Tomasz KISIELEWICZ[1], Fabio FIAMINGO[1], Carlo MAZZETTI[1], Bolesław KUCA[2], Dominik KRASOWSKI[2]

University of Rome “La Sapienza” (1), Warsaw University of Technology (2)

Impact of Overvoltage Shape Caused by Lightning Stroke on Sensitive Apparatus Protection by Means of SPD

***Abstract**. Flowing lightning current may cause overvoltages by resistive or inductive coupling. These occurrences may be particularly dangerous for the apparatus of telecom and signalling networks within modern structures. To reduce the probability of electrical equipment damage and potential consequential loss, the surge protective devices (SPD) can be used as protection measure. The paper deals with influence of lightning overvoltage shape on SPD protection features. Present contribution has an experimental character.*

***Streszczenie.** Przepływający prąd piorunowy powoduje przepięcia powstające na skutek sprzężeń indukcyjnego i rezystancyjnego.. Zjawiska te są szczególnie niebezpieczne dla delikatnych urządzeń telekomunikacyjnych i informatycznych. W celu zapewnienia stosownej ochrony powszechnie stosowane są urządzenia ochrony odgromowej (SPD). Artykuł przedstawia wpływ kształtu przepięcia na poziom ochrony. Praca ma charakter laboratoryjny(**Wpływ kształtu przepięcia atmosferycznego na wrażliwe urządzenia chronione przez SPD**).*

Keywords: Lightning protection, Surge Protective Device, SPD protection level.
Słowa kluczowe: Ochrona odgromowa, urządzenie ochrony przepięciowej, poziom ochrony.

Introduction

Lightning phenomena are extremely random in natural environment and there are no devices and methods capable of preventing these discharges. Appearance of the lightning flash create impulsive fast surges which could be sources of damage for sensitive apparatus, e.g. for apparatus of telecom and signalling networks within modern structures. The apparatus of such networks are sensitive to electromagnetic fields produced by current of direct and nearby lightning flashes.

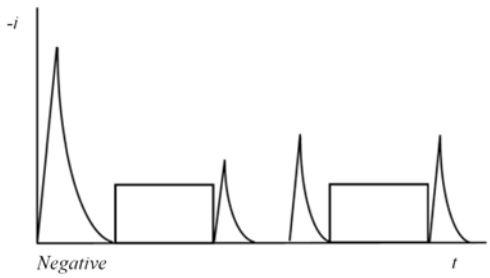

Fig.1. Possible components of negative downward flashes

A lightning flashes consists of one or more different strokes with positive or negative polarity. However during lightning phenomena is possible to distinguish short strokes, it means first or subsequent strokes with impulsive current of duration in the range of microseconds, and long strokes with current duration longer than 2 ms (see Fig. 1 adapted from [1]). Further differentiation of flashes comes from their position:

S1: flashes to the structure

S2: flashes to ground or to grounded objects near the structure

S3: flashes to the connected lines;

S4: flashes nearby the connected lines.

In case S2 or S4 overvoltages are practically impulse shaped, with approximately the same front time as the inducing current (10 μs for first stroke and 0,25 μs for subsequent stroke) and a time to half-value sometimes much shorter, i.e. of the order of a few microseconds, very different from the standard lightning impulse [2].

To reduce the probability of electrical apparatus failure and potential consequential loss, the surge protective devices (SPD) can be used as protection measure.

The paper deals with influence of lightning overvoltage shape on SPD protection features for sensitive apparatus. For this aim several laboratory tests were performed in order to ascertain this influence.

Case study under consideration

The laboratory setup was formed by an impulse voltage generator with peak value of 450 V whose electrical parameters were selected in order to obtained different voltage shapes: 1,2/50 μs, 12/50 μs, 0,25/50 μs, 12/500 μs, 8/20 μs; typical low voltage limiting SPDs with different protection levels: U_P = 40 V, U_P = 80 V, U_P = 100 V; telecommunication wires of length d = 30 m, connecting SPD to equipment characterized with a high value of input resistance. The voltage was measured at SPD and apparatus terminals and the influence of front steepness of incoming overvoltage was recorded and analysed.

The considered arrangement is shown in Fig. 2. It consists of the impulse voltage generator (*G*), the typical low-voltage limiting SPDs, the conductors leading the SPD and the apparatus to be protected and high value resistive (*R*) loading element.

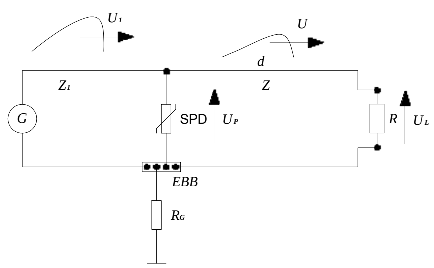

Fig.2. Analysed circuit: G - impulse voltage generator; U_1 – surge voltage; Z_1 – surge impedance left by the surge; EBB – equipotential bonding bar; R_G – earth resistance; U_P – voltage on the SPD terminals; d –length of lead connecting SPD to equipment to be protected; Z – surge impedance right by the line; U – overvoltage incoming through distant SPD; U_L – voltage on the terminals of apparatus to be protected

Test setup

In laboratory tests as the impulse voltage generator the HAEFELY recurrent surge generator type 48 has been used. This device has a possibility of generating a different forms of overvoltages. The peak value as well as times T_1 and T_2 generated impulses can be obtained. Equivalent electric circuit of surge generator is shown Fig. 3.

The peak value of stressing impulse was kept on 450 V during the tests. The overvoltage shapes with corresponding circuit parameters of generator are reported in Table 1.

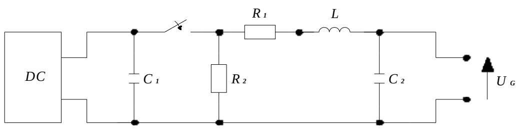

Fig.3. Equivalent electric circuit of impulse voltage generator

Table 1. Settings of impulse generator

Wave shape T_1/T_2 [µs]	R_1 [Ω]	R_2 [Ω]	C_1 [nF]	C_2 [nF]	L [µH]
0,25/50	3,3	68	1000	1	0
1,2/50	4,7	68	1000	100	0
8/20	68	10	1000	100	0
12/50	47	68	1000	100	0
12/500	47	680	1000	100	0

The typical low-voltage limiting SPDs with different level of protection U_P = 40 V, U_P = 80 V and U_P = 100 V, signalling copper wires with 0,14 mm^2 cross-section adapt to nominal voltage 150 V, high value of resistance R (open circuit) as a load have been used. Analysed circuit has been connected to the local ground system of laboratory, where the earth resistance is R_G = 0,1 Ω.

Voltages at SPD and at apparatus terminals were measured by a digital oscilloscope Yokogawa mod. 2022 with maximum samples rate 2,5 GS/s, frequency bandwidth 200 MHz and maximum record length 62.5 Mpoints.

The following voltages have been measured during the tests:

- U_P - voltage on the SPD terminals (CH1)
- U_L - voltage on the terminals of equipment to be protected (CH2)

Voltage conditions

The condition for analysed arrangement may be defined in terms of involved voltages as follows [3, 4]:

(1) $$U_L = U_P + U_B + U_{OS} + U_I$$

where:
U_L – voltage stressing the equipment to be protected, U_P – SPD protection level, U_B – voltage drop on the SPD branch, U_{OS} – voltage increase on the protected distance, U_I – induced voltage in this circuit.

At the assumption that the voltage drop U_B on SPD branch is neglected due to short length connection of SPD and the induced voltage U_I in the circuit loop formed by SPD and equipment is effectively reduced, the condition (1) may be simplified to the following [5]:

(2) $$U_L = U_P + U_{OS}$$

It means that the voltage on the apparatus terminals is greater than that on SPD. U_{OS} depends on the feature of connecting leads and stressing overvoltage. It may be demonstrated that voltage increase through the distance *d* can be describe by fallowing general equation [6]:

(3) $$U_{OS} = 2 \cdot s \cdot t_t = 2 \cdot s \cdot \frac{d}{v} = k \cdot d$$

where:
s – front steepness of the incoming overvoltage to SPD (V/µs)
$k = \frac{2 \cdot s}{v}$ – increasing of the voltage for unit length of the circuit (V/m)

The steepness is related to the voltage increment ΔU and Δt:

(4) $$s = \frac{\Delta U}{\Delta t}$$

The travel time (t_t) is related to the length of circuit (d) and to the surge speed (v) of the travelling wave in the circuit

(5) $$t_t = \frac{d}{v}$$

Influence of lightning overvoltage shape

The SPD function in real occurrence results in the initiation of travelling waves caused by lightning current. In analysed arrangement the travelling waves are caused by the impulse voltage generator. However in both cases the wave propagation model is applied. The voltage wave may be reflected and modified along the circuit towards the apparatus. Due to very high value of the input impedance (open-circuit) on the apparatus terminals, the voltage may build up to $2\ U_P$ [5].

Some results obtained by laboratory tests and calculations by applying simple relations from (3) to (5) are reported in Table 2, 3 and 4 for three SPD protection levels: U_P = 40 V, U_P = 80 V, U_P = 100 V.

Table 2. Measured and calculated values of voltage on apparatus to be protected terminals for U_P = 40 V, R = 1 MΩ load condition, connecting leads d = 30 m and different wave form

Wave shape T_1/T_2 [µs]	U_L [V]			
	Measured	Calculated		
		$\Delta U/\Delta t_{max}$	$\Delta U/\Delta t_{30\text{-}90\%}$	$\Delta U/\Delta t_{10\text{-}90\%}$
0,25/50	79,5	81,85	180,50	149,22
1,2/50	64,7	66,30	154,66	139,12
8/20	47,3	49,38	55,82	54,75
12/50	46	47,45	49,85	51,55
12/500	45,6	46,29	50,73	52,62

Table 3. Measured and calculated values of voltage on apparatus to be protected terminals for U_P = 80 V, R = 1 MΩ load condition, connecting leads d = 30 m and different wave form

Wave shape T_1/T_2 [µs]	U_L [V]			
	Measured	Calculated		
		$\Delta U/\Delta t_{max}$	$\Delta U/\Delta t_{30\text{-}90\%}$	$\Delta U/\Delta t_{10\text{-}90\%}$
0,25/50	160	164,00	456,00	380,00
1,2/50	120	123,33	143,74	155,47
8/20	80	85,71	98,28	97,5
12/50	79	85,42	93,18	94,27
12/500	78	82,13	94,90	92,91

Table 4. Measured and calculated values of voltage on apparatus to be protected terminals for U_P = 100 V, R = 1 MΩ load condition, connecting leads d = 30 m and different wave form

Wave shape T_1/T_2 [µs]	U_L [V]			
	Measured	Calculated		
		$\Delta U/\Delta t_{max}$	$\Delta U/\Delta t_{30\text{-}90\%}$	$\Delta U/\Delta t_{10\text{-}90\%}$
0,25/50	194	200,00	511,50	403,00
1,2/50	146	150,40	175,35	191,24
8/20	95	103,72	119,64	117,5
12/50	94	101,71	110,89	109,54
12/500	94	101,20	112,70	114,08

Uncertainty may arise in the definition of voltage steepness $s = \Delta U/\Delta t$, where:
$\Delta U/\Delta t_{max}$ – voltage increment in range of time from 0 to 100% peak value,
$\Delta U/\Delta t_{10\text{-}90\%}$ – voltage increment in range of time from 10 to 90% peak value,
$\Delta U/\Delta t_{30\text{-}90\%}$ - voltage increment in range of time from 30 to 90% peak value,

The results from laboratory tests and calculations show that good correlation of voltage values could be achieved if $\Delta U/\Delta t_{max}$ is assumed as steepness definition. In this case comparable results are obtained for each wave form of stressing overvoltage. The differences in results using different definition of steepness are well spotted when steepness of stressing overvoltage has a very sharp shape.

Fig. 4 and 5 represents the case where stressing overvoltage has a 0,25/50 μs and 1,2/50 μs form respectively.

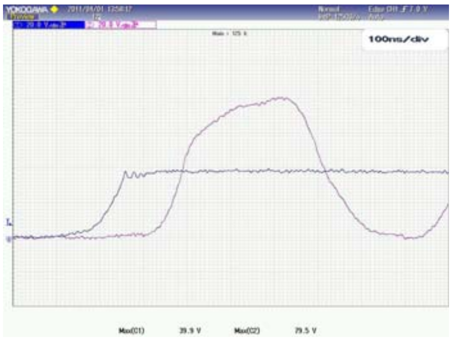

Fig.4. Oscillograms of voltage: CH1 voltage on the SPD terminals (U_P = 40 V), CH2 voltage at apparatus to be protected, represented by resistive load, R = 1 MΩ; Stressing impulse voltage wave shape 0,25/50 μs; connecting leads length d = 30 m

Fig.5. Oscillograms of voltage: CH1 voltage on the SPD terminals (U_P = 40 V), CH2 voltage at apparatus to be protected, represented by resistive load, R = 1 MΩ; Stressing impulse voltage wave shape 1,2/50 μs; connecting leads length d = 30 m

In Table 5, 6 and 7 the values of voltage measured on the SPD terminals *(U_P)* and on the load terminals *(U_L)* are reported together with increment of voltage for unit of length of circuit for different wave shape.

Table 5. Measured values of voltage on the SPD and on apparatus to be protected terminals for U_P = 40 V, R = 1 MΩ load condition, connecting leads 30 m and different wave form

Wave shape T_1/T_2 [μs]	U_P [V]	U_L [V]	$\frac{U_L - U_P}{d}$ [V/m]
0,25/50	39,9	79,5	1,32
1,2/50	39,7	64,7	0,83
8/20	36,5	47,3	0,36
12/50	36,5	46	0,32
12/500	36	45,6	0,32

It is to note that the voltage on the SPD terminals depends on the current flowing in the branch according to the SPD V-I characteristics, so that the measured value of U_P can be less than the nominal values 40 V, 80 V and 100 V.

Table 6. Measured values of voltage on the SPD and on apparatus to be protected terminals for U_P = 80 V, R = 1 MΩ load condition, connecting leads 30 m and different wave form

Wave shape T_1/T_2 [μs]	U_P [V]	U_L [V]	$\frac{U_L - U_P}{d}$ [V/m]
0,25/50	80	160	2,67
1,2/50	80	120	1,33
8/20	74	80	0,20
12/50	74	79	0,17
12/500	74	78	0,13

Table 7. Measured values of voltage on the SPD and on apparatus to be protected terminals for U_P = 100 V, R = 1 MΩ load condition, connecting leads 30 m and different wave form

Wave shape T_1/T_2 [μs]	U_P [V]	U_L [V]	$\frac{U_L - U_P}{d}$ [V/m]
0,25/50	100	194	3,13
1,2/50	100	146	1,53
8/20	90	95	0,17
12/50	92	94	0,07
12/500	92	94	0,07

Conclusions

On the base of laboratory tests the following conclusions could be formulated:

- for an incoming voltage very sharp, like 0,25/50 μs form, the voltage may be doubled at load in 30 meters due to oscillation phenomena;
- increment for unit of length of the voltage at apparatus to be protected depends on the steepness of stressing overvoltage and on the type of cable;
- good agreement between tested and calculated results has been achieved for $\Delta U/\Delta t_{max}$ - voltage steepness in range of time from 0 to 100% peak value - used in calculation.

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REFERENCES

[1] IEC 62305-1, "Protection against lightning – Part 1: General principles", Ed.2, December 2010
[2] C.A. Nucci, CIGRE WG 33.01.01: Lightning-induced voltages on overhead power lines. Part II Coupling models for the evaluation of the induced voltages, Electra n.162, 1995
[3] C. F. Barbosa, R. Pomponi, R. Tommasini: SPD characteristics for equipment protection, ICLP 2010, Cagliari, Italy, 13-17 September 2010
[4] D. Krasowski, T. Kisielewicz, B. Kuca, Z. Flisowski, F. Fiamingo, C. Mazzetti: On critical distance between an spd and protected appliance with respect to their voltage coordination, ICLP 2010, Cagliari, Italy, 13-17 September 2010
[5] IEC 62305-4, "Protection against lightning – Part 4: Electrical and electronic systems within the structures", Ed.2, 12. 2010
[6] G. L. Amicucci, F. Fiamingo, Z. Flisowski, G.B. Lo Piparo, C. Mazzetti: Surge protective devices for low voltage systems: practical approach for the protection distance evaluation, IEEE Power Tech, Lausanne (Switzerland), 1-5 July 2007

***Authors**: M. Sc. Tomasz Kisielewicz, University of Rome "La Sapienza", Via Eudossiana 18, 00-184 Rome, Italy, t.kisielewicz@uniroma1.it; Dr. Fabio Fiamingo, University of Rome "La Sapienza", Via Eudossiana 18, 00-184 Rome, Italy, f.fiamingo@fastwebnet.it; Prof. dr Carlo Mazzetti, University of Rome "La Sapienza", Via Eudossiana 18, 00-184 Rome, Italy carlo.mazzetti@uniroma1.it; Dr. Boleslaw Kuca Warsaw University of Technology, ul. Koszykowa 75, 00-662 Warsaw, Poland kucab@ee.pw.edu.pl; M.Sc. Dominik Krasowski, Warsaw University of Technology, ul. Koszykowa 75, 00-662 Warsaw, Poland, dkra@pgi.gov.pl*