	Fail Load off L-N MOV7 CF3, open L-G MOV5, CF1, short All other MOV- CF0, OK F1 = open F2 = open

* The packages of SPD 1 and 2 failed but did not disconnect the load, leaving it exposed to a second TOV occurrence (or a subsequent surge). Such a failure mode is not recommended for a series-connected (“two-port”) SPD.

Effects of TOVs on Permanently Connected SPDs

Both SPD 6 and SPD 7 survived the “expected possible” occurrences of TOVs as defined by tests 1 through 4. The highly abnormal and rare Test 5 scenario of commingling, as defined by 360 V for a 120-V-rated device, did cause an acceptable internal failure of one of the multiple parallel paths. See Table 6-3 for details. The significance of that performance is that the SPDs emerged with neither loss (albeit somewhat reduced capability) of its primary surge-protective function nor cut-off of the power to the connected loads. Maintaining power to the loads is an implicit requirement for a shunt-connected (“one port”) SPD.

Table 6-3
Results and Postmortems of Permanently Connected SPDs 6 and 7

Type	Technology	Test 5
		360 V – 1 Second
SPD6 permanently connected	multiple MOV + multiple gas discharge + sine-wave tracking	Internal partial failure Acceptable One path with three MOVs + associated spark gap open (see Figure 6-5) Load still on (no provision to open the load) Parallel MOV paths OK (see Figure 6-5)
SPD7 permanently connected	multiple MOV + multiple gas discharge	Internal partial failure Acceptable One MOV short (see Figure 6-5) Load still on (no provision to open load) Parallel MOV paths OK (see Figure 6-6)

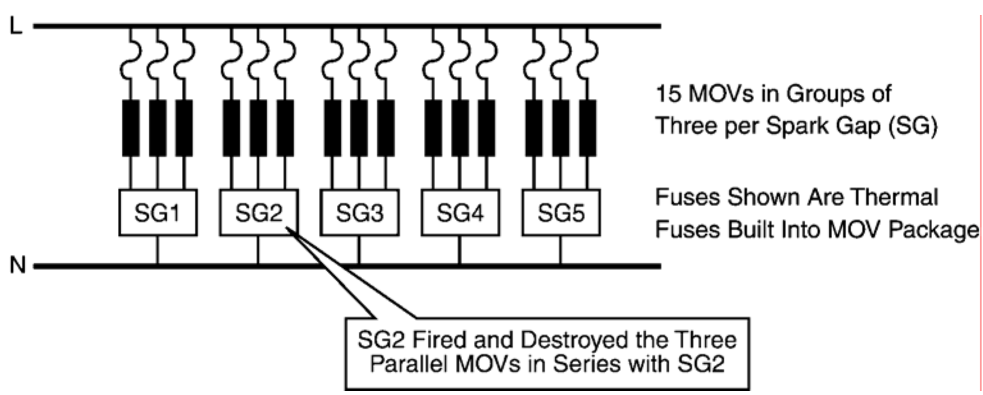

Figure 6-5
Simplified Diagram of the SPD6 Power Circuit (One L-N Circuit Shown)

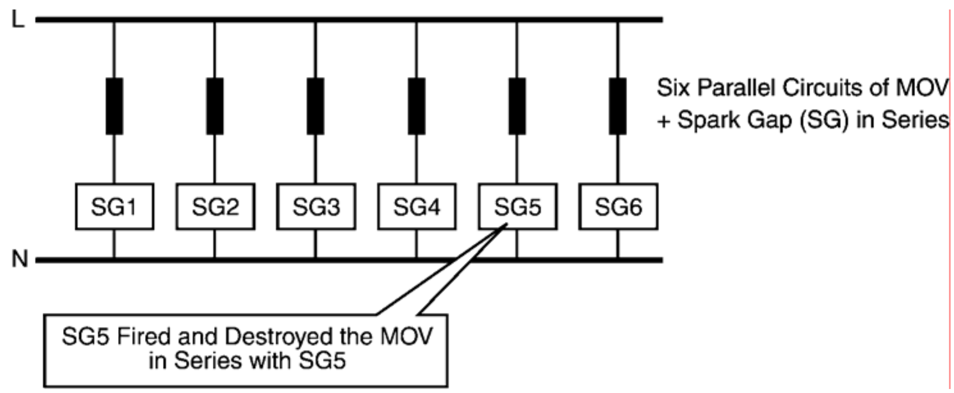

Figure 6-6
Simplified Diagram of the SPD7 Power Circuit (One L-N Circuit Shown)

Effects of TOVs on SPD Components

The special category called SPD components was created for surge protective elements that are intended to be packaged into an SPD product for installation in a low-voltage power distribution system. The high-capacity heat sink proved effective in avoiding a fatal thermal runaway for the stressful Test 4 conditions, although a noticeable temperature rise occurred. Once the SPD is installed in a particular equipment, the heat-dissipation capability of the SPD will be dominated by the environment provided by that equipment.

One of their features is a failure mode especially designed to be a low-impedance short, resulting in rapid operation of an upstream overcurrent-protective device. This protective scheme ensures positive protection of the load against a second occurrence of a fatal surge, as well as effectively disconnecting the load —if it survived at all—for the scenario of Test 5 (accidental contact with a higher-voltage power system, which is likely to be fatal for most residential equipment). See Table 6-4 for details.

Table 6-4
Results and Postmortems of SPDs 4 and 5

Type	Technology	Test 4	Test 5
		240 V – 1 Minute	360 V – 1 Second
SPD4 component	Single MOV 40 mm	Hot Not failed	Fail Acceptable Permanent short
SPD5 component	Single MOV 80 mm	Hot Not failed	Fail Acceptable Permanent short

Effects of TOVs on Computers

The personal computers survived Tests 1, 2, and 3 and are not discussed in detail. The three surviving samples were put aside. Tests 4 and 5 both resulted in failures. In both cases, failures occurred in the computer power supplies and in the monitor power supplies. Table 6-5 gives details of the failure analysis.

Protection fuses built into the power supplies played a role in the survival of these computers and monitors. The higher voltage of Test 5 seemed to produce the more desirable result, in which both the computer and monitor were functional after replacing a fuse. However, this result might be attributable to the particular brand of computer and monitor under test. A much larger sample count is required to make such a determination.

An attempt was made to restore both of the failed PCs to working condition after the power supplies had been removed, diagnosed, and either repaired or replaced. However, neither computer was able to boot when offered a functional power supply. Unfortunately, it cannot be said with any certainty that the computers were damaged during the TOV event because there were cases of human error or other uncertainties that occurred during the failure analysis. This would be a very interesting further study with a higher sample count and special attention paid toward this effort at the onset of the project.

Table 6-5
Results and Postmortems on Personal Computers

Type	Test 4	Test 5
	240 V – 1 Minute	**360 V – 1 Second**
PC	Input fuse open Small MOV failed open See Figure 6-7	Input fuse open. Fuse replaced. Power supply functional with new fuse.
Monitor	Apparent failure, but monitor worked normally when nominal voltage was applied.	Input fuse open. Fuse replaced. Monitor functional with new fuse.

Figure 6-7
MOV Failure Inside the Computer Power Supply of PC4

Effects of TOVs on Programmable Logic Controllers

Because of the robust response of PLCs to the temporary overvoltage tests, there is not much to report in the way of failure analysis. Investigators were pleasantly surprised to see that two out of the three PLCs survived every test, including the unusual Test 5. The sample that failed was found to have blown its input fuse. Additionally, a large resistor found on the DC side of the input rectifier was damaged. See the large, white power resistor in Figure 6-8, which failed open.

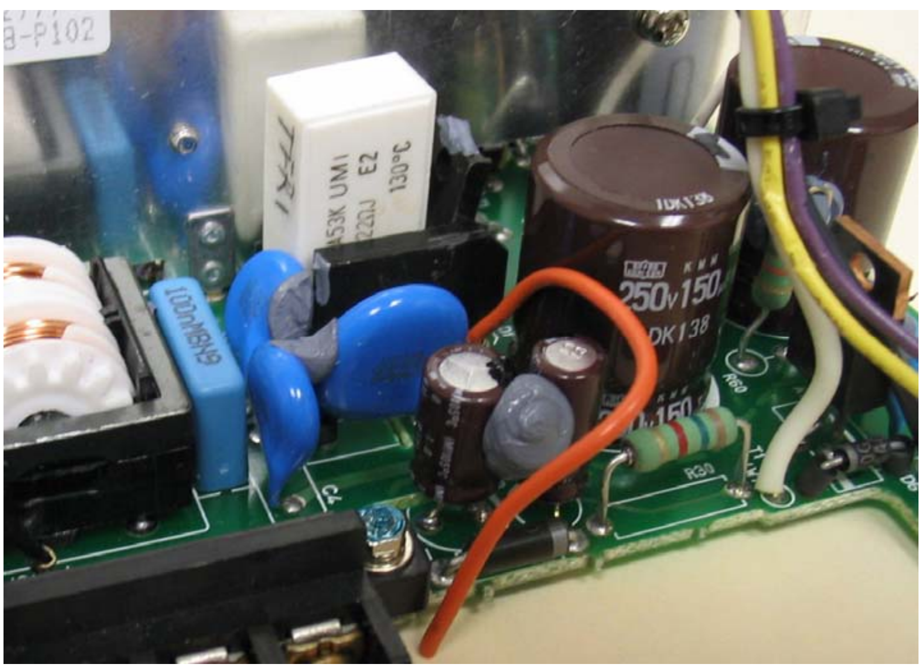

Figure 6-8
PLC1 Power Supply Circuit

As with the personal computers, an interesting study would be to determine whether or not damage during a temporary overvoltage can propagate past the power supply and into the microprocessor. A much higher sample count would be required in order to conduct such a study.

Effects of TOVs on Incandescent Lamps

As a complementary test to the main test regimen, the test schedule included two 120-V, 60-W incandescent lamps, one supplied with the nominal 120-V building supply the other supplied with the test TOV regimen. The two lamps were placed side by side to give the test operator an immediate subjective evidence of the application of the TOV and allow the test operator to note any difference in brilliance during the TOV application, in addition to noting survival or burnout of the lamp. The results are shown in Table 6-6.

Table 6-6
Test Results and Subjective Observations

Test 1	Test 2	Test 3	Test 4	Test 5
138 V – 6 Hours	156 V – 2 Seconds	180 V – 4 Hours	240 V – 1 Minute	360 V – 1 Second
Survives Visibly brighter	Survives Appears as flicker	Survives Visibly quite brighter	Burns out Visibly much brighter	Burns out Just a flash

It is noteworthy that Test 1 and Test 3, emulating conditions that could endure for hours, might give a noticeable indication that something is wrong with the power supply if the occupant were depending on incandescent lighting at the time of the incident. The test results on the other appliances included in the scope of the project also show survival for Test 1 and Test 2. Thus, given the hint that something is unusual, the occupant might have a chance to take corrective action or report the problem to the energy service provider.

The effects on incandescent lamps during Test 2 are likely to be dismissed because evidence of the effects was only a momentary flicker. Furthermore, Test 2 did not cause the immediate failure of appliances included in the scope of the project. However, that does not eliminate the possibility of a “walking wounded” condition for some appliances.

On the other hand, a Test 4 TOV, which as a higher-magnitude but a brief effect, is unlikely to give the occupant any time to take corrective action before both the incandescent lamps in the house burn out and some appliances fail while others might then have reached the state of walking wounded. Nevertheless, the evidence of massive (multiple) incandescent lamp failures would give the occupant a motivation to report the incident to the energy service provider.

The conditions emulated by Test 5 are likely to produce massive failures throughout the residence, as well as adjacent residences, before the occupant has any chance of taking corrective action, so it is most likely that the energy service provider will be the target of immediate complaints.

7 CONCLUSIONS

The information presented in this report gives the reader an understanding of temporary overvoltage events and the damage that can be caused by these events. Typical causes of TOVs include loss of a secondary neutral, overvoltages due to poor regulation, and ferroresonance. The magnitudes of these events range from 1.2 per unit to 2 per unit, with durations ranging from seconds to hours. A rare but potentially catastrophic event is an accidental contact with high-voltage circuits that can produce TOVs in excess of 3 per unit. A review of the data obtained during EPRI power quality monitoring projects shows agreement between the theoretical predictions and the field data. The test regimen applied to the appliances selected for the project included a crescendo of representative stresses associated with these events.

Postmortem analysis of failed specimens revealed interesting and practical points that invite further study. For example, the metal-oxide varistor (MOV), which is designed to protect sensitive electronic equipment from damage due to transients, can itself be the weakest link during a temporary overvoltage.

Laboratory creation of TOV events also revealed that appliances, such as personal computers, with no built-in MOVs were able to survive TOV events better than those appliances that had MOVs installed internally if these MOVs were provided by the PC manufacturer for the function of surge protection but selected with ratings that made them more susceptible to TOV than the other components of the PC power supply. The limited number of specimens and tests allowed by the scope of the project make it risky to draw general conclusions, but failure of PCs and monitors, in two cases, occurred in the computer power supplies and in the monitor power supplies. Looking deeper into the circuitry would be a very interesting further study with a higher sample count and special attention paid toward this effort at the onset of the project.

A note of caution should also focus on the possible disappointment of users when offered a "whole house surge protection" scheme involving service-entrance protection and point-of-use surge-protective devices if these are not correctly selected to perform as expected. The issues are somewhat complex but should not be ignored when offered by a reliable energy service provider. Also see Appendix B for a tutorial on cascaded, coordinated surge protection.

Programmable logic controllers were found to be quite robust, with only one failure observed in the power supply. As with the personal computers, an interesting study would be to determine whether or not damage during a temporary overvoltage can propagate past the power supply and into the microprocessor. A much higher sample count would be required in order to conduct this study.

If this project can be continued to accumulate test data for larger populations, the results will enable electric utilities and insurance companies to develop a knowledge base of power-related failure for classes of equipment. Understanding common failure modes among classes of equipment will also enable manufacturers of end-use equipment and mitigation devices to improve the surge and TOV-withstand capabilities of equipment, resulting in fewer claims of damaged equipment for electric utilities and insurance companies, as well as reduced inconvenience for end users.

8
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- Questions and answers, installation hints.
- 20 pages (*large file takes some time to download*).

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B
SPD CASCADE COORDINATION CONSIDERATIONS

Background

When two or more SPDs are installed in a low-voltage power distribution system, one upstream and the other(s) downstream, this combination is called "cascaded SPDs." During a surge, if each device receives an amount of energy commensurate with its capacity, the cascade is declared "coordinated." The paper "Coordinating Cascaded Surge-Protection Devices: High-Low versus Low- High," cited in Appendix A, Annotated Bibliography, and accessible on line, provides detailed information on the subject, including its pitfalls and limitations.

Considerable attention, and some implementation by energy service providers, has been given to the concept of "whole house surge protection," whereby an SPD with large surge capability is installed at the service entrance to establish overall surge protection of the residence, with additional SPDs connected at the point of use, which might have a lower (less expensive) surge capability but are expected to "finish the job" of surge protection, perhaps by having a low clamping voltage ("suppressed voltage rating, SVR," as defined in UL 1449) that would erroneously be selected lower than that of the service entrance SPD. The paper "Selecting Varistor Clamping Voltage: Lower Is Not Better!," cited in Appendix A and accessible on-line, provides information in support of that aphorism.

Coordinated Cascade Dilemma

When implemented by an energy service provider, this coordinated combination has a chance of being correctly engineered without falling in the trap frequently found when a homeowner would entrust an electrician to install a service-entrance SPD and purchase a point-of-use strip SPD. The service-entrance SPD design, influenced by reliability and ruggedness considerations (and increasingly by recognition of the need to provide TOV immunity), is likely to have a higher maximum continuous operating voltage (MCOV) and SVR than the "lower is better" point-of-use SPD offered by typical electronic stores, where marketing considerations among SPD suppliers prevails.

In the latter case of a homeowner selecting the downstream SPD while uninformed about the issues, coordination might be an illusion rather than a reality, with the "lower bidder" downstream SPD absorbing most of the surge energy. This means that the upstream SPD remains passive: not only a waste of resources but also a possible problem of inviting the large surge currents to flow deep into the power distribution system, where they can cause interactions with adjacent circuits, defeating one of benefits of whole-house surge protection.

Based upon the very encouraging results of the TOV response of SPD6 and SPD7 demonstrated by this report, exuberant enthusiasm might encourage selection of such TOV-immune SPDs by energy service providers promoting whole-house surge protection. Indeed, the idea has merit, as demonstrated by the paper "Gapped Arresters Revisited: A Solution to Cascade Coordination," cited in Appendix A and accessible on line. That paper reports experiments conducted at EPRI PEAC Corporation in the mid-nineties, and it is possible that these considerations influenced the offering of SPDs such as the two SPDS 6 and 7 devices included in this project.

This series gap-MOV combination that achieved the remarkable TOV immunity (but at the price of a higher SVR) as demonstrated in this project has the potential problem of lost surge coordination if a low SVR device is installed downstream. Therefore, the exuberance should be tempered by carefully assessing the reality of effective cascade coordination through exhaustive testing under a variety of real-world surge scenarios.

Emerging Solutions

Two kinds of SPS are emerging in the market that might offer a workable solution to these potential problems and eliminate the risk of unfulfilled expectations. First, there are now available permanently connected SPDs, where the simple gas-discharge gap of SPDs 6 and 7 is replaced by a semiconductor that is turned on in response to a fast-rising surge but is not turned on by a slow-rising TOV. Second, there are also available point-of-use SPDs that include a disconnecting function, which protects not only the SPD itself but also the downstream loads, and is manually or automatically reset after the disturbance. Both of these emerging improvements could be the object of an assessment performed under the sponsorship of EPRI members to ensure both objectives of TOV immunity and effective cascaded SPD coordination in a carefully engineered "whole house surge protection" program.

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