Protection of Low-Voltage Equipment and Systems

Hélio Eiji Sueta, Sergio Roberto Santos, and Ruy Alberto C. Altafim

Abstract This chapter describes the main aspects related to the protection of electrical equipment and low-voltage systems. It initially addresses the way lightning surges can occur in such systems—they can be induced by lightning strikes inside the clouds, or between different clouds; those conducted by low-voltage network conductors due to direct lightning strikes; surges from lightning strikes on medium-voltage networks; discharges that reach points near networks and are, therefore, induced in low-voltage systems; discharges that reach the LPS (Lightning Protection Systems) and return to the systems by the MEB (Main Earthing Busbar), and those induced in low-voltage systems by lightning strikes through the LPS conductors are also analyzed. The chapter details the main surge protection measures, such as earthing and bonding, shielding, routing, surge protection devices coordination, and isolating interfaces. The chapter defines the concept of Lightning Protection Zone (LPZ) for the positioning of Surge Protection Devices (SPD) and specified and detailed, types and characteristics of these devices. The chapter also covers grounding concepts, resistance and resistivity measurements, and describes the main elements and use of the earth-termination system.

Keywords Surge Protection Devices · Earthing · Overvoltage protection · Surge Protection Measures · Lightning Protection Zone

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1 Surge Protection Scenario

Low-voltage electro-electronic equipment and systems are quite vulnerable to lightning surges (Lightning ElectroMagnetic imPulses—LEMP). While lightning strikes are megajoule-energy phenomena, electro-electronic equipment can be damaged by only a few millijoules. All such damages from LEMP may be caused by either effect of electromagnetic fields radiated directly to the equipment, or conducted or induced surges transmitted to the equipment by connecting metal conductors (power cables and/or metal signal cables).

Lightning surges can affect installations, damage electronic equipment, and cause dangerous sparks that may start a fire, explosion, or electric shock, as described below.

i. Surges in low-voltage systems due to lightning strikes
a. Surges caused by cloud-to-cloud or intracloud discharges

Approximately 75% of lightning strikes occur between clouds or within them [1]. Such discharges typically last between 200 and 500 ms [2], and are especially important for studies on aircraft protection [3]. According to aviation agencies, commercial aircrafts are hit by lightning at least once a year. The electromagnetic fields generated by these lightning currents can induce surges in electrical networks. Because of the large distance between such discharges and networks, the intensity of surges caused by them is extremely low. The number of studies on this type of discharge is small, in comparison to those on cloud-to-ground discharges, whose harmful effects are much more significant [4].

b. Direct lightning in low-voltage networks

If a lightning directly strikes a low-voltage network, an extremely high voltage surge may penetrate into the facility's electrical installation, thus damaging equipment, or generating sparks that can start a fire, explosion, or electric shock. The relatively short length of such networks and especially those "shielded" by the primary network (Medium Voltage), nearby structures (e.g., buildings, houses, trees), and, in many cases, underground, substantially reduces the possibility of damage. In low-voltage rural grids, those lengths may not be so short, and lines may be more exposed, therefore, when directly hit by lightning, the damage can be severe, especially if such lines are not adequately protected.

c. Direct lightning in medium voltage networks

If a lightning directly strikes a medium-voltage network (e.g. 13,8 kV), the current injected into the struck conductor splits into two waves that propagate in directions opposite the point of impact. The value of each portion of the current multiplied by the line surge impedance, i.e., approximately 400–550 Ω [5], produces over voltages that will shutdown the power grid through disruptive discharges at some points in the line. Such disruptive discharges that occur between phase conductors and/or between phase conductors and ground will cause several voltage and current waves reflections and a reduction in the effective grounding impedance. The electrical charges (consumers near the lightning impact point) will suffer a voltage drop during the short-circuit and there will be a small interruption of the electrical energy due to the actuation of the protection system for the elimination of the failure [6]. If a lightning strikes primary networks, part of its current will be injected into a neutral conductor, thus causing overvoltages in low-voltage networks [4]. A potential rise results from the current flow through the ground resistance, which follows the operation of the lightning arrester for the protection of the transformer and/or occurrence of flashover of insulators in the medium-voltage network. Such transferred surges (medium- to low-voltage) have a wide range and depend on several factors, such as location of incident, observation point, network configuration, lightning current amplitude and waveform, and characteristics of both transformer and protective devices [4].

d. Induced surges in electrical networks

A lightning striking near electrical networks will cause induced surges, which can directly damage equipment, whether or not followed by hazardous sparks, if they occur in low-voltage networks.

Such overvoltages in low-voltage conductors can be subdivided according to the following components [7]:

- Voltages transferred from primary networks;
- Voltages associated with the lightning current portion intercepted by the neutral conductor grounding points, and;
- Voltages directly induced to low-voltage cables due to the electromagnetic coupling between the LV line and the lightning discharge channel.

In the case of voltages transferred from the primary network, we also emphasize those transferred to low-voltage networks by distribution transformers [8].

Regarding voltages associated with the current portion intercepted by the neutral grounding points, experiments performed at ICLRT (International Center for Lightning Research and Testing) in Camp Blanding, Florida, USA, must be highlighted, since lightning rockets were used [9]. According to the study, when lightning strikes a few dozen meters from the line, a substantial portion of the total current can enter the system through grounding points of the neutral conductor. For 60, 40 and 19 m distances between the line and the impact site, peak values of the currents injected into the system range from 5 to 18% of the total current of the lightning discharge.

Among the studies on surges directly induced in low-voltage networks [10] conducted experiments in which lightning induced by rockets and simultaneous measurements of induced voltages in a 210 m long low-voltage overhead line with twisted conductors showed maximum values of phase-to-ground and neutral-ground voltages between 2 and 12 kV. The line was connected at one end to a transformer and at the other to a 60 m long underground cable terminated by low-voltage surge arresters. Some launches were made and the lightning hit a tower near the cable termination and also 50 m from this point. Induced voltages were measured at the low-voltage terminals of the transformer, where current measurements were also varied from 4 to 50 kA.

Piantini and Janiszewski [11] studied the influence of several parameters on induced voltages by indirect discharges for a 300 m long single-phase line. In 2005 [12], Silva Neto and Piantini analyzed the case of multiplexed line and observed the main difference between multiplexed cable and conventional-type network was the former was characterized by a much stronger coupling between much closer conductors. The greater the mutual surge impedance between phase and neutral conductors, the smaller the amplitude of induced voltages. In the case of multiplexed cables, the conductors are braided and their impedance varies along the line. However, as the distance between the conductors is shorter than their height from the ground, the impedance variation is extremely small and can be neglected in practical cases.

All those studies confirmed the substantial impact of induced voltages on low-voltage networks [4].

If lightning strikes some point near a medium-voltage network, the surges may be transferred to low-voltage networks, thus harming the installation and probably shutting it down.

The knowledge of induced voltages in a primary distribution transformer and its frequency-related behavior is fundamental, as highlighted by Piantini [7]; Piantini [13]; Piantini and Malagodi [14]; De Conti and Visacro [15]; Borghetti et al. [16]; Piantini et al. [17].

e. Lightning in Lightning Protection Systems (LPS)

If lightning strikes LPS, the lightning current must flow through the conductors towards the earth-termination system; part of the current flows to the ground, whereas the other portion returns to the MEB. Some portions flow through MEB equipotentialized metallic conductors, which may be low-voltage cables, phone cabling, or computer networks, TV cabling, metal pipes, among others.

IEC 62305-1: 2010 [18], Protection against lightning, Part 1: "General principles", presents a calculation methodology for verifying the portion of surge currents that will flow through external conductive parts and lines connected to structures when lightning reaches the LPS of the structure in Annex E, "Surges due to lightning at different installation points".

The portion of the current that returns to the MEB will be part of the lightning current expected to strike the structure, and depends on the number of parallel paths, conventional grounding impedances of buried conductive parts (Z_1), or their grounding resistances to the aerial parts (Z_2) connected to other buried parts and the conventional grounding impedance of the earth-termination system (Z).

This IEC annex provides two formulas for buried installations and aerial installations, which calculate both current portions as a function of impedances (Z, Z_1 and Z_2) and total number of external parts of buried (n_1), or overhead (n_2) lines, and a table of the conventional grounding impedance (Z and Z_1) values as a function of ground resistivity and Lightning Protection Level (LPL) considered for protection. The data enable the estimation of the lightning current portion that will flow through the lines or metal pipes that enter the structure. After such values have been obtained, the impulse discharge current of the Surge Protection Devices (SPD) can be specified for each line, for example.

f. Surges induced in low-voltage installations due to lightning currents circulating in the LPS

The same current flowing through LPS conductors toward the earth-termination system will induce surges in the facility's internal conductors. Due to the proximity between the down-conductors and the metallic conductors inside the building, the intensities of the induced surges are high, thus threatening both their installation and structures.

IEC 62305-1: 2010 [18] in Annex E presents Tables E.2 "Conventional surge currents due to lightning flashes in low-voltage systems" and Table E.3 "Conventional surge currents due to lightning flashes in telecommunication systems". The last columns for 8/20 μs waveform for induced currents in the internal systems of the tables show surge values from the currents flowing in the down-conductor system. 10, 7.5, and 5 kA currents are estimated for Lightning Protection Levels I, II and III or IV, respectively, which enable the specification of the nominal discharge current values (8/20 μs) of the SPD to be installed in internal systems.

g. Surges in equipment and components caused by a direct effect of lightning electromagnetic fields

Electromagnetic fields generated by lightning can directly damage the electrical equipment and its components. Electromagnetic Compatibility Studies should be performed for structures containing sensitive electro-electronic equipment.

The same IEC 62305-1 [18] Tables (E.2 and E.3) show values estimated for surges induced in internal systems due to lightning strikes near the structure. 0.2, 0.15, and 0.1 kA currents are estimated for each conductor for Lightning Protection Levels I, II, and III or IV, which enables the specification of the nominal discharge current values (8/20 μs) of the SPD to be installed in internal systems closest to the equipment.

ii. Surge Protection Measures (SPM)

Surge Protection Measures (SPM) should be taken for avoiding the harmful effects of LEMP on both structures and their contents' protection, including people.

The main SPM are earthing, bonding measures, electromagnetic shielding, conductor shielding, line routing, Coordinated Surge Protection Devices system, and isolating interfaces.

a. Earthing and bonding measures

Earthing and equipotential bonding are essential for the effectiveness of SPM. The earth-termination system conducts and disperses lightning currents in the soil. Equipotentialization is a set of measures that minimize potential differences between parts of the installation and elements of the LPS and reduce both magnetic field within structures and risk of electric shock.

The Brazilian standard [19] emphasizes this concept applies only to direct current systems or, approximately, low frequencies, which is not exactly the case of lightning strikes. Such connections should be as short as possible for higher frequencies, for a voltage reduction effect between the points of equipotential bonding.

The ring earth electrode around the structure buried in the ground, the natural electrode formed by the foundation of the building and reinforced concrete, and meshed electrodes are good earth-termination system options for protection against lightning and their surges.

Main Equipotentialization Busbars (MEB) and Local Equipotentialization Busbars (LEB) are important elements for installations, since they reduce the voltage between service conductors that feed the structure (e.g., energy, telecommunication, network, cable TV, etc.), protective conductors of the electrical installation, metallic components of internal systems (e.g., enclosures and racks), and any magnetic shielding that defines, for example, a Lightning Protection Zone (LPZ) on the periphery or within the structure.

b. Shielding

Shielding, which can be a space shield in a room, or even an entire shielding building, attenuates induced surges. The space shield can be a mesh formed by conductors or metal sheet that covers the environment, or comprise "natural components" of the structure itself, such as steel from reinforced concrete columns or steel for the constructions of slabs and floors.

The conductors can be shielded by metal covers in the form of shielded cables or embedded in properly grounded metal conduits.

In general, space shields define protected zones, which can cover the entire structure, part of it, a room, or only the enclosure of the equipment to be protected.

Space shielding should preferably be defined in the early design stages of a structure, since natural components are better used and the necessary connections are more appropriately made, which reduce costs.

The shielding of internal lines, e.g. cables used in metal ducts, shielded cables and equipment in properly grounded metal enclosures, is also a good practice.

Space shields can mitigate risks calculated in accordance with IEC 62305-2: 2010 [20]. Risk management must take into consideration the widths of the grid-like shielding, distances between down-conductors, or spacing between the reinforced concrete structures acting as natural LPS.

c. Routing

The loops formed by the installation of the conductors result in surges due to the coupling with electromagnetic fields. Hazardous sparks can occur at some points of those loops, thus damaging equipment and components, and causing fire, explosion, or electric shock.

In equipment whose power is supplied with a routing and signal is fed by a different one, the route can be damaged when the electromagnetic field is generated by lightning coupling with the loop formed by the conductors, and a sparking or surge may also occur.

According to IEC 62305-2:2010 [20] and for risk analysis purposes, an unshielded cable whose installation was not regarded for the avoidance of loops can be considered an "Unshielded cable—no routing precaution to avoid loops", for loop conductors with different routings in large buildings. In this case, loops may occur with areas of the order of 50 m^2. If the looping conductors are routed in the same conduit, or if the installation is a small building of an approximately 10 m^2 loop area, "routing to avoid large loops" is considered. If loop conductors are routed on the same cable (e.g., parallel cable, three-pole cable, etc.) with a 0.5 m^2 loop area, then "routing to avoid loops" is taken into consideration, according to Table B.5 of standard [20]. Such considerations significantly influence the risk considered.

d. Coordinated Surge Protection Devices (SPD) system

Surge Protection Devices (SPD) are the main facility's components for reduction in surges. They must be installed in a coordinated manner and can reduce surges to levels withstood by the equipment with no damage caused to it. They will be defined and specified in an appropriate item.

The concept of Lightning Protection Zones (LPZ), described below, is fundamental for the establishment of locations SPD in the installation. In this respect, Annex E (informative) of IEC 62305-1 [18] (Surges due to lightning at different installation points), and the several parts of IEC 61643 standards [24] (Low-voltage surge protective devices) shall be used for power and signal systems.

e. Isolating Interfaces

Isolating interfaces are surge protection measures. In telecommunication and computer networks, the use of optic fibers is fundamental for a higher data transmission rate, since they are immune to LEMP.

Isolating interfaces are especially used for a proper separation of an existing installation from a new one in the same structure. Interference can be avoided through the use of insulating interfaces, such as class 2 insulated equipment (e.g., double insulated, without a PE conductor), isolation transformers, optic fiber cables with no metal components, and optocouplers.

2 Zonal Concept

i. General

The concept of Lightning Protection Zones (LPZ) is important for the definition of the effects of lightning on structures and their surroundings, which can be direct discharges, electromagnetic fields, and surges driven by the facility's metal conductors.

ii. Zonal concept

The concept of lightning protection zones is fundamental for the definition of Surge Protection Measures (SPM), especially for the SPD (Surge Protection Devices) location in the facility. It enables adaptations of environments with different LEMP exposures to the supportability of electronic systems. Therefore, LPZ can be defined according to the characteristics necessary for protection against lightning of an electric-electronic system (Table 1).

Zone 0, represented by light blue and green in Fig. 1, is outside the structure. It is divided into Zone 0_A and Zone 0_B. The former (light blue color, Fig. 1) is outside the structure and the protection volume given by the LPS. Objects, including people, are exposed to direct lightning strikes and their total electromagnetic field. Zone 0_B (green color, Fig. 1) is also external to the structure; however, the objects are protected against direct lightning, but not against effects of the electromagnetic fields.

The other Lightning Protection Zones are located in the structure. Zone 1 (yellow color, Fig. 1), admits no direct lightning strikes, and their electromagnetic field is attenuated by the metal in the walls of the structure.

Some structures can be divided by other LPZs internal to zone 1 (e.g., LPZ 2, 3,… n, and an LPZ 2 as a computer room with an elevated floor above the grounding screen

Table 1 Characteristics and protection conditions of an LPZ

LPZ	Characteristics	Protection conditions
LPZ 0_A	Zone of a possible direct impact from a lightning strike and no attenuation of the electromagnetic field generated	LPZ 0_A is a totally unprotected environment
LPZ 0_B	Zone of a highly improbable direct impact from a lightning strike and no attenuation of the electromagnetic field generated	LPZ 0_B is an environment protected against direct lightning, but unprotected against the effects of lightning electromagnetic impulses (LEMP)
LPZ 1	Zone of no direct impact of a lightning strike. The electromagnetic field generated is reduced by space shields created with metallic materials separating LPZ 0_B from LPZ 1	LPZ 1 is an environment protected against direct lightning strikes and effects of LEMP. Shields, equipotentialization, isolating interfaces and surge protection devices installed at the boundary between this zone and the previous zone are the SPM used for protection
LPZ n	Zone of no direct impact of a lightning strike. The electromagnetic field generated is successively reduced by the space shields created with metal structures separating LPZ 0_B/LPZ 1/LPZ 2/…LPZn	LPZ n is an environment protected against direct lightning strikes and LEMP effects. Shields, equipotentialization, isolating interfaces and surge protection devices installed at the boundary between this zone and the previous one are the SPM used for protection

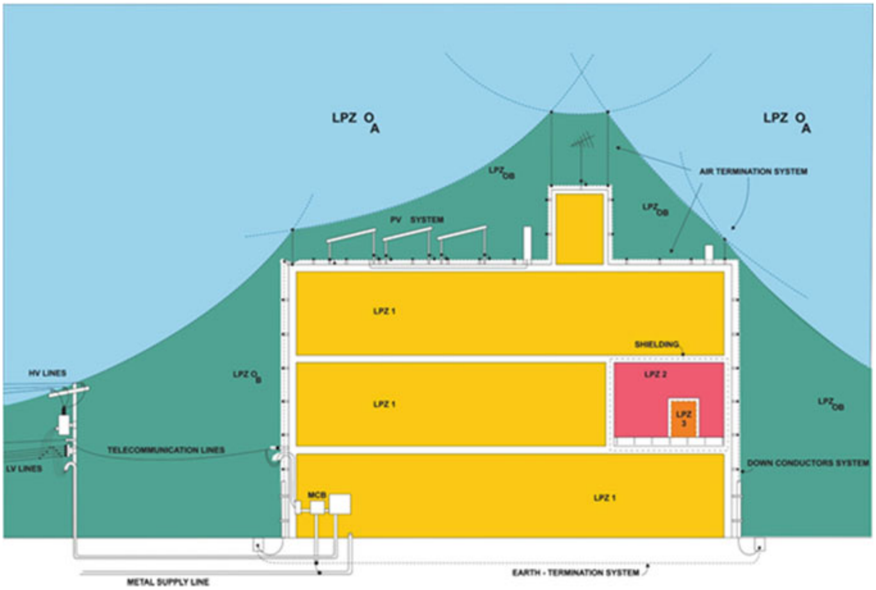

Fig. 1 Lightning Protection Zones (LPZ)

and shielding by the walls). In this case, the electromagnetic field of the lightning is further attenuated (pink color, Fig. 1).

Zone 2 might have a Zone 3 inside it (e.g., a computer network metal rack whose electromagnetic field is further attenuated (orange color, Fig. 1)).

iii. SPD positioning in LPZ

SPD should be positioned at the boundary, between the LPZs. Typically, Type 1 SPD are close to the Main Equipotentialization Busbar, at LPZ O_B and LPZ 1 interface. Type 2 SPD can be positioned at the interfaces of LPZ 1 and 2 (for example, in a Distribution Board), whereas Type 3 SPD can be located at the interfaces of LPZ 2 and 3 (for example, when entering a metal rack or entering equipment to be protected). SPD types represent the characteristics of SPD regarding the way they were tested.

Type 1 SPD, tested with a lightning surge current (10/350 μs waveform), shall be installed at the interface of LPZ O_B and 1 and subject to total or partial lightning currents reaching lines, and those that reach LPS and return to the lines through MEB.

Type 2 SPD, tested with a nominal discharge current (8/20 μs waveform), can be installed on internal LPZ interfaces and shall be subject to lightning-induced currents.

Type 3 SPD, tested with a combined wave of 1.2/50 μs waveform open circuit voltage and 8/20 μs short-circuit current of a combined wave generator with a relationship between them of 2 Ω, shall be installed at the equipment.

3 SPD Specifications

i. General

Surge Protection Devices (SPD) are electrical devices that protect an entire electrical installation, parts of it, or specific electrical equipment against transient overvoltages or surge currents. Their use is part of the Surge Protection Measure (SPM), as established by international standard IEC 62305-4:2010 [21], Protection against lightning—Part 4: Electrical and electronic systems within structures and their respective equivalent national standards. SPD protect electrical and electronic systems against transients overvoltages and surge currents originated from lightning or switching operations. They prevent electrical withstanding (dielectric strength) of an installation element from being exceeded, limiting the voltage in the system points to levels withstood by the components [22].

The operating principle of an SPD is based on a change in its internal impedance, which decreases with increasing voltage at its terminals promoting a surge current deviation to the equipotential bonding system, common mode protection, or short circuiting the conductors, differential mode protection, thus avoiding a voltage increase above that withstood by an electrical installation element, i.e. equipment electrical supportability [23].

Regarding applications, SPDs are divided into three classes or types (1, 2 and 3) arranged throughout the installation, from its origin to the equipment to be protected, and following the LPZ concept. Type 1 SPD protects the entire installation against the effects of a direct atmospheric discharge in either the building, or the utility distribution network and the electrical earthing system. Type 2 SPD are installed in switchboards or electrical panels to protect the circuits originated from these elements against residual Type 1 SPD overvoltage or installation-induced overvoltage caused by remote lightning. Type 3 SPD protects electronic devices against overvoltage originated in the installation itself and caused by voltage variations from motor starting, circuit breaker tripping or other types of switching. The specification of an SPD requires, initially, the understanding that SPD depends on its correct positioning throughout an installation according to the concept of lightning protection zones (LPZ).

Since SPDs protect power and signal lines, some parameters are common to both applications, while others are specific to power or signal. They can also be divided into two groups. The first is related to the operation of the SPD, and their parameters, called here performance parameters, refer to the protection effectiveness. The second group is comprised of compatibility parameters, related to the non-interference of SPD with the normal operation of the systems.

According to standard IEC 61643-11:2011 [24], Low-voltage surge protection devices—Part 11: Surge protective devices connected to low-voltage power systems—Requirements and test methods, the most important parameters are:

a. **Cut-off frequency ($\mathbf{f_G}$)**, which describes the behavior of an SPD as a function of frequency. It causes an insertion loss (aE) of 3 dB under specific test conditions

(IEC 61643-21). Unless otherwise specified, the specified cut-off frequency refers to a 50 Ω system.

b. **Lightning impulse current (I_{imp})**, an impulsive current standardized by waveform 10/350 μs used in SPD class 1 test. Its parameters (charge, peak value, specific energy) simulate the stress caused by real lightning currents.

c. **Maximum continuous operating voltage (U_C)**, i.e., the root mean square (rms), or D.C voltage, value of the maximum voltage in SPD input terminals during their operations. It is the maximum voltage applied to SPD in the non-conductive state, and its value depends on the nominal voltage of the system where SPD will be installed.

d. **Nominal discharge current (I_n)**, which is the peak value of the current conducted by SPD. It has an 8/20 μs waveform and classifies the test of type 2 SPDs.

e. **Temporary Overvoltage (TOV)**, which describes temporary power–frequency surges in SPDs and results from faults in high-, medium- and low-voltage systems. The SPD must have a TOV withstand capability.

f. **Voltage protection level (U_P)**, i.e., the maximum instantaneous value of the voltage on SPD terminals that represents the SPD's ability to limit the overvoltage in the protected installation.

ii. Types of SPD components and their characteristics

The SPD components can be classified into two different families, namely voltage switching SPD and limiting voltage SPD, according to their nonlinear behavior. The manufacture of an SPD involves different components and technologies. The main component is its nonlinear element, responsible for the most important SPD characteristics. The most used nonlinear components are Spark gaps, Gas discharge tubes (GDTs), Metal-oxide varistors (MOV) and suppressor diodes.

The technology defines the characteristics of the nonlinear components and the way SPD will be manufactured. Performance characteristics of an SPD and its constructive aspects interfere with its efficiency as a surge protector, its life cycle, maintenance and selling price.

As addressed elsewhere, SPDs are divided into 3 different classes or types of protection, namely 1, 2 and 3, of specific purposes in the surge protection. Although any nonlinear component can be used in the manufacture of an SPD of any type, spark gaps, varistors, and diodes are typically used in type 1, 2 and 3, respectively. Variations in their use are considered exceptions, rather than rules, at the time of publication of this book.

a. Surge Protection Device Switching type

The SPD switching type has an extremely high impedance when the voltage in its terminals is the normal, but to chance suddenly its impedance to a low value when the voltage increase. Typical examples of switching components in the manufacture of an SPD switching type are spark gaps, gas tubes, thyristors and triacs. Such types of SPDs are also called crowbar types.

b. Surge Protection Device Voltage Limiting type

The SPD voltage limiting type also has extremely high impedance when no voltage surge occurs and the voltage in its terminals is normal; however, it is continuously reduced when the voltage starts to increase. The most common examples of components used in the manufacture of an SPD voltage limiting type, also called SPD clamping type, are varistors and suppressor diodes. A clamping device absorbs much more transient energy internally than a similarly rated crowbar device [25], i.e., a crowbar device is more appropriate for conducting an energy of a surge.

c. Spark-gap

Studies on electric discharges in gases date from the late nineteenth century [26], and have led to the development of the first spark gap devices and their use as electric switches. Spark gaps were the first option for the manufacture of an SPD, and consist, basically, in an arrangement of two electrodes separated by a certain distance by an insulating medium, usually a gas, such as air, calculated in a way a sparking can occur from a specific voltage value between the two terminals. When the potential difference between the conductors exceeds the dielectric stiffness of the insulating medium, the sparking occurs and an electrical current flow until the path of the ionized gas is either broken or reduced to below a minimum value. When the voltage between the two electrodes reaches a value higher than the dielectric strength of the air, i.e., approximately 3 kV/mm under specific conditions, an electric arc is created. In comparison to the impedance under normal conditions in the order of giga-ohm, the impedance of the electric arc is very low, and the spark gap changes its state to a closed electrical switch, where the drop voltage between the electrodes is the residual voltage of the spark gap.

An advantage of the spark gap technology is its exceptionally low impedance, which promotes the passage of a high surge current in the SPD without dissipating much energy. The spark gap characteristic is especially useful when discharging lightning currents. The spark gap can discharge extremely high lightning currents (10/350 μs) of the several tens of kilo Amperes. Because the lower the residual voltage of the spark gap, the lower the energy input to electrical installation protected. Due to the extremely fast change in the internal impedance of the spark gap and the behavior of the voltage difference across their electrodes, the spark gap is known as voltage-switching device.

Spark gaps suffered from two serious drawbacks in the past. The first was the electrical arc caused the release of hot gases, which might damage the SPD and the surrounds. The other, and much more significant drawback was the short circuit between the line and the ground caused by the electrical arc was not spontaneously interrupted after the lightning current had finished.

To avoid the first drawback, the new Spark Gaps are encapsulated in enclosures, so that in discharge situations, no ionized hot gases created by the electric arc escape into the environment and burn the electrical components around the SPD. Another important characteristic of modern spark gaps are their triggering devices, which

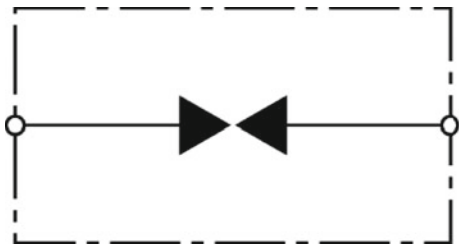

Fig. 2 Spark gap symbol

decrease their response time to limits the voltage protection level to a very low value, lower than the voltage of older spark gap based on the dielectric strength of the air.

Regarding the second drawback, modern spark gaps have built-in follow current interruption systems that interrupt these currents that might pass through the SPD after it has conducted surge currents. Figure 2 shows a spark gap symbol.

d. Varistors

Varistors (voltage-dependent resistors) are nonlinear resistors, whose resistance decreases when the voltage magnitude increases in the terminals, thus exceeding the maximum continuous operating voltage. The correlation between the voltage in the varistor terminal and the current it conducts is given by:

$$I = K \cdot V^{\alpha} \tag{1}$$

where α is the non-linearity coefficient of the varistor and represents a V/I ratio. The greater its value, the better the varistor surge protection. Because of their characteristics, varistors are known as voltage limiters, or clamping devices.

Due to their attributes, MOVs are currently the most widely used components in SPD manufacture. They are composed of a thin disk wafer of a material (metal oxide) of a known voltage breakdown characteristic and developed using zinc oxide because this chemical compound has better nonlinear characteristics (α), far superior to older silicon carbide varistors.

At low voltages, an MOV conducts a very weak electrical current (micro-amperes); however, when the voltage in its terminals approaches the breakdown value, it begins to conduct a much stronger current, which enables the surge current to be shunted to the equipotential bonding and avoids overvoltage in the electrical installation. When the varistor is subjected to a voltage higher than its rated voltage, the interfaces between zinc oxide grains are affected by the electric field. The main effect is a reduction in the electrical resistance and conduction of a surge current from an indirect lightning, for example. When the surge ceases, the electric field decreases, the electrical resistance between the grains rises, and the only current flowing through the varistor becomes again the leakage current.

Fig. 3 Varistor symbol

Fig. 4 Diode suppressor symbol

An important characteristic of varistors is their aging since they have a “service life” and should not be installed without proper supervision. MOVs have a large, but finite capacity to absorb energy; therefore, after a given number of operations, they suffer a failure and must be replaced. Their operations succeed when the component is new, however, when subjected to large or repetitive surge currents, the high temperature resulting from the passage of electrical current may fuse the zinc oxide grains, thus reducing the insulation between them and between the electrodes of the varistor. The fusion phenomenon increases the steady-state leakage current, which increases over time and may even result in a short circuit of the component. Figure 3 shows a varistor symbol.

e. Suppression diode

A transient-voltage-suppression (TVS) diode is an electronic component also used in the manufacture of an SPD. Standard and Zener diodes can also be used for surge protection, however, they are designed specifically for rectification and voltage regulation, and are not as reliable or appropriate as TVS diodes.

A TVS diode is a clamping device, suppressing the overvoltage and always come back to its previous state when the overvoltage is finished. It normally responds to overvoltage in less time than other SPD components (e.g., spark-gap or varistors), i.e., in picoseconds, and, consequently, is used mainly in type 3 SPD.

Figure 4 shows a diode suppressor symbol.

4 Earthing Concerns

In LPS, earthing systems are elements that enable lightning or fault currents to safely flow into the ground and protect individuals near grounded installations against critical electrical shocks or other electrical injuries. The soil normally has high electrical resistance concentrated next to the point of contact, between the electric system and

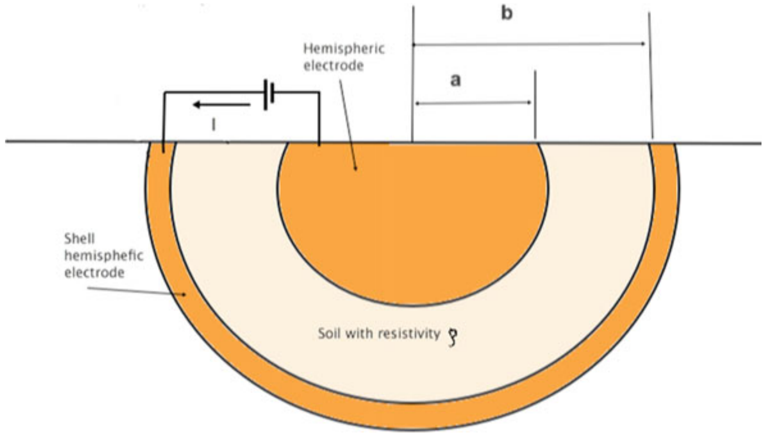

Fig. 5 Electrical Resistance (R_e) between a hemispheric electrode and a shell hemispheric electrode filled with a soil of resistivity (ρ)

the soil. Such resistance, called Earth Resistance, can be significantly reduced by the introduction of metallic elements, such as natural electrodes, rods, cables or wires, properly interconnected and defined in a specific earthing system project. However, the resistivity of the soil and existence of other metallic materials or water in its vicinity must be known for a project of this system. Such features are best described in the following topics.

i. Earthing resistance

The earthing resistance can be better understood by considering the electrical earthing resistance between a conductive hemisphere of radius (a) and a hemispheric shell of radius (b), separated by a soil of resistivity (ρ), as illustrated in Fig. 5, calculated as:

$$R_e = \frac{\rho}{2\pi}\left(\frac{1}{a} - \frac{1}{b}\right) \tag{2}$$

If the radius of the hemispherical shell (b) tends to infinity, the electrical resistance of this hemispherical system becomes only

$$R_e = \frac{\rho}{2\pi}\left(\frac{1}{a}\right) \tag{3}$$

This resistance (R_e) is called earthing resistance of the hemispheric electrode, and as it can be seen only a function of local parameters, such as soil resistivity and the hemisphere radius.

Figure 6 displays it as a linear region, which can be also determined in the field, as shown in Fig. 7. In this case, an electrical voltage (V_1) is applied between the earthing system and an auxiliary electrode away (h1), and a current (I) circulates in

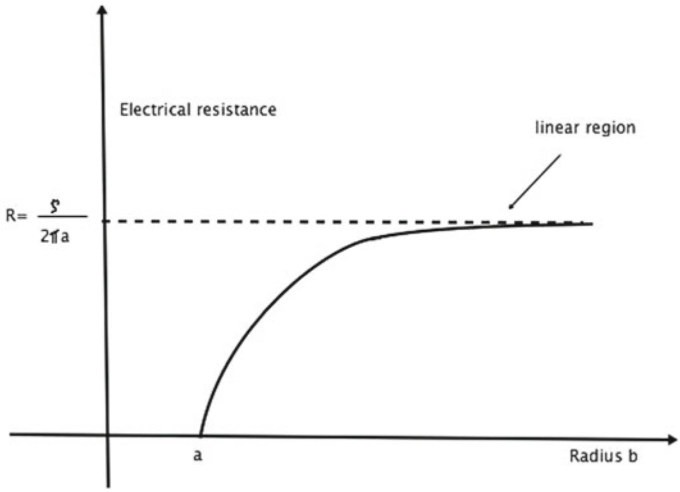

Fig. 6 Resistance of a metallic hemispheric electrode of radius (a) in the soil with resistivity (ρ)

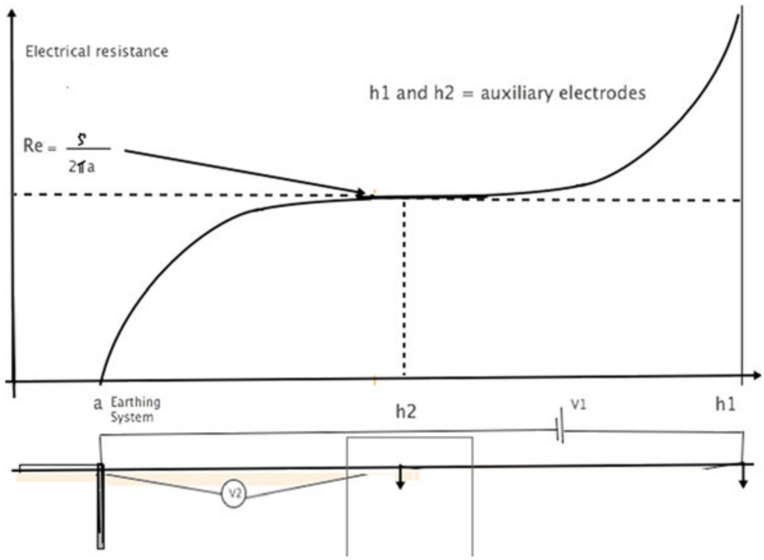

Fig. 7 Measurement of the earthing system resistance in the field

this circuit. The resistance (R_e) is given by the measurement a voltage (V_2) between some point of the earthing system and another auxiliary (h2) sticked in a middle point of the earthing system and the auxiliary electrode (h1), as

$$R_e = \frac{V_2}{I} \tag{4}$$

Special care must be taken regarding the distances of electrodes (h1) and (h2) towards the avoidance of their interference with the measurement, and presence of the linear region.

Resistance (R_e) depends on the materials of the electrodes, cables and their connections, types of contact between the electrodes or cables (whether exothermic welds or pressed connectors), soil characteristics, including temperature and humidity, and geometry of the arrangement of the electrodes on the ground. The first two factors, i.e., materials and types of contact, are often ignored, especially due to their low resistivity and low influence on resistance (R_e). However, they may increase over time because of the corrosion effect of the electrodes connections involved. The other two factors, i.e., soil resistivity and geometry, effectively influence the resistance value (R_e).

The earthing resistance of other electrode configurations can be calculated analytically or digitally by several methods. However, one of the first calculations was proposed by Dwight in 1936 [27] and has been widely applied. For instance, the earthing resistance of a cylindrical rod driven vertically into the soil of resistivity (ρ), driven length (L), and radius (r) is given by

$$R_e = \frac{\rho}{2\pi L}\left(ln\frac{4L}{r} - 1\right) \tag{5}$$

For a buried straight wire of length (2L), we have

$$R_e = \frac{\rho}{4\pi L}(ln\frac{4L}{r} - 1) \tag{6}$$

Another useful earthing system, such as two cylindrical rods driven vertically in parallel at a distance longer than 3 m, or groups of such rods we can find the formulas in the same reference [27].

ii. Soil resistivity

Soil composition, temperature, water-retention capacity and seasonal variations (Table 2) [28] strongly influence the soil resistivity value, measured in [Ω·m]. Regarding moisture retention capacity, one of the most important characteristics of the soil is, basically, a function of its porosity or compaction. In fact, according to earthing system designers, “the best soil is water”. Such a statement carries a logical meaning, because in very humid soils, soil resistivity is very low and high electrical currents rapidly tend to disperse, whereas in dry or moderately wet soils, the drainage of such currents may be hampered by water evaporation and further increase in soil resistance.

Table 2 shows typical resistivity values; however, according to ANSI/IEEE std 80 [29], Loboda [30], such values can dramatically change (see Table 3), thus requiring on-site measurements for the obtaining of effective resistivity values. Soils of heterogeneous mineral and geological formation and whose resistivities vary from one point to another are beyond the scope of this chapter. However, the determination of an equivalent electrical resistivity for those soils can be found in reference [31].

Table 2 Typical soil resistivity of various types of soil

Type of soil or water	Typical resistivity (Ω·m)
Sea water	2
Clay	40
Ground well and spring water	50
Clay and sand mix	100
Shale, slates, sandstone	120
Peat, loam and mud	150
Lake and brook water	250
Sand	2,000
Morane gravel	3,000
Ridge gravel	15,000
Solid granite	25,000
Ice	100,000

Table 3 Variation of soil type resistivity

Soil type	Resistivity (Ω·m)
Wetlands, slime, humus, mud	Up to 150
Arable, clay-sandy soils	50–500
Clay	40–5,000
Sand	1,000–8,000
Limestone	500–5,000
Granite and sandstone	100–10,000
Basalt	10,000–20,000

iii. Earthing elements

Earthing systems also comprehend three other important components, namely earthing electrodes, cables and connectors. Cables and metallic rods of different shapes and dimensions are normally used as earthing electrodes. Figure 8 shows one of such electrodes, i.e., one of cylindrical shape of length (L) and diameter (D). Electrodes can be inter-connected by cables and connectors in different geometries, thus forming the earthing system. Each geometry is used to reduce the earthing resistance and applied to a specific soil. For instance, in rocky soils, the widely used geometry is the interconnection of cables that extend horizontally over long distances. However, numerous metal elements (e.g., pillars and beams) can also be used as earthing electrodes in a building, and, when properly connected, metal structures can be an excellent earthing system.

Another solution with good results is to encapsulate the electrodes in the concrete. In contact with the soil, concrete may show approximately 3,000 [Ω·m] resistivity at 20 °C, which is generally lower than the soil itself. However, regardless of the electrodes or metal structure used, all metal elements must be interconnected for

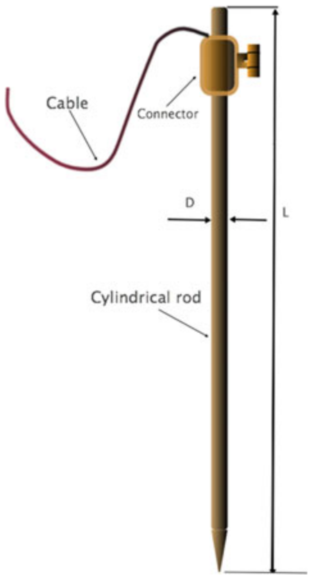

Fig. 8 Cylindrical metallic rod with connector to the cable

ensuring the grounding system becomes equipotential, with an earthing resistance below 0.25 Ω. Bare copper cables of 50 mm^2 (1/0 AWG) minimum dimensions and 7 wires of 3.00 mm diameter each are normally used for such connections. In rocky or sandy terrain, the soil tends to be very dry and show high resistivity, and foundations, metal strips or horizontally buried cables are the most suitable solutions both technically and economically. Mechanical connectors, exothermic welds, and pressure connectors are important elements for connecting cables to electrodes or metal structures. While mechanical connectors are of easy installation and disconnection of part of the grounding system during inspections and ground resistance measurements, they may suffer from corrosion or poor contact problems, which can be avoided by some special protection (e.g., paints, enamels, oxides and other metals). Crimp wire connectors are also of easy installation, have low contact resistance and face no corrosion problems; however, they enable no disconnection from the grounding system. Finally, exothermic welds promote a permanent connection between two metal components, thus preventing corrosion between them and contact-resistance problems. This technique, called aluminothermic chemical reaction, consists in an exothermic chemical reaction at 900 °C average temperatures, involving a heavy metal oxide (e.g., copper oxide) and a reducing agent (e.g., aluminum oxide). The copper oxide is reduced by aluminum, thus resulting in a copper alloy that forms permanent molecular bonds between welded materials. The corrosion process of such bonds is similar to that of the joined components. Figure 9 shows an example of this type of weld.

However, the grounding system designer decides on the most suitable type of connector to be used.

Fig. 9 **a** An electrode and a cable being prepared for exothermic welds. **b** Final results of the weld

iv. Measurement of soil resistivity

Wenner's method [32] (Fig. 10) is the main method for measurements of soil resistivity. It consists in measuring the soil resistivity of four metal rods grounded to a depth (b) and equally spaced by a distance (a). The electrical current (I) is measured by the connection of a voltage source to the two external rods located at points 1 and 4. This current (I) flowing through the ground between these electrodes produces a potential difference between points 2 and 3, called voltage (V_{23}). The relationship between voltage (V_{23}) and current (I) is the resistance (R_t) or $R_t = \frac{V_{23}}{I}$. With the resistance (R_t) known, we can have

$$\rho = \frac{4\pi a R_t}{1 + \frac{2a}{\sqrt{a^2+4b^2}} - \frac{2a}{\sqrt{4a^2+4b^2}}} \tag{7}$$

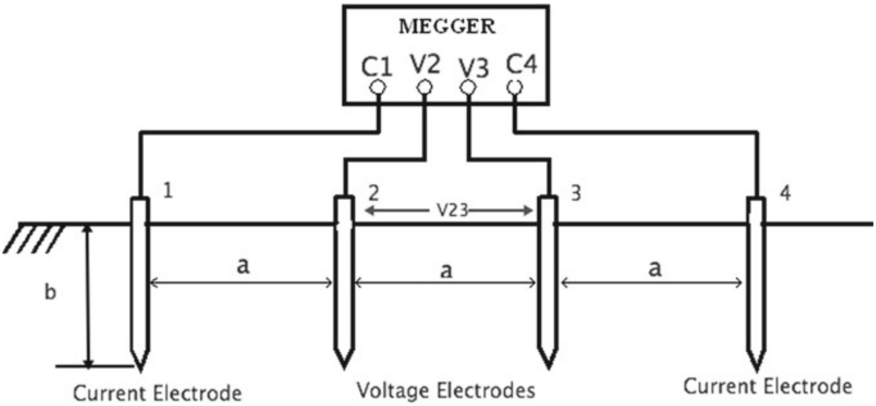

Fig. 10 Measurement of earthing resistivity

In case the parameter (b) is large in comparison with the parameter (a),

$$\rho = 4\pi a \ R_t \tag{8}$$

and in case the parameter (b) is small in comparison with the parameter (a)

$$\rho = 2\pi a \ R_t \tag{9}$$

Variations in the distances (a) between the electrodes (e.g., 1, 2, 4, 8, 16, 32, 64 m) provide data for soil stratification in two or more soil layers [31].

v. Earth-termination system for protection of structures

For lightning-protection purposes in buildings, the earthing system may be the foundation itself, a mesh system or a grounding ring around them, but also connected to the MEB inside the power distribution board to be the earth reference for the protection of internal systems and electrical equipment. An important premise to be established is all connections to the earthing system should be as short and straight as possible. It is important to reduce the effects of current reflections, since lightning currents have high-frequency components. Figure 11 shows an example of a MEB.

Fig. 11 Example of a Main Equipotentialization Busbar (MEB)

Fig. 12 Earth joint box and connections

As an effective Surge Protection Measure (SPM), all non-energized metallic elements of a building and points of earthing of some equipment, especially SPD, must be connected to the same earthing system for guaranteeing equipotentialization, since the separation distance was not achieved [33]. In the case of SPD, their grounding shall be as short as possible, i.e., at most 0.5 m.

Large buildings require the installation of Local Equipotentialization Busbars (LEB) (on the same or different floors), also connected to the MEB and always referenced to the same earthing system. A single earthing system is recommended for lightning-protection purposes and, when adopted, it must include the LPS, the electrical system, and the signal system (telecommunication and computer networks). However, if a building has more than one non-connected earthing system, spark arrestors must be used to connect them [34]. Figure 12 shows a test joint box and connections to the down-conductor system and grounding ring.

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