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A METHOD TO DETERMINE THE NEED OF SPD FOR THE PROTECTION AGAINST LIGHTNING OVERVOLTAGES OF ELECTRICAL INSTALLATION SUPPLIED BY POWER LINES

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Abstract - A simple method, based on risk assessment procedure as shown in IEC 62305-2, is proposed in order to answer to the questions if Surge Protective Devices (SPDs) shall be installed for the protection of electrical installations, internal to a structure, against lightning overvoltages transmitted by supply lines and if this installation is cost effective.

The risk due to lightning overvoltages is considered and the conditions for the safety of persons and property, as well as for the cost effectiveness of protection , are found.

Simple relations are proposed which allow to electrical contractors to evaluate if SPDs are required for safety and/ or for economic convenience in electrical installations in buildings located in rural or urban area.

Requirements for SPDs selection are given as well as values are proposed of probability of damage P_{SPD} associated to SPD to be installed for different values of impulse and nominal discharge currents.

1 INTRODUCTION

The electrical installation within a structure not only may be directly damaged by overvoltages but also they can represent the way through which lightning may cause damage to the whole structure. The consequential loss due to such damages may be severe especially from the point of view of economics and, in particular cases (i.e. hospitals and structures with explosion hazard) also for the loss of human life.

Therefore, where it is required to save primary goods as the human life, essential services to the public or the cultural heritage, the internal installation have to be protected against the effects of lightning to limit to a tolerable value the risk of

- failure of installation and then loss of service performed by the installation
- damage to the structure, its content and to the persons, due to lightning mediated by the internal installation.

On the other hand where the failure of installation and the consequential loss of service is only an economic matter, it is useful to evaluate the economic benefits of providing protection measures in order to reduce the economic loss .

In order to take the decision if the protection is:

- mandatory for the safety of persons, services to the public or cultural heritage,
- optional for reduction of the economic loss, where the cost effectiveness is established in front of the cost of the required protection measures,

a risk analysis shall be performed.

In agreement with the standard IEC 62305-2 the risk analysis involves the evaluation of:

- the risk of loss of human life (R_1)
- the risk of loss of essential services to the public (R_2)
- the risk of loss of cultural heritage (R_3)

- the risk of economic loss (R_4).

The risks R_1 and R_4 are to be evaluated in almost all the structures, while the risks R2 and R3 are relevant only in particular cases.

1 PROTECTION OF INSTALLATION TO REDUCE THE RISK OF LOSS OF HUMAN LIFE (R_1), LOSS OF ESSENTIAL SERVICES TO THE PUBLIC (R_2), LOSS OF CULTURAL HERITAGE (R_3)

For a practical approach to the problem it is convenient to distinguish the “special structures” and “common structures”.

Special structures

Some types of structures such as:

- structures with risk of explosion,
- hospitals and other structures where failure of internal installations immediately endangers human life,
- structures with risk of loss of essential service to the public,
- structures where the damage may also involve surrounding structures or the environment (e.g. chemical or radioactive emissions)

are “special” due to the importance of consequential losses and their particular characteristics.

To evaluate the risk in such structures is often a complicated matter due the type of risks involved and the number of risk components to be considered. As result a complete risk analysis should be performed according to the standard IEC 62305-2 and, if required, protection against lightning shall be designed following the requirement of IEC 62305 series standard. If the risk evaluation is not available or cannot be performed due to lack of input parameters, protection measures with LPL 1 should be adopted in any case, irrespective of the results of risk assessment.

Common structures

In the greatest majority of cases, structures have no particular characteristics (common structures) and the risk analysis to evaluate whether protection measures are needed or not for the safety of persons is limited to calculation of risk of loss of human life (R_1), which involves four components only:

$$R_1 = R_A + R_B + R_U + R_V \quad (1)$$

where the risk components are expressed as follows [1]:

$$R_A = N_g\, A_d\, C_d\, P_A\, r_a\, L_t\, 10^{-6} \quad (2)$$

$$R_B = N_g\, A_d\, C_d\, P_B\, r\, h\, r_f\, L_f\, 10^{-6} \quad (3)$$

$$R_U = N_g\, A_l\, C_d\, C_t\, P_U\, r_u\, L_t\, 10^{-6} \quad (4)$$

$$R_V = N_g\, A_l\, C_d\, C_t\, P_V\, r\, h\, r_f\, L_f\, 10^{-6} \quad (5)$$

The risk components R_A, R_B, R_U and R_V are affected by:

- ground flash density of the zone where the structure and the line are placed(N_g)
- probability of damage (P_A, P_B, P_U, P_V)
- loss, according to the type of structure (L_t, L_f)
- collection area of the structure related to its dimensions (A_d)
- collection area of the line related to its characteristics (overhead or buried) and length (A_l)
- transformer HV/LV factor (C_t)
- fire risk (r_f)
- provisions taken to reduce the consequence of fire (r),

– presence of special hazard, (h)
– location factor of the structure and the line (C_d)
– the soil resistivity (ρ, if the cable is buried)

In an unprotected structure $P_A = P_B = P_U = P_V = 1$, it follows:

$$R_A + R_B = N_g A_d C_d 10^{-6} (r_a L_t + r h r_f L_f) \quad (6)$$

$$R_U + R_V = N_g A_d C_d C_t 10^{-6} (r_u L_t + r h r_f L_f) = N_g A_d C_d C_t 10^{-6} (r_u L_t + r h r_f L_f) \quad (7)$$

It should be noted that the values of the products $r_a L_t$ and $r_u L_t$ range between 10^{-7} and 10^{-4} (most common value 10^{-6}) while the product $r h r_f L_f$ ranges between 10^{-6} and 10^{-1} (most common values between 10^{-5} and 10^{-2}); it follows that the contribution of risk components R_B and R_V is usually much higher than that of components R_A and R_U respectively. As result components R_A and R_U can be disregarded and then, according to IEC 62305-2, the main protection measures that could be adopted in practice are:

- Lightning Protection System (LPS), for the reduction of the component R_B
- Surge Protective Device (SPD) at the entry point of the connected line into the structure, for the reduction of the component R_V.

Generally SPD can be easily selected and installed by electrical installation contractors or panel board builders while design and installation of an LPS often is a task of the lightning protection engineer. Therefore, for practical purposes, it is useful to pick out the cases requiring an LPS; as a rule, in this case, a complete risk analysis shall be performed according to IEC 62305-2.

In the following an algorithm of simple application will be proposed in order to allow the designer to reach rapidly the decision if:

- the structure, and then the internal installation, does not require any protection against lightning, or
- the protection may be achieved by installing SPD at the entry point of the power line only, or
- further protection measures such as an LPS are required.

To establish such algorithm, useful is to start from the risk R_1 evaluation according to formula (1) - (7) as above and to assume that:

- the value of tolerable risk is $R_T = 10^{-5}$;
- the value of the coefficient C_d is equal for structure and the lines; three locations of structure/line are considered, namely urban, suburban and rural;
- the height of the overhead line is 6 m;
- the soil resistivity for buried line is 500 Ωm;

By replacing (6) and (7) in (1) is obtained

$$R_1 = R_B + R_V = N_g C_d 10^{-6} r h r_f L_f (A_d + A_l C_t) \leq 10^{-5} \quad (8)$$

and then

$$N_g C_d r h r_f L_f (A_d + A_l C_t) \leq 10 \quad (9)$$

By indicating with $L_p = r h r_f L_f$ formula (9) more simply may be written:

$$C_d L_p (A_d + A_l C_t) \leq 10 / N_g \quad (10)$$

If the risk component R_B (due to direct flashes to the structure) assumes itself high value in comparison with the component R_V and reaches a value higher or equal to the tolerable risk, an LPS shall be installed and its characteristics are to be dimensioned by a complete risk analysis as the case of "special" structures". This apply when:

$$R_B > R_T \quad (11)$$

and then from (10):

$A_d > 10 / (N_g C_d L_p)$ (12)

Therefore, only if the condition (12) is not verified , it is possible to conclude that there is the possibility to reduce the risk by suitable SPD only, installed at the entry point of the line. The characteristics of such SPD may be determined by means of the probability P_{SPD} associated to SPD.

Characteristics of SPD at the entry point of the line into the structure

To establish the characteristics of SPD at the entry point of the line it is necessary to recall relation (10) in which also the probability P_{SPD} is inserted:

$C_d L_p (A_d + P_{SPD} A_l C_t) = 10 / N_g$ (13)

Starting from (13) it is possible to obtained:

$P_{SPD} = [(10 / N_g C_d L_p) - A_d] / A_l C_t$ (14)

Relation (14) may be also expressed as follows

$P_{SPD} = \{[10 / (N_g C_d L_p)] - A_d \} / K_d L_c$ (15)

being:
- L_c the length of the line connected to the structure in [m]
- K_d a coefficient related to the line characteristics; its values are reported in Table 1 according to the characteristics of the considered line.

Table 1 – Values of the coefficient K_d for different characteristics of the line

	Flash to line	
	Overhead	**Buried**
Low Voltage ($C_t = 1$)	36	18
High Voltage ($C_t = 0.2$)	7.2	3.6

If the line is composed by sections of different type (overhead, buried, HV, LV) the (15) becomes

$P_{SPD} = \{[10 / (N_g C_d L_p)] - A_d \} / 36\, L_{ct}$ (16)

being L_{ct} the equivalent total line length evaluated referring the length of each section of line to the value of the low voltage overhead line

$L_{ct} = L_{AL} + 0{,}5 \cdot L_{BL} + 0{,}2 \cdot L_{AH} + 0{,}1 \cdot L_{BH}$ (17)

where
L_{AL} length of aerial low voltage line (m)
L_{BL} length of buried low voltage line (m)
L_{AH} length of aerial high voltage line (m)
L_{BH} length of buried high voltage line (m)

Tools for a quick evaluation of P_{SPD} are:
a) N_g ,lightning ground flash density relevant to the location of the power line and connected structure, see (IEC 62305-2 clause A.1);
b) location factor C_d, see Table 2
c) L_p loss coefficient related to the characteristics of the structure, see Table 3
d) A_d collection area of the structure related to its dimensions, see Figure 1

Table 2 – Location factor C_d of structure and line

Structure/line location	C_d
Urban	0,25
Suburban	0,5
Rural	1

Table 3 – Values of the factor L_p

Structure	r_p	h_z	r_f	L_f	L_p
Small house	1	1	1,00E-03	1,00E-01	1,00E-04
Multi-apartment house	1	5	1,00E-03	1,00E-01	5,00E-04
Small church	1	2	1,00E-03	2,00E-02	5,00E-04
Large church	1	5	1,00E-03	2,00E-02	1,00E-04
Small school	0,5	5	1,00E-03	5,00E-02	1,00E-04
Large school	0,5	10	1,00E-03	5,00E-02	2,00E-04
Public entertainement (small)	0,2	5	1,00E-02	2,00E-02	2,00E-04
Public entertainement (large)	0,2	10	1,00E-02	2,00E-02	5,00E-04
Commercial (small)	0,5	2	1,00E-02	5,00E-02	5,00E-04
Commercial (large)	0,5	5	1,00E-02	5,00E-02	1,00E-03
Industry (small)	0,5	1	1,00E-02	5,00E-02	2,00E-04
Industry (large)	0,5	2	1,00E-02	5,00E-02	5,00E-04
Small hotel	0,5	2	1,00E-02	1,00E-01	1,00E-03
Large hotel	0,5	5	1,00E-02	1,00E-01	2,00E-03

The values of probability P_{SPD} for different values of discharge current, impulse I_{imp} and nominal I_n, of the SPD are reported in Table 4:

Table 4 – Values of the probability P_{SPD}

P_{SPD}	SPD tested with class I tests (I_{imp} kA; 10/350 µs)	SPD tested with class II tests (I_n kA; 8/20 µs)
1	No SPD provided	No SPD provided
0,03	5	2.5
0,01	10	5
0.005-0.001	Enhanced protection (*)	

(*) SPD dimensioned for higher impulse or nominal current, lower protective level, etc…

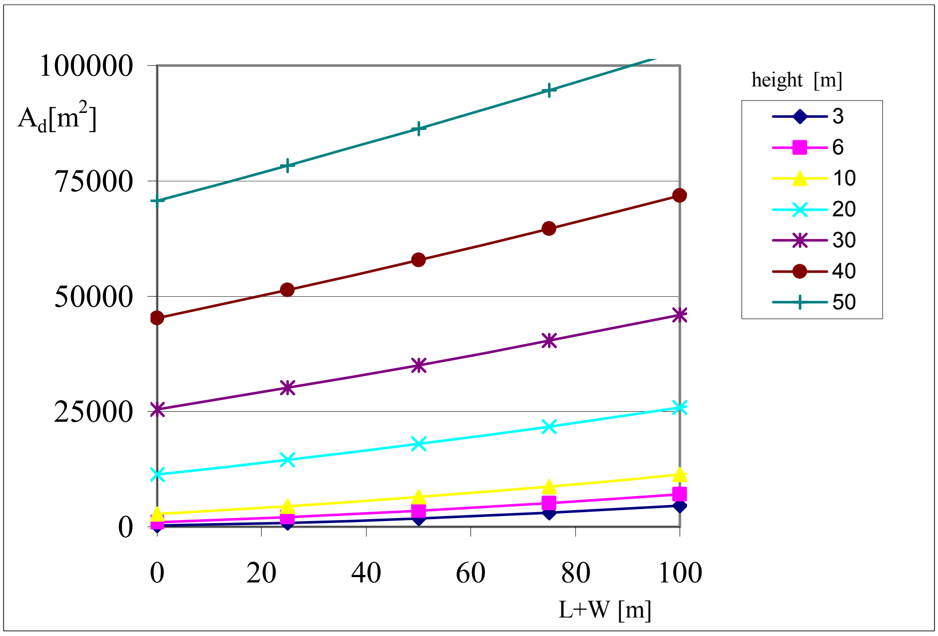

Figure 1 - Collection area A_d in $[m^2]$ of the structure related to its dimensions L and W in [m] for different heights H [m]

On the base of the result of application of formula (16), it is possible to conclude that if:

$P_{SPD} \geq 1$ → no SPD should be installed

$1 > P_{SPD} \geq 0.001$ → SPD should be installed and dimensioned according to Table 4

$P_{SPD} \leq 0.001$ → SPD are not able to provide full protection; further protection measures are needed and a complete risk analysis shall be performed.

A flow diagram summarizing the logic scheme to follow for the protection of installation within a structure against lightning overvoltages in order to limit loss of human beings is reported in the following Figure 2.

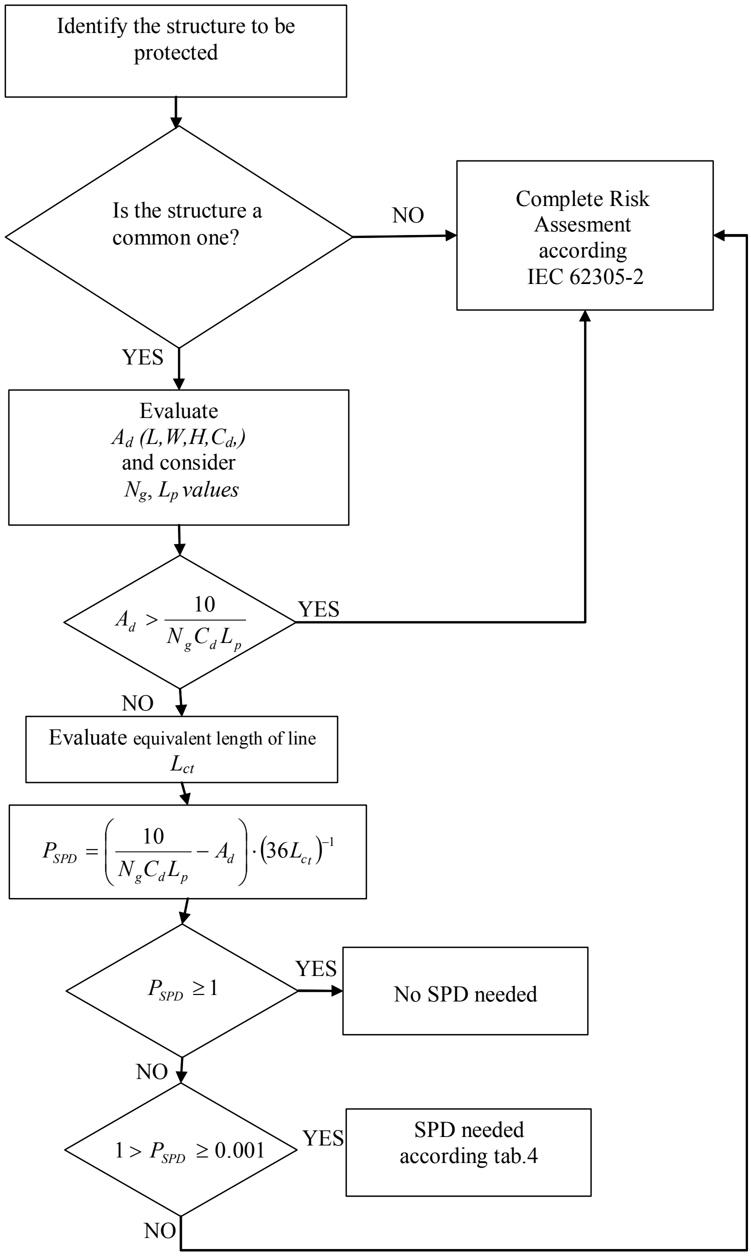

Figure 2- Flow chart relevant to the protection against lightning overvoltages of electrical installation in order to reduce risk of loss of persons

2 PROTECTION OF INSTALLATION TO REDUCE THE RISK OF ECONOMIC LOSS (R_4)

Document IEC 62305-2 provides a procedure for the evaluation of such risk and to ascertain the economic benefits of installing protection measures in order to reduce the economic loss.

The risk evaluation procedure allows to assess the components of the risk and to identify those making up the risk R_4.

With reference to the different risk components and the protection measures most effective to reduce their value, it is possible to establish the following conditions useful to ascertain the cost effectiveness of the relevant protection.

By using the same notations as in [1], protection is cost effectiveness if:

$$R_4 C_t \geq C_P (i+a+m) + R^*_4 C_t \quad (18)$$

or

$$C_P / C_t \leq (R_4 - R^*_4) / (i+a+m) \quad (19)$$

where
- C_t : total value (cost) of the structure
- C_P : cost of protection measures
- i : interest rate
- a : amortization rate
- m : maintenance rate
- R_4 : risk of economic loss without protection measures
- R^*_4 : risk of economic loss with protection measures

To provide protection of the electrical and electronic installation within a structure by incoming overvoltages, SPD at the entry point of the power line only may be not sufficient and a coordinated system of SPD is needed.

The cost effectiveness of the coordinated system of SPD may be established by considering that such protection measure essentially mitigates the risk components R_V, R_W and R_Z, it means the risk of physical damages and of failure of internal installation due to overvoltages by direct flash to the line (R_V and R_W) and the risk of failure due to induced overvoltages by flashes near the line (R_Z).

In this case the cost effectiveness of the coordinated system of SPD may be expressed by the following condition:

$$C_{CSPD} / C_t \leq N_g C_d C_t (A_l L_p + A_l L_o + A_i L_o)(1-P_{CSPD}) 10^{-6} / (i+a+m) \quad (20)$$

where
- C_{CSPD}: cost of coordinated system of SPD
- L_o : loss due to failure of internal installation.

or, by neglecting $A_l L_o$ in comparison to $A_i L_o$,

$$C_{CSPD} / C_t \leq N_g C_d C_t (A_l L_p + A_i L_o)(1-P_{CSPD}) 10^{-6} / (i+a+m) \quad (21)$$

With the same notations introduced in the preceding section the expression (21) becomes

$$C_{CSPD} / C_t \leq N_g C_d (L_p K_d L_c + L_o K_i L_c)(1-P_{CSPD}) 10^{-6} / (i+a+m) \quad (22)$$

where the values of coefficients K_d (for direct flash to line) and K_i (for indirect flash to line) are reported in Table 1 and Table 5 respectively.

Table 5 – Values of the coefficient K_i for different characteristics of the line

	Flash nearby line	
	Overhead	**Buried**
Low Voltage (C_t = 1)	1000	500
High Voltage (C_t = 0.2)	200	100

If the line is composed by sections of different type (overhead, buried, HV, LV), formula (22) may be written as follows:

$$C_{CSPD} / C_t \leq N_g C_d L_{ct} (36 L_p + 1000 L_o)(1-P_{CSPD}) 10^{-6} / (i+a+m) \quad (23)$$

being L_{ct} the equivalent total line length evaluated referring the length of each section of line to the value of the low voltage overhead line, as expressed in (17).

If the values of L_p and L_o reported in Annex C of IEC 62305-3 are assumed, usually 36 L_p can be disregarded in comparison with 1000 L_o, so that formula (23) may be simplify as follows:

$$C_{CSPD} / C_t \leq N_g \, C_d \, L_{ct} \, 1000 \, L_o \, (1-P_{CSPD}) 10^{-6} / (i+a+m) \quad (24)$$

and then for N_g = 1 flash per km^2 per year

$$L_{ct} \geq (C_{SPD} / C_t) / K \, L_o \quad (25)$$

where

$$K = 1000 \, (1-P_{CSPD}) \, C_d \, 10^{-6} / (i+a+m) \quad (26)$$

The values of factor K for urban, suburban and rural locations are reported in Table 5, evaluated with P_{CSPD} = 0,01 and (i+a+m) = 0,2.

Table 6 – Values of factor K for different structure locations

Structure location	C_d	K
Urban	0.25	1.24 10^{-3}
Suburban	0.5	2.5 10^{-3}
Rural	1	4.95 10^{-3}

The application of condition (25) allows to build the following Table 7, which gives, for different types of structure and location, the values of the equivalent line length L_{ct} over which the installation of a coordinated system of SPD is cost effective.

Table 7 – Equivalent length of a line for different structures in different locations

Structure	Lo	C_{CSPD}/C_t (10^{-6})	L_{ct} (m) Urban	Suburban	Rural
Small house	10^{-4}	400	3200	1600	800
Multi-apartment house	10^{-4}	40	320	160	80
Small church	10^{-3}	50	40	20	10
Large church	10^{-3}	15	12	6	3
Small school	10^{-3}	125	100	50	25
Large school	10^{-3}	40	32	16	8
Public entertainement (small)	10^{-3}	50	40	20	10
Public entertainement (large)	10^{-3}	80	65	32	16
Commercial (small)	10^{-2}	400	32	16	8
Commercial (large)	10^{-2}	400	32	16	8
Industry (small)	10^{-2}	160	13	6	3
Industry (large)	10^{-2}	400	32	16	8
Small hotel	10^{-2}	165	13	6	3
Large hotel	10^{-2}	83	6	3	2

As an example, let us consider a large commercial building in urban area, if the supply line is formed by one section HV buried cable of 200 m length, it follow that the equivalent line length (see formula (17)) is L_{ct} = 20 m (lower than 32 m) and then to install coordinated set of SPD is not cost effective. If the same building is supplied by one section HV overhead line of the same 200 m length, the equivalent line length is L_{ct} = 40 m (higher than 32 m) and in this case there is an economic convenience to install a coordinated set of SPD.

From Table 7 it is possible to note that the values of equivalent length of the line are in most of cases lower than 100 m; taking into account that supply lines are often longer than 100 m, it follows that a coordinated SPD system is cost effective in almost all cases.

3 CONCLUSIONS

In order to answer to the questions if Surge Protective Devices (SPDs) shall be installed for the protection of electrical installations, internal to a structure, against lightning overvoltages transmitted by supply lines and if this installation is cost effective, the structures should be distinguished in “special structures” and “common structures”.

Structures with risk of explosion, hospitals, structures where the damage may also involve surrounding structures or the environment (e.g. chemical or radioactive emissions) and other structures where failure of internal installations immediately endangers human life, as well as structures with risk of loss of essential service to the public, are to be considered “special” due to the importance of consequential loss and their particular characteristics. In these cases is not possible to give answer to such question without performing a complete risk analysis according to the standard IEC 62305-2. Moreover protection measures, if required, shall be designed following the requirement of IEC 62305 series standard and installed all together to assure the effective protection against lightning of the structure and of its internal electrical and electronic systems.

For “common structures” a simplified procedure for risk analysis and simple relations are proposed which allow to electrical contractors to evaluate if SPDs for protection of electrical installations in buildings located in rural, urban or suburban area are required for safety and/ or for economic convenience.

For safety reasons, a simple relation is given, which allows to select the characteristics of SPD, if required, at the entry point of the line into the structure, as function of the line length and of ground flash density where the structure and the line is located.

For economic convenience, coordinated SPD protection is cost effective for the protection of installation internal to the structure in almost all cases except for small houses in urban and suburban locations.

4 REFERENCE

[1] IEC 62305-2, Ed. 1, 2006 : Protection against lightning. Part 2 : Risk management for structures and services.

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[3] IEC 60364-4-44, August, 2001, Electrical installations of buildings – Part 4-44: Protection for safety – Protection against voltage disturbances and electromagnetic disturbances.

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