Selection of Surge Protective Devices for Low-Voltage Systems Connected to Overhead Line

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***Abstract*--This paper presents a procedure of choosing an appropriate surge protective device for low-voltage systems connected to an overhead line. For a typical surge protection application an appropriate EMTP model is devised. The energy overload is calculated for a surge protective device following a simulation of the lightning effect. This way it is possible to determine the required class for the surge protective device in question. The procedure has been tested on some typical overhead low-voltage networks. The results of such calculations, as well as very good service experiences, demonstrate that the use of Class II surge protective devices seems to be appropriate for service entrances in buildings that have no lightning protection systems.**

***Index Terms*--Overhead low-voltage distribution line, probability of energy overloading, procedure, protected building, surge protective device classes.**

I. Introduction

THE occurrence of numerous damages to low-voltage (LV) equipment due to incidents of voltage surges, especially in suburban areas, suggests that there is a great need for installation of appropriate surge protective devices (SPD) in LV systems. In general, there exist three types of SPD according to [1]: SPDs of Classes I, II and III. Relevant laboratory test procedures for each of the said three classes have been provided and they will be adhered to. The SPDs of Class I are tested using current waves 8/20 µs, 10/350 µs and voltage wave 1,2/50 µs; the SPDs of Class II are tested using current waves 8/20 µs and voltage wave 1,2/50 µs; finally, the SPDs of Class III are tested using the combined wave 1,2/50 / 8/20 µs (open circuit / short circuit of a generator). There exists a discrepancy between IEC standards 61643-1 [1], 61643-12 [2] and IEEE standard C62.45 [3] as far as the introduction of current wave 10/350 µs for testing of Class I SPD. The paper [4] calls for a unification of the current waves for testing of SPDs in the abovementioned documents. Other papers [5]-[9] have also concluded that a simulation using current wave 10/350 µs should be regarded as an extremity with a very low probability scenario.

II. Surge Protection and Surge Protective Devices

Unlike SPDs that are based on a spark gap, the protective devices that are based on a metal-oxide (MO) varistor, in general, are not suitable for tests with current waves of a longer duration. In order to explain this fact, let us assume that the 10/350 µs current wave is a long duration wave, and that the 8/20 µs current wave is a short duration wave. The difference between the two current waves is shown in Fig. 1.

When the current wave 10/350 µs passes through a spark gap, the voltage drop on the spark gap appears relatively low (arc voltage). Now, the integration of the product of instantaneous current, voltage and time values yield a much lower amount of energy that needs to be absorbed by the spark gap. This is the reason why the spark gap is suitable for tests with long duration waves.

When the current wave 10/350 µs passes through a MO varistor, the voltage drop on the MO varistor appears relatively high compared to the one appearing on a spark gap. The integration of the product of instantaneous current, voltage and time values yields a large amount of energy that needs to be absorbed by the MO disc. The MO disc is able to absorb only a limited amount of energy in order to remain stable (it heats up), since it is supplied from a voltage source.

The energy absorbed by the MO varistor is proportional to the surface below the curves shown in Fig.1. Clearly, conducting tests using a current wave 10/350 µs requires much higher energy levels for SPDs which are based on a MO varistor. That is why SPDs, which are based on a MO varistor and of usual cross sectional area of the disc, can thermally withstand current waves 10/350 µs with relatively low amplitudes only (up to approx. 7 kA). The newly developed MO varistors (ZnO disks) with the surface area of 2265 mm^2 can thermally withstand the current waves 10/350 µs with amplitude of 14 kA [10] and with surface area of 4300 mm^2 with amplitude of 25 kA [11].

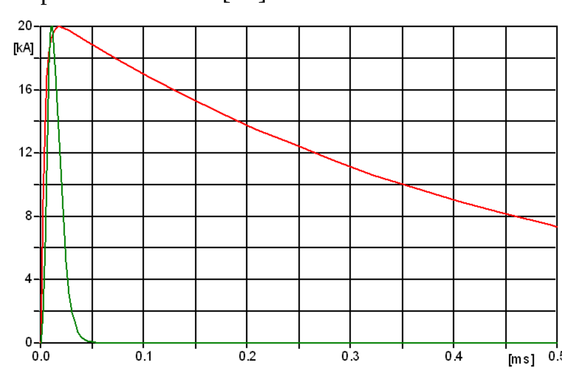

Figure 1: Current waves 10/350 µs and 8/20 µs, 20 kA

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Table I shows the allocation of SPDs into relevant surge categories, as well as the associated task of a particular surge category. It is clear that every line that is entered into a building (whether a communication or electrical line) in the area where a lightning strike is possible needs to be protected by an appropriately located SPD of Class I. For a building that is supplied by an overhead LV network, the case is illustrated in Fig. 2. It is necessary to install a SPD of Class I (lightning current arrester) in front of the consumer watt-hour meter. The distribution panel is a typical installation location for a SPD of Class II.

The SPD of Class II can safely discharge the current waves 8/20 μs with amplitudes in the order of tens kA, as well as to decrease the remaining voltage of the SPD Class I. The SPD of Class III is usually located between the distribution panel and the end consumer, or within the power socket. Some more sensitive consumers have their own surge protection installed inside the housing.

TABLE I
ALLOCATION OF SURGE PROTECTIVE DEVICES [12]

Installation Location / Task of SPD	Overvoltage categories		
	IV Utility terminal	III Distribution panel	II Power Socket
- Potential compensation (equalizing) / surge protection - Discharging part of lightning current	SPD of Class I - Lightning current arrester		
- Surge protection - Reduction of remaining voltage of Class I SPD - Limitation of induced surges		SPD of Class II	
- Surge protection - Limitation of switching surges - Voltage reduction of preceding SPD			SPD of Class III

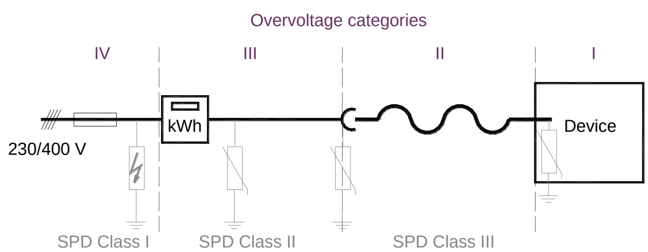

Figure 2: Surge protection according to IEC standards

The configuration that is described above presents an almost ideal surge protection. To protect the most valuable installations, it is advisable to adhere to this IEC concept. However, to protect the simpler installations (e.g. family homes), it is necessary to simplify the above configuration due to the following. First of all, such a form of surge protection for simpler installations is not commonly used. Very often such buildings have no surge protection whatsoever. Second of all, as a consequence of the above mentioned, such surge protection has a prohibitive price tag.

The combined SPD Class I, which also includes an SPD Class II, represents a possible simplification to the surge protection configuration. Such combined SPD of Class I retains the attributes of Class I, together with the capacity to conduct relatively high current waves of 10/350 μs, but also the attributes of an SPD Class II – a low remaining voltage. Although this configuration seems optimal at first, its major drawback is its high price.

The other possible solution for a simplified configuration is to leave out the first stage (SPD of Class I), as illustrated in Fig. 3. Instead, an SPD of Class II should be installed in its place, thus the surge protection would be configured within two stages, as is the practice in the USA for power distribution [4]. The anticipated drawback of such a configuration would be a possible overload of an SPD of Class II at the service entrance.

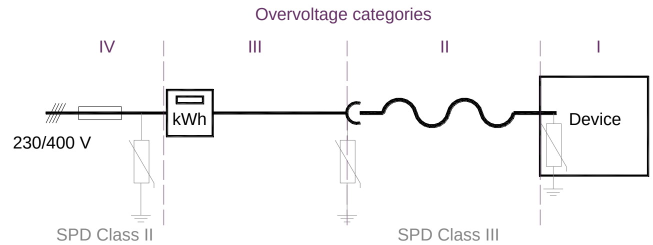

Figure 3: Two stages surge protection

The following chapter describes the energy overload analysis procedure of an SPD of Class II at the service entrance. This is an attempt to provide an answer to the fundamental question of how to utilize an SPD of Class I (lightning current arrester)? This would also require testing with a current wave 10/350 μs. IEEE C62.45 [3] does not envisage tests with such current wave. The purpose of the following analysis is to check the installation of SPDs of Class II at the service entrance by taking into account a relatively low probability (relative frequency) of energy overloading during its lifespan (once every hundred or once every two hundred years). The procedure is based on a premise that a very low number of SPD faults caused by energy overloads can be acceptable, while, simultaneously, taking into account the probability of occurrence of the lightning current waves with defined amplitude and duration.

III. SELECTING SURGE PROTECTIVE DEVICE IN LV SYSTEMS

This paper deals with buildings that have no lightning protection system, and therefore only direct lightning stroke to an overhead LV network is considered herein. Usually, the lightning strikes the ground in the vicinity of a building or an overhead LV network, and the induced overvoltages on the overhead LV (or telecommunication) network travel towards the buildings and may damage electric and electronic equipment. Induced overvoltages cannot cause such high energy load of SPD as caused by a direct lightning stroke. Induced overvoltages cannot energy overload SPD of Class II at the service entrance, and they are, therefore, not significant in the context of the paper. As an example, induced overvoltages and currents that travel to the beginning and to the end of a LV overhead network were calculated. Induced currents (for a very high subsequent return stroke of 45 kA and front steepness ≈100 kA/μs) in three phases of LV line are shown in Fig. 4. Clearly, the amplitude, the front of wave and wave tail duration of the induced current do not reach the test wave for Class II SPD (for example 10 kA, 8/20 μs). This shows that induced overvoltages in an LV overhead network cannot be a barrier to use of Class II SPD at the service entrance.

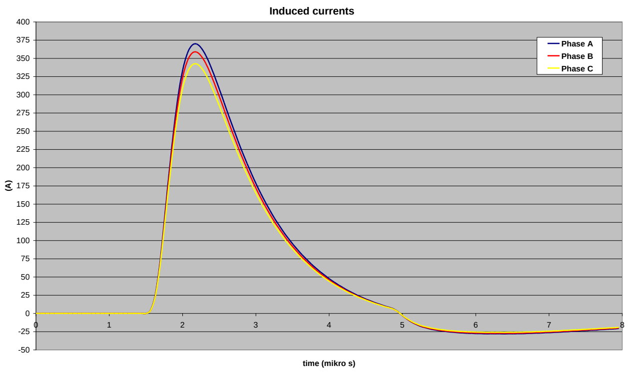

Figure 4: Induced currents in all three phases at the beginning and at the end of an LV network (resistive load is matched to surge impedance).

A. Procedure

In this paper the procedure of choosing the SPDs in LV networks is presented. For each typical surge protection application an appropriate EMTP model is devised. The acceptable probability of energy overload for SPDs of Class II is then adopted. An appropriate lightning current is chosen according to the adopted probability. The lightning stroke simulation is performed, and the energy load of the SPD is calculated. The relative frequency of energy overload is thus obtained, which is then associated with the adopted probability. Based on above, a conclusion is drawn whether SPD of Class II is adequate. The block diagram describing such procedure is shown in Fig. 5.

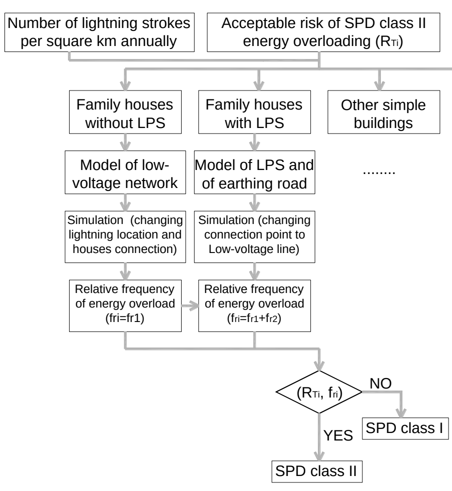

Figure 5: Choice of adequate SPD for buildings

For example, the acceptable risk of fault, due to energy overload for a SPD of Class II at the service entrance of a family home without lightning protection system (LPS), of $R_{Ti} = 10^{-2}$ (once in a hundred years) is suggested.

B. Model of an LV network

An LV network with aluminum/steel (Al/St) conductors (and self carrying cable bundle) was modeled taking into account the frequency dependence. The same model was adopted for buildings connected to the LV network.

When a lightning strikes the highest conductor of a post (Fig. 6) in the LV network, the flashover happens to other conductors as well. The electrical arc can be modeled in different ways. Most frequently, a typical voltage/time characteristic, with its correlation between the voltage peak value for a specific wave shape and the time required for a flashover, is used. According to [13], for a plain analysis, the electric arc, resulting from the flashing over the insulator, does not need to be modeled in detail. The voltage/time characteristic for a typical overhead LV network with Al/St conductors was used.

Usually, in the overhead LV network the SPDs of Class II are located in a transformer substation (TS) cabinet and at the end of the network. Recently, the SPDs of Class II have also been located on the first post of the LV network, in front of the TS. It has also been assumed that the SPDs of Class II were installed at the service entrance of a building. In order to model a SPD in EMTP, it is essential to obtain its voltage-current characteristic. Since voltage-current characteristics of LV SPDs are usually not offered in manufacturers' catalogues, they can be obtained in the laboratory. An example of a voltage-current characteristic of a LV SPD, partly made in the laboratory, is shown in Table II. The same characteristic was used to model the SPD. The ATPDraw model of an LV network is illustrated in Fig. 7.

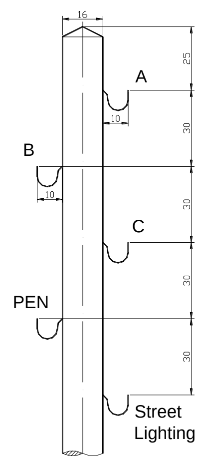

Figure 6: Top part of an LV wooden post

There are the following earthings in the considered LV network: Earthing of TS, earthing of the first pole (on this pole the SPDs are installed) and earthing of the PEN conductor placed every 200 m. TS earthing consists of three connected rings made out of galvanized steel. The rest of the earthings are made out of one ring. As a consequence, the earthing resistance of the TS is much lower than all the other earthing resistance in the LV network.

TABLE II
REMAINING VOLTAGE AT CURRENT WAVE 8/20 μS, SPD OF CLASS II

U_c = 280 V~, I_n = 10 kA, I_{max} = 20 kA, U_p = 1.1 kV							
1.03 kA	1.53 kA	2.03 kA	2.5 kA	4.5 kA	5.05 kA	5.75 kA	6.45 kA
750 V	800 V	840 V	880 V	980 V	1020 V	1030 V	1050 V

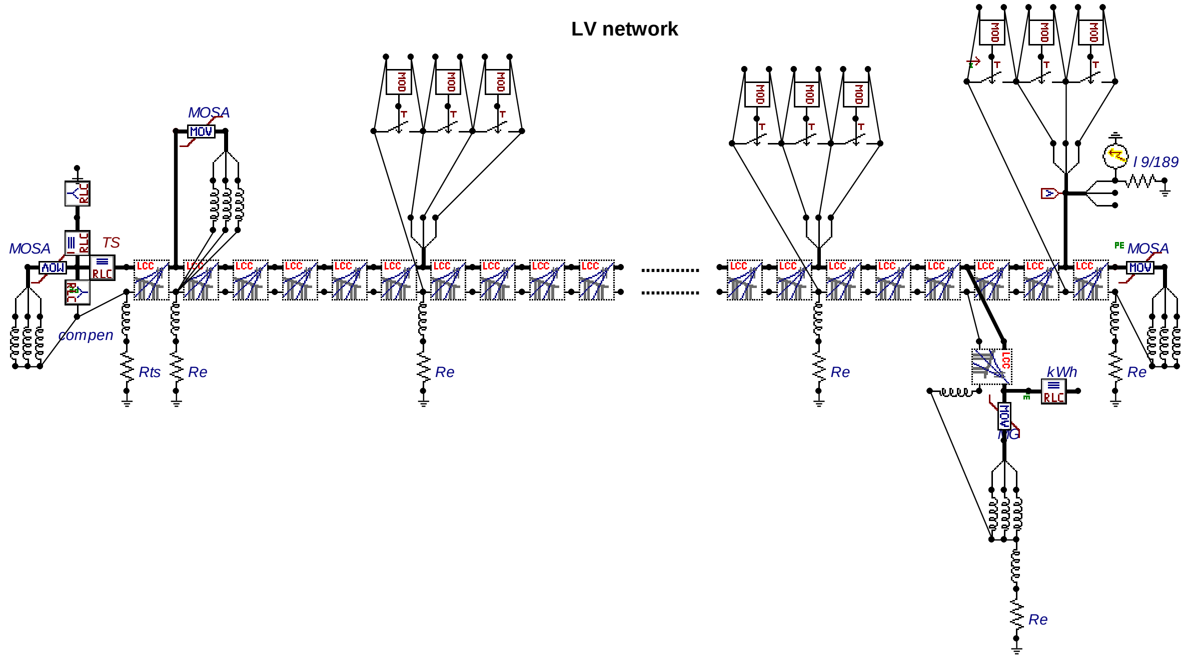

Figure 7: ATPDraw Model of a LV network (400/231 V) with Al/St conductors

C. Probability of occurrence and distribution of lightning currents striking the LV network

The probability of lightning striking the LV network depends on the density of lightning striking the ground, i.e. on the keraunic level of the network area.

To determine the number of lightning strokes to the LV network, it is possible to use an expression from [14], which is normally used for high voltage lines:

$$N_L = 0.004 \cdot T^{1,35} \cdot (b + 4 \cdot h^{1,09}) \qquad (1)$$

Where:

N_L - number of lightning strokes to the power line of 100 km in length per year

T - keraunic level (number of days with thunder per year)

h - average height of the grounding conductor (m), (in case of an LV network it is the height of the tallest conductor)

b - horizontal distance between the grounding conductors (in case of an LV network this equals zero).

If a keraunic level (for example T=35 days) is adopted, it is possible to calculate the expected number of lightning strokes per unit length of the LV network. With an average height of 7.1 m, above the ground for the tallest conductor in the LV network, an expression can be obtained:

$$N_L = 16{,}46 \left[\frac{1}{km \cdot 100 \cdot year} \right] \qquad (2)$$

Therefore, for the length of 1 km of an LV network 16.46 lightning strokes in 100 years can be expected.

It is well known that more than 90% of lightning strokes have a negative polarity [15], whereas lightning with a positive polarity is common for high buildings (i.e. buildings at mountain summits, high rises, etc.).

According to [14], the most frequently used expression for distribution of peak values for negative polarity lightning strokes is:

$$P_I = \frac{1}{1 + \left(\frac{I}{31} \right)^{2,6}} \text{ (p.u.)} \qquad (3)$$

Where:

P_I probability that lightning current is greater than I

I lightning current, (kA)

If in expression (3) the value 1/16.46 = 0.06075 is substituted for P_I, it leads to:

$$I = 31 \cdot \left(\frac{1 - P_I}{P_I} \right)^{\frac{1}{2,6}} = 88.87 \text{ kA} \qquad (4)$$

According to (4), only 6.075% of all lightning currents will be of amplitudes equal to or greater than 88.87 kA. It can be anticipated that a single lightning strike to 1 km of an LV network, during the period of 100 years, will have amplitude equal to or greater than 88.87 kA. Therefore, the probability of a lightning stroke at 1 km of an LV network with amplitude is equal to or is greater than 88.87 kA is 0.01.

Similarly, a calculation can be carried out to analyze the front of a wave and the wave tail duration of a lightning current. This is why a simulation of the lightning stroke on the LV network shall be performed using the lightning current wave 9/189 μs, whose amplitude equals 88.87 kA.

D. Explanation of the simulation

In the probability theory, it is well known that the relative frequency of an event approaches the probability of that event when the number of tests approaches infinity. Since it is difficult to carry out a large number of simulations in practice, it is necessary to use the event relative frequency. Since there are many variables when modeling the overhead network (location of the lightning stroke, parameters of lightning stroke or location of the building connection relative to the location of a lightning stroke) some of those variables had to be kept constant. Subsequently, all simulations were carried out with the same lightning current 88.87 kA, 9/189 μs. Both network and connection parameters were also kept constant. The location of the lightning stroke, as well as the location of the building connection was left variable.

The energy absorbed by the SPD using a MO disc is determined by the following expression:

$$E = \int u(t) \cdot i(t) \cdot dt \qquad (5)$$

It is a well-known fact that the SPD limits the voltage; therefore *u(t)* in the above expression changes very slightly. The current *i(t)* changes from less than 1 mA to several tens of kA. This is the reason why the integration must be performed for as long as a significant current flows through the SPD, or for as long as the voltage drop on the SPD is greater that its continuous operating voltage.

In transient processes varying in time, it is practically impossible to use the above expression for energy calculations. For such purpose, the EMTP uses the numerical integration based on the trapezoid rule (6).

$$E = \sum_{j=1}^{j=n} \frac{u_j + u_{j-1}}{2} \cdot \frac{i_j + i_{j-1}}{2} \cdot \Delta t \qquad (6)$$

If the energy absorbed by the SPD requires to be numerically calculated, it is necessary to perform the calculation for as long as a significant current flows through the SPD. The whole transient state needs to be observed until it is fully attenuated. In case of a lightning strike into a 1 km long LV network, this would take approx. 2.5 ms, in some cases, even longer.

If the time of calculation is then divided by the calculation step (increment) (Δt = 0.01 μs), it yields to 250000 calculation steps. Such a calculation would take approx. 1.5 minutes on present-day PCs.

This is the reason why the calculation with both the building connection distance and the lightning stroke distance of 100 m was performed first. A calculation, changing lightning stroke position and building connection at every post spacing (33 m), was also performed but the results were almost the same.

E. Results of simulation

The results of energy load simulations for an SPD installed at the service entrance of a building are presented in this chapter. These are the results for a model of an LV network with Al/St conductors and with a self carrying cable bundle.

As illustrated in Table III to Table VI, the lightning stroke location varies from the TS to the end of the LV line in steps of 100 m. The location of a building connection also varies from the beginning to the end of the LV network. The lightning always strikes the highest conductor (phase A), in accordance with the electro-geometrical model. In a great majority of cases, there will be an arcing to phase B, then to phase C, and finally to PEN conductor immediately after a stroke. In an LV network with a self carrying cable bundle (Table IV) the probability of arcing to phase B, C and PEN conductor is equal.

Designations A, B and C in Table III to Table VI showed an energy-overloaded SPD of Class II which was located at the service entrance of the connected building and in such particular phase. Designations (1), (2) and (3) showed the number of energy-overloaded SPDs of Class II in the TS for the given lightning stroke and building connection locations. The dash -(-) showed no energy-overloaded SPD of Class II at the service entrance nor in the TS.

The accepted energy overloading criterion for all SPDs was 1.5 kJ (a conservative value). There were SPDs of Class II with nominal current 20 kA and maximum current 65 kA (even 150 kA). Roughly, it can be assumed that an SPD of Class II can discharge its nominal current 20 times, while it can discharge its maximum current at least once [16]. When a current wave 8/20 μs with amplitude of 65 kA is impressed into an SPD of Class II, the dissipated energy of more than 2 kJ is obtained. In [10] it is noted that the current wave 14.1 kA, 10/350 μs, impressed into the newly developed MOV, produces energy of 4.8 kJ. Also, a current wave of 24 kA produces energy of 8.0 kJ.

When taking into account the possibility of multiple lightning strokes, the level of the dissipated energy was assumed to be 75% of 2 kJ, i.e. 1.5 kJ. Thus, the criterion for an overloaded SPD (based on a MO disc) is accepted, and which defines this device as energy-overloaded whilst the lightning stroke at the LV network produces absorbed energy greater than **1.5 kJ**.

After summing up all the cases in Table III, the following relation was obtained. Out of 363 possible cases, the energy overloading of an SPD of Class II, placed at the service entrance of a building, was noted in 66 cases, which represents a relative frequency of energy overload of approx. 18.2%. After summing up all the cases in Table IV, the relative frequency of energy overload is approx. 14.0%. Considering the adopted probability for the occurrence of lightning current amplitude, and also considering the adopted, worst-case configuration with only one building connection, this constituted an encouraging result and lead to the conclusion that the SPD of Class II is appropriate for installation at the service entrance.

Apart from energy loading of the SPD of Class II at the service entrance, the calculations performed in the above simulations also included energy loads of an SPD of Class II installed at the post TS. In most cases, it was accepted that an SPD installed at the post TS was of Class II (MO). The adopted criterion for energy overloading is the same as for the SPD at the service entrance. Therefore, if the energy absorbed by an SPD, at the moment of the lightning strike to the LV network, is greater than 1.5 kJ, such SPD is energy overloaded. The results from Tables III are unexpected. Almost every stroke to the LV network resulted in an energy-overload for one, two or three SPDs of Class II that were installed at the TS. The relative frequency of the energy overload for the SPD of Class II installed at the TS equaled to 72.2% (262/363). The relative frequency of energy overload for the SPD of Class II at the TS in Table IV is 30.9%. On the other hand, the capacitors required for compensation of reactive power in the TS did not decrease the energy load of the SPD installed at the TS. The results in Table III and Table IV are for typical earthing resistances for the LV network in question (TS 2 Ω, all other earthing resistances 10 Ω). The results for the increased TS earthing resistance to 5 Ω are shown in Table V whereas Table VI shows results for the increased TS earthing resistance to 10 Ω. It needs to be mentioned that TS earthing resistances are atypically high for the TS in comparison to all other earthings in the LV network. When the TS earthing resistance is increased to 5 Ω (Table V), the relative frequency of energy overload of the SPD of Class II at the service entrance (in LV network with Al/St conductors) is greater than 24.2% whereas at the TS, is lower than 9.6%. Similarly, when TS earthing resistance is increased to 10 Ω (Table VI), the relative frequency of energy overload at the service entrance equals 32.5% and at the TS 8.8%.

It needs to be stressed out that SPDs of Class II were also located on the first post of the LV network, in front of the TS. Such SPDs absorbed portion of energy and have decreased the energy loading of SPDs class II at the TS.

Most of the overloading of SPDs at service entrance and at TS are characterized by absorbed energy just above 1.5 kJ. That means, according to [10] and [11], SPDs based on MO disk have good prospects for installation at the service entrances.

TABLE III

ENERGY OVERLOAD FOR SPD OF CLASS II AT THE SERVICE ENTRANCE AND THE TS - AL/ST CONDUCTORS (TS = 2 Ω)

Distance of Building Connection from TS	Distance from TS of Lightning Strike to Low-Voltage Network (Strike to Phase A)										
	0 m	100 m	200 m	300 m	400 m	500 m	600 m	700 m	800m	900 m	1000 m
0 m	A (1)	- (1)	- (1)	- (1)	- (1)	- (-)	- (-)	- (-)	- (-)	- (-)	- (1)
100 m	A (1)	A, B, C (1)	- (3)	- (3)	- (2)	- (2)	- (2)	- (2)	- (2)	- (2)	A (3)
200 m	A (1)	A (3)	A, B, C (1)	- (3)	- (3)	- (3)	- (2)	- (2)	- (2)	- (3)	A (3)
300 m	A (1)	- (3)	- (3)	A, B, C (2)	- (3)	- (3)	- (3)	- (3)	- (3)	- (3)	A (3)
400 m	A (1)	- (3)	- (3)	A (2)	A, B, C (1)	- (3)	- (3)	- (3)	- (3)	- (3)	A (3)
500 m	A (1)	- (3)	- (3)	- (2)	- (2)	A, B, C (2)	- (3)	- (3)	- (3)	- (3)	A (3)
600 m	A (1)	- (3)	- (3)	- (2)	- (2)	A (1)	A, B, C (1)	A (3)	A (3)	A (3)	A, B, C (3)
700 m	A (1)	- (3)	- (3)	- (3)	- (2)	- (2)	- (1)	A, B, C (2)	A (3)	A (3)	A, B, C (3)
800 m	A (1)	- (3)	- (3)	- (3)	- (2)	- (2)	- (2)	- (1)	A, B, C (1)	A, B (2)	A, B, C (3)
900 m	A (1)	- (3)	- (3)	- (3)	- (2)	- (2)	- (2)	- (1)	- (2)	A, C (2)	A, B, C (3)
1000 m	- (1)	- (3)	- (3)	- (3)	- (2)	- (2)	- (2)	- (1)	- (2)	- (1)	A, B, C (3)

TABLE IV

ENERGY OVERLOAD FOR SPD OF CLASS II AT THE SERVICE ENTRANCE AND THE TS - SELF CARRYING CABLE BUNDLE (TS = 2 Ω)

Distance of Building Connection from TS	Distance from TS of Lightning Strike to Low-Voltage Network (Strike to Phase A of SCCB)										
	0 m	100 m	200 m	300 m	400 m	500 m	600 m	700 m	800m	900m	1000 m
0 m	A (1)	- (1)	A (1)	- (-)	- (1)	- (-)	- (-)	- (-)	- (-)	- (-)	A (1)
100 m	A (1)	A (1)	- (1)	- (2)	- (1)	- (-)	- (1)	- (-)	- (-)	- (-)	A (1)
200 m	A (1)	- (3)	A (1)	- (2)	- (1)	- (2)	- (-)	- (2)	- (-)	- (-)	A (1)
300 m	A (1)	- (3)	A (1)	A, B, C (1)	- (1)	- (-)	- (-)	- (-)	- (-)	- (-)	A (1)
400 m	A (1)	- (3)	- (1)	- (2)	A (1)	- (2)	- (-)	- (2)	- (-)	- (-)	A (1)
500 m	A (1)	- (3)	- (1)	- (2)	- (1)	A, B, C (1)	A (-)	- (-)	- (-)	- (-)	A (1)
600 m	A (1)	- (3)	- (1)	- (2)	- (1)	- (-)	A (-)	- (2)	A (-)	- (2)	A, B, C (1)
700 m	A (1)	- (3)	- (1)	- (2)	- (1)	- (-)	- (-)	A (-)	- (-)	- (2)	A, B, C (1)
800 m	A (1)	- (3)	- (1)	- (2)	- (1)	- (-)	- (-)	- (-)	A (-)	A (2)	A, B, C (1)
900 m	A (1)	- (3)	- (1)	- (2)	- (1)	- (-)	- (1)	- (-)	A (-)	A (-)	A, B, C (1)
1000 m	- (1)	- (3)	- (1)	- (2)	- (1)	- (-)	- (1)	- (-)	A (-)	- (-)	A, B, C (1)

TABLE V

ENERGY OVERLOAD FOR SPD OF CLASS II AT THE SERVICE ENTRANCE AND THE TS - AL/ST CONDUCTORS (TS = 5 Ω)

Distance of Building Connection from TS	Distance from TS of Lightning Strike to Low-Volatage Network (Strike to Phase A)										
	0 m	100 m	200 m	300 m	400 m	500 m	600 m	700 m	800 m	900 m	1000 m
0 m	A (1)	- (-)	- (-)	- (-)	- (-)	- (-)	- (-)	- (-)	- (-)	- (-)	- (-)
100 m	A (1)	A, C (1)	- (-)	- (-)	- (-)	- (-)	- (-)	- (-)	- (-)	- (-)	A (-)
200 m	A (1)	A, B (1)	A, B, C (1)	- (-)	- (-)	- (-)	- (-)	- (-)	- (-)	- (-)	A (-)
300 m	A (1)	A (1)	A (-)	A, B, C (1)	- (-)	- (-)	- (-)	- (-)	- (-)	- (-)	A, C (-)
400 m	A (1)	A (1)	A (-)	A, B (-)	A, B, C (1)	A (-)	A (-)	A (-)	A (-)	A (-)	A (-)
500 m	A (1)	A (1)	- (-)	A (-)	A (-)	A, B, C (1)	A (-)	A (-)	- (-)	- (-)	A, B (1)
600 m	A (1)	- (1)	- (-)	- (-)	- (-)	A (-)	A, B, C (1)	A, B (-)	A, B (-)	A, B (-)	A, B, C (1)
700 m	A (1)	- (1)	- (-)	- (-)	- (-)	- (-)	- (-)	A, B, C (1)	A (-)	A (-)	A, B, C (1)
800 m	A (1)	- (1)	- (-)	- (-)	- (-)	- (-)	- (-)	A (-)	A, B, C (1)	A, B (-)	A, B, C (1)
900 m	A (1)	- (1)	- (-)	- (-)	- (-)	- (-)	- (-)	- (-)	- (-)	A, C (1)	A, B, C (1)
1000 m	A (1)	- (1)	- (-)	- (-)	- (-)	- (-)	- (-)	- (-)	- (-)	- (-)	A, B, C (1)

TABLE VI
ENERGY OVERLOAD FOR SPD OF CLASS II AT THE SERVICE ENTRANCE AND THE TS - AL/ST CONDUCTORS (TS = 10 Ω)

		Distance from TS of Lightning Strike to Low-Volatage Network (Strike to Phase A)										
		0 m	100 m	200 m	300 m	400 m	500 m	600 m	700 m	800 m	900 m	1000 m
Distance of Building Connection from TS	0 m	A (1)	- (-)	- (-)	- (-)	- (-)	- (-)	- (-)	- (-)	- (-)	- (-)	- (-)
	100 m	A, B (3)	A (1)	- (-)	- (-)	- (-)	- (-)	- (-)	- (-)	- (-)	- (-)	A (-)
	200 m	A, B, C (3)	A, B (-)	A, B, C (1)	- (-)	- (-)	- (-)	- (-)	- (-)	- (-)	- (-)	A (-)
	300 m	A, B, C (3)	A (-)	A, B (-)	A, B, C (1)	- (-)	- (-)	- (-)	- (-)	- (-)	- (-)	A, C (-)
	400 m	A, B, C (3)	A, B (-)	A, B (-)	A, B (-)	A, B, C (1)	A (-)	A (-)	A (-)	A (-)	A (-)	A, B, C (-)
	500 m	A, B (3)	A (-)	A (-)	A (-)	A (-)	A, B, C (-)	A (-)	A (-)	A (-)	A (-)	A, B, C (-)
	600 m	A, B, C (3)	- (-)	A, B (-)	A (-)	A, B (-)	A, B (-)	A, B, C (1)	A, B (1)	A, B (-)	A, B (-)	A, B, C (-)
	700 m	A (1)	- (-)	- (-)	- (-)	- (-)	- (-)	A (-)	A, B, C (-)	A, B (-)	A, B (-)	A, B, C (-)
	800 m	A, B, C (1)	- (-)	- (-)	- (-)	A (-)	A (-)	A (-)	A (-)	A (1)	A, B (-)	A, B, C (-)
	900 m	A (1)	- (-)	- (-)	- (-)	- (-)	- (-)	- (-)	- (-)	- (-)	A, B (1)	A, B, C (-)
	1000 m	A (1)	- (-)	- (-)	- (-)	- (-)	- (-)	- (-)	- (-)	- (-)	- (-)	A, B, C (1)

F. Experience

There exist some practical experiences with a network similar to one simulated in the above example. Thirty TS that were exposed to lightning with installed SPDs of Class II on the LV side were observed. The examination of the said 30 TS still showed a number of failed SPDs of Class II (failure represents tripping of the heat-dependant member, thus disconnecting the SPD from the LV network). A considerable number of such failures can be attributed to energy overloading. All of the failed SPDs of Class II were old-fashioned with nominal current 5 kA (8/20 μs). In addition, during the above examination, it was detected that in some TS only a single SPD failed, whereas in some two, but no TS was found where all three SPDs failed. A similar effect was noticed in the simulations, in some cases there was only one overloaded SPD of Class II, in some other cases two or three overloaded SPDs.

Since our experience with the SPDs of Class II that were installed on a post TS (and in LV networks) is rather good, the criterion for choosing the SPD for the service entrance can be based on the comparison of its relative frequency of energy overloading with the relative frequency of TS.

Throughout the world, there are hundreds of thousands kilometers of overhead medium voltage 10(20) kV lines on wooden posts, without the shielding wire. Flashover characteristics of those lines are higher than flashover characteristics of LV lines on wooden posts. Our own experience, as well as that experience through the world with MO surge arresters (tested with surge wave 8/20 μs) in such lines is rather excellent. Namely, in a distribution region (the same as the one for the examined LV network) on 10 kV lines, of which about 80% are on wooden posts, 1500 MO surge arresters were installed. In the last 5 years, during the supervision, only two failures were registered. This also suggests that the SPDs based on a MO disk are suitable for service entrance installation.

IV. CONCLUSION

A procedure of choosing the SPD to be applied in a typical overhead LV network was presented.

According to the probability of lightning stroke occurrence in an overhead conductor, a peak value and a wave shape of the lightning current were selected. The LV network was modeled with its main components. The EMTP simulations of lightning strokes were carried out, changing the stroke locations and the locations of the building connections. The energy overloading criterion of the SPD of class II was considered in the LV network as well as at the service entrance point. First of all, the relative frequencies of the overloading of the SPD were calculated and were afterwards compared to the adopted risk of failure (overloading), and a conclusion was drawn that the SPD of class II was suitable for this application. The conducted simulations in the network, protected by the SPD of class II, have proved that overloading occurs equally in the TS as well as at the service entrance point of the connected building.

The presented procedure can be carried out for any such typical construction of the overhead line LV network, and can help to decide whether an SPD of class I or of class II is suitable to be applied.

It is concluded that a two-stage surge protection of buildings, without lightning protection system, connected to the LV overhead network, would be appropriate.

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