**SPD in illumination system of HV air insulated substation**

*Anton Kosorukov, Pavel Karpov, Nataliya Kutuzova, Svetlana Pashicheva, and Vasily Titkov*

1 JSC «Lenhydroproect», Ispytateley Street, 22, St. Petersburg, 197227, Russia
2 LLC «EMC-project», Obruchevyh Street, 5A, St. Petersburg, 194064, Russia
3 JSC «NPO «Streamer», Nevsky Prospect, 147, St. Petersburg, 191024, Russia
4 Peter the Great St.Petersburg Polytechnic University, Polytechnicheskaya Street, 29, St. Petersburg, 195251, Russia

**Abstract.** The article discusses the distribution of the lightning current between communications of the object as the main aspect determining surge protective devices (SPDs) parameters for applying in substation’s low voltage networks. Wireframe model was designed to compute field-circuit model of earthing device (ED) and define the element potentials and currents using circuit analysis methods. Transients were calculated using operator method. Results of calculation and measurements of the lightning current’s distribution in ED and cables in illumination network of air insulated substation presented. Experimental study results obtained in training ground PJSC «Lenenergo», one of the largest electric power distribution company in Russia. Case of lightning strike in the floodlight mast combined with lightning rod in 110 kV air insulated substation was studied. Requirements for the parameter "impulse discharge current amplitude" SPD defined. Described general approaches to the illumination network’s lightning surge protection on air insulated substation.

**1 Introduction**

Lightning overvoltages perform the most significant impact on requirements for ensuring EMC of at high-voltage substations up to 220 kV. Other interference sources, including the high-voltage network, have significantly lower energy.

Due to the relatively small dimensions of the objects, cable lines (CL) of substation’s low voltage systems are located close to the elements of the lightning protection system. However, air insulated substations are not compact objects, being compared with lower voltage class indoor switchgears or with other infrastructural facilities, for example, mobile communication station, etc. In described conditions the routs of CL are not restricted by shielded volume (in terms of IEC 62305 standard [1] – within one lightning protection zone (LPZ)).

One of the most effective means of limiting overvoltage is the hardware protection of equipment using SPD. SPD is an additional element of the low voltage network that can

* Corresponding author: pashicheva.sv@gmail.com
reduce reliability. Incorrect selection of SPD parameters and its installation location can lead to damage to protected equipment by lightning current [2-6].

SPDs class I placed in LPZ 0 and 1 must be capable of conducting partial lightning currents of 10/350 $\mu$s wave form without being destroyed. The main parameter determining the SPD class I applicability is an impulse discharge current. This parameter has an influence on the device’s price. Standardized impulse discharge current values for class I test defined in [7].

Impulse current evaluation methods described in IEC 62305 and 61643 standards [1, 8], do not consider the design characteristics of the power facilities such as developed grounding network and the absence of low-voltage networks extending beyond the ED. Parameters of other protected objects also aren’t considered in terms of lightning current distribution. The aforesaid problems may be the cause of incorrect selection of SPDs parameters at the design stage.

It has to be noted, that impulse discharge current parameters recommended to test SPD do not consider data published in [9]. The main concern is the lack of consideration for the multi-component nature of lightning discharges.

The purpose of the measurements and calculations presented in the article is to evaluate the distributed currents in conductors on air insulated substation.

The illumination system of HV air insulated substation is one of the most exposed to conductive surges due to the placing of the lightning equipment directly on tower with lightning rods. It seems appropriate to use SPDs for this system protection. Placing other equipment on structures with lightning rods is less common, and the topology of the power supply networks of such equipment is more complicated. The certainty in the mutual position of the interference source and the cable network of the illumination system allows us to create the required calculation model. An analysis of the processes of distribution lightning current was carried out for the lighting equipment of the floodlight masts located in air insulated substation.

2 Model and parameters

Wireframe model of 110 kv air insulated substation (Fig.1) was designed to compute the field-circuit model of ED [13, 15] and to demonstrate the impact of substation design on the part of the lightning current distributed in the conductors of the illumination system. The results obtained using FDTD method was excluded due to the inconsiderable difference and the prolonged computation [10-12]. The software program ZYM (AutoCAD application) also was used for electromagnetic fields and transients calculations [14].
Overvoltages evaluation was performed in order to justify the necessity of the use of SPD in the substation illumination system. The impact of the CL’s length and the presence of metal pipe in a CL construction were considered. The floodlight mast had multiple connections through the ED to the illumination control system earthing point placed in the building of the substation. An assessment of overvoltage and currents in CL was carried out with an impulse with a waveform $10/350 \, \mu s$ and amplitude of $100 \, kA$, which is considered a simulation of lightning current [1].

Lightning strikes in floodlight masts combined with lightning rod were simulated. Cable length between illumination control switchboard and masts is 50m and 220m. Different cable lying conditions were considered: shielded CL in metal pipe, not shielded CL in metal pipe, not shielded CL without pipe. Parameters of a single-phase cable were used.

The PE conductor was connected to the illumination distribution board located on the mast, to the floodlight and to the illumination control system earthing point. The capacity of the power supply of the floodlight is taken equal to 100 nF. The cable from the side of the substation control house is disconnected, the phase conductor is broken, the neutral conductor is grounded.

Computation results of lightning current distribution in modeled illumination network also were carried out with an impulse with a waveform $10/350 \, \mu s$ and amplitude of $100 \, kA$. In calculations weren’t considered the presence of a shield at the CL and the resistance of the SPD. All conductors of CL were grounded.

3 Computation results discussion

Obtained results of overvoltages values for a floodlight mast placed 50 m (via a cable line) away from the illumination control board in substation control house are summarized in Table 1.

As seen, the overvoltage level is determined mainly by the type of cable lying conditions. The pipe and the shield due to capacitive and inductive coupling with cable conductors significantly reduce the level of overvoltage. It corresponds to the theoretical concepts.
Table 1. Overvoltage values for different cable lying conditions.

| Cable lying condition | Soil resistivity ρ, Ω ∙m | Earthing resistance at the main frequency of exposure z, Ω | U, kV | |
|-----------------------|---------------------------|-------------------------------------------------------|-------|---|
|                       |                           | L-P E | N-P E | L-N | L-P E | N-P E | L-N | L-P E |
| Pipe with shield      |                            |       |       |     |       |       |     |       |
| 100                   | 5.4                       | 3.63  | 4.09  | 4.09| 3.77  | 3.77  | 0.16| 0.16  |
| 250                   | 6.5                       | 3.63  | 4.09  | 4.09| 3.77  | 3.77  | 0.16| 0.16  |
| 500                   | 7.8                       | 3.63  | 4.09  | 4.09| 3.77  | 3.77  | 0.16| 0.16  |
| 750                   | 8.8                       | 3.63  | 4.09  | 4.09| 3.77  | 3.77  | 0.16| 0.16  |
| 1000                  | 9.6                       | 3.63  | 4.09  | 4.09| 3.77  | 3.77  | 0.16| 0.16  |
| Pipe                  |                            |       |       |     |       |       |     |       |
| 100                   | 5.4                       | 10.55 | 10.96 | 10.96| 10.96| 10.96| 0.18| 0.18  |
| 250                   | 6.5                       | 10.55 | 10.96 | 10.96| 10.96| 10.96| 0.18| 0.18  |
| 500                   | 7.8                       | 10.55 | 10.96 | 10.96| 10.96| 10.96| 0.18| 0.18  |
| 750                   | 8.8                       | 10.55 | 10.96 | 10.96| 10.96| 10.96| 0.18| 0.18  |
| 1000                  | 9.6                       | 10.55 | 10.96 | 10.96| 10.96| 10.96| 0.18| 0.18  |
| Absence of pipe and shield |                        |       |       |     |       |       |     |       |
| 100                   | 5.6                       | 64.32 | 64.50 | 64.50| 64.50| 64.50| 0.37| 0.37  |
| 250                   | 6.8                       | 64.32 | 64.50 | 64.50| 64.50| 64.50| 0.37| 0.37  |
| 500                   | 8.1                       | 64.32 | 64.50 | 64.50| 64.50| 64.50| 0.37| 0.37  |
| 750                   | 9.1                       | 64.32 | 64.50 | 64.50| 64.50| 64.50| 0.37| 0.37  |
| 1000                  | 9.9                       | 64.32 | 64.50 | 64.50| 64.50| 64.50| 0.37| 0.37  |
If the shielded cable and metal pipe are used in CL construction, the level of overvoltage from the side of the substation control house is close to permitted 4-6 kV with moderate and low soil conductivity. However, as the front of the lightning current pulse decreases, the level of overvoltage increases (Fig. 2). In conditions of low soil resistivity, considering equipment insulation strength margin, studied network is reliable to lightning overvoltage. In other conditions, application of SPD is justified.

![Fig. 2. Overvoltage in CL of illumination system with different waveforms of current pulse, when using a shielded cable and a metal pipe.](image)

Recommended for illumination system of air insulated substation SPDs installation scheme is shown in Fig. 4. Due to the overvoltage growths when currents flow in the ED, SPDs have to be installed according to the L-PE, N-PE scheme (Fig. 3) to provide common-mode interference protection.

![Fig. 3. SPDs installation scheme.](image)
It has to be noted, that interference transmission gain value (ratio of overvoltage amplitude on floodlight mast to overvoltage in substation control house) is less than minimum value 10 defined in [1]. So, according to calculation results, the impulse attenuation is slower. Overvoltage from floodlight mast direction rises with an increase in the length of the CL. The reason is neutral wire’s grounding point moving away from the grounding area of the floodlight mast. Thus, necessity of SPD appliance in illumination system of air insulated substation is reasonable.

Computation results of current values in conductors of CL divided on two sections: from floodlight to distribution board on mast and from mast to substation control house, are summarized in Table 2. Not shielded cable without metal pipe was studied in order to determine the maximum value of the current flowing through the SPD. For the short CL the impact of the current impulse front on the current value in the CL also was studied.

**Table 2.** Current values in CL conductors for different cable length.

| Soil resistivity $\rho$, $\Omega \cdot m$ | Distance from mast to illumination control system, m |
|----------------------------------------|------------------------------------------------------|
|                                        | 50                                                   |
|                                        | 220                                                  |
| Current impulse, $\mu$s                |                                                      |
| 10/350                                 | 1.2/50                                               |
| 10/350                                 | 10/350                                               |
| CL without shield in pipe              | Absence of pipe and shield                          |
| Absence of pipe and shield             | Absence of pipe and shield                          |
| Current, A                             |                                                      |
| По мачте¹) From mast²) From mast From |                                                        |
| mast From mast From mast From mast     |                                                        |
| Помачте From mast From mast From mast From mast |                                      |
| 100 190 956 1153 4500 1278 3528 971 | 1083                                                  |
| 250 200 1045 1184 4739 1335 4613 982 | 1196                                                  |
| 500 210 1089 1198 5191 1383 5156 991 | 1322                                                  |
| 750 214 1100 1203 5225 1406 5415 994 | 1373                                                  |
| 1000 214 1091 1227 5300 1418 5589 997| 1402                                                  |

Note: ¹ Current in CL section from floodlight to distribution board on mast – computed current value flowing in one conductor of CL section from floodlight to distribution board on mast; ² Current in CL section from distribution board on mast to the illumination control system in substation control house – computed current value flowing in one conductor of CL section from distribution board on mast to the illumination control system in substation control house.
4 Experimental study results

Experimental study results obtained in training ground PJSC «Lenenergo». In training ground territory placed open switchgears 110, 35, 10 kV, buildings and complete transformer substations. The voltage unavailability in high voltage network allows conducting experiments.

Unfortunately, there are some differences between the illumination system of the training ground and the real substation conditions. First of all, floodlight masts located far from the open switchgear and horizontal grounding network has a big step (up to 20 m) near the masts. Secondly, the illumination control board placed in security building (illumination is mainly used as security lighting). CL not shielded and the metal pipe was not used for cable laying. In described conditions we expected that the measured partial current, flowing into the cable conductors during experiment, should be much higher than in the functioning substation.

Floodlight masts are powered in series, that is, two three-phase CLs outgoing from the mast. Thus, the number of CL conductors is 10. According to design documentation CL length in one direction from the mast is 160 m and in another - 200 m (real lengths have to be shorter). The measurement scheme is shown in Fig. 5. Voltage was measured on generator circuit shunts and CL with Fluke 190-504 oscilloscope.
At the day of the measurement, the soil was frozen and the upper layer had a resistivity 1200 $\Omega \cdot \text{m}$. A voltage impulse of 1.2/50 $\mu$s and an aperiodic current of 8/20 $\mu$s with an amplitude 9 A was applied to the floodlight mast, the phase and neutral conductors were grounded on both sides of CLs in the illumination control board placed in security building and on another floodlight mast. The second output of the generator was grounded to the footing of the pole also placed in training ground but not connected to the ED. The voltage ratio made it possible to estimate the part of current flowing in CL. The oscillogram of voltage on the shunts of the generator and CL is shown in Fig. 6.

Voltage amplitude on the shunt of the CL is approximately 33% of the voltage amplitude at the shunt between the generator and the mast. If the lightning current impulse had amplitude of 100 kA, then a current impulse with amplitude of about 3.5 kA would flow through each of the CL conductors. Considering the real illumination network
parameters and if an SPD installed the amplitude of the current impulse in PE and N conductors would be slightly higher.

According to data from Table 2 value of current flowing in one conductor of CL section from distribution board on mast to the illumination control system in substation control house for CL length 220 m and soil resistivity 1000 Ω · m is 1402 A. Then in the training ground conditions (two five-conductor CL with length 360 m and soil resistivity 1200 Ω · m) approximate evaluation of the part of lightning current 10/350 µs impulse can be found from the equation:

\[
\delta = \frac{I_{CL}}{I_{st}} = \frac{1}{i} \sum_{i=1}^{n} \left( \frac{N \cdot I_{c} \cdot l}{l_m} \right),
\]

where: \( n \) – number of CLs, \( N \) – number of CL conductors; \( L_e \) – CL length from calculation model; \( l_m \) – CL length in training ground; \( I_{CL} \) – current flowing in CL (sum of currents in all CL conductors); \( I_{st} \) – standardized value of the lightning current impulse amplitude (100 kA); \( I_c \) – calculated current value in CL conductor CL length \( L_e \) (1402 A).

The expected part of the current flowing in all the conductors of two studied in training ground CLs is 17.5% of the calculated current amplitude. In the training ground conditions part of the current flowing from the mast to CLs have to be higher than in a real substation, due to ED and masts footing design features.

The obtained values of the currents in the CL conductors are significantly lower than the impulse discharge current of SPDs installed in substation. It can be explained by the following circumstance:

1. selection of SPDs parameters based on unreasonable methods or the absence of any methods in the presence of biased recommendations of the manufacturers of SPDs;
2. the design characteristic of the substation such as developed grounding network due to which a significant part of the lightning current is redirected to the ground is not considered;
3. the impact of cable length and cable lying conditions are not considered.

As a result, even in the 110 kV substations conditions, in case of cable laying without pipe and simplifying the ED design, the use of an SPD with an impulse discharge current parameter higher than 10 kA is inappropriate. At substations of a higher voltage class the length of the CL of the lighting network increases significantly. Thus, the conclusion made about the necessity and sufficiency of using SPDs with impulse discharge current parameter lower than 10 kA, is also relevant for substations of a higher voltage class.

### 5 Conclusions

In illumination system of air insulated substation application of SPDs for lightning protection is justified. The substation is characterized by developed grounding network and this is the one of the decisive features in the SPD parameters selection.

SPD parameters selection methodology for low-voltage substation networks protection, based on "estimated calculations" of lightning current part in the CL conductors, should be reviewed, since its use can lead to unjustified costs.

Recommended value of SPD impulse discharge current parameter for appliance in in illumination system of 110 kV air insulated substation is 10 kA or lower.

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