SURGE PROTECTION

Because of the increasing use of electronic components in all electric equipment and for all types of applications, the need for surge protection has escalated. Whether it is for domestic or industrial applications, surge protection is now required for many applications such as alarms, washing machines, TV sets, motor speed control systems, computers, and process control equipment. Many of these devices have quite low withstand-to-surge currents and overvoltages. These may be lower than 1 kV. In the past, electron tubes, motors, and so on, had a larger tolerance to overvoltages, with typical values being equal to or higher than 2.5 kV.

This increased equipment susceptibility to surge voltages has led to two parallel actions:

First, an identified need for extensive research in the field of surges occurring in low-voltage (LV) systems. Surge characteristics in LV systems are not as well documented as those for high-voltage electric power transmission, where power utilities have studied and documented surge phenomena over many years.

Second, better surge protective devices (SPDs) or transient voltage surge suppressors (TVSS) as they are known in the United States, specifically designed for low-voltage applications, have been developed, which have proved to be very reliable when properly selected and installed and have readily adapted into the new and emerging needs.

Almost everybody has encountered SPDs today, because they may be found on the supermarket shelves in the form of protected plugs or protected power strips. These SPDs, however, should be used only near the equipment they were intended to protect. They are not able to handle the very high energy surges that can arrive on power lines at a building entrance; additional SPDs are needed. All these SPDs should be selected with care and installed by qualified people. In addition to power equipment, other services such as data, telecommunications, and local area networks should also be equipped with SPDs. A further potentially damaging phenomenon comes from the ground potential rise resulting from lightning strikes. The electric effect of ground potential rise is similar to that of a surge arriving on a phase or neutral wire. Grounding techniques and provision of low-impedance grounding can play a significant role in reducing electric stress on equipment and ensuring proper SPD performance.

As a consequence of the evolution of both the needs and the technology, world standards-making committees have been developed to specifically set recommended levels of performance and safety for SPDs. Many SPDs now on the market are capable of passing the severe tests described in these standards. Consumers should observe that standards compliance is specified on such products.

Furthermore, additional remote information on the state of SPDs, surge counters, and SPD fault indicators has been developed to make the use of SPDs easier.

TECHNOLOGY TRENDS

Low-Voltage Phenomena

Surges on high-voltage (HV) lines have been extensively studied, and many technical articles may be found on this subject. Relatively few articles have been published about surges on LV lines. The characteristics of LV systems are complex, with many factors affecting the severity of surges. There is also the effect of many parallel load drops and the characteristics of the actual loads. Thus, it has been necessary to study LV systems thoroughly and to include their interaction with surges.

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As an example, many LV surges are generated within a building by motor controls and local switching.

Nowadays, software programs running on PCs can provide basic information to researchers about surges, and simulation of systems is less of a problem. Software programs such as EMTP or ESACAP (1) are easy to use and allow engineers to accurately determine the characteristics of surges on typical systems configurations. In general, it is not necessary to study each particular case to select an SPD. Calculations made on specific configurations have permitted the setting of broad rules and guidelines regarding SPD selection, and these are now appearing in the relevant standards.

These software studies have been compared with actual measurements made in the field with transient analyzers. Such data are reported in this article. LV surge characteristics are better known today, and SPDs may now be more efficiently selected.

Standards

Standards include both performance and safety tests because SPDs must be very reliable. They should fail in a safe manner in case of a surge energy that exceeds the rating of the SPD or a high temporary overvoltage.

Within the International Electrotechnical Commission (IEC), there are two Committees dealing with lightning and surges. Committee 37A is responsible for producing an SPD standard for both power and data lines and for writing the SPD application guides. Committee 81 is in charge of the standard for lightning directly striking the structure (2). An advisory group ensures basic cooperation between these two committees and with others in charge of electromagnetic compatibility (EMC) (3), electric installation of buildings, and low-voltage insulation coordination (4).

Today, in the market it is possible to find SPDs that do not age, that are able to cope with very high energy surges, and that will disconnect themselves from the mains when they fail. Diagnostics in modern devices are capable of providing additional remote information of their internal state.

The relevant IEC standards are as follows:

IEC 61643-1 is the standard for surge protective devices connected to low-voltage power distribution systems (5). Part 1 is the product standard. This document was published in 1998. This standard includes the most recent data regarding LV surges and includes the following tests:

1. *Operating Duty Test.* A series of surges at the nominal discharge current followed by a few high-magnitude surge currents. This test demonstrates the ability of the SPD to withstand the surges for which it was rated and fixes a level of performance.
2. *Thermal Runaway Test.* This test is a safety test to prove that no thermal problem or fire hazard will occur when the components are damaged by higher surges than expected.
3. *Short-Circuit Test.* This test is a safety test that demonstrates the ability of a failed SPD to be disconnected from the mains or to withstand the short-circuit current.
4. *Temporary Overvoltage (TOV) Test.* This test is an optional safety test. It may be necessary to perform such a test when high-magnitude TOVs are expected in the LV system.
5. *Additional Tests.* Tests for mechanical withstanding, corrosion resistance, and so on are very similar to the tests used for other electric devices such as circuit breakers.

IEC 61643-2, Part 2 is the application guide. It does not include all of the North American LV power distribution systems. It is being reviewed by other standards organizations such as IEEE. It gives details on LV systems, types of surges existing in such systems, how to select an SPD, and what are the main parameters. The coordination between various SPDs is also explained.

IEC 60664-1 Insulation coordination for equipment within low-voltage systems, Part 1: Principles, requirements and tests (4) deals with insulation coordination (basically what is the needed surge withstanding of equipment and the associated SPD level required). It defines four categories of equipment surge withstanding. For example, for a 230/400 V system (respectively, 120 V system) the withstanding voltage between phase and ground are 1.5 kV, 2.5 kV, 4 kV, and 6 kV (respectively, 0.8 kV, 1.5 kV, 2.5 kV, and 4 kV). Electric appliances inside the structure connected to the power lines are required to have in general a 2.5 kV surge withstanding (respectively 1.5 kV). Sensitive equipment should withstand at least 1.5 kV (respectively, 0.8 kV). Surge withstanding is defined by a standardized overvoltage waveshape.

IEC 61000-4-5 Electromagnetic compatibility (EMC), Part 4: Testing and measurement techniques, Section 5—Surge immunity test (3). This standard deals with surge immunity. All equipment in accordance with this standard is tested with a combination wave generator. The levels defined in this standard are 0.5 kV, 1 kV, 2 kV, and 4 kV wire to ground and 0.5 kV, 1 kV, and 2 kV between wires.

The differences between these two sets of testing values are due to the fact that immunity is a slightly different concept from surge withstanding. Both of them refer to surges, but immunity means that the operation of the equipment is not disturbed by surges arriving on the power system. The combination wave generator used in this case is, by definition, applying a voltage impulse and a current impulse simultaneously. A part of the surge current can then circulate inside the equipment under test. For the surge withstanding test, the overvoltage waveshape is used mainly to check the insulation of the devices and is then tested only phase to ground. The generator delivers only a voltage impulse, and no significant current is circulating in the equipment. The equipment may experience a malfunction without having any insulation breakdown or component failure. The immunity level is generally lower than the surge withstanding.

In the United States the relevant documents are IEEE C62–41(9) and the UL 1499 standard (23). There is a lot of coordination between IEEE and IEC and many delegates from the United States are working in IEC. This means that the concerns are very similar even if test procedures may slightly differ.

Overvoltages

In general, the most severe transient stress is due to lightning.

A lightning ground stroke corresponds to an electric breakdown between a cloud and a conductive element connected to the ground. This is triggered by the electric charges accumulated in the cloud, which may exceed 100 MV. The lightning discharge creates a surge current with a magnitude ranging from a few kiloamperes to about 200 kA. The typical waveshape of a lightning surge current is an impulse with a front time that may be as short as 1 μs and a total decay time that may exceed 1 ms. Due to the extremely high driving voltage and the impedance of the lightning channel, which may exceed a length of 5 km, the resulting waveform is similar to that from a current source. Ground impedance has virtually no effect on the waveshape. When lightning strikes power or telecommunication line, it is the role of the SPD to divert the lightning current to ground and, in the process, to limit overvoltages from being transmitted to electric equipment connected downstream of its installation point.

Depending on the strike point we can define, by reference to a structure, the following stresses:

- *Direct stress:* when the stroke is to the structure itself. It corresponds to very high surge current.
- *Indirect stress:* when the strike point is in the vicinity of the structure. In this case, a significant part of the initial surge current is flowing toward the structure. It may be a stroke to the ground near the structure or to the services entering the structure.
- *Induced stress:* when the strike point is close enough to the structure to create overvoltages in electric circuits by induction. Such surge currents are much weaker than the initiating surge but have the capability to create high overvoltages with steep wavefronts. Induced stress may result from a stroke in the vicinity of the HV or LV power line or of any service entering the structure. Even a remote stroke to the earth may induce overvoltages directly inside the structure. Figure 1 represents these various possible paths for the surges to reach the structure.

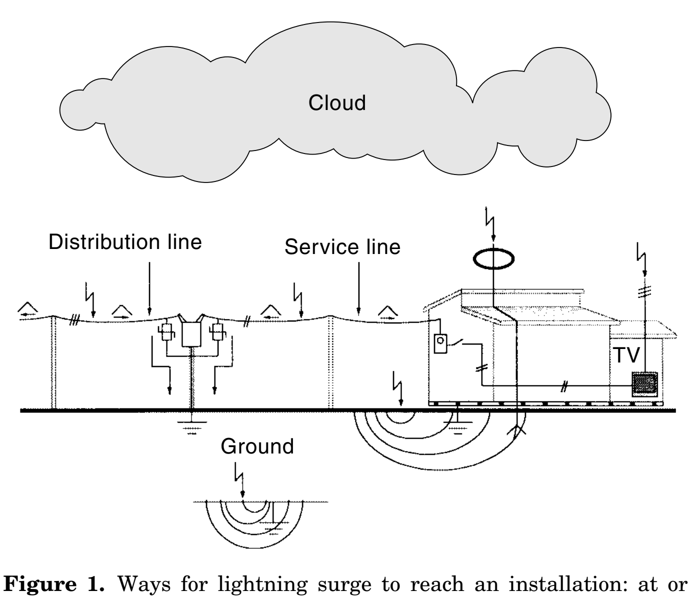

Figure 1. Ways for lightning surge to reach an installation: at or near a structure and at associated power lines.

Tests on surge protective devices use standardized waveshapes to simulate the lightning surges. They are defined by a biexponential wave defined by a front time T_f (time to reach the peak magnitude), a tail time T_q (time to decay to half the magnitude), and a magnitude I. By convention, such a waveshape is defined by T_f/T_q, where T_f and T_q are expressed in microseconds. Usual current waveshapes are 8/20, 10/350, and 10/1000. The overvoltages associated with the surge currents (for example, for induced surges) are also defined in the same manner and are 1.2/50 and 10/700. Sometimes other parameters are also given: the charge $Q = \int i \, dt$ and the specific energy $W/R = \int i^2 \, dt$, but of course T_f, T_q, and I are sufficient by themselves to define the surge.

Sometimes switching surges may be a significant transient stress as well. Any switching operation, fault initiation, or interruption in an electric installation is followed by a transient overvoltage. The magnitude of this overvoltage depends on many parameters—for instance, the type of circuit, the kind of switching operation (closing, opening, restriking), the loads, the circuit breaker, or the fuse. Typically, inductive circuits exhibit the highest magnitude of overvoltage caused by switching operations.

Another significant stress is that of temporary overvoltages. It is an overvoltage of relatively long duration (typically between 0.05 s and 10 s). It originates from switching operations, faults on power distribution systems, or nonlinearities (6).

The ideal surge protective device would be capable of handling all types of surges and disconnecting in a safe manner with an appropriate alarm when it is damaged. In practice, most SPDs are rated according to the lightning characteristic and experience difficulty in handling long-duration overvoltages (such as those due to system faults).

SPDs

SPDs for power lines are described by a few parameters:

1. Voltage Protection Level (U_p): This characterizes the performance of the SPD in limiting the voltage across its terminals. U_p is an IEC term. In the United States the term SVR [suppressed voltage rating, defined by UL (23)] is preferred.
2. Residual Voltage (U_{res}): This is the peak value of voltage between the terminals of an SPD as a result of the passage of a discharge current. It is a term applied to SPDs containing voltage-limiting components. U_{res} is the residual voltage passing to downstream protected equipment after the correct functioning of the SPD (also called let-through voltage in the United States).
3. Sparkover Voltage: This is the maximum voltage value before disruptive discharge between the electrodes of the SPD. It is a term applied to SPDs with switching components.
4. Nominal Discharge current (I_n): This is the crest value of the current through the SPD having a current waveshape of 8/20. I_n is confirmed with a multiplicity of test pulses applied in the presence of the maximum continuous operating voltage, and it is taken as a measure of expected service life.
5. Maximum discharge current ($I_{\max}$): This is the crest value of a current through the SPD having an 8/20

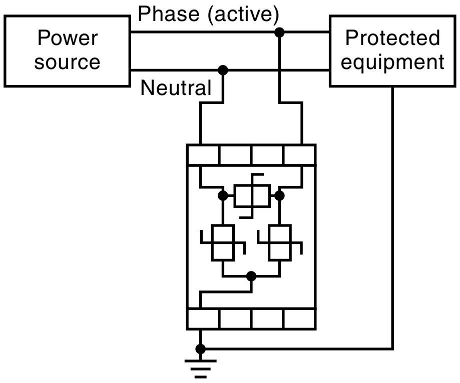

Figure 2. SPD with three modes of protection.

waveshape and magnitude greater than I_n. Basically it is the maximum 8/20 impulse current that the device can handle.

6. Impulse current (I_{imp}): This is defined by a current peak value (I_{peak}) and the charge (Q). It is the maximum current using the 10/350 impulse that the device can handle. The test is representative of a direct strike to a structure, a portion of which is conducted to the SPD.
7. Maximum continuous operating voltage (U_c): This is the maximum rms or dc voltage may be continuously applied to the SPD. The SPD must also withstand this voltage during a surge according to its rating.

A few other definitions are also useful, such as:

1. One-Port SPD or Shunt SPD: An SPD connected in shunt with the circuit to be protected.
2. Two-Port SPD or Series SPD: An SPD with two sets of terminals, input and output. A specific series impedance is inserted between these terminals. Equipment to be protected is connected to the output terminals. It must be designed and tested according to the rated load current to ensure that neither excessive voltage drop nor overheating due to the series impedance occurs.
3. Modes of Protection: SPD modes of protection are defined by their protection against overvoltages that are between line to earth, line to neutral, or neutral to earth. An SPD with a single mode of protection protects only between two terminals—for example, between phase and neutral. An SPD with three modes of protection protects between three terminals consisting of phase to earth, phase to neutral, and neutral to earth. This is shown in Fig. 2.

SPDs for communications lines are described by the same type of parameters used for power-connected devices, although the actual terms used may differ. For example, one port–two port for power-connected SPDs are generally called 3 point–5 point in the telecommunications industry. The voltage protection level is often called clamping voltage, because mostly switching components are used for protection of communications lines. In addition, there are many other parameters related to SPDs used in communication circuits as, for example, bit-error ratio (bit errors caused by the insertion of the SPD) and near-end crosstalk (amount of signal that is coupled from one circuit to another caused by the SPD).

COMPONENTS

The protective components of SPDs belong to two categories: the voltage-limiting components (such as varistors, avalanche or suppressor diodes, etc.) and the voltage-switching components (air gaps, gas discharge tubes, silicon-controlled rectifiers, etc.). For a voltage-limiting component, the curve for voltage versus current is nonlinear. The component will react when a surge current flows through it to maintain the voltage under a defined level. After the surge the current through the component is negligible. Such a component is characterized by a current discharge.

For a switching component, the relevant curve is the curve voltage versus time. The component will react when an overvoltage occurs by switching to a low-impedance mode to divert the current. After the discharge, a power current flows through the component. This current may be switched off by the component itself, or more generally it is cut off by the current protective devices of the installation. The main parameter is then the voltage above which the component starts to react.

These two types of components have very different behavior, and consequently the relevant tests are quite different. Some solid-state components have a switching-type behavior, whereas others are of the limiting type.

Varistors

Varistors are ceramic. In the past they were made of silicon carbide (SiC). For many years, zinc oxide (ZnO) varistors have been prevalent on the market under the generic name MOV (metal oxide varistor). The MOVs have a very nonlinear curve, which makes them useful for surge protection (see Fig. 3). Under normal conditions the current is very low (several tens of milliamperes or even less), and when a surge occurs the voltage is limited to a low level (from a few hundred volts to a few kilovolts). SiC varistors are mainly used in series with a spark gap because their leakage current under normal conditions is too big. Voltage and current are expressed in the equation $i = k * u^{\alpha}$, where i is the current through the MOV, u is the voltage between the terminals of the MOV, k is a constant, and α is the nonlinearity coefficient. Typically, α ranges from 1 to 50, depending on the current applied to the MOV.

Varistors are composed of many microscopic elements that act as bipolar diodes. Each of these elements has a protective

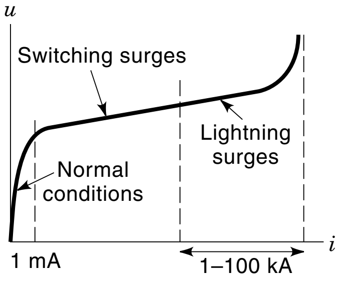

Figure 3. Typical MOV voltage versus current curve.

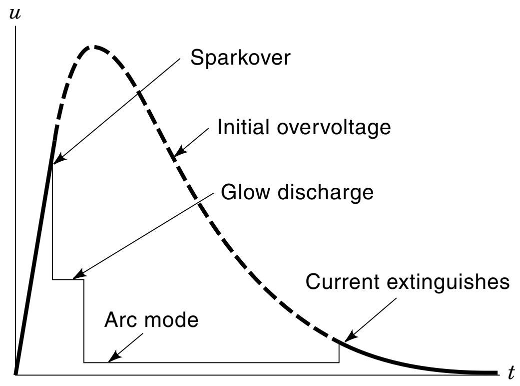

Figure 4. Typical GDT voltage versus time curve.

level (typically 3 V) and can withstand a limited surge current (j). The thermochemical process used to create an MOV is equivalent to having n elements in series and m in parallel. The thickness of the MOV then gives the protective level of the component (n times 3 V), and its diameter gives the maximum surge current that it can handle (m times j). A varistor of 20 mm diameter, for example, can withstand current up to 10 kA, 8/20.

Spark Gaps

Spark gaps fall into two key categories: (1) those operating at normal atmospheric pressure and (2) sealed units encompassing a low-pressure inert gas, which are better known as gas discharge tubes (GDTs). All types of spark gaps are characterized by very high impedance and low capacitance in their off state. GDTs are further characterized by their ionizing voltages, which mostly range from 70 V to 2000 V. Spark gaps operating at normal air pressure usually have minimum strike voltages of approximately 3 kV. Reducing the airgap to further lower the strike voltage generally leads to lower reliability as a result of pitting and burning, plus the appearance of metallic fingers, which can form a short circuit.

Both spark gaps and GDTs are classified as “crowbar” or “switching” devices. They transform from high to low impedance with arc voltages typically in the range of 30 V to 50 V. When the applied impulse voltage falls below the arc voltage, the arc is extinguished and the devices reset to the open-circuit state.

Figure 4 shows a typical voltage current curve for a GDT. The impulse rises to a point where a glow discharge occurs. The voltage is clamped at this point until the current rises to the avalanche level. The glow discharge then converts from a cold to hot state and the voltage across the device falls to the arc voltage. There is a minimum current and voltage required to sustain this arc; below that level the arc will extinguish.

This characteristic of the GDT has made it ideal for use in telecommunications operations. Typically the glow voltage would be 230 V. This value lies above the peak line voltage that occurs under ringing conditions. Under arc conditions the arc voltage would range from 30 V to 70 V. Reset would occur in the presence of the normal 50 V line voltage as a result of line impedance limiting current to a value below that required to sustain the arc. Arc extinction usually occurs when currents fall below 250 mA.

Spark gaps are more commonly used in power circuits where their low arc voltage allows high-impulse currents to be conducted with low internal heating. However, this advantage is offset on active circuits due to power follow current. Once the arc is established, and after passage of the impulse, thousands of amperes sourced from the alternating current (ac) supply can continue to flow through the existing arc. The phenomenon is known as power follow current.

The arc due to power follow current is usually maintained until the next zero crossing of the power supply. If the power supply has a prospective short-circuit current that exceeds the follow current rating of the device, special measures such as series fusing of the SPD are required. The aim is to limit the follow current flow to be within the tolerance of the device. Other measures to extinguish the arc include use of a series connected varistor (SiC or MOV), use of horn gap configuration to increase arc voltage by expansion of arc length, and the use of comb plates to split the arc into many segments.

When spark gaps are specified, it is important to ensure that low-voltage downstream protective devices such as MOVs installed within equipment do not try to clamp voltages below the spark gap strike voltage. This is a matter of coordination of devices according to their characteristics (see the sections entitled “Decoupling Components (Thermistors, Resistors, Inductances, etc.)” and “Power Systems”).

Solid-State Components (Silicon-Based)

Silicon devices (limiting type) have the characteristic of zener diodes with special on-chip heat sinking to increase their current impulse capability. Their v versus i nonlinearity is superior to that of varistors, while their cost and performance with respect to energy handling is inferior. Compared with a 20 mm MOV handling 10 kA 8/20, an avalanche diode array would require a series–parallel arrangement of about 40 devices with a significant cost penalty.

Silicon voltage-switching devices take the form of thyristors and triacs. Many have a special adaptation to increase their energy capability, to control their reset current for specific applications, and to attain internal control of the switching voltage. The later devices are now packaged in a two-terminal, bipolar format and are supplanting gas arresters in many telecommunications applications.

Figure 5 shows the avalanche characteristics of such devices, which is not unlike that of the gas arrester. During testing of silicon devices, care should be taken to test in both

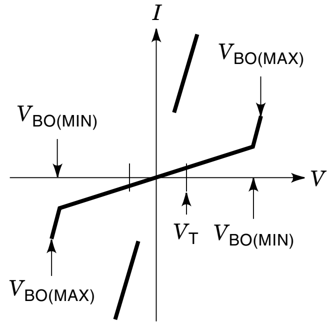

Figure 5. Bipolar voltage versus current curve of a silicon avalanche switch.

polarities. Triac-based devices can have different operating modes according to polarity, and they may be significantly slower to operate in one polarity.

GDTs operate significantly slower that silicon devices resulting in a much higher let through voltage. On the other hand, GDTs have a much greater energy handling capability than silicon devices. A hybrid circuit of these two components is very often employed in telecommunication protective devices in order to accommodate the mutual benefits of the two discrete technologies.

In general, varistors and spark gaps have medium to high pulse-handling capability, while individual silicon devices have low peak current rating. The pulse capability of silicon devices is usually increased by forming series and parallel strings within specific products.

Some manufacturers then go further by paralleling the diodes with varistors, claiming that the varistors are backup protection. Care should be taken in reading the specifications of such products since the voltage clamping of the silicon is frequently quoted together with the energy rating of the varistors. There is actually no coordination between the characteristics of directly paralleled devices. They must be regarded as separate entities with the silicon failing when peak energy is exceeded, thereafter the varistor becomes the sole clamping device, albeit at about three times the residual voltage of the silicon.

Aging and End of Life

There are two failure modes for SPDs with voltage-limiting components. The first one occurs in presence of a too-high surge compared with the surge withstanding ($I_{\max}$ or I_{imp}) of the component. The failure mode is a short circuit and is almost immediate. The failure mode of the SPD in the presence of an excessive surge also depends on the environment of the components (encapsulated in resin or not) and on the presence of such additional devices as disconnectors (devices used to disconnect the component from the mains in case of failure).

The second failure mode is more gradual. The SPD components in normal conditions have a very low leakage current. In such circumstances as very high ambient temperature or as a result of aging, leakage currents may slowly increase to unacceptable values. This can cause increased internal temperature and lead to thermal runaway.

The failure mode characteristics of SPDs from unexpected surges or slow evolution of their characteristics are from now on known phenomena. Tests to force failed SPDs to observe risk of fire are covered in current standards. Thermal fuses or disconnectors are used to prevent continuing currents through failed SPDs to avoid any fire hazard. Modern varistors do not age if operated within their specification. There are now tests to check this in the various standards. In particular, UL 1449 (23) includes extensive testing to ensure SPDs fail in a safe state. A specific test includes subjecting the SPD to abnormal overvoltages up to twice the nominal voltage of the PSD for extended periods (seven hours).

Switching-type components are isolated in normal conditions. There is not really a progressive degradation, and normal failure mode is open circuit. However, repetitive sparkover may lead to a degradation of electrodes, which may lead to sparkover and a short-circuit under normal operating conditions. Some GDTs are offered with an external device that short-circuits the component in the case of an excessive temperature rise. This condition generally arises from telephone line contact with an ac supply.

Most of the time, the failure mode of the solid-state devices is by short-circuit of a component due to their relatively poor surge capability compared with MOV devices. This low surge capability means that current fuses are generally quite adequate as disconnectors.

Decoupling Components (Thermistors, Resistors, Inductances, etc.)

Association of components with different characteristics can bring together the best parameters of each. But in this case they must be decoupled to allow optimum use of all the components. The most common and proven hybrid device would be the three stage signaling and data line protector. This is shown in Fig. 6 with a three-element gas arrester as the upstream primary protector. Such a GDT will strike at around 450 V on a rising pulse of 10 kV/μs. This is too high for the protected equipment. Placing series resistors of 5 Ω in each line restricts the maximum current passing to a downstream protector to 45 A. That device can be an appropriately rated varistor, which would clamp at 75 V. A further stage of 5 Ω resistors leading downstream to the next device would limit current to 7.5 A. A high-speed silicon component can then be used to clamp the final voltage to around 8 V.

In this type of hybrid, a 20 kA, 8/20 impulse is so reduced that only 8 V reaches the protected equipment.

A modification of this concept would be to replace the first series of resistors with positive temperature coefficient thermistors (PTC) to prevent any continuous-power voltage destroying the low-voltage components. An example would be application of a voltage of 200 V (for example, induced by the

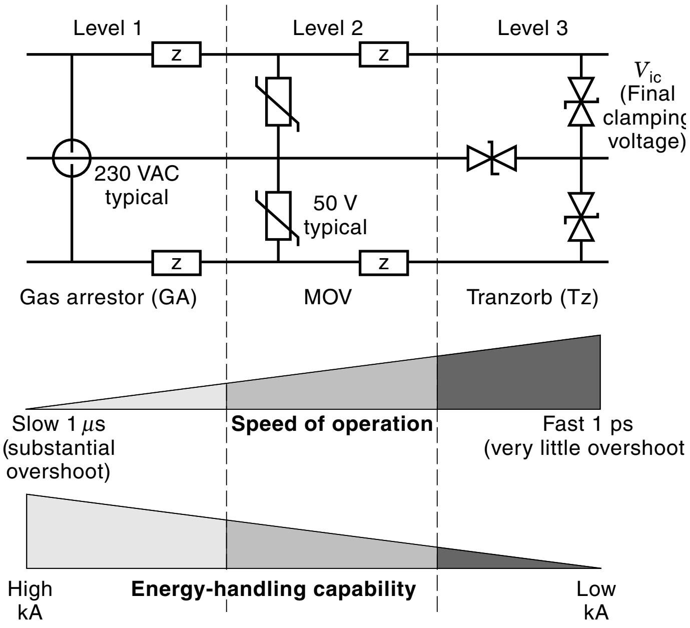

Figure 6. A three-stage hybrid SPD for telecommunications applications showing energy and speed optimization according to individual device characteristics.

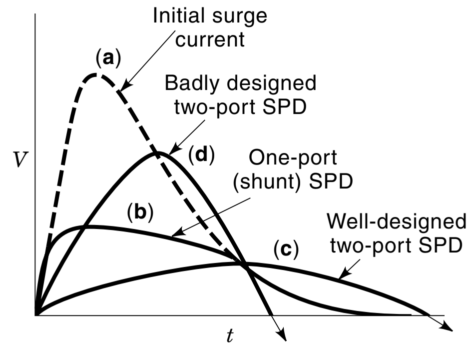

Figure 7. Various one-port and two-port SPD responses to a surge. (a) Applied impulse waveshape. (b) Voltage protective level of MOV only. (c) MOV + Filter 1 showing reduction in both *dV*/*dt* and voltage protective level. (d) MOV + Filter 2 showing lesser reduction in *dV*/*dt* with increase in voltage protective level.

mains), a value below the primary GDT sparkover voltage. Current would then be drawn by all downstream components and lead to their failure. The heating of the PTC thermistors would send them into their high-impedance state and thus protect both components and equipment.

Decoupling is also important in power circuits. In this case, the decoupling is usually achieved by use of a series inductor to reduce the heating that would occur with an inline resistive device. In one well-known case, upstream protection was provided by a high-current spark gap with a 50 kA, 10/350 impulse capability. As stated earlier, such devices require around 3 kV to trigger into their arc mode. Thereafter, the voltage seen by the equipment is that of the arc, which may be on the order of 50 V to 100 V. This specific installation also included provision of varistors at the distribution panel a few meters away. These were rated at 275 Vrms and would commence clamping slightly above 400 V. The obvious happened. The varistors held the voltage below the spark gap sparkover voltage, until they and other low-energy devices inside equipment all exploded. The fitting of decoupling inductors in the line between the spark gap and downstream devices can solve the problem.

Another hybrid is the SPD/filter combination, which uses the SPD as a primary clamp. The following filter has an inline inductor and shunt capacitor. The filter has two effects: First, it can reduce the rate of voltage rise being passed to downstream equipment. Second, it can reduce the peak voltage and, hence, further lower the protective level to values below that of the upstream SPD.

It is important to note that the filter characteristic must relate to an impulse and not to sine wave performance. A unipolar impulse will charge the shunt capacitor of the filter with current passing through the inline inductor. This inductor is charging with magnetic energy through the rise time of the impulse. During the decay of voltage, the inductor returns stored energy, causing the capacitor to continue charging. Figure 7 shows the expected responses from a shunt SPD and SPDs with various filters.

LOW-VOLTAGE SYSTEMS

Different Types of Power Systems

LV systems are described based on their earthing systems (TT, IT, and TN as described in IEC standards and also, for example, the split-phase system, one of the various systems used in the United States). In IEC, two letters are used for the description of the system: the first letter describes the link between the neutral conductor of the MV/LV transformer and the earth, and the second letter characterizes the grounding of the equipment.

In the TT system, the neutral conductor of the transformer is directly connected to the earth. The grounding of the equipment is made also to the earth. It may be the same earthing system (see Fig. 8).

In the TN system, the neutral conductor of the transformer is also directly connected to the earth, but the grounding of the equipment is made through a protective earth (PE) conductor. In the TNC system, the PE and the neutral conductor are combined (PEN conductor). In TNS, the PE and the neutral conductor are separated but connected at the same point. A system that is TNC outside the building and TNS inside the building is called TNC-S (see Fig. 11).

In IT systems, the neutral conductor of the transformer is isolated (with high impedance or no connection at all except stray capacitances) and the grounding of the equipment is made to the earth.

In the US split-phase system, the neutral conductor is the midpoint of the secondary winding and is connected to the ground at the service entrance. The power may be distributed between this midpoint conductor and one conductor of the winding (120 V) or between the two conductors of the winding (240 V).

The connection of the SPD depends on the earthing system according to Table 1.

The temporary overvoltages occurring in these systems are also very different (7) as shown in Table 2.

Direct Strikes on the Lightning Protection System, the Structure, or the Surroundings

When lightning strikes a structure or its lightning protection system directly, or even the ground surrounding it, some of the lightning current flows through the ground system of the structure. This leads to a potential rise of the local ground

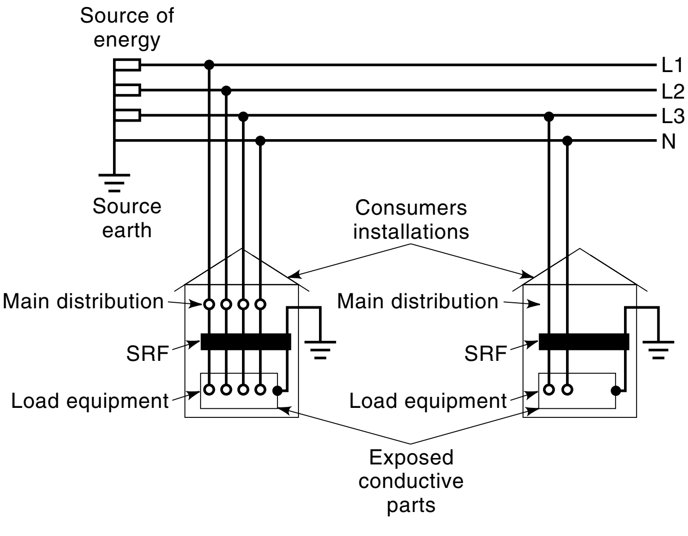

Figure 8. Typical TT system, where the neutral is not grounded at the point of entry.

Table 1. Connection of SPDs for the Different Power Systems

SPD	TT	TN-C	TN-S	IT
Between line and neutral	Yes, recommended	Not applicable	Yes, when the distance between the SPD and the common point (PE and N) is higher than 10 m	Possible when neutral is distributed
Between line and PE	Yes	Not applicable	Yes	Yes
Between line and PEN	Not applicable	Yes	Not applicable	Not applicable
Between neutral and PE	Yes	Not applicable	Yes, when the distance between the SPD and the common point (PE and N) is higher than 10 m	Yes, when neutral is distributed

compared with a remote location, which is at 0 V by definition. Ground potential rise at the lightning strike point may exceed 100 kV. For safety reasons, equipment inside the structure is bonded to this earthing system but may also be connected to services such as the power supply and telecommunications/data lines. Local ground potential rise may cause significant potential differences between the connected equipment enclosures and those services entering the enclosures that are connected directly or indirectly to remote ground. These potential differences can cause internal flashover of insulation and lead to system failure.

In addition to damaging the equipment, some of the lightning current may consequently flow through the service cables and damage other equipment within the building. Application standards now specify that equipotential bonding is necessary between all the services entering the structure and the building ground system. When SPDs are used for this bonding, their rating should be sufficient to withstand the stress of the equalizing currents flowing between the various ground points. When exact calculation of the sharing of current is not available, a rough assumption is that 50% of the lightning current flows in the earthing system and that up to 50% may flow in the power supply conductors plus telephone and cable TV conductors (8). It is generally accepted that the neutral conductor is 2 to 5 times more stressed in terms of impulse current flow than the phase conductors. A maximum value of 5% is usually assigned for the proportion of lightning current that may flow in the communication lines.

Probability of Lightning Surges on Low-Voltage Systems

There is little data regarding overvoltage statistical distribution for LV systems. The IEEE 587–1980 guide (9) gave such a distribution for locations considered as low, medium, and high exposure. IEEE 587 was upgraded to a recommended practice, IEEE C62-41 (1991). These data are based on measurement campaigns made by different bodies. More recent measures (10) have been made for overhead lines of 1 km length in different environments (open area, surrounded by trees). In addition, Electricité de France and France Telecom (11) have performed extensive research based on simulations for lines of 300 and 800 m, and this research is validated by measurements in the field. All these data present rather homogeneous trends even if direct comparison is difficult because of very different measurement conditions. Figure 9 presents all these measurements as discussed in Ref. 12. The main conclusions of the authors are as follows:

Table 2. Maximum Temporary Overvoltages for Different Power Systems

Location of the Temporary Overvoltages	System	Maximum Values for the Temporary Overvoltages
Between phase and earth	TT, IT, and TN	U_o + 250 V for duration > 5 s U_o + 1200 V for duration up to 5 s
Between neutral and earth	TT, IT, and TN	250 V for duration > 5 s 1200 V for duration up to 5 s
These values are extreme values related to faults in the high-voltage system. Exact values (in general much lower) may be calculated depending on the type of system (see IEC 364-4-442).		
Between phase and neutral	TT and TN	$\sqrt{3} \times U_o$
This value is related to a loss of the neutral conductor in the low-voltage system.		
Between phase and earth	IT system	$\sqrt{3} \times U_o$
This value is related to an accidental earthing in the low-voltage system.		
Between phase and neutral	TT, IT, and TN	1.45 × U_o for a duration up to 5 s
This value is related to short circuit between a line conductor and the neutral conductor.		
Between phase and neutral	US split system	2 × U_o for 7 h
This value is related to a loss of the neutral conductor in the low-voltage system.		
U_o is the voltage phase to ground of the system when U_n is the nominal voltage phase to neutral.		

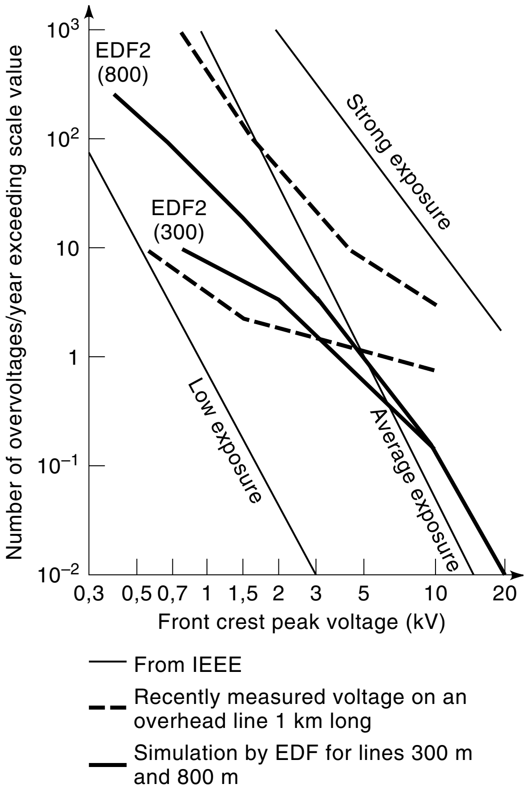

Figure 9. Overvoltage statistical distribution based on various sources.

- Recent statistical distributions are between the IEEE low and high exposure lines.
- The same lines in different environments may experience a very different number of overvoltages.
- For $N_g = 2$ strikes per year and per square kilometer, conditions corresponding to the recent curves, the statistical distributions are consistent with the IEEE medium exposure one.

In conclusion, in medium exposure conditions, when more accurate data are not available, an overhead line 1 km long in an area of $N_g = 1$ will experience between 1 and 100 overvoltages above 1.5 kV and between 1 and 10 overvoltages above 2.5 kV. This is mainly representative of induced stresses. Direct stresses are, of course, less frequent (between 5 and 10 surges per year and per 100 km for an area where $N_g = 1$), but they are more severe.

Recent calculations (13) have shown that an SPD rated to $I_{\max} = 65$ kA, 8/20 in an area where $N_g = 1$, with a 100 m long LV overhead line 8 m above ground supplying a structure of 10 m height, will have a failure rate of 1 over 1700 years in case of direct stress (direct strike on the structure) and of 1 over 5000 years in case of indirect stress (strike on the LV line far away from the structure).

Risk Assessment

Risk assessment is used to determine whether equipment must be protected against surges (14,15). Very often the answer is obvious because the equipment is so expensive or so strategic that surge protection is a minor cost compared with the potential damage to the equipment and the consequences of such damage. When guidance is necessary, however, IEC 1662 and its amendment (16) should be used. The method described in this document is very complete; however, in some circumstances it may be difficult to apply because some of the parameters may not become obvious until a system is operational. Many institutions and countries have developed simplified risk assessment methods. For example, document UTE C 15-443 (17) describes a method based only on a few parameters such as LV line length, surge withstanding of equipment, and equipment cost, among others.

INSTALLATION OF LV SPDs

Power Systems

There are several general rules to take into account when SPDs are installed on the power supply, because many phenomena may prevent the SPD from protecting the equipment.

First of all, it is recommended to install SPDs at the entrance of the installation for EMC reasons. It is always better to divert the surge at the entrance to avoid electromagnetic disturbances from surge currents flowing inside the building. Equipotential bonding should occur at the entrance to avoid flashover between conductors.

Another SPD should be installed close to the equipment if the equipment is not near the entrance SPD. At a certain distance from the SPD, located at the entrance, equipment may no longer be protected as a result of the effect of induction adding voltage to the internal cables. The maximum distance at which equipment is considered to be protected by the entrance SPD, called protective distance, may be as short as 10 m.

The need for additional SPDs near the equipment being protected arises because oscillations between the inductance of the conductor and the capacitance of the equipment may lead to a voltage at the equipment terminals, which is sometimes more than two times higher than the protective level of the SPD. Figure 10 shows a simulation of this effect for a distance of 10 m between equipment and SPD.

Total protection involves an SPD at the entrance to divert surges being conducted into the building supplemented by lower-rated SPDs, in terms of surge capability, located at the equipment to be protected. These secondary SPDs act to quench surges produced by induction and oscillations. As a general rule, a single SPD cannot protect a complete installation unless the whole area is very compact.

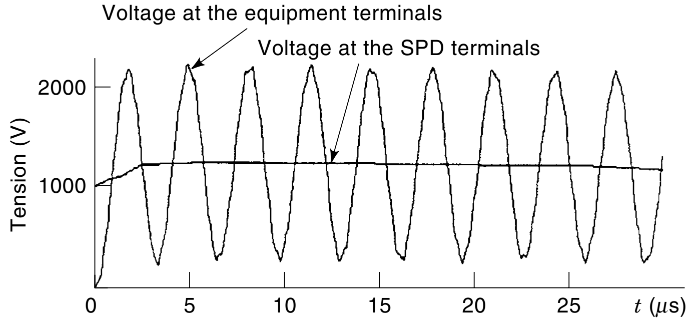

Figure 10. Doubling of voltage and oscillatory effects due to load capacitance and line inductance.

When more than one SPD is being used, the SPDs should be coordinated to share the stress between them based on their ratings (18–21). This is achieved through an impedance (which may be a lumped component or an equivalent length of conductor, which is generally calculated at 1 μH per meter length) between the two SPDs so that, for each surge below the maximum rating of the front SPD, the energy dissipated through the downstream SPD is equal to or lower than its rating. Many means for confirming coordination are available: Simulation of a particular case may be performed for complex installations, or impulse testing may be performed in laboratories. An installation may also follow the rules of a single manufacturer with access to the performance parameters of each SPD.

The SPD must be also connected to the line with minimum lead length because the length of a tee connecting conductor will add inductance in series with the SPD. As a result of the rise time of the surge current, a significant incremental voltage will be added to the protective level of the SPD. For example, consider an SPD installation with 6 in. (15 cm) total leads in line and neutral connections during a 10 kA 8/20 μs lightning surge. The inductance of the combined leads will be about 0.2 μH, and the maximum rate of rise current will be about 2 kA/μs. This will result in an inductive voltage on the leads of about 400 V, which is in addition to the normal protective level of the SPD.

There are two systems that require special attention:

1. The TT system for which an SPD between phase and neutral conductors is recommended (see the section entitled "Different Types of Power Systems"). The ground resistance of the neutral conductor at a distribution transformer is usually much lower than the resistance of the building. This leads to an imbalance of current between the phase conductor and the neutral conductor. The consequence is that, in the worst case, the voltage between phase and neutral conductors may be two times the U_p of the SPD between phase or neutral and earth. An SPD installed between phase and neutral conductors will solve this problem (SPD with three modes of protection).
2. The TNC-S system: As soon as the distance between the transition point from TNC to TNS and the SPD is too long (typically more than 10 m), a voltage drop can occur in the PE conductor; another SPD close to the equipment is then needed with a protection between neutral and earth, as illustrated in Fig. 11.

Other Systems

Basically all the phenomena detailed in the preceding section on power systems are also applicable to telecommunications and data systems, even if the situation is generally less complex. SPDs are usually installed at the interfaces close to the equipment to be protected. For telecommunications lines or other balanced lines they are installed between the pair conductors and between each conductor and the earth. For other applications, SPDs are generally directly included in connectors (RS-232 plug, coaxial connector) in front of the equipment to be protected, (see Fig. 12). In many cases, additional parameters such as SPD capacitance must be considered because of the shunt effect on high-speed signaling. GDTs in their static state offer very low capacitance, typically on the order of 1 pF to 2 pF. However, their performance to fast impulses at low voltage is restricted by the gas pressure and electrode spacings used. Modern GDTs offer good response to fast pulses, with a 230 V unit able to strike at around 450 V on a wave rise time of 10 kV/μs.

The inherent low capacitance of GDTs also makes them useful in radio circuits, where an acceptable voltage standing

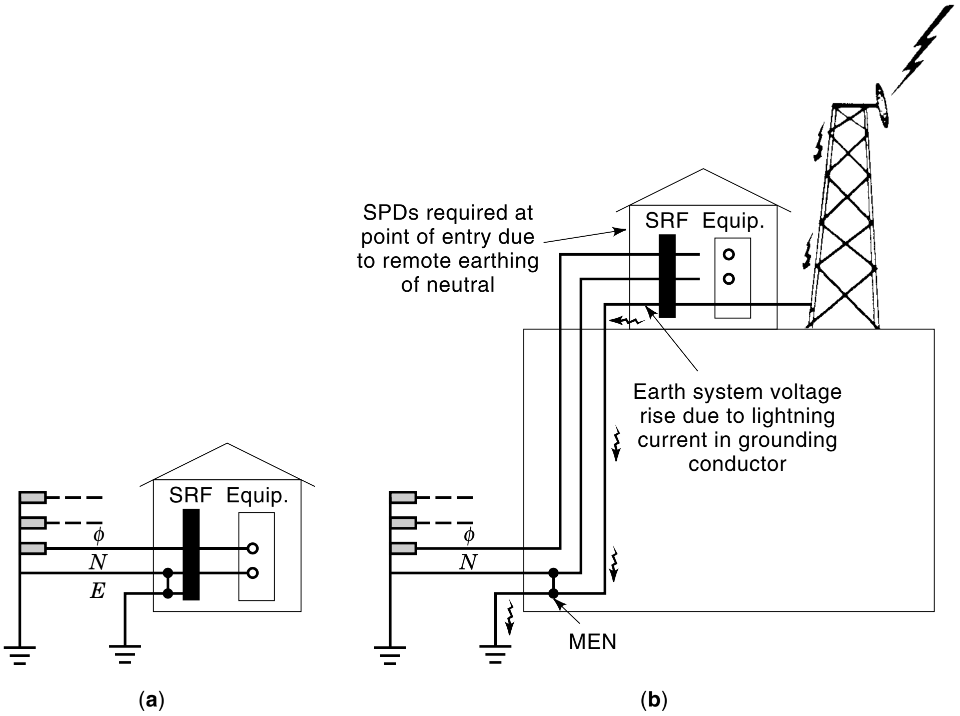

Figure 11. TNC-S system. (a) Small distance between the SPD and the TNC/TNS transition point. (b) Longer distance between the SPD and the TNC/TNS transition point. In the diagram, E = Earth; ϕ = phase; N = neutral; SRF = surge reduction filler; MEN = multiple Earthed neutral.

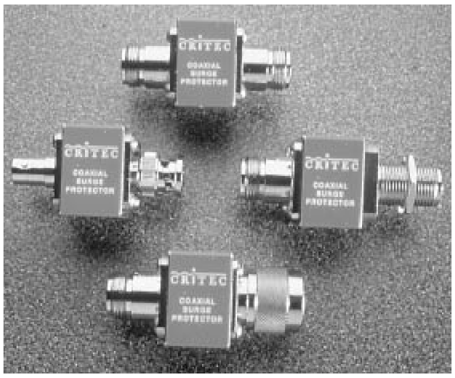

Figure 12. Typical coaxial shunt SPDs with gigahertz operation.

wave radio (VSWR, which measures the reflection due to impedance mismatch) can be maintained up to the gigahertz region. In recent years, the short-circuit stub coaxial protector has gained popularity because of its high current capability. The main restriction is that this type of protector maintains a high-impedance state over a relatively small frequency band. This frequency dependence means that these protectors must be specified or field- tuned to a specific frequency. Most coaxial gas arrester SPDs are independent to frequency.

The use of avalanche or zener diodes in bipolar format usually introduces unacceptable levels (to 1000 pF) of shunt capacitance. One technique to reduce capacitance is to use unipolar devices with a normal diode in series. The lower capacitance of the normal diode reduces the overall capacitance. Values can be reduced to about 100 pF, but bipolar operation requires paralleled reverse polarity units, which will increase shunt capacitance to 200 pF.

MOVs present high capacitance due to their close disk plate construction. Values depend on voltage and can range from 600 pF to 2000 pF.

The current trend to increase signaling rates on normal two-wire telephone circuits has presented special problems for SPDs. Signal rates of 8 Mbs are now common. The use of series resistance to act as decoupling is constrained, with resistors requiring very low self-inductance and very close resistive matching.

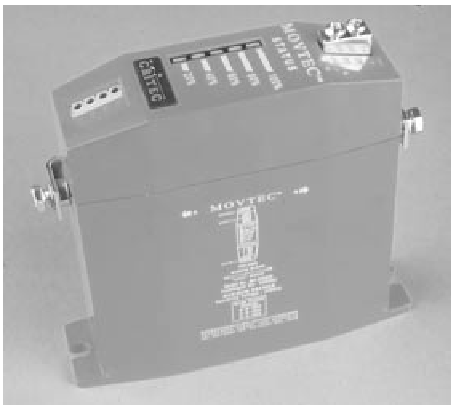

Figure 13. Typical power shunt SPD with two terminal and integrated relay for remote indication.

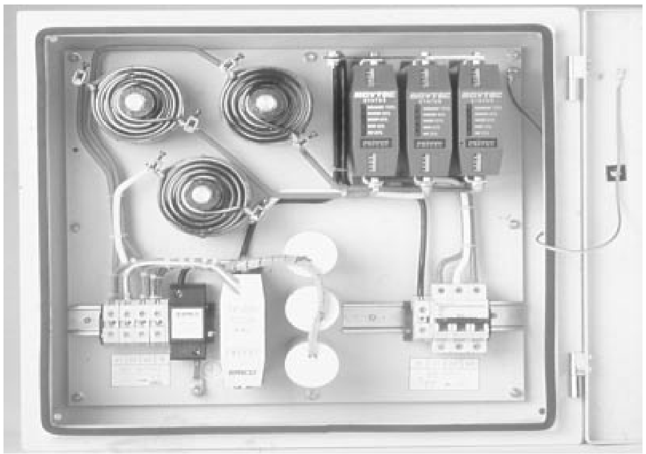

Figure 14. Typical series SPD with front shunt SPD, filter made of capacitor and inductance and second-stage SPD.

POWER SPDs

The basic families are shunt SPDs (one-port) and series SPDs (two-port). Figure 13 shows a typical shunt SPD rated for high lightning surges (waveshape 10/350). Figure 14 shows a series SPD including a shunt MOV combined to a filter.

SPDs must be protected against excessive heating (thermal protection) and against a short circuit (disconnector). For TT systems they should also be protected against high temporary overvoltages (see the section entitled “Different Types of Power Systems”).

In general, the thermal protection is included inside the SPD. The disconnector itself may be external or internal. When it is internal, the operation of the disconnector disconnects the SPD from the mains in case of SPD failure. When it is external, the disconnector (in general a fuse or a circuit breaker) may be installed in series with the line or in series in the SPD circuit. This disconnector avoids the chance that a failure of the SPD triggers the operation of the power supply current protection devices. In the first case, the system is no longer energized but is then protected against the following surges, provided that the disconnector has sufficient sparkover withstanding not to be bypassed by the following surges. In the second case, the SPD is disconnected only from the mains as in the case of the internal disconnector. The system is then still energized but no longer protected. The disconnector of the SPD should be coordinated with the power supply protection devices to ensure that this disconnector operates first (22). It is possible to simultaneously achieve continuity of power supply and continuity of surge protection, as in Fig. 15. In this case, the two varistors always have slightly

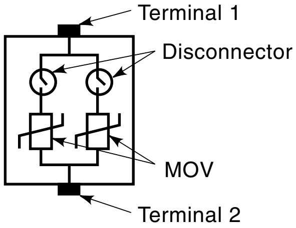

Figure 15. SPD with continuity of power supply and continuity of surge protection as a result of the use of two internal disconnectors.

different ratings (even if they belong to the same batch). One of them is weaker and will fail first, protecting the other one. Only this one will be disconnected from the mains, and thus surge protection and service continuity are ensured.

As discussed, a good general policy is to have very heavy duty SPDs at a building entrance where they can provide the lowest possible protective level. This ensures maximum energy diversion to ground and a minimum overvoltage being sent downstream to the protected equipment, assuming that the surge enters at the building service entrance. Conversely, experience has shown that fault conditions such as a loose neutral connector can cause voltage doubling at an SPD. This can result in burnout and fire, unless the thermal protector or disconnector operate properly. A conflict can therefore arise between achieving safety from fire and the lowest voltage protection level.

Two new types of SPD have been recently developed to optimize these requirements. The first is known as a transient discriminating suppressor (TDS). This type of device uses normal MOVs at the rated line voltage but places a high-speed frequency-sensitive switch in series. In the absence of a surge, line voltages may more than double, with no more than 1 mA to 2 mA leakage; under surge conditions, the protective level is virtually unaltered from that achieved in past practice.

The second concept uses a spark gap that would usually trigger at approximately 3 kV and then add a series transformer to produce an incremental voltage such that when the surge exceeds 500 V the gap will be triggered. Such a triggered spark gap (TSG) is inherently hardy and capable of handling faults because of neutral disconnection and a large range of temporary overvoltage. The novelty of this concept lies in the trigger transformer, which has a secondary that can produce a trigger voltage of 4 kV, handle a 50 kA, 10/350 surge, and have a series inductance as low as 150 nH.

Testing

Tests covered by IEC 61643-1 are performance tests, safety tests, and mechanical tests.

Performance Tests: Basically an operating duty test confirms that the SPD will work properly and will not be damaged when tested with nominal discharge current, maximum discharge current, or impulse current surges.

IEC Test Standard 61643-1 contains three basic waveshapes for surge generator testing. The waveshape chosen is determined by a manufacturer according to the declared test category.

Class 1 tests are high-energy tests carried out using a 10/350 waveshape to a maximum pulse current of 20 kA. Long tail pulses are usually associated with conducted currents such as the partial lightning currents that would arrive at a building entrance as a result of lightning striking the protection system.

Testing according to Class 2 uses a 8/20 μs wave. These tests ascertain the residual voltage and then the voltage protection level U_p. These ratings are obtained at a peak current of I_n, which is a value declared by the manufacturer, to produce a 20 impulse withstand capability. The Class 2 test is the most commonly accepted, and the upper peak pulse current (maximum discharge current) is not limited by specification.

The third test regime classifies a product according to values obtained from a combination wave generator. The generator produces an open-circuit voltage wave of 1.2/50 form and a short-circuit current of 8/20 form. Typically, such a generator is assigned a fictive source impedance. A 6 kV generator will produce a short-circuit current of 3 kA showing that it has a fictive impedance of 2 Ω. Since the device tested with a combination generator may present a variable peak current according to the device characteristic, it is usual to specify the SPD at a given charging voltage of the generator.

In the UL 1449 standard (23) the SVR is defined with a single generator (6 kV, 500 A). This allows easy comparison of various SPDs.

The devices tested according to Class 1 are not better than those tested according to Classes 2 or 3. The different test regimes are a recognition of country by country preferred test techniques. For example, the maximum peak current for a 10/350 Class 1 test is 20 kA. It is a high-energy long tail pulse. The same energy rating may be achieved using a Class 2 test wave of 8/20 form at a peak current of 90 kA. The highest test wave in the Class 3 category common in the United States is provided by a 20 kV/10 kA combination generator. This wave produces dV/dt levels to 16.7 kV/μs, which can produce high voltage as a result of the inductance of connecting conductors.

Product comparison according to the various test regimes must be carefully considered in conjunction with SPD location, exposure, among other factors. Other selection criteria include the type of power distribution system, the risk of temporary overvoltage, inclusion of thermal and fuse disconnection devices, and the ability to clamp a given surge to a level compatible with the limits of the protected equipment.

In addition, there is a test to measure the protection level of two-port SPDs and to measure the voltage drop between the two ports and the effect of the load current.

Safety Tests: These involve the end-of-life failure mode and especially the thermal protection, short-circuit disconnection, and sometimes temporary overvoltage failure mode.

Recently, UL promulgated its UL1449, 2nd ed. (23) Standard requiring a 7 h test at double line voltage without fire. Product failure was allowed, but not fire. Similarly, in France with TT distribution systems, a 1000 h test at 1.5 times U_n is required to meet the temporary system overvoltages that can cause SPD destruction. In addition, a very high TOV test (U_n + 1200 V) is also proposed for such a system. This is also noted as an IEC requirement in Standard IEC 61643-1.

Mechanical Tests: These include the usual tests preferred for other devices (e.g., circuit breakers), such as corrosion resistance, and resistance to fire.

Choice of SPDs

The protective level U_p should be lower than the surge withstanding of the equipment to allow for some margin.

The value of U_c should be selected according to Table 3.

The nominal discharge current I_n, the maximum discharge current I_{max}, and the impulse current I_{imp} should be selected based on the severity of the location and the configuration of the installation (e.g., presence of a lightning protection system, overhead lines). Risk assessment may also provide information on the selection of the rating of the SPD.

The other parameters for the SPD selection (disconnector type, short-circuit current, load current for two-port SPDs, etc.) should be based on usual electric installation rules.

Table 3. Value of U_c for Different Power Systems

System of Nominal Voltage U_n (e.g., 230 V) for a 230/400 V System)	Between Phase or Neutral and PE Conductors	Between Phase and PEN Conductors	Between Phase and Neutral Conductors
TN	Not applicable	$U_c \geq 1.1$ times Un	Not applicable
TT	$U_c \geq 1.5$ times U_n	Not applicable	$U_c \geq 1.1$ times U_n
IT	$U_c \geq \sqrt{3}$ times U_n	Not applicable	$U_c \geq 1.1$ times U_n

OTHER SPDs

Modern techniques for surge protection show the need for single-point grounding for all services. There is one ground to which all protective devices connect. In large installations, this would be located at the service entrance.

However, this principle also applies to such portable devices as power strips, which combine a power filter with an upstream SPD and a telephone/fax SPD. In such cases, all SPDs connect to the same ground, namely the power ground. This means that the downstream protected equipment has one ground that is the frame and that each service is referenced to that ground. To avoid perturbation coming from the power side propagating toward the data side, it is possible to use a GDT internally between the data ground point and the power/frame ground.

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SURGE PROTECTOR. See OVERVOLTAGE PROTECTION.

SURGERY. See LASER APPLICATIONS IN MEDICINE.