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Lightning electromagnetic pulse (LEMP) influence on the electrical apparatus protection

Streszczenie. *Impulsowe zmiany pól elektromagnetycznych mogą zaburzyć funkcjonowanie współczesnych urządzeń elektronicznych i elektrycznych. Pola te mogą powstać w wyniku uderzenia pioruna, a zetem przepływu prądu udarowego. Wartość impulsu pola elektromagnetycznego prądu piorunowego (LEMP) mogącego zaburzyć funkcjonowanie urządzeń, uzależnione jest od miejsca uderzenia piorunu oraz rodzaju obiektu budowlanego, w którym urządzenie jest zainstalowane. Z punktu widzenia ochrony odgromowej można wyróżnić cztery niebezpieczne przypadki tzn. uderzenie piorunu bezpośrednio w obiekt chroniony (S1), uderzenie w pobliżu obiektu chronionego (S2), uderzenie piorunu bezpośrednio w linię (S3) oraz uderzenie piorunu w pobliżu linii (S4). W artykule zawarte są analizy dotyczące spodziewanej wartości amplitudy i kształt prądu indukowanego przez LEMP (efekt indukcyjny S1), w celu prawidłowego doboru SPD. Wyniki analiz są skonfrontowane z wymaganiami doboru SPD sugerowanymi przez normy międzynarodowe.*

Abstract*. Nowadays structures are more and more equipped with electrical and electronic apparatus sensitive to electromagnetic field influence. Such field among others can be caused due to lightning occurrences. The intensive of lightning electromagnetic pulse (LEMP) which can affect the regular operations of apparatus depends on the strike point as well as on the specific features of structure to be protected. From the lighting protection point of view it is possible to distinguish four dangerous events, or sources of damage, namely flashes to the structure (S1), flashes to ground or to grounded objects near the structure (S2), flashes to the connected lines (S3), flashes nearby the connected lines (S4). The paper intends to give a contribution to the investigation on the expected surge current, peak value and shape, due to LEMP by flashes to the structure (inductive coupling of source of damage S1) for the SPD proper selection in order to assure electronic apparatus operation. The obtained results are discussed with the SPD requirements of international standard.* ***Wpływ impulsowych zmian pola elektromagnetycznego na zabezpieczenia aparatów elektrycznych***

Słowa kluczowe: Ochrona odgromowa; LEMP; Ograniczniki przepięć
Keywords: Lightning protection; LEMP; Surge Protective Device

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Introduction

Electrical and electronic systems within a structure are subjected to damage from Lightning Electromagnetic Pulse (LEMP) [1-5]. Therefore LEMP protection measures (LPM) need to be provided to avoid failure of such systems. The IEC standards [6] introduce the following LPM: earthing and bonding measures, magnetic shielding, line routing, isolation interface, coordinated surge protective device (SPD) system.

In previous papers [7, 8] simple rules were established for the selection of effective SPD with regard to the discharge current and its protection level in the case of surges due to flashes to the structure (source S1), protected by a lightning protection system (LPS). The influence of the main factors and parameters which affect the selection and installation of an SPD of both types (switching and limiting) installed at entry point of line into the structure (*SPD1*) and at apparatus to be protected terminals (*SPD2*) have been discussed (see Figure 1) by help of several computer simulations validated by the experimental results performed in HV laboratory.

In particular it was established that:

• the high values of the induced voltage U_i confirm the need to install the downstream *SPD2* near or at the terminals of the apparatus, even for circuits with PE and phase conductors in the same cable and

• if *SPD1* is of switching type, induction effect is the decisive factor in determining the current I_{SPD2} flowing through *SPD2* and the voltage drop ΔV on its connection leads.

Aim of the contribution is to supply a comprehensive information on the induced expected surge current, peak value and shape, due to LEMP by flashes to the structure (source of damage S1) for the *SPD*2 proper selection in order to assure electronic apparatus operation. This case is of particular importance when *SPD1* of switching type is bonding the phase conductor to the equipotential bonding bar for reduction of the surge voltage by resistive coupling at the entry point of a power line into the structure.

A critical comparison and discussion of the obtained results with the SPD requirements of international standard [5] is performed.

Calculation of induced voltages and currents

A. Reference configuration

The lightning flash near or to a structure induces common mode surge voltages and currents into the electrical circuit within the structure due to very high value of the time derivative of the lightning current.

Figure 1 represents a simple example of flash to a lightning protection system (LPS) conductor near an electrical circuit loop, where: I - stroke current; d – distance between lightning current flowing in the electrical conductor and the induced circuit loop; l – loop length; w – loop width;

r – wire radius; Z – earthing system impedance; *SPD1* – SPD bonding the phase conductor to the equipotential bonding bar (EBB); *SPD2* – SPD at the apparatus terminals.

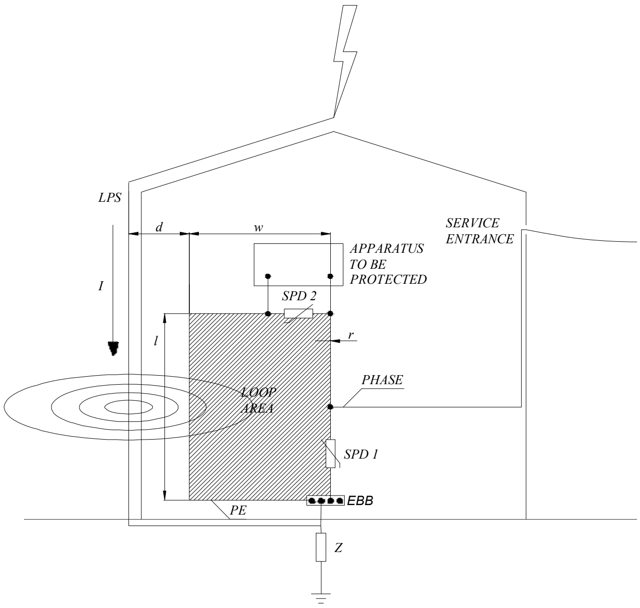

Fig.1. Considered arrangement: lightning strokes to LPS near an electric circuit

While in [7] the conditions for selection and dimensioning of the *SPD1* have been established in order to limit surge voltage by resistive coupling at the entry point of a power line into the structure, attention is focused here on the surge threat of the *SPD2* due to coupling of the induced circuit loop with the lightning current. The results of this investigation have been useful as an intermediate step in the research relevant SPD system selection, where some master points can be find in [6, 9].

In order to compare the obtained results with the requirements of IEC 62305, the value of distance d is fixed at d = 1 m; the earth conventional impedance Z = 10 Ω .

B. Normative aspects

The international standards [5, 10] consider the problem of protection against LEMP. In document [5] the expected values of surge currents due to flashes on low voltage systems are presented. In document [10] aspects of telecommunication systems are included. In table 1 the values of the induced current due to flash to the structure (source of damage S1) and for different lightning protection levels (LPL) are reported.

Table 1. On low-voltage systems due to lightning flashes to a structure-source of damage S1 (induced current)

LPL	I_i [a, b] [kA]
III - IV	5
II	7,5
I	10
NOTE All values refer to each line conductor.	
[a] Current shape: 8/20 µs. Loop conductors routing and distance from inducing current affect the values of expected surge overcurrents.	
[b] Loop inductance and resistance affect the shape of the induced current.	

The values in table 1 refer to short-circuited, unshielded loop wires with different routing in large buildings (loop area in the order of 50 m^2, w = 5 m), 1 m apart from the structure wall, inside an unshielded structure or building with two down conductors LPS (k_c = 0,5). For other loop and structure characteristics, current values should be multiplied by reducing factors, by which screening effectiveness of internal and external shields as well as characteristics of internal wiring are taken into account.

The induced current shape required for SPD dimensioning is 8/20 µs. Moreover the standard notes that the loop inductance and resistance affect the shape of induced current.

Case study under consideration

The considered arrangement is shown in figure 1. The investigation is focused on the influence of:

• the induced circuit configuration (cross section of the loop wire, width and length of the loop, distance of the loop from the inducing current);

• the installed protection devices, namely switching or limiting *SPD2*, assuming *SPD1* of switching type;

on the parameters:

• peak value and shape of induced voltages at apparatus to be protected terminals;

• peak value and shape of induced currents;

• charges associated to induced currents.

The analyses have been performed by means of the transient software EMTP-RV.

The lightning stroke has been simulated as an ideal current generator by means of the following equation (Heidler function):

$$I = \frac{I_p}{k} \cdot \frac{(t/\tau_1)^{10}}{1+(t/\tau_1)^{10}} \cdot \exp(-t/\tau_2) \qquad (1)$$

where: k – is the correction factor for the peak current; t – is the time; I_p – is the peak value of the lightning current; τ_1 – is the front time of the lightning current; τ_2 – is the tail time constant.

Four shapes of lightning current, namely representative of positive stroke (10/350 µs), first negative stroke (1/200 µs), subsequent negative stroke (0,25/100 µs) as well as normalized shape (8/20 µs) dedicated for SPD II class test, have been considered.

A summary of the computer modeling assumptions adopted in the present investigation are reported in [9].

Results and discussion

Loop inductance and resistance of internal circuits affect the shape of induced current. Where the loop resistance is negligible, the shape of induced current is similar to the lightning inducing current. It means that SPDs tested with I_{imp} (test class I with typical current shape 10/350 µs) should be selected; if the loop resistance is not negligible, the shape of induced current is shorter (see figure 2) and SPDs tested with I_n (test class II with typical current shape 8/20 µs) could be selected.

The analysis performed on the loop with the same characteristics of the one assumed by the IEC standard 62305-1 as basic reference configuration (d = 1 m; loop area 50 m^2) shows that:

• peak of induced current I_i is slightly increasing with the cross section S of the loop wire (see figure 3);

• the peak value of induced current I_i is not affected by the wave shape of inducing current I_s, as shown in figure 3;

• the charge Q_i associated to the induced current depends on the wire cross section as well as on the steepness of stressing source, as shown in figure 4. The highest values are obtained for the positive stroke (current 10/350 µs) and the lowest values for the negative subsequent stroke (current 0,25/100 µs). The influence of loop wire cross section is well spotted for first positive stroke;

• the shape of the induced current is the same of the inducing current;

• as far as the total charge Q_{SPD2} associated to the current flowing through *SPD2*, the worst case is relevant to the first lightning stroke (10/350 μs) and to the largest circuit loop.

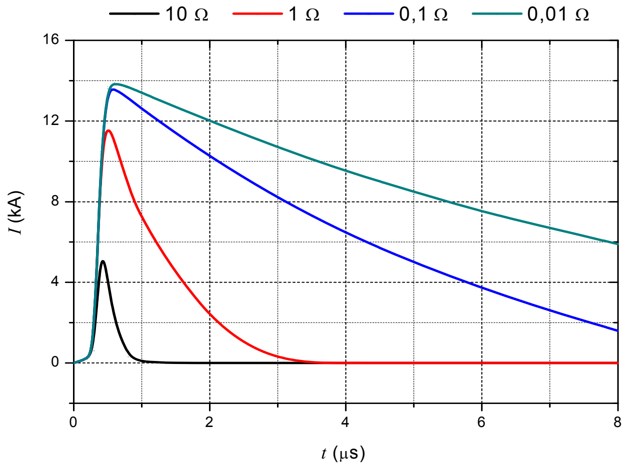

Fig.2. Induced current in a loop of 50 m^2 area for different values of its resistance; inducing current of a subsequent stroke (simulated by the Heidler function) flowing in a vertical down conductor at 1 m distance from the loop

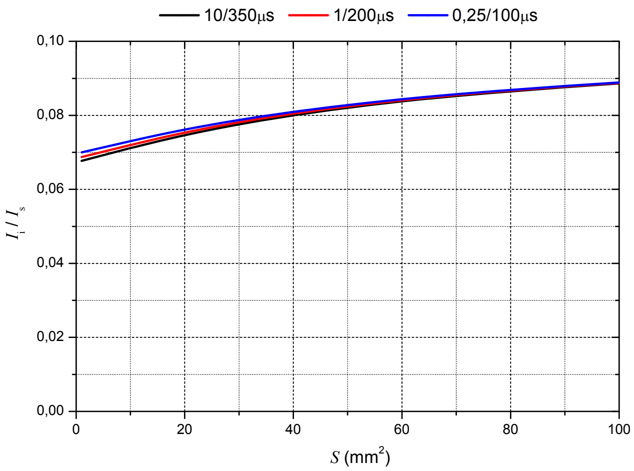

Fig.3. Ratio between induced current I_i and source current I_S in case of loop with an *SPD1* switching type and *SPD2* limiting type and the following parameters loop area 50 m^2, d = 1 m , as a function of loop wire cross section, for three source current shapes

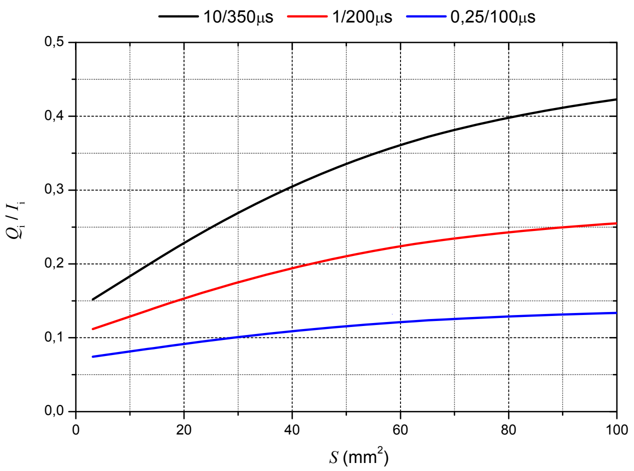

Fig.4. Ratio between charge of induced current Q_i and induced current I_i in case of loop with an *SPD1* switching type and *SPD2* limiting type and following parameters loop area 50 m^2, d = 1 m as a function of wire cross section, for three source current shapes

***SPD2* dimensioning**

A. Selection of protection level U_{p2}

As reported in details in [7, 8], for the *SPD2* installed at secondary distribution board, the selection of protection level U_{p2} should take into account:
a) the inductive voltage drop ΔV of the leads/connections of *SPD2*;
b) the effect of surge travelling along the protected circuit;
c) the overvoltages U_i induced by lightning current in the protected circuit formed by the *SPD2* and the apparatus to be protected.

Following the IEC 62305-4 [6], if an 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 ΔV.

As shown in [8], the following formulas may help in the selection of U_{p2} according to the length l of the protected circuit:

(2) $U_{pf2} \leq U_w$ for $l = 0$ m

(3) $U_{pf2} \leq (U_w - U_i) / (1 + 0{,}1l)$ for $0 < l \leq 10$ m

(4) $U_{pf2} \leq (U_w - U_i) / 2$ for $l > 10$ m

where: U_w - the rated impulse withstand voltage of the apparatus to be protected.

For the *SPD2* installed at secondary distribution board, the selection of protection level U_{p2} should be made with reference to the subsequent strokes of negative flashes, which represent the more severe case [9].

It should be noted that it is crucially important to reduce the high values of ΔV and the induced voltage U_i caused by inductive coupling in the loop of circuit between *SPD2* and apparatus. Possible suitable installation provisions are:
• reduction of the loop area by using circuit routing with PE and phase conductors in the same cable, better if twisted;
• use of screened circuits or their laying in a closed metallic conduit;
• reduction of the length of *SPD2* leads connection as much as possible.

In the absence of such provisions it is likely that a further SPD (*SPDa*) with $U_{pfa} \leq U_w$ should be installed just at apparatus terminals.

Once *SPDa* is provided, the fulfillment of conditions a), b) and c) is no longer required for *SPD2*: only the energy coordination between *SPD1*, *SPD2* and *SPDa* should be considered.

B. Selection of discharge current I_{SPD2}

As reported in [6], the impulse current I_{imp} of a class I test SPD and the nominal current In of a class II test SPD should be selected in such way that both the following conditions are fulfilled:
a) the value of U_{p2} at the current I_{SPD2} expected at the point of *SPD2* installation, does not overcome the rated impulse withstand voltage level U_w of the apparatus to be protected;
b) the energy associated to the discharge current does not overcome the value tolerated by the *SPD2*.

Therefore, 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 that associated to the standard current 8/20 μs is Q_n = 0,027 C/kA, the relations to be respected for *SPD2* dimensioning are the following:

a) for *SPD2* class I test

(5) $I_{imp} \geq I_{SPD2}$

(6) $Q_{imp} \geq Q_{SPD2}$ or numerically $I_{imp} \geq 2\ Q_{SPD2}$

b) for *SPD2* class II test

(7) $I_n \geq I_{SPD2}$

(8) $Q_n \geq Q_{SPD2}$ or numerically $I_n \geq 37\, Q_{SPD2}$

If an *SPD1* switching type is installed, values of I_{SPD2} and of Q_{SPD2} are reported in figure 5. In this figure the contribution of inducing effect to the I_{SPD2} and to the charge Q_{SPD2} is shown.

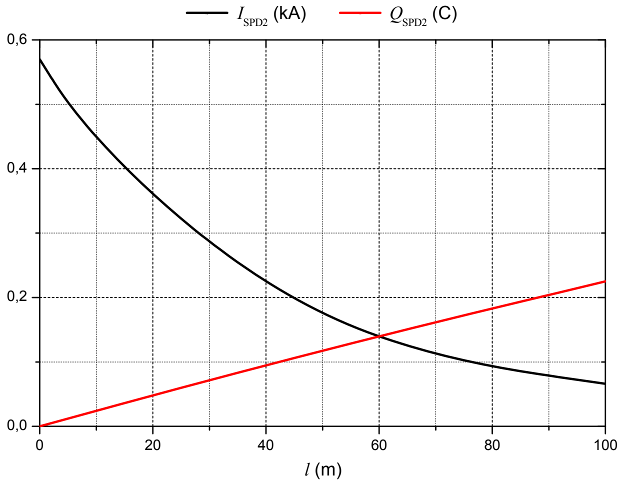

Fig.5. Current (I_{SPD2}) and charge (Q_{SPD2}) due to induction effects in case of loop with an *SPD1* switching type as a function of loop length l for positive stroke current; w = 0,5 m; d = 1 m.

The arrangements of loop as by the IEC 62305 standard, are here considered, namely:
- active and PE conductors follow different routing (e.g. w = 0,5 m);
- active conductor and PE are in the same conduit (e.g. w = 0,1 m);
- active conductor and PE are in the same cable (e.g. w = 0,005 m).

In table 2 the calculated values of charge induced in the three mentioned conditions show that the values proposed by the standard are adequate for limiting type *SPD2* class II test if switching type *SPD*1 class I test is installed.

Moreover the values required by the standard are several times higher than the ones calculated if switching type *SPD2* class I test is selected.

Table 2. Induced charge in case of LPL I for positive stroke

Induced loop width (m)	Calculated Charge Q_i (C)	IEC 62305-1 Current shape 8/20μs Q_i (C)	IEC 62305-1 Current shape 10/350 μs Q_i (C)
0,5^A	0,23	0,54	10
0,1^B	0,052	0,108	2
0,005^C	0,0003	0,0054	0,1

^A Active conductor and PE in different routing
^B Active conductor and PE in the same conduit
^C Active conductor and PE in the same cable
Distance of the induced circuit loop d = 1 m; loop length l = 100 m; cross section of the loop wire S = 3 mm^2

Conclusions

On the base of performed simulations the following conclusions could be formulated:
- where *SPD1* switching type is installed the values of expected induced current proposed by IEC 62305-1 for *SPD2* are on safety side for both types SPD class I and II tested;
- for the *SPD2* installed at secondary distribution board, the selection of protection level U_{p2} should be made with reference to the subsequent strokes of negative flashes, which represent the more severe case;
- for the *SPD2* installed at secondary distribution board, the selection of discharge current I_{SPD2} should be made with reference to positive lightning stroke (10/350 μs), which represent the more severe case;
- highest values of total charge Q_{SPD2} flowing in *SPD2* is due to positive lightning stroke (10/350 μs) and to the largest circuit loop;
- the high values of the induced voltage U_i confirm the need to install the downstream *SPD2* near or at the terminals of the apparatus, even for circuits with PE and phase conductors in the same cable.

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