An approach to assess the probability of damage when a coordinated SPD system is installed

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***Abstract*— Aim of the paper is to give the rationale for the evaluation of the probability of damage of electrical and electronic equipment within a structure when a coordinated SPD system is installed for their protection against lightning surges.**

*Index Terms- **Lightning protection; Surge Protective Device***

I. Introduction

Failure of electrical and electronic systems within a structure can be caused by surges arising from different sources of damage [1], namely: direct flashes to the structure (source of damage S1), flashes to ground nearby the structure (source of damage S2), flashes to power and communication lines connected to the structure due to flashes to and near the lines (sources of damage S3 and S4).

The typical protection measure suggested by the standard [2] with aim to assure the apparatus is not damaged is a coordinated system of surge protective device (SPD). For practical applications the probability with which a given SPD system will reduce the risk of failure of apparatus is a key point for their proper selection and installations.

In this subject is essential to know the stress, in terms of energy and current,, which an SPD will experience under surge conditions at its installation point.

Since the stress varies with the source of damage, also the probability P_{SPD} that a surge will damage an apparatus protected by an SPD system varies with the source of damage and therefore with the risk component to be reduced.

Aim of the paper is to give the rationale for the evaluation of the probability P_{SPD} taking into account the source of damage, the type of SPD system and the characteristics of the upstream power line and of the downstream protected circuit.

II. Probability of SPD System

A. *Terms and definitions:*

For the purposes of this paper the following terms and definitions apply:
− I_{SPD} is the expected current flowing through SPD at its installation point
− I_{imp} is the current (10/350 μs) of class I test SPD
− I_n is the nominal current (8/20 μs) of class II test SPD
− I_{pr} the current relevant to required protection level U_{pr}
− Q_{SPD} is the charge associated to I_{SPD}
− Q_{imp} is the charge associated to the current I_{imp}
− Q_n is the charge associated to the current I_n
− U_{SPD} is the voltage across SPD when the current I_{SPD} is discharged
− U_p is the voltage across SPD when the current I_{imp} or I_n is discharged (SPD protection level)
− U_l is the voltage at the terminals of the apparatus to be protected
− U_w is the rated impulse withstand voltage of the apparatus to be protected
− U_{pr} is the SPD protection level required in order to make $U_l \leq U_w$

B. *Probability P_{SPD} evaluation*

Failure of an apparatus protected by an SPD system may come either from:
a) residual voltage U_{SPD} exceeding the required protection level U_{pr} of SPD;
b) energy associated to the current I_{SPD} exceeding the value tolerated by the SPD.

The probability P_{SPD} that an overvoltage will damage an apparatus protected by an SPD system is the probability that either condition a) or condition b) will occur, being :
− P_{SPDa} the probability associated to condition a)
− P_{SPDb} the probability associated to condition b)

Condition a) will occur if the value of U_{SPD} exceeds the protection level U_{pr} of SPD, required to limit the voltage U_l at the terminals of the apparatus to be protected at values lower than his rated impulse withstand voltage U_w, taking into account:
− the inductive voltage drop ΔU of the leads/connections of SPD,
− the effects of surge travelling along the protected circuit,
− the overvoltages U_i induced by lightning current in the protected circuit.

Condition a) may be expressed by:

$$U_{SPD} > U_{pr} \tag{1}$$

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or in terms of currents:

$$I_{SPD} > I_{pr} \quad (2)$$

being I_{pr} the current relevant to required protection level U_{pr}. If the value of current I_{pr} is equal to the nominal current I_n of SPD ($I_{pr} = I_n$), then the required protection level U_{pr} is equal to the nominal protection level U_p of SPD ($U_{pr} = U_p$).

The needed protection level U_{pr} of SPD can be evaluated as reported in [2].

Condition a) should be verified with reference to the subsequent strokes of negative flashes, which represent the more severe case, as discussed in [2].

As a first approximation condition b) will occur if the charge Q_{SPD} associated to I_{SPD} exceeds the tolerable one for the SPD.

If we consider that the charge for unit of current associated to the standard current 10/350 μs is Q_{imp} = 0,5 C/kA and that the one associated to the standard current 8/20 μs is Q_n = 0,027 C/kA, condition b) becomes:

– for SPD tested with I_{imp} (class I test)

$$Q_{SPD} > Q_{imp} = I_{imp} / 2 \quad (3)$$

– for SPD tested with I_n (class II test)

$$Q_{SPD} > Q_n = I_n / 37 \quad (4)$$

Condition b) should be verified with reference to the positive strokes, which represent the more severe case, as discussed in [2].

Therefore the probability P_{SPD} is given by:

$$P_{SPD} = 1 - (1 - P_{SPDa}) \cdot (1 - P_{SPDb}) \quad (5)$$

The probability P_{SPDa} that the value of U_{SPD} exceeds the required protection level U_{pr}, relevant to the current I_{pr} of the SPD, is the probability that, for the subsequent stroke of negative flashes, I_{SPD} exceed I_{pr}.

Assuming that P_{SPDar} is the probability relevant to an SPD with $I_{pr} = I_{SPD}$, SPD with $I_{pr} > I_{SPD}$ will have P_{SPDa} values lower than P_{SPDar}; SPD with $I_{pr} < I_{SPD}$ will have P_{SPDa} values higher than P_{SPDar}.

The value of P_{SPDa} relevant to SPD with $I_{pr} \neq I_{SPD}$ is obtained from cumulative frequency distribution of lightning current relevant to the subsequent stroke of negative flashes (see IEC 62305-1), in correspondence to the values of an equivalent current I_{eq} which depends on SPD system configuration.

The probability P_{SPDb} is the probability that the value of Q_{SPD}, relevant to positive and negative first strokes, exceed Q_{imp} or Q_n respectively for class I or class II SPD.

Assuming that P_{SPDbr} is the probability relevant to an SPD with $Q_{SPD} = Q_{imp}$ (class I SPD) or with $Q_{SPD} = Q_n$ (class II SPD), SPD with Q_{imp} (or Q_n) > Q_{SPD} will have P_{SPDb} values lower than P_{SPDbr}; SPD with Q_{imp} (or Q_n) < Q_{SPD} will have P_{SPDb} values higher than P_{SPDbr}.

The value of P_{SPDb} relevant to SPD with Q_{imp} (or Q_n) $\neq$ Q_{SPD} is obtained from cumulative frequency distribution of lightning charge relevant to positive and negative first strokes (IEC 62305-1), in correspondence to the values of an equivalent charge Q_{eq} which depends on SPD system configuration.

Being the assessment of probability P_{SPD} based on comparison between the current I_{SPD} and charge Q_{SPD} at the point of installation with those relevant to the SPD, prior evaluation of parameters I_{SPD} and Q_{SPD} are needed.

III. TYPE OF SPD SYSTEMS

As known, two main types of SPD are used for the protection against lightning surges of electrical and electronic equipment within a structure, namely switching type SPD (spark gap) and limiting type SPD (varistors). The following SPD systems are considered in this paper:

A. SPD system consisting of only one SPD1 switching or limiting type (type S/L).

The probability P_{SPD} that an overvoltage will damage an apparatus protected by an SPD system type S/L is the probability that either condition a) or condition b) will occur.

Therefore the probability P_{SPDA} relevant to type S/L SPD system is:

$$P_{SPD(S/L)} = 1 - (1 - P_{SPDa}) \cdot (1 - P_{SPDb}) \quad (6)$$

where:
P_{SPDa} is the probability that for the subsequent stroke of negative flashes I_{SPD} exceed I_{imp} or I_n respectively for class I or class II SPD;
P_{SPDb} is the probability that for the positive stroke and negative first strokes Q_{SPD} exceed I_{imp} / 2 or I_n / 37 respectively for class I or class II SPD.

B. SPD system consisting of two SPDs: SPD1 switching type + SPD2 limiting type (type SL).

For SPD1 condition a) is shadowed by the presence of the SPD2; as a consequence condition b) only is to be considered. Therefore $P_{SPD1} = P_{SPD1b}$

For SPD2 both conditions a) and b) are to be considered. Probability P_{SPD2} can be obtained by

$$P_{SPD2} = 1 - (1 - P_{SPD2a}) \cdot (1 - P_{SPD2b}) \quad (7)$$

The probability P_{SPDB} relevant to type SL SPD system can be obtained by

$$P_{SPDB} = 1 - (1 - P_{SPD1}) \cdot (1 - P_{SPD2}) \quad (8)$$

C. SPD system consisting of two SPDs: SPD1 limiting type + SPD2 limiting type (type LL)

As in type SL system, for SPD1 condition b) only is to be considered. Therefore $P_{SPD1} = P_{SPD1b}$

For SPD2 both conditions a) and b) are to be considered. Probability P_{SPD2} can be obtained by

$$P_{SPD2} = 1 - (1 - P_{SPD2a}) \cdot (1 - P_{SPD2b}) \qquad (9)$$

The probability P_{SPDC} of type LL SPD system can be obtained by

$$P_{SPDC} = 1 - (1 - P_{SPD1}) \cdot (1 - P_{SPD2}) \qquad (10)$$

The types of SPD system that can be used depend on the source of damage against which protection is required; in particular:

– SPD system type SL is suitable for sources S2, and S4. It can be used also for source S3 when the line is stricken far away from SPD

– SPD system type SL or type LL is to be used for sources S1. In fact, as reported in [1], due to high values of ΔU, even if overvoltage U_i induced in the circuit is negligible, the distance between SPD1 and apparatus (or the value of U_p) should be kept so low that practically in all cases installation of a downstream SPD2 is required. SPD systems type SL or type LL are to be used also for source S3 when the line is stricken close to SPD.

IV. PARAMETERS FOR SPD PROBABILITY EVALUATION

For evaluation of probability P_{SPD}, the current I_{SPD} expected at installation point of SPD and the associated charge Q_{SPD} are needed.

Current I_{SPD} and associated charge Q_{SPD} depend on a lot of factors among which, mainly:

– the installation point of SPD (SPD1 or SPD2);
– the source of damage (S1,S2,S3 or S4);
– the amplitude and waveform of lightning current.

Moreover I_{SPD} and Q_{SPD} depend, for SPD1, on:

– the characteristics of line on which SPD1 is installed;
– the conventional impedance of the earth arrangement (Z);
– the connected external services;
– the stricken point of the line connected to SPD (for source S3);

and for SPD2, on:

– the characteristics of circuit on which SPD2 is installed;
– the type of SPD1 (switching or limiting);
– the location of circuit relative to inducing lightning current.

V. CASES UNDER STUDY

In the present paper source of damage S1 only, which is the most critical case, is considered.

SPD system type SL or type LL only are investigated.

For these types of SPD system current I_{SPD} and associated charge Q_{SPD} have been evaluated both for SPD1 and SPD2 in [3] and [4].

VI. PROBABILITY P_{SPD} EVALUATION

The probability P_{SPD} as function of factors influencing the dimensioning of the SPD system are reported in figures from Fig. 1 to 7 for some selected cases. The volt-current characteristics of the adopted limiting type SPD are reported in Fig. 8.

From Fig. 1 it is clear that P_{SPD1} of class I SPD increases with the length of the supply line; this is due to the increasing of time to half value of the current flowing through the SPD1 and then to the increasing of the associated charge.

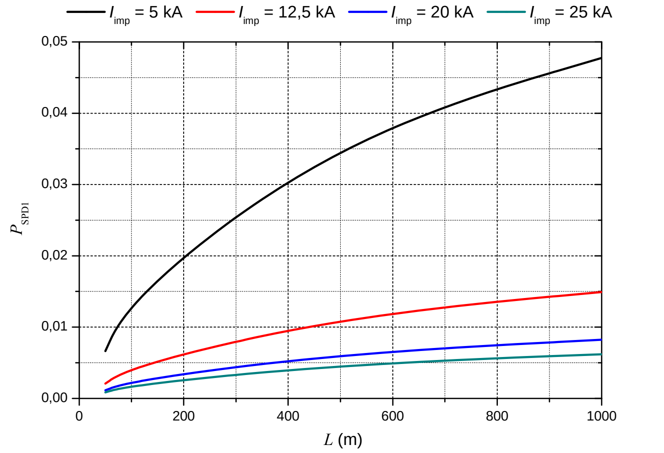


Figure 1. Probability P_{SPD1} of class I SPD as a function of supply line length L (condition b); $n*n'$ = 4 where n is the overall number of external conductive parts and lines, n' number of the line conductors; SPD X characteristic as in Fig. 8 is adopted.

From Fig. 2, for a given selected SPD1, the probability P_{SPD1} decreases with the number of parallel paths on which the lightning current is flowing (the current on the SPD1 is decreasing). It results that the most critical condition for probability P_{SPD1} is where the internal equipment is connected to a long one phase supply line.

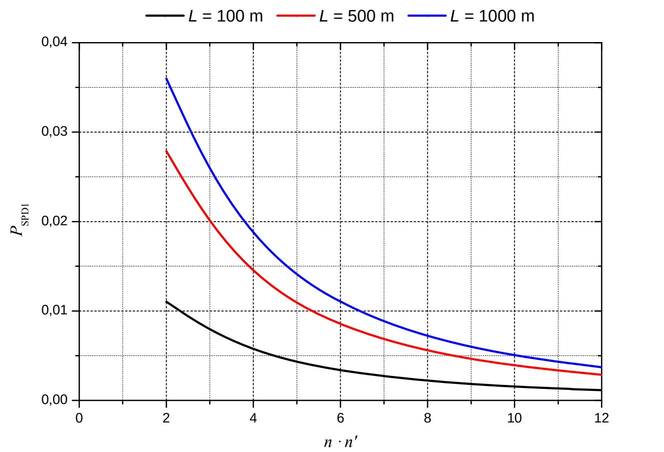
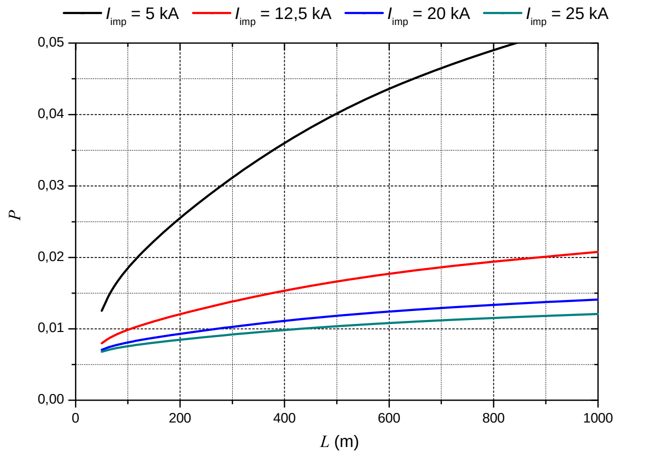


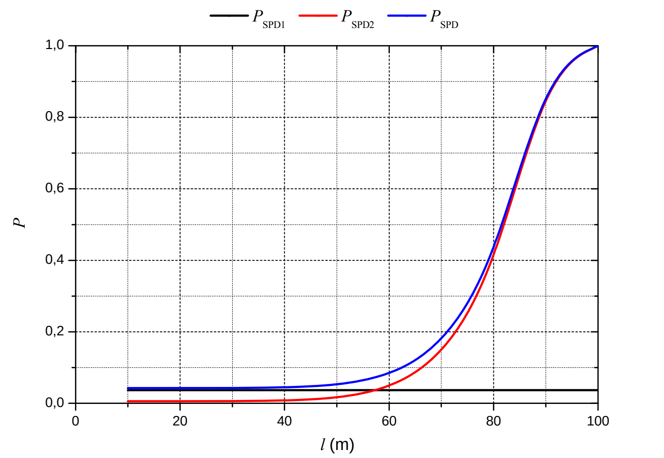
Figure 2. Probability P_{SPD1} of class I SPD as a function of product $n*n'$ for different values of supply line length L; SPD X characteristic as in Figure 8 is adopted; I_{imp} = 12,5 kA.

For the conditions of Fig.3, the probability of type SL SPD system is determined essentially by the SPD1 (as shown in Fig. 1); Where the internal circuit is longer than 50 m the effects of surge travelling along the protected circuit, determines a rapid increasing of PSPD2 , which affects the overall probability PSPD of the system, as shown in Fig. 4. An increase of the I_{imp} of SPD1 has not significant influences to the overall performance of the SPD system.



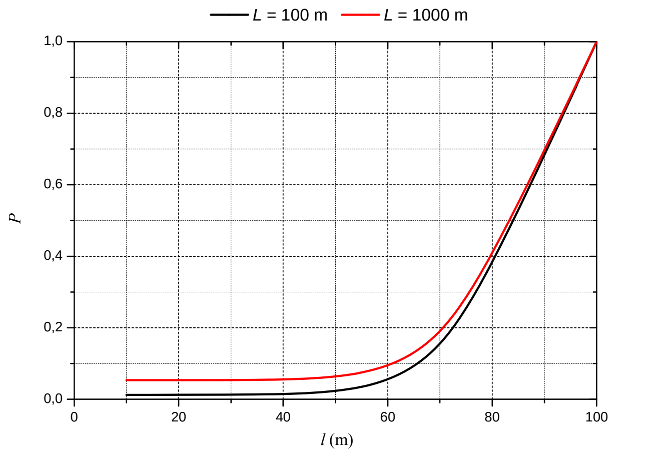
SPD2	Circuit upstream SPD1	Circuit SPD1-SPD2	Circuit SPD2-apparatus
SPD2→ SPD X	*n · n' = 4*	*w* = 0,5 m *kc* = 0,5 *d* = 1 m	*w* = 0,005 m k_c = 0,5 *d* = 1 m l_c = 0,02 m l_v = 1 m *l* = 10 ÷ 50 m

Figure 3. SPD system type SL. Probability P_{SPD} as a function of supply line length *L*); k_c lightning current sharing coefficient; *d* – distance between lightning current flowing in the electrical conductor and the induced circuit; *w* - width of the circuit; *l* length of the circuit; l_v vertical length of the circuit; l_c - length of the SPD connecting leads; SPD X characteristic as in Fig. 8 is adopted.



SPD1	SPD2	Circuit upstream SPD1	Circuit SPD1-SPD2	Circuit SPD2-apparatus
I_{imp} = 5 kA	SPD2→ SPD X	*n · n'* = 4 *L* = 500 m	*w* = 0,5 m k_c = 0,5 *d* = 1 m	*w* = 0,005 m k_c = 0,5 *d* = 1 m l_c = 0,02 m l_v = 1 m

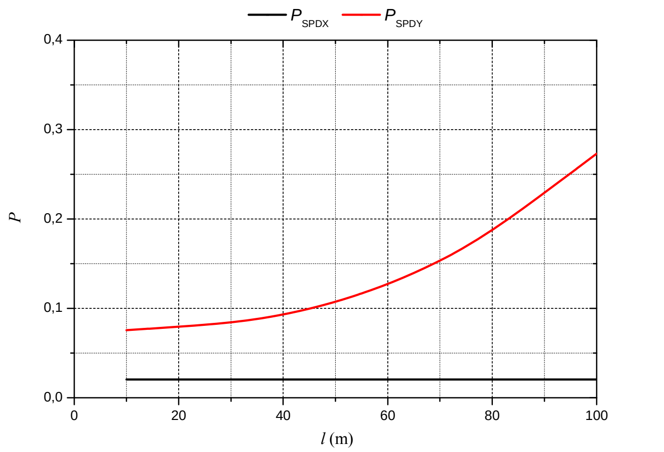
Figure 4. SPD system type SL. - Probability P_{SPD1}, P_{SPD2} and P_{SPD} as a function of circuit length *l*.



SPD1	SPD2	Circuit upstream SPD1	Circuit SPD1-SPD2	Circuit SPD2-apparatus
I_{imp} = 5 kA	SPD2→ SPD X	*n · n'* = 4	*w* = 0,5 m k_c = 0,5 *d* = 1 m	*w* = 0,005 m k_c = 0,5 *d* = 1 m l_c = 0,02 m l_v = 1 m

Figure 5. SPD system type SL. - Probability P_{SPD} as a function of circuit length *l* for two values of supply line length *L* ; SPD X characteristic as in Fig. 8 is adopted.

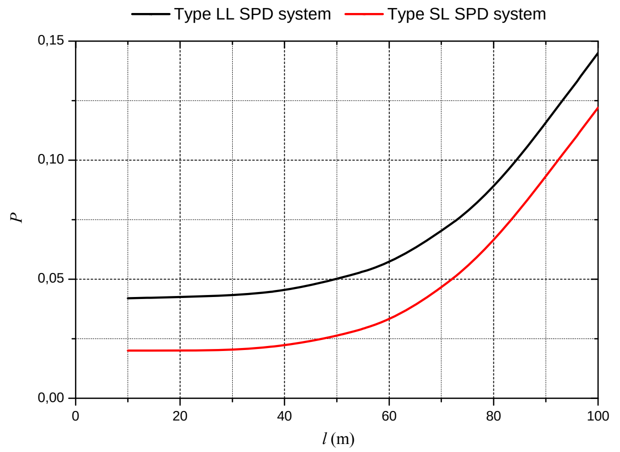
The *U-I* characteristic of the selected SPD2 determines the probability P_{SPD} of the complete system, as shown in Figs. 6 and 7.



SPD1	Circuit upstream SPD1	Circuit SPD1-SPD2	Circuit SPD2- apparatus
I_{imp} = 5 kA	*n · n'* = 4 *L* = 100 m	SPD2→ SPD X or SPD Y *w* = 0,5 m k_c = 0,5 *d* = 1 m	*w* = 0,005 m k_c = 0,5 *d* = 1 m l_c = 0,02 m l_v = 1 m

Figure 6. SPD system type SL. - Probability P_{SPD} as a function of circuit length *l*, for two types of SPDs (for the characteristics of SPD X and SPD Y see Fig. 8).

In the comparison of SPD systems type SL and type LL, Fig. 7 shows that type SL SPD assure lower P_{SPD} due to lower threats that may stress SPD2 where an SPD1 of switching type is installed.



SPD1 switching	*SPD1 limiting*	*Circuit upstream SPD1*	*Circuit SPD1-SPD2*	*Circuit SPD2-apparatus*
I_{imp}= 5 kA	SPD X I_{imp} = 5 kA	$n \cdot n' = 4$ L = 100 m	SPD2→ SPD Z w = 0,5 m k_c = 0,5 d = 1 m	w=0,005 m k_c = 0,5 d = 1 m l_c = 0,02 m l_v = 1 m

Figure 7. Probabilty P_{SPD} for 2 types of SPD sistem type SL and LL as a function of circuit length l ; supply line length L = 100 m (for the characteristics of SPDX and SPD Z see Fig. 8).

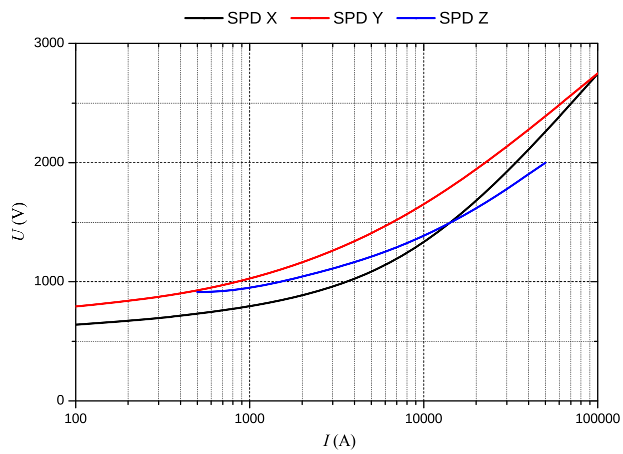


Figure 8. Characteristic *U-I* of three SPDs used in SPD systems *(type SL* and *type LL)*.

In conclusion, in the selection of an SPD system:

- the selection of SPD1 is determined by the condition b), it means that the energy associated to the current I_{SPD1} should not exceed the value tolerated by the SPD1; such condition depends on the supply line: the current I_{SPD1} is the higher the longer the line;

- the selection of SPD2 is determined by the condition a), it means that residual voltage U_{SPD} should not exceed the required protection level U_p of SPD; such condition depends on the internal circuit; where its length is enough high, P_{SPD} of the system is determined by the P_{SPD2}.

VII. CONCLUSIONS

Probability P_{SPD} by which an SPD system reduce the risk of failure of electrical and electronic equipment within a structure depends on:

– type of SPD system (one or more SPD in the system);
– type of SPD (switching or limiting);
– characteristics of the circuit between SPDs;
– ability of SPD to withstand the energy expected at the installation point;
– value of protection level U_p at the expected current able to protect the apparatus, which on turns depends on characteristics of the circuit between SPD and apparatus.

In type SL or type LL SPD system, P_{SPD1} probability depends only on the ability of SPD1 to withstand the charge Q_{exp} at the installation point, while P_{SPD2} probability of SPD2 depends both on its ability to withstand the charge Q_{exp} at the installation point and on its ability to provide the required protection level U_{pr} at the expected current I_{exp}. Therefore P_{SPD} should be evaluated by means of cumulative frequency distribution of:

– lightning charge Q_{short} relevant to positive and negative first stroke and of
– subsequent lightning impulse current.

In particular P_{SPD} depends on the rated current I_n and I_{imp} of SPD in front of the expected current I_{exp} at the installation point; as I_{exp} changes with the source of damage is wrong to assign the same value of P_{SPD} for all sources of damage.

To express P_{SPD} only in term of U_p is misleading: for the same value of U_p, P_{SPD} changes in accordance with *U/I* characteristic of the considered SPD, then it is wrong to assign the same value of P_{SPD} to all SPD for a source of damage.

Furthermore, in practice, a lot of new SPD are of the combination type and different installation configurations appear; for this reason further investigations are needed to cover these cases.

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