Abstract—Aim of the paper is to investigate on the probability of a coordinated surge protective device (SPD) system to reduce the risk of failure of electrical and electronic equipment within a structure against lightning surges due to direct lightning stroke to the connected low voltage overhead lines (source of damage S3 according to IEC standard 62305). Two SPD systems are considered, namely SPD system type SL, consisting of a SPD1 switching type and a SPD2 limiting type, and an SPD system type LL, consisting of a SPD1 and a SPD2 limiting type. The approach here presented and discussed takes into account the type of SPD system and the characteristics of the upstream power line and of the downstream protected circuit. The analysis has been performed by several simulations obtained by means of the transient software EMTP-RV. The results are compared with those obtained with only one SPD (switching or limiting type) installed for the protection of apparatus within the structure.

Keywords—Apparatus safety; Overvoltage protection; Surge Protective Device

I. INTRODUCTION

Flashes to power and communication lines connected to the structure (source of damage S3 according to IEC standard 62305) can cause severe failure of electrical and electronic systems within a structure [1-5].

The typical protection measure suggested by the standard [6] with aim to assure equipment protection is a coordinated system of surge protective device (SPD). In [7] and [8] the stress, in terms of energy and current, which an SPD will experience under surge conditions at its installation point has been investigated.

In the contribution [9] an approach to evaluate the probability of a given SPD system to reduce the risk of failure of apparatus has been presented and discussed 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. According to this approach the probability $P_{\text{SPD}}$, that a surge will damage an apparatus protected by an SPD system, is associated to the probability that, at the installation point, the expected charge overcome the one tolerable by the SPD system and to the probability that the SPD system protection level is higher than the value of impulse rated voltage ($U_i$) of equipment to be protected.

In the contribution [10] the probability of damage $P_{\text{SPD}}$ relevant to a SPD system consisting of only one SPD (SPD1), switching or limiting type, installed at the entry point of the line into the structure, was investigated taking into account not only the surges transmitted to the apparatus traveling along the line but also the inductive coupling of the lightning current, striking different points of the line, with the internal circuit supplying the apparatus to be protected.

The investigation confirmed that, by installing a single SPD1 at the entry point of the line into the structure, low value of $P_{\text{SPD}}$ may be reached only for long multi-conductor power lines provided that shielded or multi-conductor cable are used for protected circuit. Otherwise a second SPD (SPD2) close to apparatus to be protected should be installed.

Aim of this paper is to evaluate the probability of damage of an SPD system formed by two SPDs. Two main types of SPD are considered in the following, namely type SL SPD system (SPD1 switching plus SPD2 limiting type) and type LL SPD system (SPD1 and SPD2 both limiting type).

The analysis has been performed by several computer simulations obtained by means of the transient software EMTP-RV. The results are discussed with those [7] obtained in the case of only one SPD (switching or limiting type) installed for the protection of apparatus within the structure.

II. PROBABILITY $P_{\text{SPD}}$ EVALUATION

As reported in the contribution [10] and assuming the same notations, the probability $P_{\text{SPD}}$ that an overvoltage will damage an apparatus protected by an SPD system type SL or LL is:

$$P_{\text{SPD}} = 1 - (1 - P_{\text{SPD1Q}}) \cdot (1 - P_{\text{SPD2L}}) \quad (1)$$

where:
- \(P_{SPD10}\) is the probability that for the positive stroke and negative first strokes \(Q_{SPD1}\) exceed \(I_{imp}/2\) or \(I_t/18.5\) of SPD1, respectively for class I or class II test SPD;
- \(P_{SPD2U}\) is the probability that for the subsequent stroke of negative flashes the voltage \(U_{SPD2}\) of SPD2 exceeds the required protection level \(U_{p}\) of the SPD2;
- \(I_{imp}\) is the current (10/350 μs) of class I test SPD;
- \(I_t\) is the nominal current (8/20 μs) of class II test SPD;
- \(U_{SPD}\) is the voltage across SPD when the current \(I_{SPD}\) is discharged;
- \(U_{p}\) is the SPD protection level required for apparatus protection.

For evaluation of probability \(P_{SPD10}\), the current \(I_{SPD1}\) expected at installation point of SPD1 and the associated charge \(Q_{SPD1}\) are needed. The current \(I_{SPD1}\) flowing through the SPD1 and the associated charge \(Q_{SPD1}\) depend on the stricken pole and on its conventional earthing impedance \(Z_p\); moreover the charge \(Q_{SPD1}\) is also affected by the installed SPD1 type (switching or limiting).

For evaluation of probability \(P_{SPD2U}\) the current \(I_{SPD2}\) expected at installation point of SPD2 and the associated charge \(Q_{SPD2}\), the voltage drop \(ΔU\) on the SPD2 connecting leads, the ratio \(k = U/U_p\) between voltage on the apparatus terminals \(U\) and the protection level of SPD2 \(U_p\) and the voltage \(U\) induced by lightning current in the protected circuit are needed. Moreover it is to be expected that \(P_{SPD2U}\) will remain constant regardless of the stricken pole.

Such parameters were investigated in [7] and [8].

III. CASES UNDER STUDY

The case investigated in the present paper refers to:

- source of damage S3;
- SPD system type SL and type LL;
- switching type SPD able to extinguish the perspective short circuit current at installation point without the help of back up disconnector.

The analyzed system is shown in Fig. 1 similar to that presented in [7] and [8]. Low voltage supply TN system with a two conductors overhead line is considered as basic arrangement. The overhead line is terminated by the HV/LV transformer and apparatus to be protected. The distance between poles is assumed as 50 m. The poles are 6-m high and grounded by surge impedance \(Z_p\) in the range of 10 to 50 Ω. The impulse insulation level of the line is 15 kV. The conventional earthing impedance of the structure is assumed \(Z = 10 \Omega\).

Information on the models used in transient software EMTP-RV to simulate the components of the system are presented in [8] and more in details in [11-19].

IV. THE INFLUENCE OF STRICKEN POLE ON THE PROBABILITY \(P_{SPD}\)

As reported in [8] the stricken pole affects the peak value and shape of the current \(I_{SPD1}\) flowing through the SPD1, while has virtually no influence on the charge \(Q_{SPD1}\) and on the current \(I_{SPD2}\). On the contrary:

a) the charge \(Q_{SPD1}\) increases with the pole earthing impedance \(Z_p\) and with decreasing the number \(n’\) of line conductors. Moreover it is to be expected that \(P_{SPD10}\) will remain constant regardless of the stricken pole.

b) the voltage drop \(ΔU\) on the connections leads of the SPD2, the ratio \(k = U/U_p\) between voltage on the apparatus terminals \(U\) and the protection level of SPD2 \(U_p\) and the voltage \(U\) induced by lightning current in the protected circuit decrease with increasing distance between the stricken pole and the SPD system and with decreasing of conventional earthing impedance \(Z_p\) of poles.

As the probability \(P_{SPD2U}\) is strongly influenced by \(ΔU\), \(k\) and \(U_v\), to is be expected that \(P_{SPD2U}\) decreases with increasing distance between the stricken pole and the SPD system.

In conclusion, the probability \(P_{SPD}\) changes with the length of the line and may be calculated as average of different values of probability \(P_i\), related to each stricken pole of the line: this has an influence on the probability \(P_{SPD}\), which should be calculated as average of different values of probability \(P_i\), related to each stricken pole:

\[
P_{SPD} = \frac{\Sigma P_i}{n} \tag{2}
\]

where:
- \(n\) the number of line poles.

V. DISCUSSION OF THE RESULTS

The probability \(P_{SPD}\) as function of factors influencing the dimensioning of the SPD system is reported in:
- Fig. 2 for probability \(P_{SPD10}\);
- Fig. 3 and 4 for probability \(P_{SPD2U}\).

Fig.5 shows the probability \(P_{SPD2U}\) as function of the voltage characteristic of the selected limiting types SPD. The voltage characteristics of the selected SPD are reported in Fig. 6.
Fig. 2 shows that, as for S/L SPD system [8], at the same conditions and at the same value of the rated current $I_{imp}$, type L SPD1 class I test may assure lower value of probability $P_{SPD1O}$ than type S SPD of the same class test.

Moreover, from Fig. 2 it is clear that the probability $P_{SPD1O}$ of SPD1 class I test is decreasing with its rated current $I_{imp}$.

In addition, for a given selected SPD1, the probability $P_{SPD1O}$ decreases with the earthing impedance $Z_p$ of the poles and with the number $n'$ of line conductors, it is the number of parallel paths, on which the lightning current is flowing. A reduction of $P_{SPD1O}$ has been found:
- 8 times for a LL system, and 5.5 times for a SL system, going from a value of $Z_p = 50 \, \Omega$ to a value of $Z_p = 10 \, \Omega$;
- 3 times going from a $n' = 2$ to a $n' = 4$.

It results that the most critical condition for probability $P_{SPD1O}$ is where the internal equipment is connected to a two conductors supply line with high value of pole earthing impedance $Z_p$.

Fig. 3. Probability $P_{SPD1O}$ of the SPD2 in an SL and LL SPD system as a function of the length $L$ of line for different width $w_{2a}$ of circuit SPD2 - apparatus. Number of line conductors $n' = 2$; earthing impedance of poles $Z_p = 50 \, \Omega$; length the connections leads of the SPD2: $l_c = 0.5 \, m$; length of the circuit between SPD1 and SPD2: $l = l_{2a} = 50 \, m$; SPD = SPD Y, as in Fig. 6.

Figs. 3 and 4 show the values of probability $P_{SPD2U}$ that the voltage $U_{SPD2}$ of SPD2 is exceeding the required protection level $U_{pr}$. It is clear that such probability strongly depends on the dimensions of the circuit between the SPD2 and the apparatus to be protected, in particular on the length $l_{2a}$ and on the width $w_{2a}$ of circuit SPD2-apparatus, as well as on the length $l_c$ of SPD2 connections. The probability $P_{SPD2U}$ is also decreasing with the line length $L$, due to decreasing of $\Delta U$, $k$ and $U_i$ with increasing distance between the stricken pole and the SPD2, as already mentioned.

While the characteristics of the circuit-SPD1-SPD2 have little influence on $P_{SPD2U}$, the determining factor is the width $w_{2a}$ of circuit SPD2-apparatus; if it is $w_{2a} > 0.005 \, m$ it is unlikely to get low values of $P_{SPD2U}$ unless the line is longer than several hundred meters.

Fig. 4. Probability $P_{SPD2U}$ of the SPD2 in an SL and LL SPD system as a function of the length $L$ of line for different width $w_{2a}$ of circuit SPD2 - apparatus. Number of line conductors $n' = 2$; earthing impedance of poles $Z_p = 50 \, \Omega$; length the connections leads of the SPD2: $l_c = 0.5 \, m$; length of the circuit between SPD1 and SPD2: $l = l_{2a} = 50 \, m$; SPD = SPD Y, as in Fig. 6.

When circuits SPD2-apparatus are made with multiconductors or shielded cable ($w_{2a} \leq 0.005 \, m$), comparison
between Fig. 3 and Figs. 4 and 5, leads to the conclusion that $P_{\text{SPD}}$ is generally much less than the $P_{\text{SPD1Q}}$, and that therefore the probability $P_{\text{SPD}}$ of the SPD system is in practice coincident with $P_{\text{SPD1Q}}$.

In Fig. 5 the values of probability $P_{\text{SPD}}$ as a function of the line length $L$ are given for two types of type L SPD class I test with the characteristics reported in Fig. 6, as SPD type X and SPD type Y. Lower values of probability may be obtained with SPD X, which, according to the $U/I$ characteristic, assure a lower protection level $U_p$ at higher values of impulse current.

**VI. EXAMPLE OF FREQUENCY OF DAMAGES EVALUATION**

The frequency of damage $F_{s3}$ relevant to source of damage S3 is the value of the number of damages in the internal systems of structure to be protected, caused by lightning flashes to the line.

For internal systems with rated impulse withstand voltage $U_{w} = 2500$ V supplied by an aerial line, the evaluation of the frequency of damage $F_{s3}$ related to source S3, may be performed according to the following relationships:

$$F_{s3} = N_{l} \cdot P_{\text{SPD}}$$  \hspace{1cm} (3)

where:

- $N_{l} = N_{G} \cdot L \cdot 40 \cdot 10^{-6}$ is the average annual number of dangerous events due to flashes to an aerial line in rural environment [20];
- $N_{G}$ is the lightning ground flash density of the area where the line is installed (1/km$^2$ x year);
- $L$ is the length of the power line (m).

In this section it is considered the evaluation of the frequency of damages $F_{s3}$ for a structure located in area with lightning ground flash density $N_{G} = 4$, protected by an SPD system type L and type LL. Information on the characteristics of supplying line and the SPD adopted are given in Tab. 1.

<table>
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<th>TABLE I. BASIC CHARACTERISTICS OF THE STRUCTURES UNDER CONSIDERATION</th>
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<td><strong>SPD</strong></td>
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In Fig. 7 the results of the reduction of the frequency of damages $F_{s3}$ by using an SPD system type LL for different values of impulse current $I_{imp}$ of SPD1 are reported.

**Figure 6.** $U/I$ characteristic of SPD type L selected for probability evaluation.

**Figure 7.** Frequency of damages $F_{s3}$ as a function of impulse current $I_{imp}$ of SPD1 at different values of impulse current $I_{imp}$ of SPD1 and SPD2 both limiting type. $N_{l} \rightarrow$ Structure unprotected.

**Figure 8.** Frequency of damages $F_{s3}$ as a function of power line length $L$ for SPD system type L and type LL. NL $\rightarrow$ Structure unprotected.
In Fig. 8 the results of the frequency of damages $F_{S3}$ of an apparatus protected by an SPD system type LL are compared with those obtained with only one SPD type L, installed at the entry point of line into the structure, for two values of impulse current $I_{imp}$ of the SPD.

In the SPD system type L, because the high value of the loop area of the circuit SPD1 – apparatus, the probability $P_{SPD1}$ is the component which contributes most to the buildup of probability $P_{SPD}$; therefore, the attempt to lower the frequency of damage $F_{S3}$, by installing SPD with high values of $I_{imp}$, is vain. However, low values of $P_{SPD}$, and thus of the frequency of damage $F_{S3}$, can be obtained with an SPD system type LL, by installing an SPD close to apparatus to be protected.

VII. CONCLUSIONS

Probability $P_{SPD}$ of an SPD system to reduce the probability of failure of electrical and electronic equipment within a structure depends on SPD system provided as well as on the upstream power line characteristics and on characteristics of the circuit between SPD and apparatus to be protected.

The probability that an apparatus, protected by a single SPD1 installed at the entry point of line into the structure, will be damaged by a lightning flash to the line, strongly depends on the length and on the width of circuit SPD1-apparatus, as well as on the length of SPD1 connections. When it is impractical for installation difficulties to reduce the length of SPD1 connections and the loop area of circuit SPD1-apparatus, lower values of probability may be obtained by installation of an SPD2 close to apparatus to be protected.

While the characteristics of the circuit between SPD1-SPD2 have little influence on $P_{SPD}$, the determining factor is the loop area of circuit SPD2-apparatus.

When circuits SPD2-apparatus are made with multiconductors or screened cable ($w_{2a} \leq 0.005$ m), the $P_{SPD2}$ is generally much less than the $P_{SPD1}$, and therefore the probability $P_{SPD}$ of the SPD system is in practice coincident with $P_{SPD1}$.

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