Dimensioning of SPD for the protection against surges due to lightning to LV overhead lines

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***Abstract*—The papers deals with the selection of SPD for protection of apparatus within a structure against lightning surges from the connected LV power supply lines. The basic arrangement includes an aerial ten poles low voltage line closed on one side by HV/LV transformer and on other side by apparatus to be protected. By several computer simulations information have been obtained for the selection of SPD to be installed at the entry point of the line into the structure and discussed on the light of international standard.**

Keywords: Lightning protection; Surge Protective Device; SPD protection level

I. INTRODUCTION

Failure of electrical and electronic systems within a structure can be caused by different sources of damage [1-2]. As suggested by the standard [3], surge protective device (SPD) are considered as typical protection measure. For practical applications and proper selection of SPD, it is essential to know the stress which an SPD will experience under surge conditions at the installation point and the SPD protection level to limit transient overvoltages below the rated impulse withstand voltage of the system to be protected.

In the previous contributions [4, 5, 6] the problem of selection and installation of SPD in the case of direct stroke to a structure, namely S1 source of damage, was discussed and adequate conclusions were formulated. The analysis was performed on the base of computer simulations with models coherent with the real circuits tested in the high voltage laboratory of University of Rome "La Sapienza" and Warsaw University of Technology.

Aim of this paper is to perform an analysis for the case of lightning to the line (source of damage S3), in order to establish simple rules for the selection of effective SPD1 with regard to the discharge current and its protection level.

Comments and comparison with the requirements of the international standard IEC/ EN 62305-4 are presented.

II. ANALYSED SYSTEM

The analysed system is shown in Fig. 1. Low voltage supply TN system with a two conductors overhead line is considered as basic arrangement. The overhead line is closed by the HV/LV transformer and apparatus to be protected. The distance between poles is assumed as 50 m. The pole high is 6 m and grounded by surge impedance Z = 10 ÷ 50 Ω. The impulse insulation level of the line is 15 kV.

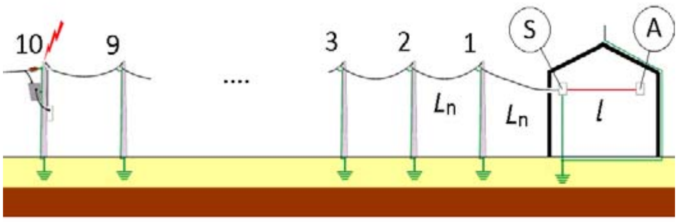

Figure 1. Schematic representation of system analysed where: A – apparatus to be protected; S – switchboard with SPD1 installed; 1-2-3-…-9-10 – number of pole stricken by lightning current; L_n – overhead line span length; l – length of internal circuit.

The simulations are performed with two standardized lightning current, namely wave shape 10/350 µs, and 0,25/100 µs, respectively assumed by [1,7] as typical waveform of first positive stroke and of subsequent stroke of negative flashes. The wave shape 10/350 µs, is responsible of the highest values of charge transferred to SPD1 and then affects the SPD1 dimensioning in terms of I_{imp}. The wave shape 0,25/100 µs, due to high value of current steepness, is responsible of highest voltage drop on connection leads of SPD1 and of reflection phenomena in the circuit analyzed and then affects the SPD1 dimensioning in terms of U_p. For the analysis the lightning current is represented by Heidler function [4]; LPL I as defined by [1] is assumed. The investigation includes both switching and limiting SPD1 types simulated to match adequate characteristic *U-I* and *U-t* according to previous methodology presented in [8]. The SPDs used have similar value of U_p in the range of 1,5 kV. The lossy-line model and pole representation are simulated according to [9]. The transient characteristics of HV/LV transformer are taken from [10, 11]. In this paper only common mode overvoltages are considered.

The paper also report on the influence of stricken pole on the peak value and shape of the current flowing through the SPD1, which affect its protective performances.

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For this investigation a commercial transient program EMTP-RV is used.

III. INVESTIGATION ON CURRENT AND CHARGE

The typical waveform of the current I_{SPD1} flowing through the SPD1 switching type installed at entrance point of the structure to be protected in case of 1, 5 and 10 pole stricken is shown in Fig. 2 for positive stroke and in Fig. 3 for subsequent stroke of negative flash. The current I_{SPD1} flowing through the SPD1 and the associated charge Q_{SPD1} depends on the stricken pole and on its conventional earthing impedance; moreover the charge Q_{SPD1} is also affected by the installed type of SPD1 (switching or limiting).

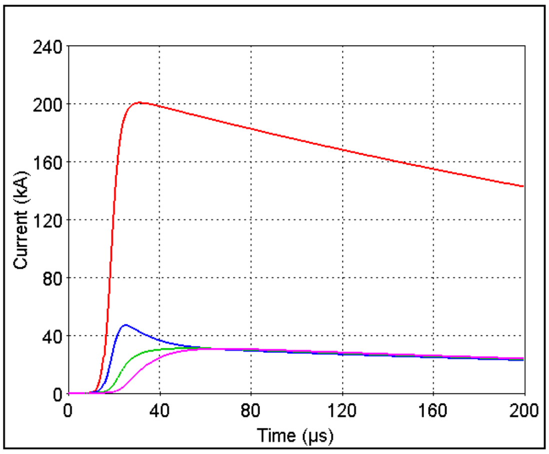

Figure 2. Expected wave shape of current flowing through the SPD1 switching type installed at entrance point of the structure to be protected in case of 1 (— I_{SPD1}), 5 (— I_{SPD1}) and 10 (— I_{SPD1}) pole stricken for positive stroke 200 kA (— I).

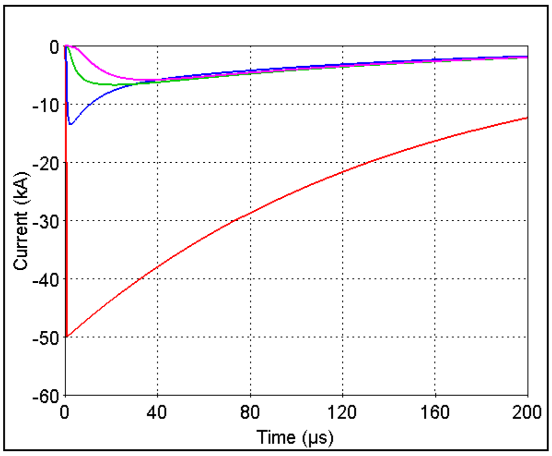

Figure 3. Expected wave shape of current flowing through the SPD1 switching type installed at entrance point of the structure to be protected in case of 1 (— I_{SPD1}), 5 (— I_{SPD1}) and 10 (— I_{SPD1}) pole stricken for subsequent stroke of negative flashes 50 kA (— I).

An approximate value of charge (Q_{mSPD}) associated to the current flowing through SPD1 can be calculated by means of following general formula:

a) for SPD limiting type

$$Q_{mSPD1} = 0{,}2 \cdot Z \quad [C / \Omega] \tag{1}$$

b) for SPD switching type

$$Q_{mSPD1} = 0{,}4 \cdot Z \quad [C / \Omega] \tag{2}$$

where:
Z – pole conventional earthing impedance in Ω.

As example, for a positive stroke of 200 kA and a pole conventional earthing impedance Z = 10 Ω, is Q_{SPD1} = 4,5 C independently from the stricken pole for SPD1 switching type, while for SPD1 limiting type the charge increases with the number of stricken pole from 1,5 C to 4,5 C.

The value of the current I_{SPD1} is practically inversely proportional to the number n' of the line conductors.

In Fig. 4 the ratio I_{SPD1}/I of current I_{SPD1} and the lightning current I is shown as a function of stricken pole. It is to note that the value of ratio I_{SPD}/I significantly decrease as the distance of stricken pole from SPD1 increases, but after 5 pole stricken these values have quasi constant character. Highest values of the ratio I_{SPD1}/I are related to the highest values of pole conventional earthing impedance Z.

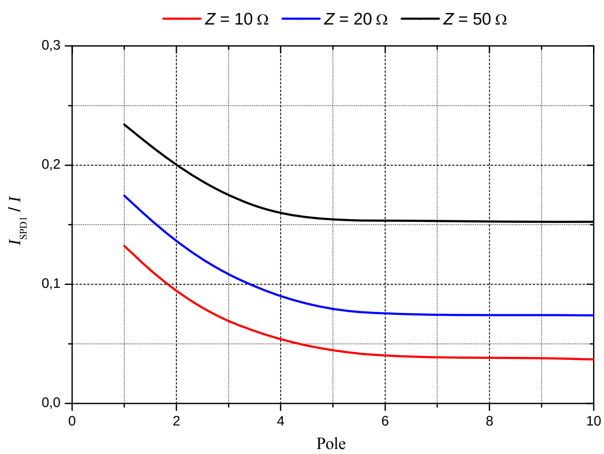

Figure 4. Ratio of current I_{SPD1} flowing through the SPD1 and the lightning current I as a function of stricken pole for different values of pole conventional earthing impedance Z.

In Fig. 5 the influence of stricken point on the rise time T_1 of current I_{SPD1} is shown. It is to see that T_1 significantly increase after 5 pole stricken for first positive stroke as well as for subsequent negative stroke.

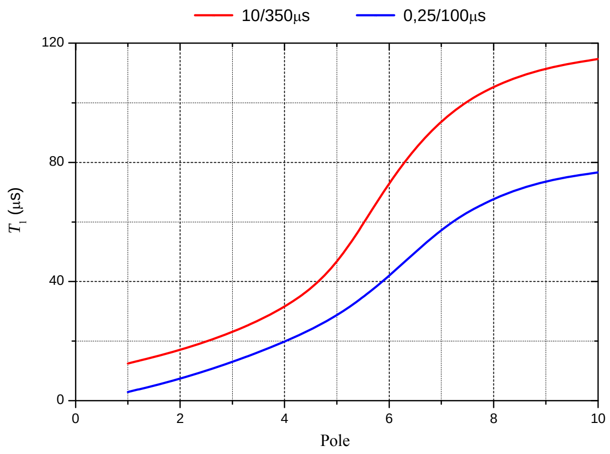

Figure 5. Rise time T_1 of the current I_{SPD1} as a function of the stricken pole.

In Fig. 6 the voltage drop ΔU on SPD1 connection leads as a function of stricken pole for subsequent strokes of negative flashes is shown. It is evidence that in the case 5 pole stricken or further, the voltage drop ΔU can be disregarded.

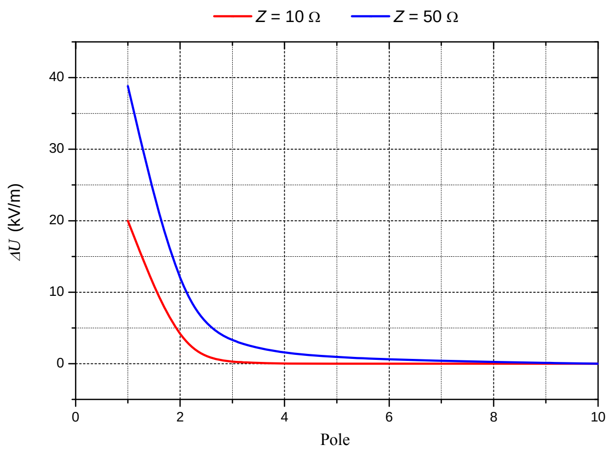

Figure 6. Voltage drop for unit length of SPD1 connection leads as a function of stricken pole for two values of pole conventional earthing impedance *Z*.

IV. INVESTIGATION ON VOLTAGES

Due to the reflection phenomena in the circuit between SPD1 and apparatus, the voltage U_L on the apparatus terminals may be higher than the voltage protection level U_p of SPD1.

As for the ratio U_L/U_p between voltage on the apparatus terminals (U_L) and voltage protection level of SPD1 (U_p) the worst case is the one relevant to subsequent strokes of negative flashes. The value of the ratio U_L/U_p is shown in Fig. 7 for SPD1 switching type and in Fig. 8 for SPD1 limiting type. It is to be noted the better protective performance of SPD1 limiting type in front of SPD1 switching type.

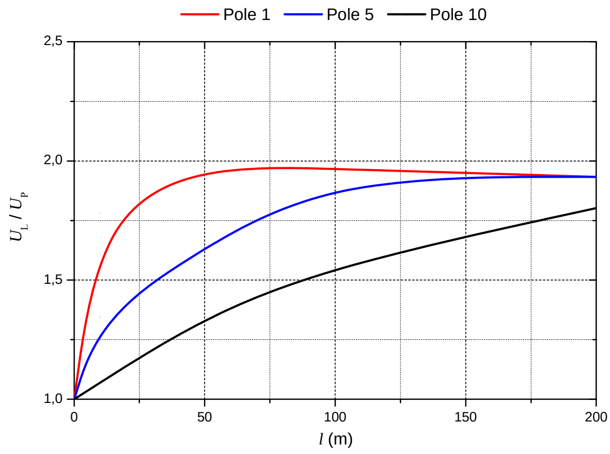

Figure 7. Voltage ratio U_L / U_P as a function of length of circuit *l* for SPD1 switching type.

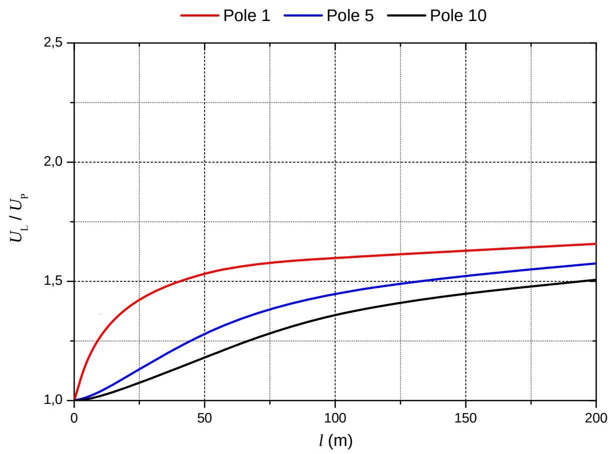

Figure 8. Voltage ratio U_L / U_P as a function of length of circuit *l* for SPD1 limiting type.

V. SPD1 DIMENSIONING

A. *Selection of discharge current I_{SPD}*

As reported in [3], SPD1 should be selected in such way that both the following conditions are fulfilled:

a) the value of U_p at the current I_{SPD1} expected at the point of SPD1 installation does not give rise to voltage U_L at the terminals of the apparatus to be protected higher than his rated impulse withstand voltage U_w;
b) the energy associated to the current I_{SPD1} does not overcome the value tolerated by the SPD1.

The impulse current I_{imp} of a class I test SPD1 and the nominal current I_n of a class II test can be selected if we consider that the charge Q_{SPD} for unit of current associated to the standard current 10/350 µs is Q_{imp} = 0,5 C/kA and the one associated to the standard current 8/20 µs is Q_n = 0,027 C/kA;

therefore the relations to be respected for SPD1 dimensioning are the following:

a) for SPD1 class I test

$$Q_{imp} \geq Q_{SPD1} \text{ or numerically } I_{imp} \geq 2\, Q_{SPD1} \quad (3)$$

b) for SPD1 class II test

$$Q_n \geq Q_{SPD1} \text{ or numerically } I_n \geq 37\, Q_{SPD1} \quad (4)$$

Taking into account that the charge Q_{mSPD} associated to the LPL I current of a positive stroke is expressed by (1) and (2), the following relation can be written for the selection of I_{imp} of SPD1 class I test:

a) for SPD limiting type

$$I_{imp} \geq 2\, Q_{SPD1} = 2 \text{ x } 0{,}2 \text{ x } Z \text{ x } (I/200) \text{ x } 2\,/n' \quad (5)$$

b) for SPD switching type

$$I_{imp} \geq 2\, Q_{SPD1} = 2 \text{ x } 0{,}4 \text{ x } Z \text{ x } (I/200) \text{ x } 2\,/n' \quad (6)$$

where:
n' is the number of the line conductors and I is the lightning current.

For a SPD1 limiting type and for protection level LPL I, in Tab. I. the values are reported of the current I_{imp} according to the number of the line conductors and the pole conventional earthing impedance Z.

TABLE I. VALUES OF I_{IMP} [KA] ACCORDING TO THE THE NUMBER N'OF LINE CONDUCTORS AND THE POLE CONVENTIONAL EARTHING IMPEDANCE Z FOR PROTECTION LEVEL LPL I AND SPD1 LIMITING TYPE.

n'	$Z = 10\Omega$	$Z = 30\Omega$	$Z = 50\Omega$
2	4	12	20
3	2,5	8	13
4	2	6	10

For a SPD1 switching type, the values of Tab. 1 should be doubled.

Similar evaluation for SPD1 class II test gives values of I_n ranging from 74 and 170 kA for SPD limiting type and double foe SPD switching type, so that in practice only an SPD1 class I test is convenient to install as SPD1.

B. *Selection of protection level* U_P

According to the [1] the overvoltage protection level U_p of an SPD shall be selected in such a way that the voltage U_L at the terminals of the apparatus to be protected does not overcome 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 circuit between SPD and apparatus to be protected (protected circuit).

The inductive voltage drop ΔU on the leads/connections of SPD should be combined with the protection level U_p in order to obtain the so-called "effective protection level" U_{pf} of the SPD [3]. The voltage drop depends on the length of the connecting leads and on the steepness of the current flowing through the SPD. Following the IEC 62305-4 [3], the effective protection level U_{pf} is defined as the voltage at the output of the SPD resulting from its protection level U_p and the voltage drop ΔU, namely:

$$U_{pf} = U_p + \Delta U \text{ for limiting type SPD} \quad (7)$$

$$U_{pf} = \max(U_p\,, \Delta U) \text{ for switching type SPD} \quad (8)$$

Due to the propagating effects of surge travelling along the protected circuit [4, 5, 6] the selection of protection level U_p according to the length l of the protected circuit can be performed by the following formulas:

$$U_{pf} \leq U_w \text{ for } l = 0 \quad (9)$$

$$U_{pf} \leq U_w / f(l) \text{ for } l > 0 \quad (10)$$

where:
$f(l) = a \cdot l^b$ is a function of the length l of the protected circuit.

The values of coefficients a and b for the two types of SPD, namely switching or limiting type, are shown in Fig 9 and in Fig. 10 respectively.

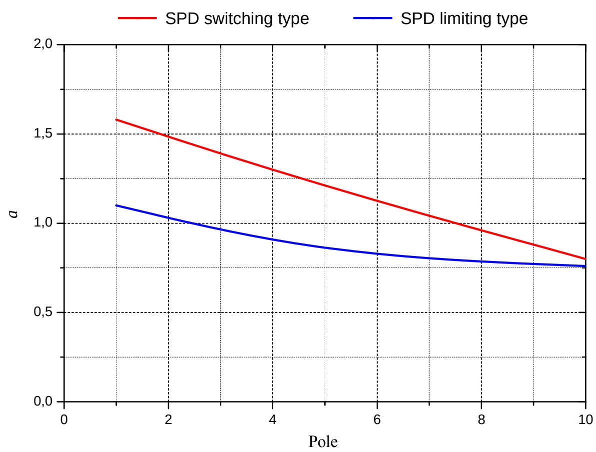

Figure 9. Values of coefficient a as a function of pole stricken for SPD1 switching and limiting type.

Figure 10. Values of coefficient *b* as a function of pole stricken for SPD1 switching and limiting type.

From the obtained results it is clear that the more severe condition for selection of protection level of the SPD at the entry point of the line is when the first pole closest to the structure is stricken. In such condition:

- the voltage drop ΔU on SPD1 connecting leads is so high (see Fig. 6) that apparatus will be damaged even if the length of the circuit is very short (SPD1 at apparatus terminals). In this case protection of the apparatus may be obtained only if the length of SPD1 connecting leads is kept to minimum;

- to equal the length of the circuit, the switching type SPD gives rise to an increase in voltage on the apparatus higher than that caused by the SPD limiting type; in other words, to equal conditions the circuit length protected by an SPD switching type is lower than that protected by an SPD limiting type (see Fig. 7);

- due to the high steepness of the voltage at SPD1 switching type terminals, the distance l_2 at which the voltage is doubled on apparatus terminals is only some tens of meters; this means that a usually a downstream SPD2 should be installed close to apparatus to be protected if the upstream SPD1 is switching type.

Indeed it is worth considering that the protective effect of the SPD improves as far away as the pole is stricken; therefore, the reduction of the probability of damage by an SPD1 should be evaluated taking into account not only the more severe condition of first pole stricken, but also taking into account the probability that even the other poles could be stricken and then the probability that the whole line could be stricken.

VI. Conclusions

On the base of performed analyses the following conclusions can be formulated:

- apparatus to be protected can be damaged by the lightning surges coming from the incoming lines. The most severe stresses are related to the stricken points on the line close to apparatus;

- protection of apparatus by means of an SPD1 installed at entrance point of line in the building can be achieved only if the stricken point on the line is far away from the apparatus;

- for stricken points on the line close to apparatus, protection of apparatus is practically impossible to achieve, unless the length of SPD1 connecting leads is kept in the range of few centimeters and a SPD1 limiting type is used. In addition, the length of protected circuit should be kept in the range of few meters if a SPD1 switching type is used;

- for stricken points on the line close to apparatus, protection of apparatus can be achieved if a downstream SPD2 is installed close to apparatus;

- the probability with which an apparatus will be damaged depends on the stricken point on the line;

- the probability with which an SPD installed at the entry point of the line (SPD1) will protect an apparatus should be assessed taking into account that the whole line could be stricken;

- 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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