



Protection of Electronic Equipment Inside Buildings: A Hidden Source of Damages

A. R. Panicali
Proelco
Campinas, Brazil

J. Pissolato Filho
Unicamp
Campinas, Brazil

C. F. Barbosa
CPqD
Campinas, Brazil

J. C. O. Silva
APTEMC
S. J. Campos, Brazil

N. V. B. Alves
Termotécnica
Belo Horizonte, Brazil

Abstract — This paper shows that the criteria for the installation of surge protective devices (SPD) in power distribution panels as prescribed in standards on lightning protection and on low-voltage electrical installations may not prevent damages of sensitive electronic equipment, regardless of the protection level of the SPD and ground impedance. This is due to a not so evident source of damages related to incidental flashovers occurring between the equipment frame and grounded structures such as the floor underneath. This paper investigates this issue from experimental and theoretical approaches and provides some procedures in order to avoid such type of damages.

Keywords - *electronic equipment; sensitive equipment; surge protective devices; SPD; flashover; spark; explosive (flammable) atmosphere; lightning; lightning protection.*

I. INTRODUCTION

The protection of electronic equipment against lightning surges is a subject of increasing concern due to the ever-growing and widespread use of information and communication technology (ICT) equipment and their relevant role in modern life. This fact has been recognized by the international standards for lightning protection, where requirements are stated both for the equipment intrinsic resistibility [1]-[2] and for the installation of protection measures in the buildings [3]. There are also a number of publications in the technical literature addressing the shielding effect provided by the building structure on the inducing electromagnetic fields, as well as the assessment of the induced voltages into metallic loops [4-11].

The protective measures and the calculation techniques, as stated in these publications, work fine when the topology of the cabling is known. However, lightning flashes may create hidden flashovers within the installation that will lead to formation of unexpected closed metallic loops. As discussed in this paper, the voltages induced by these loops due to the current circulating on them may jeopardize the ICT equipment, even if they are protected according to the standards, even with idealized SPD and perfect, zero-ohm grounding impedance. Furthermore, the eventual sparks in unexpected, hidden locations may represent severe risks of fire and explosion in flammable atmospheres.

II. THE HIDDEN SOURCE OF DAMAGES

When a lightning flash strikes a building, the stroke current flows through the building grounding system and through the metallic services connected to the building, i.e. power lines, telecommunication lines, metallic water plumbing etc. Fig. 1, adapted from IEC 62305-4 [3], shows this situation for a building attended by a single metallic service (low-voltage power line). As a first approximation, the standard considers that 50% of the stroke current flows through the grounding system and the other 50% flows through the power line. This latter portion of the stroke current goes through the SPD installed at the service entrance.

Fig. 2, adapted from [12] (also [13]), shows the restrictions usually placed on the length of the SPD connecting wires, in order to limit the inductive voltage drop. It is clear in the figure that the inductive voltage drop in the SPD connecting wires will add to the nominal protective level of the SPD.

It is worth mentioning that the standards [12]-[13] do not limit the length of the conductor connecting the main earthing terminal (MET) to the building grounding system. However, as shown in Fig. 3, the inductive voltage drop in this conductor leads to an impulsive voltage between MET and ground. The longer this conductor, the higher the impulsive voltage. Moreover, part of the voltage drop across the building grounding conductors may add to the impulsive voltage. However, as shown in this paper, depending on the length of the conductor between MET and ground, flashover may occur even for perfectly conducting ground plane. As indicated by the blue arrow in Fig. 3, a similar phenomenon may occur if the power line carries a lightning surge towards the building.

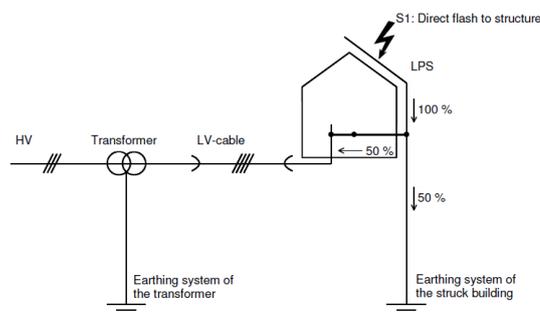


Figure 1. Part of the stroke current flowing through the low-voltage power line (adapted from [3]).

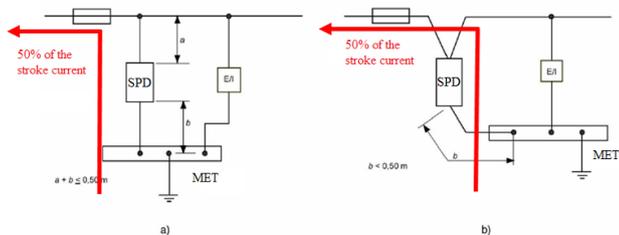


Figure 2. Limiting the SPD connecting leads in order to limit the inductive voltage drop (adapted from [12],[13]).

Depending on the length of the conductor between the MET and the grounding system (see L_{bt} in Fig. 3), the resulting voltage V_{bt} between the MET and the ground may lead to a flashover between the equipment cabinet and ground. This flashover will lead to a current I_{bb} flowing between the MET and the ground through the equipment frame, resulting in an inductive voltage, which adds to the SPD voltage, leading to a total voltage V_{bb} between the power conductors and the equipment frame.

A similar situation can take place, even without flashover, when I_{bb} flows through interconnecting cables, e.g. protective PE conductors, equipotential bonding and cable shields, as shown in Fig. 4.

Also, in case of large closed loops in buildings hit by direct lightning, with no participation of the grounding system, an induced current will flow and give rise to common mode (CM) induced voltage (V_{bb}) on the AC ports of the interconnected equipment, by the same coupling mechanism (transfer inductance between PE conductor and live conductors). Note that for this configuration the better the SPD (lower protection level), the higher the voltages transferred to the AC ports. Other equipment interfaces (signal and data lines) can also be stressed by similar mechanisms: transfer inductance or transfer impedance in case of shielded cables.

III. EXPERIMENTAL RESULTS

A set of experiments was carried out in order to assess the magnitude of the impulsive surges described in the previous section. The experiments were conducted at the High Voltage Laboratory of the State University of Campinas (UNICAMP), using a current impulse generator.

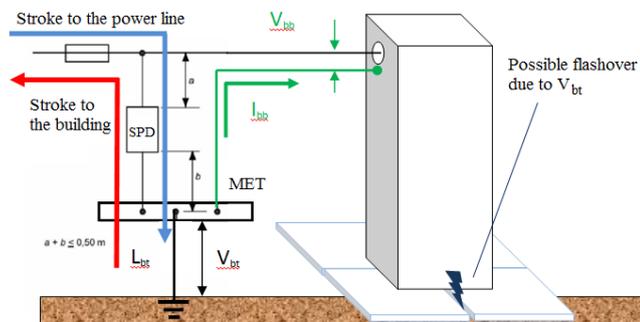


Figure 3. Unexpected surge current path (I_{bb}) due to flashover between the equipment cabinet and ground.

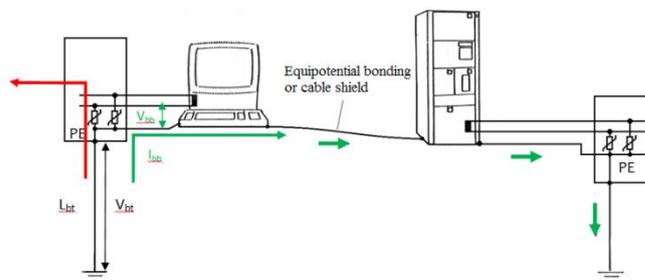


Figure 4. Current path through interconnecting cables.

A. Description of the test setup

Fig. 5 shows a diagram of the test setup. The current impulse generator was connected to a ground plane formed by copper plates covering the laboratory floor. The impulse generator discharges to the ground through a copper bar intended to represent the MET of an installation, which is connected to the ground plane by a 5 m cable that passes inside a current probe (Pearson model 110). A 2 m conductor connects the MET to the equipment frame, whereas another similar conductor connects the MET to a high voltage probe (Tektronix model P6015A) installed inside the equipment frame and referred to it. This voltage probe emulates the equipment circuitry inside the frame. Note that an SPD that would be connected to the MET was replaced by a short circuit, in order to highlight the inductive voltage drop V_{bt} .

The frame of an electrical panel box (40 cm \times 30 cm) was used to emulate the equipment frame, which was placed over insulating tiles normally used as floor covering. Sheets of paper were placed between the floor tiles and the copper ground plane, in order to provide visual marks of flashover. Figs. 6 and 7 show the panel box placed off the floor and on the floor, separated by an insulator, respectively.

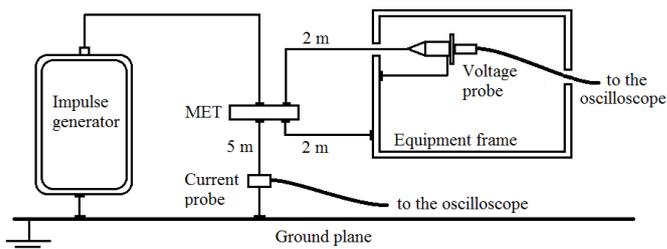


Figure 5. Description of the experimental setup.

B. Experimental results

This section presents the results of the experiments. The electrical panel box was initially placed over an insulator, as shown in Fig. 6. The impulse generator was activated, in order to inject an impulsive current to the ground plane (see Fig. 5). Fig. 8 shows the current waveform measured by the current probe shown in Fig. 5, with no flashover occurrence. As seen, this current looks like a sinusoidal half-cycle, with a duration of about 35 μ s. The current peak value reaches 14.5 kA, corresponding to a maximum time-derivative of 1.1 kA/ μ s.



Figure 6. Electrical panel box over an insulator.

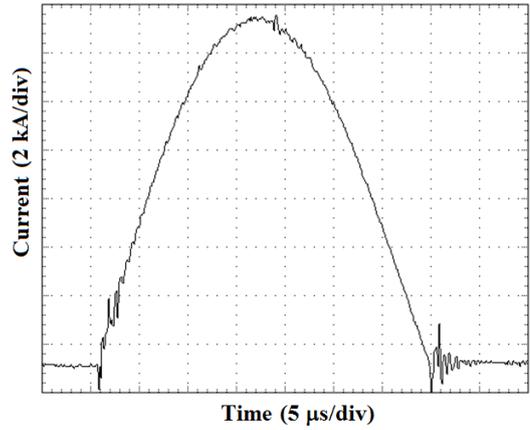


Figure 8. Current flowing from the MET to the ground plane (see Fig. 5) without flashover under the electrical panel box.



Figure 7. Electrical panel box on the floor, over insulated tiles and paper sheets.

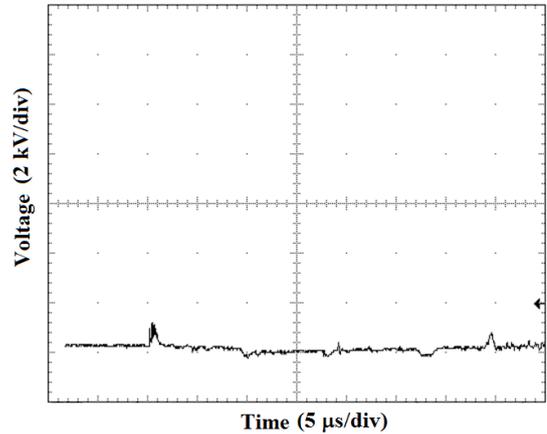


Figure 9. Voltage recorded inside the electrical panel box (see Fig. 5) when there is no flashover to ground.

Fig. 9 shows the voltage recorded inside the electric board (see Fig. 5). As expected, this voltage is relatively small, whereas the peaks result from stray capacitive coupling with the instrumentation and some inductive coupling to the wiring between MET and electrical panel box.

Next, the electrical panel box was placed directly over the covered floor, as shown in Fig. 7. This situation is closer to that in real electrical installations. The experiment was repeated, with the impulse generator applying a current pulse to ground (see Fig. 5), which caused a flashover from the electrical panel box to the copper plates. The flashover was clearly identified by the charring of the paper sheets installed between the insulating tiles and the copper plane, as shown in Fig. 10.

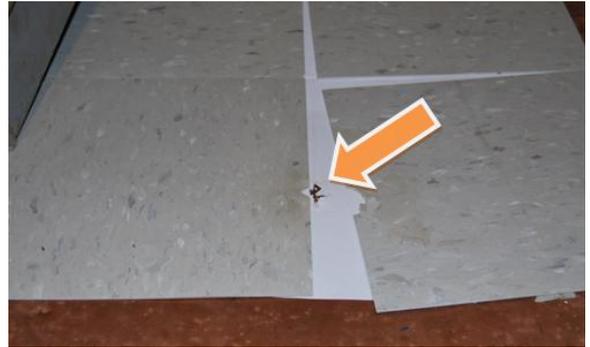


Figure 10. Charring of paper sheets due to flashover.

Fig. 11 shows the waveform of the current flowing directly from the MET to the ground plane (see Fig. 5), with 5.3 kA peak value. Assuming that the total current delivered by the impulse generator was close to the one shown in Fig. 8, it comes out that a current having peak value around 9.2 kA passed through the electrical board to ground. The higher portion of the current flowing through this path may be explained by the shorter conductor (2 m) connecting the MET to the panel box, in comparison with the one between the MET and the ground plane (5 m).

As shown in Fig. 10, the CM voltage between the MET and the ground plane was sufficient to produce a flashover between the electrical panel box and the ground plane. The experiment was repeated a number of times and the flashover always took place through the junction between the insulating tiles. Indeed, a previous (unpublished) investigation has shown that impulse flashover voltage at the center of similar tiles was about 50 kV, while at its borders it felt to values around 5 kV.

Fig. 12 shows the voltage recorded by the voltage probe placed inside the electric board (see Fig. 5), which reaches a value close to 3.5 kV. This voltage is due to the flow of the impulsive voltage through the inherent inductance of the connection between the MET and the panel box. The waveform shows discontinuities at the inception and at the end of the flashover, when the current time-derivatives reach its positive and negative peak values. The inductive nature of this voltage can also be observed from its zero-crossing at about 20 μ s, which corresponds to the peak value of the current (null time-derivative). Moreover, the voltage polarity is also related to the current time-derivative, being positive for an increasing current and negative for a decaying current. It is important to highlight that, in a real installation, this impulsive voltage will add to the residual SPD voltage, so that the resulting voltage may exceed the resistibility level of the equipment.

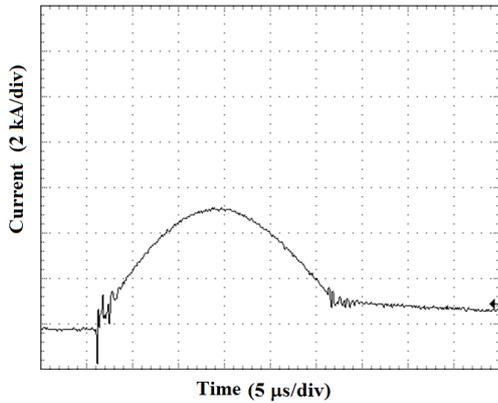


Figure 11. Current flowing from the MET to the ground plane (see Fig. 5) with flashover under the electrical panel box.

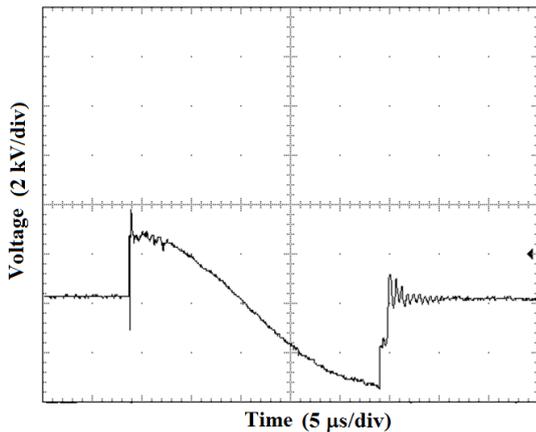


Figure 12. Voltage recorded inside the panel box (see Fig. 5) when there is flashover to ground.

IV. NUMERICAL RESULTS

Fig. 13 shows the configuration used to model the experiment described in the previous section. The numerical calculation was carried out with software 4NEC2 [14], which is based on the Method of Moments. The translation of the results to the time domain was carried out using the methodology described in [8].

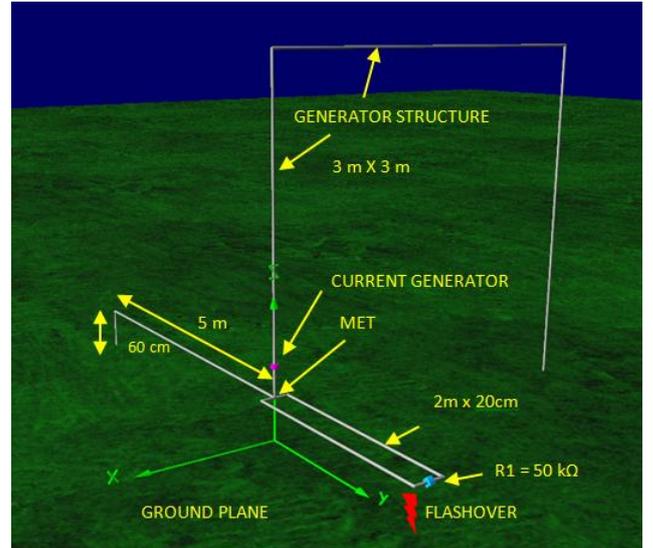


Figure 13. Model used for the numeric simulation of the experiment.

The impulse current generator was modeled as an ideal generator in series with a 9 m conductor arranged in an inverted U, as shown in Fig. 13. The current delivered by the generator was forced to be 50% of the return stroke current (see Fig. 2), considering the first positive stroke, first negative stroke, and subsequent stroke. The time functions for the return stroke currents are those defined by IEC 62305-1 [15], and their peak values correspond to the Lightning Protection Level I (LPL I) of the standard.

The conductors related to the voltage recorded inside the electrical panel box (see Fig. 3) were modeled by a 2 m transmission line with 20 cm between conductors. Both conductors were symmetrically connected to the lower terminal of the generator, which is 60 cm above the ground plane. Both cases were simulated, i.e. with and without flashover to ground. The flashover was simulated by connecting one terminal of the 50 k Ω resistor to ground (see Fig. 13).

Table I summarizes the results obtained by the numerical simulations, showing the peak values and the duration of the relevant voltages, the latter defined as the duration of the voltage waveform above 10% of its peak value. The line / panel voltage is the common-mode voltage that is applied to the equipment port when there is panel to ground flashover. The panel / ground voltage (without flashover) is the voltage stressing the material between the panel box and ground plane.

The results from Table I show that very high voltages appear in both cases, with the highest peak values due to subsequent stroke. The highest duration corresponds to the first positive stroke, and the higher the duration, the lower the peak value.

As the panel / ground voltage reach very high values, it is expected to have flashovers in the installation, which may lead to high impulsive voltages at equipment input ports. It is important to highlight that the high voltage values displayed in Table I results from the pessimistic assumptions considered, such as: (i) the highest LPL level in [15]; (ii) only one incoming line to the structure; (iii) only one equipment panel;

(iv) the current waveform through the power line corresponds to the one from the lightning stroke. Regarding the latter assumption, experimental results show that the time-derivative of the current flowing through the power line conductors is significantly lower than the one of the subsequent stroke [16].

In any case, it is clear from the values in Table I that the source of damage described in this paper is very likely to take place in existing structures hit by lightning flashes.

TABLE I. RESULTS OF NUMERIC SIMULATIONS

Simulated Condition	Line / panel voltage ^a (kV)		Panel / ground voltage ^b (kV)	
	Peak value (kV)	Duration (μs)	Peak value (kV)	Duration (μs)
First positive stroke	23	12	92	12
First negative stroke	120	1.2	462	1.2
Subsequent stroke	210	0.32	860	0.32

a. With flashover: one R1 terminal grounded (see Fig. 13)

b. Without flashover: both R1 terminals floating (see Fig. 13)

V. PROTECTIVE MEASURES

This section presents some protective measures against the overvoltages induced in the equipment cabling by the phenomenon analyzed in the previous sections.

A. Installation of additional SPD

The overvoltages at the equipment input ports can be limited by the installation of SPDs between the equipment frame and the input cabling, in order to limit the common mode voltage at this very point, as shown in Fig. 14. For power conductors, these SPD should comply with IEC 61643-11 [17]. It is important that these additional SPDs be coordinated with the SPD installed at the MET. The IEC 61643-12 [18] and IEC 61643-22 [19] provide details regarding the coordination between SPDs.

This protective measure is convenient when the number of conductors entering the equipment frame is relatively small. However, in those cases where the number of cables is high, this protective measure becomes less attractive, due to the high number of SPD required.

Therefore, although the installation of Class 3 SPD at the input ports of electronic equipment is an effective protection measure, its application shall be restricted to specific cases.

B. Insulation of the equipment frame

The flashover between the equipment frame and ground, as described in Section 3, can be avoided by using an appropriate insulation. Large insulating sheets can be used to insulate the equipment frame from the floor, as shown in Fig. 15. These sheets shall have no joints below the equipment and shall extend at least 10 cm from the equipment borders. Alternatively, the equipment frame may be installed on insulating feet or fixed on walls by insulating holders, providing at least 10 cm clearances to floor, walls and ceiling

[20]. ITU-T K.27 [21] provides additional information on equipment insulation inside telecommunication buildings.

This protective measure is effective in those cases where the equipment frame is not connected to other equipment or frames through metallic elements, as otherwise the overvoltages would be transferred to these equipment and frames.

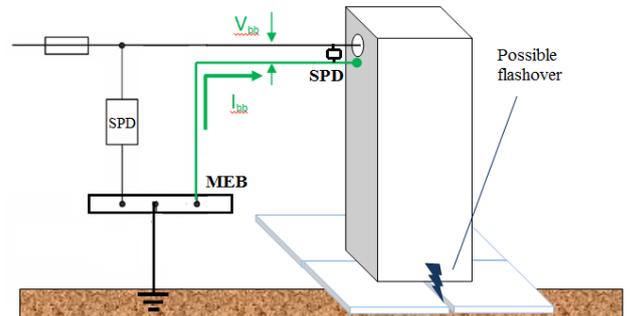


Figure 14. SPD installed at the entrance of the equipment frame.

Of course, it is possible to insulate all equipment and frames, but this becomes less interesting for large installations. It is worth mentioning that it is common to connect the equipment frames through metallic cable trays or ladders.

Therefore, the insulation of the equipment frame from ground and from grounded structures should be restricted to small installations containing a few equipment frames. Safety can also be an issue considering nearby (simultaneously accessible) frames.

As a final remark, the use of insulating layers as shown in Fig. 15, combined with the cabling may act a LC series circuits resonating somewhere in the MF/HF bands making the installation prone to interference if close to RF sources operating in these frequency bands.

C. Use of metallic cable trays or ladders

The use of metallic trays or ladders to carry the conductors from the MET to the equipment frame is an effective measure in order to mitigate the overvoltages applied to the equipment ports. In order to be effective in reducing this overvoltage, the cable trays and ladders must be electrically continuous and solidly bonded to the MET and to the equipment frame, as shown in Fig. 16.

The reduction in the overvoltages due to the use of metallic cable trays and ladders can be assessed by the shielding factors provided by ITU-T K.56 [22]. In the Annex A of this standard it is stated that the shielding factor provided by a closed metallic tray or duct is nearly zero, i.e., the overvoltages are completely removed. On the other hand, the shielding factor provided by a cable tray or ladder that has no electrical continuity is one, i.e., it does not reduce the overvoltages. Tables II to V, adapted from [22], provide the shielding factors for different types of cable ladders and trays, which are described in Figs. 17 and 18, respectively.

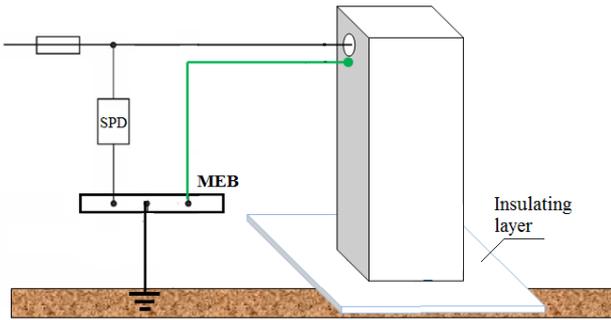


Figure 15. Equipment frame insulated from the floor.

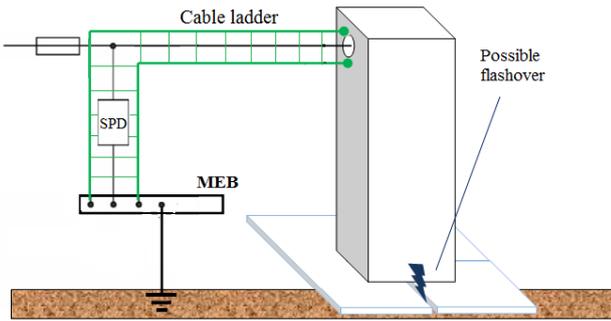


Figure 16. Use of metallic cable ladder between the MET and the equipment frame.

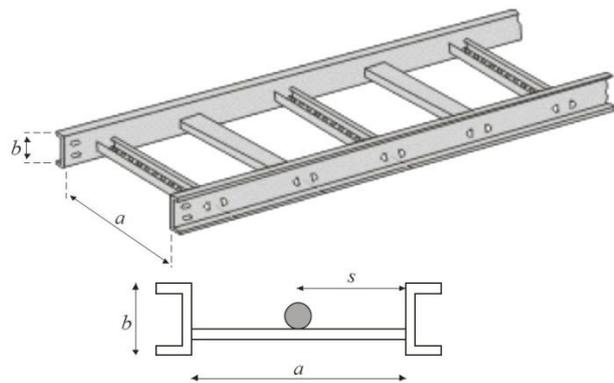


Figure 17. Cable ladder considered in Tables II and III.

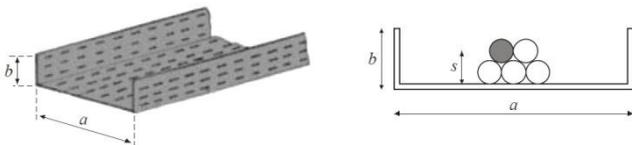


Figure 18. Cable tray considered in Tables IV and V.

TABLE II. SHIELDING FACTORS FOR CABLE LADDER ($b = 50$ mm) ADAPTED FROM ITU-T K.56 [22]

Cable position s (mm)	Ladder width a (mm)			
	100	200	300	400
50	0.08	0.13	0.15	0.16
100	-	0.15	0.19	0.22
150	-	-	0.21	0.24
200	-	-	-	0.25

TABLE III. SHIELDING FACTORS FOR CABLE LADDER ($b = 100$ mm) ADAPTED FROM ITU-T K.56 [22]

Cable position s (mm)	Ladder width a (mm)			
	100	200	300	400
50	0.04	0.08	0.09	0.11
100	-	0.10	0.13	0.16
150	-	-	0.14	0.18
200	-	-	-	0.18

TABLE IV. SHIELDING FACTORS FOR CABLE TRAY ($b = 50$ mm) ADAPTED FROM ITU-T K.56 [22]

Cable position s (mm)	Tray width a (mm)			
	100	200	300	400
2.5	0.008	0.006	0.005	0.005
5	0.016	0.012	0.010	0.009
10	0.030	0.024	0.021	0.018
20	0.057	0.047	0.040	0.035
30	0.079	0.069	0.059	0.052
40	0.099	0.088	0.077	0.068
50	0.115	0.107	0.094	0.084

TABLE V. SHIELDING FACTORS FOR CABLE TRAY ($b = 100$ mm) ADAPTED FROM ITU-T K.56 [22]

Cable position s (mm)	Tray width a (mm)			
	100	200	300	400
2.5	0.005	0.005	0.004	0.004
5	0.010	0.009	0.008	0.008
10	0.020	0.018	0.016	0.015
20	0.038	0.036	0.032	0.029
30	0.053	0.052	0.047	0.043
40	0.066	0.066	0.062	0.057
50	0.080	0.080	0.075	0.070

D. Other protective measures

It is worth to mention that there are other protective measures that can be used to mitigate the overvoltages induced in the equipment cabling by the phenomenon analyzed in this paper. Making reference to Fig. 3, it is clear that reducing the length of the connecting conductor between MET and grounding system of the installation will reduce L_{bt} and its inductive voltage drop (V_{bt}). This is an effective measure, but its application depends on the characteristics of the installation.

Another possibility to mitigate V_{bt} is to use a dense bonding network, so that the effective inductance between MET and grounding system is significantly reduced due to the multiplicity of current paths.

In some cases, the protection of a given circuit against V_{bt} could be achieved by the use of isolating interfaces on the circuits that are connected to the equipment. Of course, these isolating interfaces shall be able to withstand the overvoltage expected at the equipment input port (V_{bt}).

VI. CONCLUSIONS

The following conclusions can be drawn from the results presented in this paper:

i) The length of the bonding conductor between the MET and the grounding electrodes, as well as the impulsive behavior of the grounding system, can affect the effectiveness of the surge protective devices;

ii) The inductive voltage developed along the bonding conductor between the MET and the grounding electrodes may lead to flashover between the equipment frame and the steel reinforcement of the building, leading to impulsive voltages at the equipment ports. These voltages add to the SPD residual voltages and may be higher than the equipment resistibility level.

iii) As the above-mentioned flashovers often take place at hidden locations, they may remain unnoticed by the operating staff. As a result, the real cause of equipment failure is not detected.

iv) The paper describes some protective measures against this source of damages, alongside with the requirements for their application.

v) The occurrence of sparks at unexpected / hidden places may represent a serious risk for classified areas storing explosive (flammable) materials.

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