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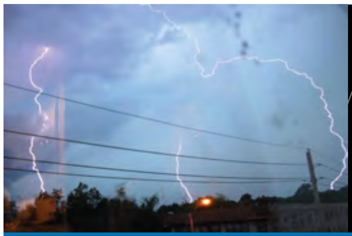

Protecting Against Surges and Temporary Overvoltages

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Contents

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EXECUTIVE SUMMARY

The electrical grid plays host to an array of electrical disturbances. Overvoltages impinging upon residential, commercial, and industrial facilities are some of the most threatening types. The two main types of overvoltages are surges and temporary overvoltages (TOVs). The category *surge* has several subcategories, such as ring-wave surges (typically generated within industrial facilities) and impulsive surges (mostly associated with lightning). Ring-wave surges typically do not cause damage to equipment fuses and other protective devices, but they have been known to cause equipment to malfunction. The impulsive surge, on the other hand, often damages components in end-use equipment.

According to interpretation of guidance provided by the Institute of Electrical and Electronics Engineers (IEEE), a TOV is equivalent to a "voltage swell" and is defined as: "An increase in rms voltage or current at the power frequency for durations from 0.5 cycles to 1 min. Typical values are 1.1 - 1.8. p.u. [per unit]."[1,2] Because TOVs have protracted durations, the TOV failure mode of protective devices such as metal-oxide varistors (MOVs) is different from a surge-related failure mode. Designers of surge-protective devices may possibly omit consideration for TOV failure modes from their designs.

MOVs are the most common front-end protective elements of most electronic appliances and equipment. When the voltage at the terminals of an MOV reaches the MOV's clamping voltage, its resistance suddenly decreases, limiting the voltage and dissipating the increased energy by shedding heat as the current through it spikes. This clamping action is designed to dissipate the energy that results from a *surge* voltage, and not necessarily from the energy imparted from a TOV. Because surges are brief compared to TOVs, the total surge energy is small and easily shed, whereas a protracted TOV can cause an MOV to enter into thermal runaway and fail catastrophically. Nevertheless, proper coordination of line fuses and MOVs may prevent equipment failure resulting from shorter-duration and lower-magnitude TOVs.

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The EPRI Power Quality Knowledge program provides a wealth of resources in well-designed, readable, and accessible formats. Paramount among these are documents covering a wide range of PQ topics, written not only for use by busy PQ professionals, but also to be shared with important end-use customers and internal utility management. The program's website, http://mypq.epri.com/, is the most comprehensive electronic PQ resource available, providing 24-7 access to proven expertise via the PQ Hotline, hundreds of PQ case studies, over 200 PQ technical documents, PQ standards references, indexes, conference presentations, and a wealth of other resources.

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WHAT IS A SURGE VERSUS A TEMPORARY OVERVOLTAGE?

Because temporary overvoltages (TOVs) and surges are both types of overvoltages that can damage equipment, novice equipment designers—who are just becoming familiar with the different types of overvoltages in the areas of power quality and system compatibility—may confuse a TOV with a surge. Because of this confusion, some putative definitions are in order. To distinguish the differences, consider the industry standard definitions developed by the IEEE for both surges and TOVs.

Definitions of Surge

Because surges are the result of natural and man-made electrical phenomena and are present on different types of power and signal circuits in the electrical environment, the word *surge* is defined in various IEEE surge-related standards as the term applies to specific electrical environments and/or equipment. Examples of these standards include those under the auspices of the IEEE Power Engineering Society (PES), namely IEEE Standard 100-2000, *The Authoritative Dictionary of IEEE Standards Terms*; IEEE Standard 1250-2011 (R2002), *IEEE Guide for Service to Equipment Sensitive to Momentary Voltage Disturbances*; and several of the IEEE C62 standards (including the recently revised *Trilogy*, which is sponsored by the Surge Protective Devices [SPD] Committee). The C62 *Trilogy* includes three documents:

- IEEE Standard C62.41.1-2002, *IEEE Guide on the Surge Environment in Low-Voltage (1000 V and Less) AC Power Circuits*
- IEEE Standard C62.41.2-2002, *IEEE Recommended Practice on Characterization of Surges in Low-Voltage (1000 V and Less) AC Power Circuits*
- IEEE Standard C62.45-2002, *IEEE Recommended Practice on Surge Testing for Equipment Connected to Low-Voltage (1000 V and Less) AC Power Circuits*

IEEE Standard C62.41.1-2002 is the document that provides the best comprehensive technical definition and description of surges and TOVs. According to that document, the word *surge* has the following definition:

- Definition 1: "A transient wave of current, potential, or power in an electric circuit. NOTE: The use of this term to describe a momentary overvoltage consisting of a mere increase of the mains voltage for several cycles is deprecated."

According to IEEE Standard 100-2000, the word *surge* has the following definitions:

- Definition 2: "A transient voltage or current, which usually rises rapidly to a peak value and then falls more slowly to zero, occurring in electrical equipment or networks in service."
- Definition 3: "A transient wave of voltage or current. (The duration of a surge is not tightly specified, but it is usually less than a few milliseconds.)"
- Definition 4: "A transient wave of current, potential, or power in an electronic circuit."

Each of these definitions of the word *surge* was developed by the IEEE PES during various standards-development activities. Definition 2 was developed for power-systems instrumentation and measurements. Here, surges that occur on the power system can affect instrumentation and measurement equipment used in the power system. Definition 3 was developed for transmission and distribution systems and applications of surge-protective devices (SPDs). The previously mentioned IEEE 1250-1995 (R2002) also adopted this definition with reference to upsetting equipment sensitive to voltage disturbances. Definition 4 was also developed for applications to SPDs. Definition 4 is the more recent definition of the word *surge* as developed by the IEEE SPD Committee within

A surge is a rapidly rising current, voltage, and/or power transient that can occur in the power system, in electrical networks, and even within equipment.

Although their magnitudes are lower than surge magnitudes, temporary overvoltages last much longer, with a duration ranging from seconds to minutes.

C62.41 and is most widely applied to end-use equipment. This definition defines a surge as a transient wave that can be a current, a potential, or a power wave. It is also described as a subcycle overvoltage event with a duration of less than one-half cycle (8.33 milliseconds for 60-hertz systems and 10 milliseconds for 50-hertz systems).

Reviewing each of these definitions, one can see that (1) a surge is technically described as a rapidly rising current, voltage, and/or power transient (a short-lived disturbance) of positive or negative polarity, and (2) a surge may occur in the power system, in electrical networks (such as facility power systems), and within equipment (such as end-use devices).

Definitions of Temporary Overvoltage

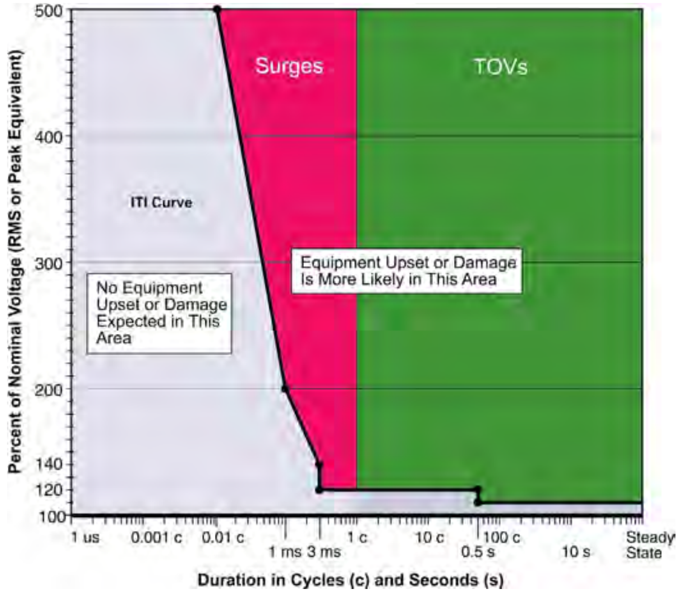
A temporary overvoltage is best defined in IEEE Standard 100-2000 and in IEEE Standard C62.41.1-2002. According to 100-2000, a TOV is defined as:

- Definition 1: "An oscillatory phase-to-ground or phase-to-phase overvoltage that is at a given location of relatively long duration (seconds, even minutes) and that is undamped or only weakly damped. Temporary overvoltages usually originate from switching operations or faults (for example, load rejection, single-phase fault, fault on a high-resistance grounded or ungrounded system) or from nonlinearities (ferroresonance effects, harmonics), or both. They are characterized by the amplitude, the oscillation frequencies, the total duration, or the decrement."
- Definition 2: "An oscillatory overvoltage, associated with switching or faults (for example, load rejection, single-phase faults) and/or nonlinearities (ferroresonance effects, harmonics), of relatively long duration, which is undamped or slightly damped."

According to definitions in IEEE C62.41.1-2002, surges are transients of positive and/or negative polarity with a duration of less than one-half cycle (a few microseconds to a few milliseconds), and TOVs are positive-polarity events of long-term duration ranging from seconds to minutes. For simplicity, consider the dividing line between a surge and a TOV to be one cycle, shown in the figure at the top of the next page. Surges incident upon end-use equipment (either through the AC power input or through communication or network cables) can damage, upset, or have no effect on equipment, according to the magnitude and duration. TOVs affect only the AC power input of equipment and typically cause damage to equipment.

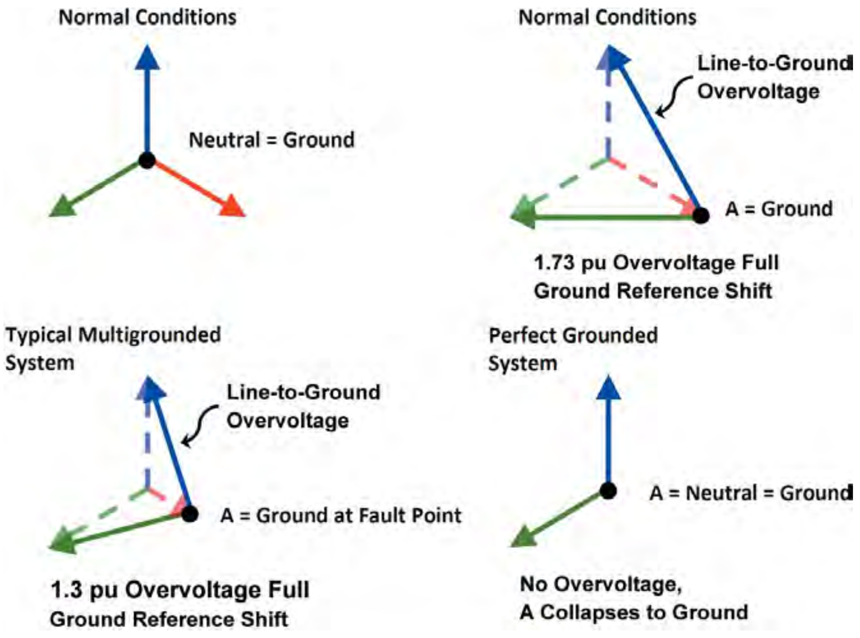
Typically, surges reach much higher magnitudes (in the voltage range of a few thousand volts). TOVs reach much lower magnitudes in the overvoltage range—typically within a few hundred percent of the line voltage—with the events of higher magnitudes being of shorter duration than the lower-magnitude events, but often with much higher energy effect than surges. However, exceptions to this "lower voltage" rule have been documented, especially when a distribution circuit contacts a transmission circuit (discussed later). Currently published by Technical Committee 3 (TC3) of the Information Technology Industry Council (ITIC), the ITI Curve is shown as a guide to manufacturers to design information technology (IT) equipment to withstand surges that occur to the left of and below the curve in the magnitude-versus-duration graph on the following page.

Magnitude-vs.-Duration Graph



A magnitude-versus-duration graph for both surges and TOVs reveals the basic relationship between the level of an overvoltage, its duration, and potential for equipment upset and damage.

A Shift in Ground Reference Caused by Line-to-Ground Faults



A single line-to-ground fault shifts the ground potential at the fault location depending on the grounding configuration.

CAUSES AND CHARACTERISTICS OF TEMPORARY OVERVOLTAGE

The five most common causes of TOVs on the electric power system are faults, loss of a secondary neutral, ferroresonance, poor voltage regulation, and accidental contact between a high-voltage transmission circuit and a distribution circuit.

Line-to-Ground Faults

The grounding configuration of an electrical system constrains the types and levels of overvoltages that can occur during a line-to-ground fault. A single line-to-ground fault may shift the ground potential at the fault location. The severity of a shift in ground reference depends on the grounding configuration, as shown in the figure at bottom left. On a solidly grounded system with a good return path to the grounding source (*Perfect Grounded System* in the figure), practically no reference shift occurs. On an ungrounded system (*Normal Conditions* on the right side of the figure), a full offset may occur—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.

In some cases, a 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 more common, systems are often designed specifically for that type of fault.

IEEE suggests overvoltage multiplier factors for determining the maximum overvoltage one can expect on an unfaulted phase from line to ground. The table on the following page shows the overvoltage factors for different ground configurations. These factors can be used to size surge-protective equipment. For example, for an ungrounded system that typically has a voltage of 1.05% of nominal, surge-protective equipment should be sized at 1.05 x 1.82 = 1.91% of the

TOVs are typically caused by faults, loss of a secondary neutral, ferroresonance, poor voltage regulation, and accidental contact between a high-voltage transmission circuit and a distribution circuit.

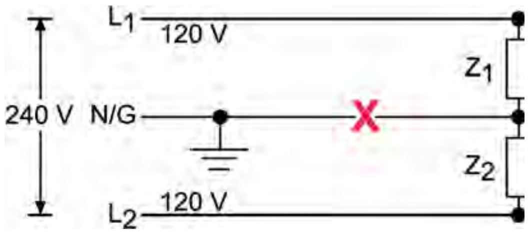
nominal voltage. This calculation accounts for the maximum overvoltage that can be expected during a line-to-ground fault on an adjacent feeder.

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

Overvoltage Factors Based on Different Grounding Configurations

Type of Ground Configuration	Overvoltage Factor
Ungrounded	1.82
Four-Wire Multigrounded (Spacer Cable)	1.50
Three- or Four-Wire Ungrounded (Open Wire)	1.40
Four-Wire Multigrounded (Open-Wire Gapped)	1.25
Four-Wire Multigrounded (Open-Wire Metal-Oxide Arrester)	1.35

A Broken Neutral at a Residential Service



A voltage divider with an open neutral causes an overvoltage on the leg with lighter loading.

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.

With a broken neutral on a 120/240-V service to a residence, the voltage on the neutral conductor can float. The overvoltage is a function of the load imbalance between the two 120-V legs, as shown in the figure at bottom left (note the broken neutral represented by a red X). The leg with lighter loading will have higher voltage, and the leg with heavier loading will have lower voltage.

In the case of a broken neutral, which is a worst-case scenario, the voltage on the lightly loaded leg can reach nearly 240 volts. Under most circumstances, even if the neutral is broken, the earth should form a connection from the earth-to-neutral bond at the service entrance back to the transformer's neutral through the pole ground. 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.[1] This most commonly happens

Faults caused by the contact between transmission and distribution circuits can expose distribution equipment and customer equipment to extremely high voltages.

on cable-fed transformers because of the high capacitance of the cables. The transformer connection is also critical for ferroresonance. An ungrounded primary connection leads to the highest magnitude of ferroresonance. Due to ferroresonance in this condition, utilities 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.[2]

Poor Voltage Regulation

Occasionally, overvoltages occur because of problems with voltage regulation. Some scenarios that could cause overvoltages include:

- Utility voltage regulator installed or set incorrectly.
- Malfunctioning voltage regulator.
- Capacitor-bank controllers with an incorrect clock setting.
- Malfunctioning capacitor-bank controller.
- Sudden loss of load.

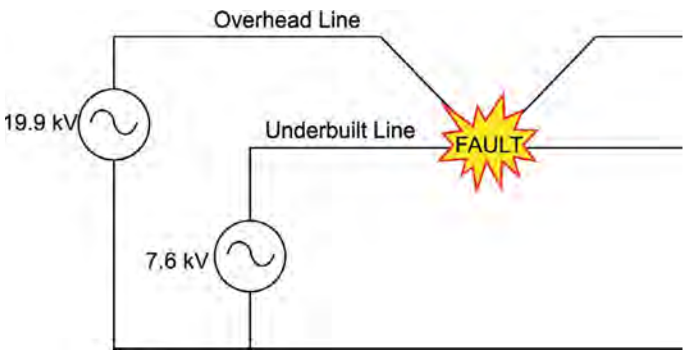
Regarding capacitor banks, if one or more capacitors are switched on at light load, the capacitors can push the voltage above normal. Regarding a sudden loss of load, if a recloser is downstream of a regulator and the recloser trips, the remaining customers may have high voltage until the regulator adjusts its taps to compensate.

Contact Between a High-Voltage Transmission Circuit and a Distribution Circuit

Faults caused by the contact between transmission and distribution circuits are another hazard that can expose distribution equipment and customer equipment to extremely high voltages. Consider the example of a fault from a subtransmission circuit to a distribution circuit, shown in the figure at bottom left. If a distribution interrupter opens the circuit, the voltage on the faulted distribution conductor jumps to the full transmission-line voltage until the substation breaker opens or the line burns in two. The distribution interrupter, either a circuit breaker or recloser, may not be able to clear the fault and may fail trying, but if it does open the circuit, the recovery voltage on part of the faulted distribution line will be many times the normal voltage. With such an overvoltage propagated to utility customers, damage to end-use equipment can be expected.

Faults further from the distribution substation cause higher voltages on faulted distribution lines, with the highest voltage at the fault location. Current flowing back toward the substation causes a voltage rise along the circuit. 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. When a 19.92-kV transmission line contacts a 7.62-kV distribution line, the maximum voltage on the 7.62-kV phase is 2.61 times the normal voltage without the dampening effect of arresters. Arresters can reduce the peak voltage, but customer circuits may still experience a substantially high voltage.

A Fault Caused by the Crossing of Transmission and Distribution Lines



If a distribution interrupter opens a circuit during a transmission-line cross, the voltage on one part of the faulted distribution conductor jumps to the full transmission-line voltage.

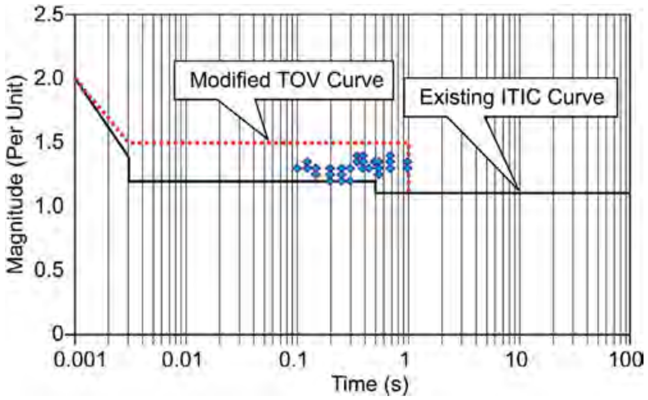
According to two extensive EPRI studies, most recorded TOV events were large enough and lasted long enough to damage equipment or cause a malfunction.

DEFINING IMMUNITY

According to two extensive EPRI studies of electrical disturbances (Distribution Power Quality I and DPQ II), most TOV events are above the upper boundary of the ITI Curve (shown in the first figure of this *TechWatch*), indicating that they may damage equipment or cause a malfunction.[3] The ITI Curve and data from the two EPRI studies could be used in establishing an immunity guideline for protecting equipment against not just transient overvoltages but TOVs as well.

The International Electrotechnical Commission (IEC) standard 62040-1-3 has an upper boundary that depends on equipment type. For example, the IEC requires that an uninterruptible power supply (UPS) be immune to TOV events up to 1.5 per unit lasting less than one second. The 1.5 per-unit boundary corresponds to the findings of the EPRI DPQ projects (note that these projects were conducted in North America, which has a completely different power system than is found in Europe). Based on the IEC UPS immunity limits for TOVs, a design curve can be established by modifying the existing ITI Curve to conform to the IEC curve, which urges manufacturers to increase equipment immunity to overvoltages, as shown in the figure below. The figure also shows several overvoltages measured during the DPQ I and DPQ II projects that are now within the suggested tolerance curve for UPSs.

A More Robust Design Curve Based on Existing Overvoltage Data, the ITI Curve, and the IEC 62040-1-3 Standard



A modified voltage-tolerance curve that envelopes more TOVs may encourage manufacturers to build products with higher overvoltage immunity.

The modified curve does not include left-branching TOVs (voltages higher than 2 per unit and lasting less than 1 millisecond) and right-branching TOVs (voltages lower than 1.2 per unit and lasting more than 100 seconds). This is because it is not practical to build equipment to withstand the type of voltages that are seen when commingling of circuits occur, nor is it practical to be able to build equipment to withstand a sustained ferroresonance condition. Fortunately, these events are rare. However, in the case where the magnitude is large and/or the overvoltage lasts more than 1 second, protection against such an overvoltage is typically performed by sacrificial components—usually some type of surge-protection device that automatically disconnects the load from the circuit and may perish in the process, requiring the device to be replaced.

ARRESTERS USED FOR LINE-SIDE PROTECTION

Very little can be done on the line side to protect against excessive temporary overvoltages caused by commingling of lines during storms or auto accidents that knock down a pole. However, over the years, a number of engineers have experimented with the application of station-class lightning arresters for protection against temporary overvoltages.

Normally, an arrester is used for transient-voltage protection due to lightning events and static discharges. However, due to the amount of energy associated with a temporary overvoltage, arresters are quick to fail. When an arrester fails, an arc forms between it and the lines, forming a low-impedance shunt until the circuit is cleared. An arrester with a disconnect can be used without seriously jeopardizing the normal performance against lightning.

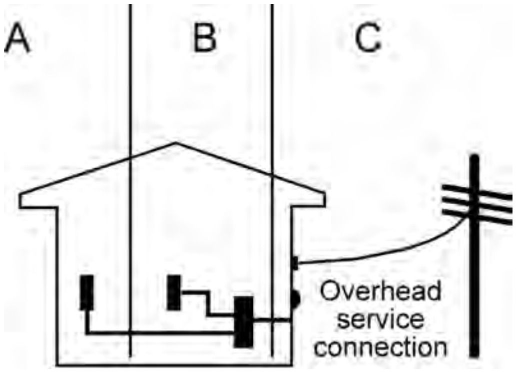
Constant-voltage transformers and uninterruptible power supplies have been used successfully to protect equipment against TOVs.

A better approach in this scheme is the use of two arresters at different voltage ratings, which increases the reliability of TOV suppression during a temporary commingling of lines. It is likely that the lower-voltage arrester will be sacrificed in the process, but the arrester is inexpensive when compared to the damage that a TOV can cause along the influenced line. Although an arrester may be an inexpensive solution, it is not a bullet-proof solution because end-user equipment still needs to be robust to ensure survival during high-energy transients and temporary overvoltages.

PROTECTION OF EQUIPMENT

Effectively protecting equipment from surges and TOVs requires a consideration of many factors, such as the surge environment within a building, physical limitations of the protective devices, front circuit components such as diodes and capacitors, and requirements for an acceptable (nondangerous) mode of failure when a protective device succumbs to a transient or TOV. The first step to ensure robustness is to address the energy-handling ability of metal-oxide varistors (MOVs) and understand the surge environment.

IEEE C62.41 Location Categories



Users and designers of SPDs use IEEE C62.41 location categories to specify stress levels according to the expected electrical environment.

There are several types of devices that are available to protect equipment against TOVs, such as constant-voltage transformers (CVTs) and uninterruptible power supplies. However, these devices are not used by the public in general. Although the average homeowner may use a UPS to protect a computer, other household appliances containing electronic controls must rely only upon built-in protection.

The following sections discuss the surge environments that equipment should be designed to withstand.

IEEE C62.41 Environment Description Versus Specification

The IEEE C62.41 guide on surges, initially published in 1980, has been updated several times. The intent of the guide is to describe the surge environment. IEEE C62.41.1 and its predecessors emphasize that the specification of an SPD stress level is the prerogative and obligation of electricity users. Nevertheless, some readers have misconstrued the guide as a product specification for SPDs, and some manufacturers of SPDs claim that their products conform to the “specifications” in IEEE C.62.41, despite the declared intent of the document to provide only a description.

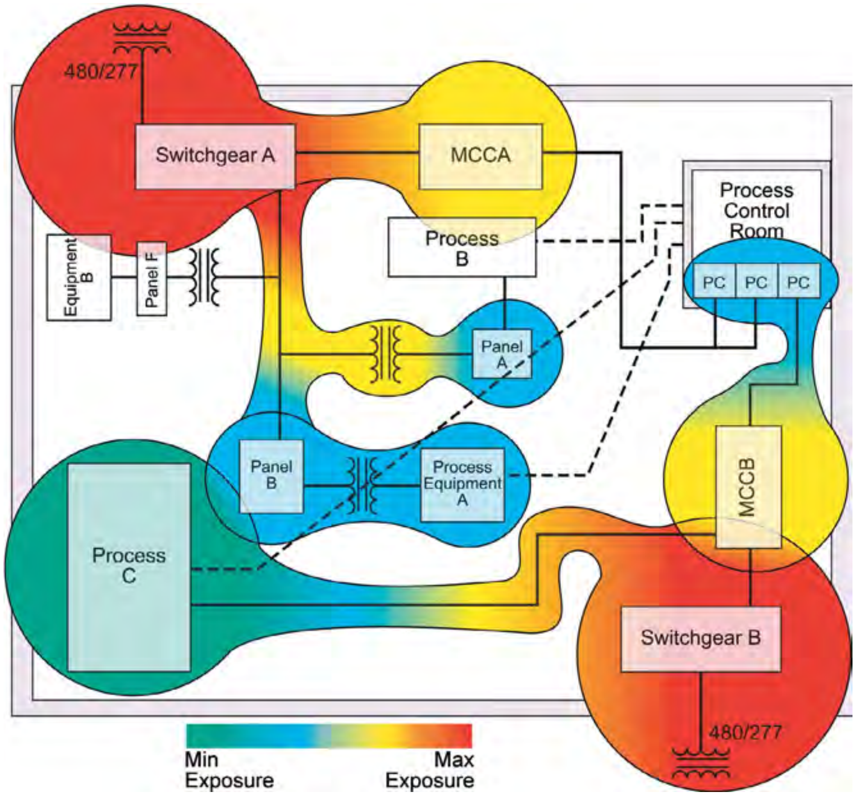
Users and designers of SPDs have used the IEEE C62.41 “stress levels” to specify an SPD according to the three location categories shown in the figure to the left, labeled A, B, and C. Location category A, which is the location of individual equipment, represents the lowest stress level. Location category C, which is at the service entrance, represents the highest stress level. Location category B is at the subpanel and circuit level.

In addition to the IEEE location categories, the threat from a surge coupled onto a distribution line within a building varies by electrical location, constituting different surge environments within a single facility. The figure on the following page shows such a facility and the various levels of threat. Typically, the most

The threat of damage caused by surges varies significantly in a single facility, with the greatest threat at the connection to the utility distribution system.

severe threat is located at facility distribution transformers and switchgear, with a moderate threat posed to motor-control centers (MCCs) and subpanels and a reduced risk at process equipment. Typically, the closer you get to end-user equipment, the lower the risk of damage caused by surges. This complexity illustrates the difficulty of selecting the right stress levels for SPDs—it is not as simple as choosing a single stress level for all locations within a facility. For example, selecting a moderate stress level would be underrating an SPD that is installed in a location with the highest surge threat but would be overrating an SPD that is installed in a location with the lowest surge threat.

Threat of Damage Varying by Electrical Location



The threat of damage caused by surges coupled onto a distribution line varies by electrical location within a single facility.

The level of stress that an SPD is likely to encounter varies not only within a structure—as indicated by the IEEE location categories—but also by geographic location. For example, Florida and New Mexico have very high lightning-flash densities, whereas the Western seaboard of North America has a much lower flash density.

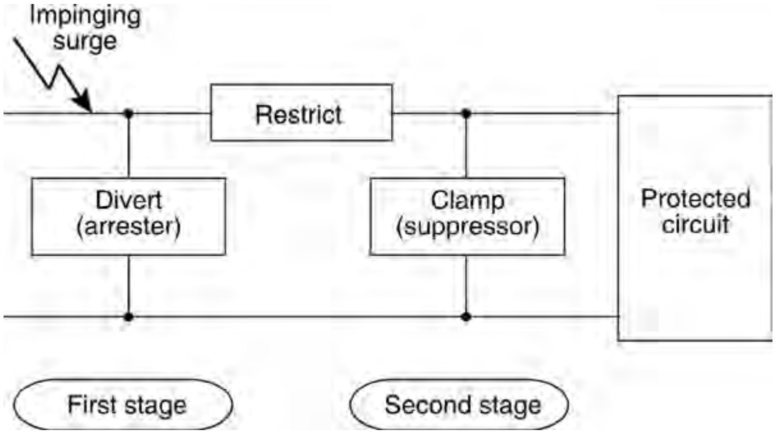
The Basics of Surge Protection

In the low-voltage (end-user) environment, surge-protection schemes act by diverting an impinging surge through a low-impedance path to return the surge current to its source, or they act by restricting the propagation of a surge between its point of origin and the equipment to be protected. Protection can be accomplished in one or several stages, depending on the system configuration and the degree of freedom available to the users for connecting protective devices at different points of their systems.

In its simplest form, diversion can be effected by a device connected in parallel (line to neutral or line to ground) as opposed to in series, hence the commonly used name "shunt-connected SPD." A shunt-connected SPD is also categorized in industry standards as a "one-port SPD." In a more comprehensive form, surge protection is effected in several stages by combining diversion, restriction, and clamping.

As shown in the figure on the following page, the first stage of a multistage approach diverts the current caused by an impinging high-energy surge through a high-energy-handling device (arrester), which is typically installed at the service entrance or other service panel. Between the first and second stages of multistage surge protection, some restriction to the propagation of surge currents in branch circuits is inherently provided by the inductance of the premises wiring or by insertion of a discrete inductor. The second stage is provided by an SPD of a lesser surge-handling capability than the arrester, often called a *surge suppressor* or *surge protector*, which is typically located close to the equipment in need of protection as an add-on, plug-in device or incorporated within the equipment by the manufacturer.

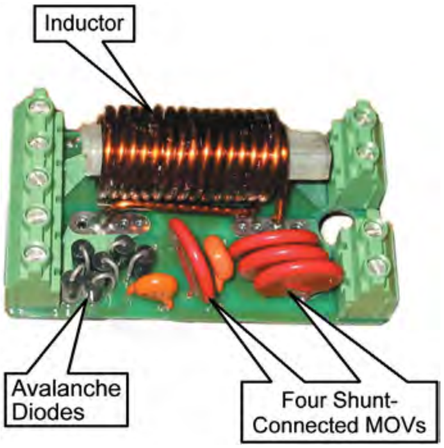
A Multistage Approach to Protecting Equipment from Surges



A multistage approach to surge protection includes diverting, restricting, and clamping high-energy surges.

The multistage approach to surge protection has been implemented by the majority of manufacturers, giving emphasis to the diverting function of a shunt-connected SPD, such as the one shown in the figure below. The definition of a *surge-protective device* adopted by the IEEE as well as by the IEC explicitly states that an SPD should contain at least one nonlinear component, such as an MOV. This position reflects the implicit design philosophy that surge protection can be accomplished by diverting the surge through a shunt-connected component. The example below illustrates the multistage approach to protecting equipment from surges. The four MOVs divert surge energy, the inductor restricts it, and the silicon avalanche diodes clamp it.

A Multistage SPD

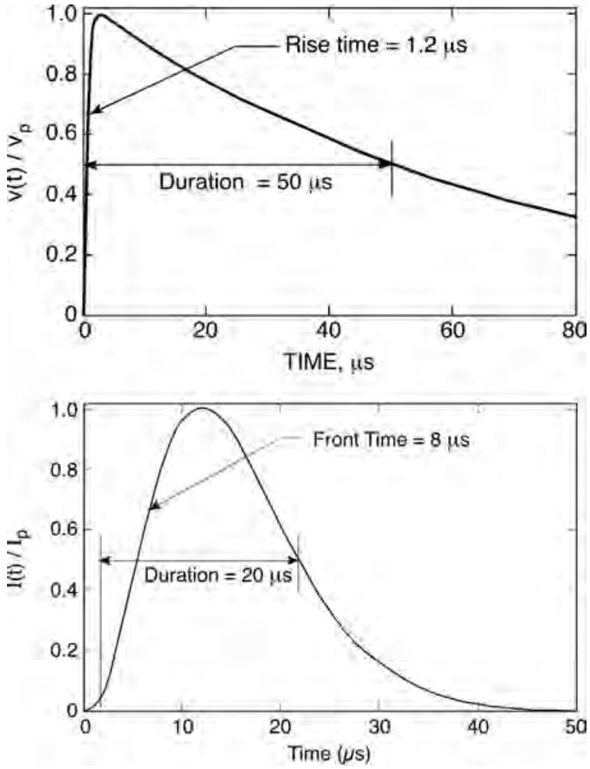


Most multistage hybrid SPDs contain both nonlinear MOVs and diodes and linear inductors but emphasize the diverting function.

Selecting the Right Stress Level for Testing SPDs

Any demonstration of robust surge protection—either through a review of existing SPD specifications or through laboratory testing—should be done at a stress level corresponding to IEEE location category C, which requires the application of a test surge with 6 kV of open-circuit voltage and 3 kA of short-circuit current. Although the most common waveform used to test SPDs is the 100-kHz/0.5-µs ring wave, which is described in IEEE C62.41-2000, it does not contain enough energy to stress SPDs to determine their endurance. This laboratory-generated surge is typically used to represent low-energy surges, which occur more often from man-made events such as disconnecting inductive loads and energizing capacitive loads for power-factor correction. On the other hand, the IEEE combination wave, which is also defined in IEEE C62.41-2000, contains enough energy to properly stress an SPD and is therefore the better choice for demonstrating SPD robustness. All laboratory-created surges should comply with the IEEE combination wave. The figure on the following page shows the characteristics of the open-circuit voltage (top) and short-circuit current (bottom) as specified in IEEE C62.41.

An IEEE C62.41 Combination Wave



A laboratory-generated combination wave that complies with IEEE C62.41 is used for surge-testing SPDs.

MOVs are designed to absorb the electrical energy contained in surges to prevent damage to active and passive electronic components of end-use equipment.

The following section discusses basic circuit protection schemes, MOV failures, and coordination of fuses and MOVs for effective TOV protection.

CIRCUIT PROTECTION USING MOVS

To protect equipment from surges, MOVs are located in various circuit locations of end-use equipment. To protect against surges incident on the AC power line, they are located at the AC power input of the equipment before the electromagnetic interference (EMI) filter, as shown in the first figure on the following page. MOVs may also be used on the DC bus of a computer power supply, on low-voltage control wiring such as in electrically activated lawn-sprinkler systems, and on the inputs of dimming circuits in electronic fluorescent and high-intensity discharge (HID) lighting ballasts, like the application shown in the second figure on the following page.

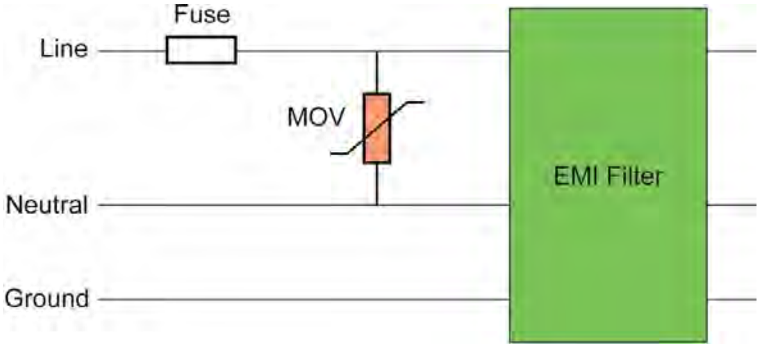
MOVs and other SPDs located on AC power inputs and low-voltage control circuits are vulnerable to failure. MOVs are designed to absorb the electrical energy contained in surges to prevent that energy from causing damage to active and passive electronic components located downstream of the line fuse and upstream of a connection to a low-voltage DC control circuit. For example, when a surge impinges upon the AC line input, MOVs effectively reduce the surge voltage to levels that will not cause damage to electronic components.

In the course of reducing the surge voltage and dissipating energy, MOVs heat up. The amount of temperature rise in an MOV is related to the amount of energy that the MOV must absorb from the surge. It is the area under the curve of the resulting surge-power waveform that determines how much energy the MOV must absorb. Surges that have higher voltage magnitudes (such as 3 kilovolts) and shorter durations (such as 50 microseconds) will cause less MOV heating than surges of lower voltage magnitudes and longer durations. Also, MOVs with larger diameters (such as 20 millimeters) are designed to handle more surge energy than MOVs with smaller diameters.

Characteristics of MOV Failures

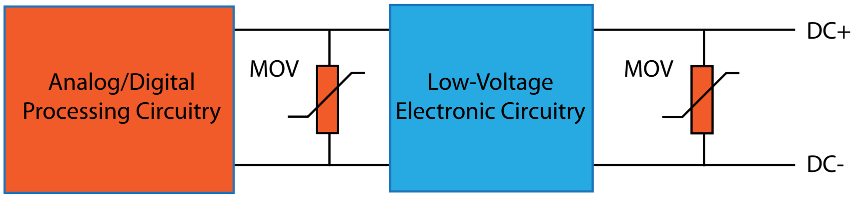
MOV failures result from the inability of the MOV to withstand the electrical energy applied to it during a surge. The energy that the MOV must absorb is a function of several variables, including the maximum overvoltage occurring on-line and the duration of the overvoltage. The energy-handling capability of the MOV is a function of the energy rating of the MOV, which is a function of the diameter and thickness of the MOV and the ability to remove the heat effectively before the MOV suffers permanent damage.

Location of an MOV to Protect the AC Power Input



For protection against surges incident upon the AC power line, most MOVs are installed at the AC power input, either line to neutral, line to ground, or both.

Low-Voltage Applications of MOVs



Some MOVs are installed on DC buses and control circuits.

Whether the overvoltage that occurs on the line voltage is a surge or a TOV, the MOV will begin to conduct current at some voltage level. The current that flows through an MOV during conduction is defined by IEEE Standard C62.41.1 as the *surge current*. If the MOV must conduct current as a result of a TOV, then the resulting initial current of the TOV during MOV conduction may damage the MOV. Damage to the MOV from conduction of TOV-initiated currents will depend upon how much TOV energy the MOV must dissipate. If the energy-handling capability of the MOV is exceeded, then the MOV will fail. After an MOV failure, the only way to tell whether the failure was caused by a surge or a TOV is to physically inspect the MOV and the line fuse.

Physical inspection of a damaged MOV will require that the equipment be opened to reveal the protection circuitry on the AC power input section. Inspection of the line fuse is also necessary because the fuse may or may not be damaged as a result of a surge or TOV. Most importantly, an opened fuse may be the result of one or more failed power electronic components in the equipment's power supply or other power-related components inside the equipment. After the fuse and MOV have been located, it should be determined whether the fuse is open. If the MOV appears to be intact, then it can be removed and tested with an MOV tester. If the MOV test reveals that the MOV did not fail, then it is likely that the equipment failure did not involve surges, TOVs, or the MOV.

The investigator must also test the fuse with an ohmmeter to determine whether the fuse element has been damaged and/or opened. In most cases, it will be obvious that the fuse has been damaged as evidenced by a disintegrated fuse element and/or charred glass (if the fuse container is made of glass). In the case of some fuses, especially ones with a time delay (called *slow blow*), element damage can be “hidden,” and a visual inspection may not reveal the damage. In fuse failures, it is also possible that the element has not been totally severed (it has a very small but measurable impedance). Using a milliohmmeter is useful in determining whether this is the case.

Upon opening a piece of equipment, one may find that, in most applications, the fuse and MOV are located on the top or on the bottom of a printed circuit board in plain sight. This makes the visual inspection of the fuse and MOV easy. The location of the fuse and MOV will be near to where the AC power is brought into the equipment and close to the EMI filter.

One may also find that the fuse and MOV are not visible. In an increasing number of equipment designs where a composite EMI filter is used, the fuse and MOV may actually be inside a metal can that is used to house the EMI filter. Such a composite EMI filter typically includes the line fuse, MOV, over-temperature protection device, and EMI filter components (capacitors and inductors). One may ask why the line fuse and MOV are included in the composite EMI filter. In some cases, the EMI filter may be required to be shielded from nearby radiated emissions sources inside the equipment. In this case, the fuse and the MOV must also be located inside the filter can to preserve the electromagnetic integrity of the AC line input.

The can of a composite EMI filter may be filled with some type of potting material. The use of potting material helps to reduce arcing between component traces on the EMI filter circuit board and between component surfaces and the grounded EMI filter can. Potting material also helps to improve heat dissipation of the fuse, MOVs, and filter elements inside the can. Dissipation of heat in this case is especially important in helping to extract heat from the MOVs when they are activated to pass surge current. Heat dissipation through potting material will also help to reduce MOV failure caused by short-duration TOVs. When conducting investigations of potential fuse and MOV failures, the potting material must be removed to expose the surfaces of the fuse and the MOVs. Removal of potting material should be accomplished in such a way as not to cause further damage to the fuse and MOVs. Mechanical, rather than chemical, removal of the potting material is the best method.

The figure below shows an example of an MOV failure in end-use equipment. This MOV is partially potted, and the line fuse is fully potted (not shown). The blue capacitors below the MOV and the common-mode inductor above the MOV are both part of the EMI filter for this equipment. This MOV failed as a result of a TOV incident upon the AC line input. The potting material helped to absorb heat from the MOV and helped prevent the MOV from disintegrating. Nevertheless, failure of the MOV resulted in displacement of the epoxy coating. Failure of the fuse and the MOV resulted in full failure of the equipment, which had to be returned to the manufacturer for repair.

Thermal runaway may also occur if an MOV with too low of a maximum continuous operating voltage (MCOV) is applied in end-use equipment. Thermal runaway can occur when an MOV is exposed to a long-term overvoltage that exceeds the maximum allowable voltage of the MOV. Thermal runaway may occur without blowing the line fuse. The two figures on the following page show two examples of MOVs in surge protectors that failed as a result of MOV thermal runaway. In both examples, the MOV ignited, and a significant part of the MOV material was burned by the resulting fire. If this type of MOV failure is found surrounded by other burned insulation and electronic components, then thermal runaway was likely caused by a temporary overvoltage.

An MOV Damaged by a TOV

This potted MOV failed as a result of a TOV incident upon the AC line input.

Long-term TOVs can cause thermal runaway in an MOV, which may ignite and cause a fire hazard to the surrounding equipment.

Coordination of Metal-Oxide Varistors and Fuses to Achieve Adequate Levels of Protection

Design requirements imposed by Underwriters Laboratories (UL) require that a fuse be located upstream of an MOV when the MOV is connected line-to-neutral or line-to-ground. However, MOVs connected from neutral to ground do not require fuse protection. Fuse protection of an MOV will reduce the likelihood of an MOV fire resulting from extreme surge currents flowing through the MOV. All of the front-end MOVs should have the same MCOV rating. In addition, it is good design practice to thermally protect the MOV to prevent potential fire hazards due to loss of neutral in facility wiring systems.

MOV Failure Caused by Thermal Runaway

This MOV failure was caused by thermal runaway and fire inside the surge-protective device.

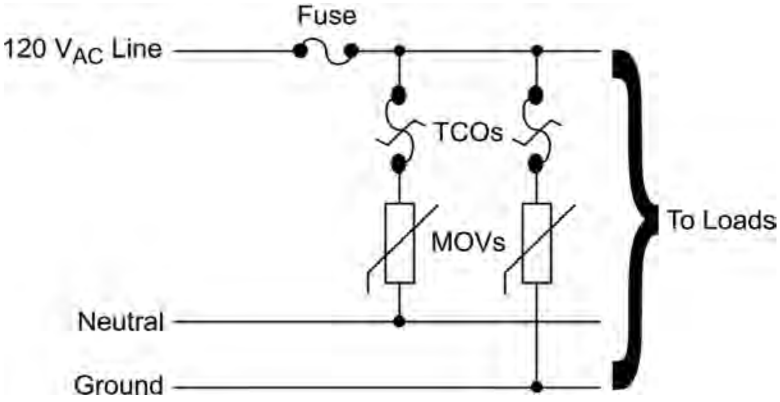
Equipment Damage Caused by the Ignition of an MOV During Thermal Runaway

In a surge-protective device, an MOV thermal runaway can lead to a fire inside the protected equipment.

Some manufacturers with little experience in the design of surge protection will try to locate the MOV upstream of the fuse in their equipment designs. Without the basic understanding of protecting equipment from fire caused by MOV failures, initially there is more concern with protecting every component (including the line fuse) from surges and reducing the number of nuisance equipment failures caused by opened fuses. Locating the MOV upstream of the fuse would reduce nuisance equipment failures but also violate UL requirements. Thus, this practice is not recommended by the power quality community for obvious reasons. Nuisance failures of equipment (caused by opened fuses and failed MOVs) can be avoided and adequate immunity against surges can be provided if the overcurrent protection offered by a fuse and the overvoltage protection offered by an MOV are sized and coordinated in the proper manner.

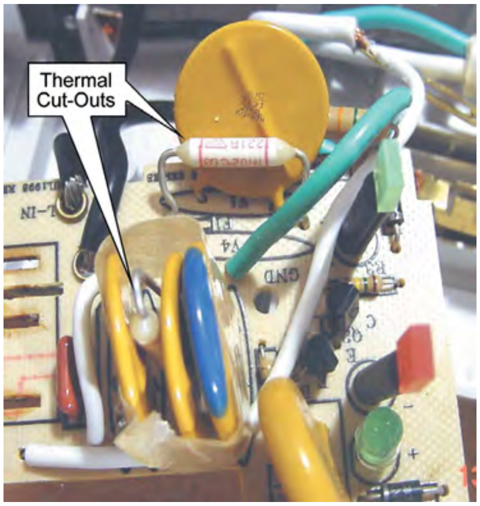
An improved MOV design provides for thermal protection for the MOV without the use of coordinating fuses. Thermal protection can be provided by external or embedded thermal cut-outs (TCOs), which are available for different operating temperatures. The first figure on the following page shows the diagram of thermally protected MOVs. An external TCO must be properly positioned and oriented next to an MOV if it is to be effective in thermally protecting the MOV. When subjected to a TOV, MOVs can short at a random point on the disk and rapidly begin to self-heat when conduction current is sustained through the MOV. Therefore, the TCO must actually touch the MOV to be protected. When TCOs are used in this way, the MOV/TCO pairs can be located upstream from the line fuse. The second figure illustrates an example of a typical arrangement of MOVs and TCOs.

Diagram of a TCO/MOV Surge-Protective Circuit



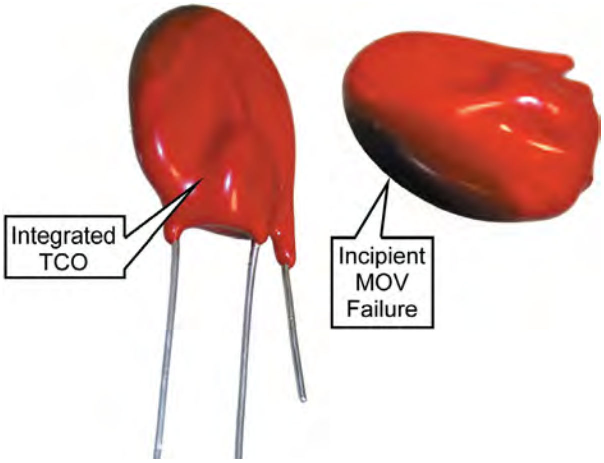
A thermal cut-out prevents an MOV from self-destruction during thermal runaway.

Locations of TCOs in a Typcal Application



External TCOs must be precisely located next to MOVs to protect them from thermal runaway.

A Thermally Protected MOV Saved by Its Internal TCO



The internal thermal cut-out of this thermally protected MOV saved the device from catastrophic failure caused by thermal runaway.

The coordination of line fuses, thermal cut-offs, and MOVs is essential for optimal protection of equipment without the nuisance failure of those sacrificial components.

Some MOVs have integrated TCOs, in which case they are called TMOVs. The figure to the top right shows a TMOV that started to fail (see the scorched upper left part of the disc) but was saved from thermal runaway by the integrated TCO interrupting the current through it.

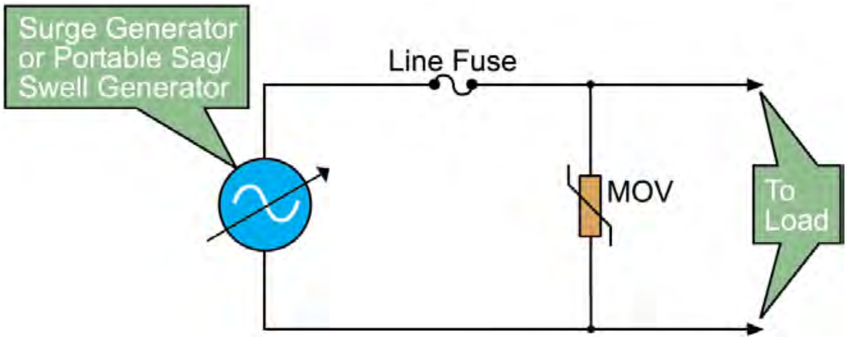
It is not uncommon for equipment users to send dysfunctional equipment from the field to the manufacturers for investigation. During failure investigations, manufacturers often find that only the line fuse has been blown, with no damage to other components, including the MOVs. Manufacturers know that there are a number of causes for the failure of line fuses, including internal component failure (especially associated with the power supply). In other cases, manufacturers may find that both the fuse and MOVs have been destroyed.

Surge- and TOV-related failures of line fuses are caused by MOV current conduction. This conduction is a function of the MOV's rating for clamping voltage. If the MOV clamping (suppression) voltage is selected too low, then there is a greater chance that the MOV will conduct as a result of a TOV, thus possibly damaging the line fuse and the MOV.

The MCOV rating of an MOV is another critical specification. If the MCOV is selected too low (too close to the maximum expected line voltage, including the expected overvoltage of about 10%), then the MOV will conduct as a result of high line voltage. Thus, selecting an MOV with a high clamping voltage and MCOV rating will help avoid failures of line fuses and MOVs caused by a high line voltage and TOVs.

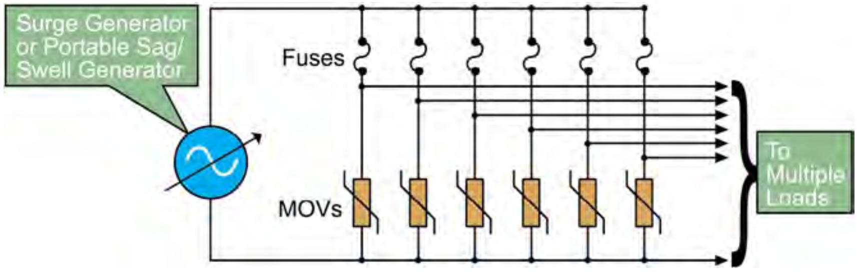
On the other hand, the equipment designer must select the clamping voltage low enough to clamp surges before they damage other internal components, such as noise capacitors inside an EMI filter and the bridge rectifier. In 120-volt applications, selecting an MOV with a clamping voltage of 395 V_{PEAK} and an MCOV of 150 V_{RMS} will be sufficient in most cases. In 277-volt applications, selecting an MOV with a clamping voltage of 850 V_{PEAK} and an MCOV of 320 V_{RMS} will be adequate.

Test Circuit Arrangement A



This simple arrangement of an MOV and line fuse represents many arrangements in electronic appliances and equipment.

Test Circuit Arrangement B



This complex arrangement of parallel MOVs/fuses represents six protective components on a single branch circuit.

EXAMPLE APPROACH TO LAB-TESTING MOV AND FUSE ARRANGEMENTS

By way of example, this section discusses how to perform an evaluation to ensure that fuses and MOVs are coordinated to achieve superior protection of a load without nuisance failure of front-end components, including the fuses and MOVs themselves. In this case, the load was an off-the-shelf electronic lighting ballast. The power circuit of this ballast was investigated to determine the arrangement and values of MOVs and fuses. The line fuse used in the ballast was a 3-amp slow-blow fuse rated at 350 V_{AC}. Slow-blow fuses are typically used to prevent nuisance fuse blowing during brief (subcycle) surges. The 20-mm MOVs used in the ballast were rated at 510 V_{RMS} for MCOV and 1,350 V_{PEAK} for the clamping voltage.

The criterion for a successful arrangement of MOVs and fuses was that the arrangement could withstand (1) a TOV with a peak voltage of 1.5 per unit and a duration of 1 second and (2) a surge (represented by an IEEE combination wave) with a peak voltage of 6-kV open voltage and a 3-kA short-circuit (at least 100 applications). To facilitate various arrangements of the circuit components and to prevent accidental damage to the sample ballast, all testing was performed outside the ballast.

Test Setup

Well-planned laboratory testing can be performed to investigate the coordination of circuit components designed to protect equipment against surges and TOVs. Coordination studies can identify weaknesses of existing designs and the potential efficacy of new designs. Investigators at EPRI tested two common arrangements of surge-protective components. The first figure (Circuit Arrangement A) shows a simple arrangement of a shunt-connected MOV with an upstream line fuse, representing a single MOV-protected appliance connected to a branch circuit. The second figure (Circuit Arrangement B) shows a more complex arrangement, with six parallel circuits, each composed of a series-connected MOV and fuse. Soldering parallel MOV/fuse circuits to a test card enabled investigators to determine whether multiple appliances connected to the same branch circuit share the overcurrent stress presented by a surge or TOV.

In Arrangement A, the current through the MOV was monitored. In Arrangement B, the current through the entire circuit was monitored. A portable voltage-sag/voltage-swell generator was used to apply TOVs to both arrangements. A surge generator capable of creating IEEE combination-wave surges was used to apply surges.

Approach for Applying TOVs to MOV and Fuse Arrangement

Type of Test	Test Parameters	Circuit Configuration and Component Selection	Ending Step
TOV Test	TOV start voltage = 1.0 pu TOV step voltage = 0.1 pu TOV end voltage = 2.0 pu	One fuse, one MOV, series connected. Six single fuse/ single MOV series circuits.	Apply TOV until end voltage is reached or fuse or MOV fails.

Approach for Applying Surges to MOV and Fuse Arrangement

Type of Test	Test Parameters	Circuit Configuration and Component Selection	Ending Step
Surge Test (Combination Wave)	8 μsec x 20 μsec Phase location = 90° Surge start voltage = 1 kV Surge step voltage = 500 V Surge end voltage = 6 kV	One fuse, one MOV, series connected. Six single fuse/ single MOV series circuits.	Apply surge until end voltage is reached or fuse or MOV fails.

Applying TOVs and Surges

Conducting the TOV Tests

Each arrangement was subjected to TOVs of various magnitudes and durations. The first table below shows the test schedule for applications of TOVs. To initiate testing, a portable sag/swell generator was set at 1.0 per unit, which is the nominal voltage of 277 volts AC. The application of a 1.0 per-unit voltage was a baseline test to ensure that the test circuits were correctly configured and that the monitoring equipment was working properly. Each test consisted of six TOV applications (2, 4, 8, 16, 32, and 64 cycles). After the six applications, the voltage was incremented by 0.1 per unit. This incrementing of magnitude and duration continued until the end voltage was reached (2.0 per unit) or a fuse or MOV failed. After each TOV application, all fuses and MOVs were visually inspected and measured with a continuity meter to determine whether the components passed or failed the applied TOV.

Conducting the Surge Tests

After completion of the TOV tests, each arrangement was subjected to a series of combination-wave surges of various magnitudes, with a duration that was compliant with IEEE C62.41. The table at bottom left shows the test schedule. To initiate testing, a surge generator was configured for a 1-kV surge. Each test consisted of a series of surge applications of increasing frequency (starting at 10 applications and ending at 1,000 applications, with 1-minute intervals between applications). After the test at 1,000 applications, the voltage was incremented by 500 V. This incrementing of magnitude and the number of applied surges continued until the end voltage was reached or a fuse or MOV failed. After each series of applications, all fuses and MOVs were visually inspected and measured with a continuity meter to determine whether the components passed or failed the applied series of surges.

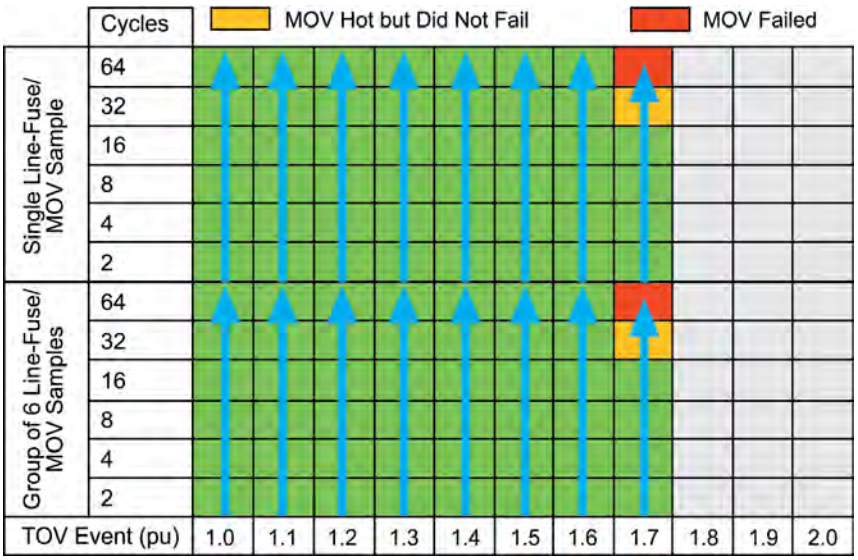
Test Results

Results of TOV Tests

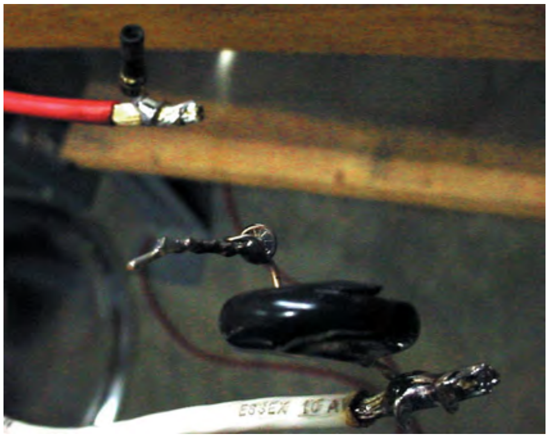
The figure below summarizes the results of the TOV tests for the two MOV/fuse arrangements. The arrows in the figure illustrate how the testing was performed: The schedule of six different durations was completed before the magnitude was incremented. The chart reveals that the results for both arrangements are identical, with each arrangement suffering damage to an MOV, fuse, or both during the application of a TOV with a magnitude of 1.7 per unit (471 V) and a duration of 64 cycles. Note that at the same magnitude and duration of 32 cycles, at least one MOV from each arrangement became warm to the touch but did not fail.

The first figure at top right shows that the line fuse in Arrangement A was completely destroyed during a 1.7 per-unit TOV, and the MOV suffered splitting of its epoxy-covered case. (The MOV was not completely destroyed in terms of its physical structure.) The second figure on the right illustrates the results of a 1.7 per-unit TOV applied to Arrangement B. Four out of the six fuses were blown, and those fuses interrupted the TOV current drawn by the MOVs that experienced the most damage, evident by the splitting of their epoxy cases.

Summary of TOV Test Data



Damage to Inline Slow-Blow Fuse and MOV



A 471-volt, 64-cycle TOV disintegrated a 3-amp, slow-blow line fuse and damaged a 510-volt MOV.

Multiple Fuse and MOV Damage Caused by a TOV

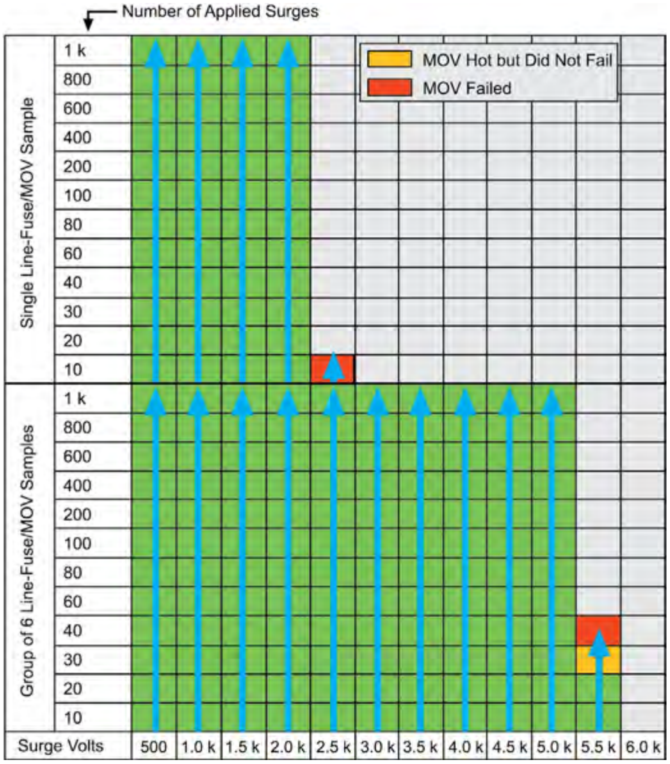
A 471-volt, 64-cycle TOV blew four of the six 3-amp, slow-blow fuses in series with 510-volt MOVs on a test card (four of six MOVs were damaged).

When MOV-protected appliances are connected to the same branch circuit, the MOVs can share the energy of a surge and reduce the likelihood of equipment failure.

Results of Surge Tests

The chart below summarizes the results of the surge tests for the two MOV/fuse arrangements. The arrows in the figure illustrate how the testing was performed: The schedule of 12 different numbers of applications was completed before the magnitude was incremented. The test results for Arrangement A are different from the results for Arrangement B. Arrangement A survived the surges ranging from 500 volts at 10 applied surges up to 2,000 volts at 1,000 applied surges, with failure of the fuse occurring at 10 applications of a 2,500-volt surge. In Arrangement B, five out of six line fuses failed when subjected to 40 surges at 5,500 volts. However, none of the six MOVs was damaged during any surge tests.

Summary of Surge Test Data



Discussion of Results from TOV and Surge Testing

The arrangement of MOVs and fuses had no effect on their ability to protect equipment against TOVs without failing in the process. Both Arrangement A (single fuse in series with a single MOV) and Arrangement B (parallel MOVs/fuses) afforded protection to the load during TOVs up to but not including 471 volts and lasting as long as 64 cycles. On the other hand, applying surges to the two arrangements resulted in an instructive divergence. Arrangement A, which represented a single appliance connected to a branch circuit, failed early in the tests at a surge level of 2,500 V. However, Arrangement B, which simulated six MOV-protected appliances connected to the same branch circuit, survived surges up to 5,500 V. This result demonstrates that for MOV-protected loads in parallel, the MOVs can share the energy of a surge and reduce the likelihood of equipment failure.

However, this cannot be said of TOVs. During a surge, an MOV's clamping voltage will be engaged, and the MOV's resistance will decrease rapidly to shunt surge current when the magnitude of the applied surge voltage rises above the MOV's clamping voltage (in this case, 1,350 V). On the other hand, during a long-duration TOV (greater than one cycle), the MCOV comes into play. When the applied RMS voltage approaches the MCOV rating of the MOV, the MOV begins to draw heavy current, resulting in a TOV energy that the MOV cannot shunt without damage to the fuse, MOV, or both.

CONCLUSION

A reasonable amount of protection against surges and temporary overvoltages can be achieved by adding protective schemes to both the line side and the equipment side of the distribution system. Although a surge is different from a TOV, the ubiquitous metal-oxide varistor is often employed to protect equipment from both types of overvoltage.

MOVs are designed specifically to reduce surge voltages appearing on input and output circuits in end-use equipment. When a surge voltage is reduced to a level that will not damage internal electronic components, surge currents must flow as a result of the voltage-clamping action designed into the MOV. However, MOVs are not specifically designed to protect end-use equipment from TOVs. Although TOVs have lower peak voltages than surges, they last much longer than surges. In equipment design, the size and type of fuse and MOV matter when trying to coordinate them to reduce premature failure of equipment. As a result, when the fuse is coordinated closer to the MOV (meaning the fuse is able to withstand surge current), it is difficult to determine the cause of equipment failure (whether the failure was caused by surges or TOVs).

There are four primary principles for selecting effective surge protection. First, the physical size of the MOV should be a minimum of 20 mm in diameter for surviving a raw surge environment. Second, to survive continually changing voltage levels, an MOV should have a maximum continuous operating voltage that is at least 25% higher than the rated line voltage. Third, the SPD information published by the manufacturer or the results of private stress testing should clearly demonstrate a robust design by showing that the SPD survived a minimum of 1,000 surges at 1-minute intervals at the selected surge environment category, preferably the IEEE C62.41.2 2002 combination wave with 6 kV and 3 kA as minimum parameter values. And fourth, MOVs should have thermal cut-outs or some other protection against thermal runaway and the consequential risk of fire. By adhering to these four principles, a robust and safe SPD design can be ensured.

NOTES

1. G. L. Goedde, E. S. Knabe, and L. A. Kojovic, "Overvoltage Protection of Distribution and Low-Voltage Equipment Experiencing Sustained Overvoltages," in Proceedings, IEEE Power Engineering Society Winter Power Meeting, 1999, vol. 2, pp. 1202–1207.
2. R. H. Hopkinson, "Ferroresonant Overvoltage Control Based on TNA Tests on Three-Phase Delta-Wye Transformer Banks," *IEEE Transactions on Power Apparatus and Systems*, vol. 86, October 1967, pp. 1258–1265..
3. *An Assessment of Distribution System Power Quality*, Volumes 1–3 (Palo Alto, CA: EPRI, 1996). TR-106294-V1, TR-106294-V2, TR106294-V3. *Distribution System Power Quality Assessment: Phase II: Voltage Sag and Interruption Analysis* (Palo Alto, CA: EPRI, 2003). 1001678.

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