cigre SIPDA
For power system expertise
SUZHOU CHINA
CIGRE ICLPS - SIPDA
International Colloquium on Lightning and Power Systems
International Symposium on Lightning Protection
Oct 09 - 13, 2023

Lightning Protection of 110 kV Power Line with Overhead Ground Wire using Multi-Chamber Open Type Line Lightning Protection Devices

Nikolay Zaretskiy
R&D dept.
Streamer Electric Company
Saint Petersburg, Russia
nikolay.zaretskiy@streamer.ru

Dmitriy Kotkin
R&D dept.
Streamer Electric Company
Saint Petersburg, Russia
dmitry.kotkin@streamer.ru

Dmitriy Belko
R&D dept.
Streamer Electric Company
Saint Petersburg, Russia
dmitry.belko@streamer.ru

Evgeniy Enkin
R&D dept.
Streamer Electric Company
Saint Petersburg, Russia
evgeniy.enkin@streamer.ru

***Abstract*— This study considers a statistical Monte Carlo analysis of the impulse currents passing through the Line Lightning Protection Devices (LLPD) on the 110 kV power line operated with overhead ground wire. The quantitative assessment of the impacts of lightning on protection devices provides the opportunity to evaluate the throughput capacity of the multi-chamber Open Type LLPD being developed. The most probable parameters of the current pulses have been calculated: amplitude, duration and time of the front, and a test program for such devices has proposed.**

Keywords—overhead line, lightning performance, protective device, LLPD, multi-chamber arrester

I. Introduction

At present, the requirements for ensuring uninterrupted power supply to large consumers are given special attention in the power-generating sector. The continuous operation of oil extraction enterprises, large factories, and plants must be maintained despite accidents at generating facilities and atmospheric phenomena. Field experience shows that 20% of all outages of power lines are lightning outages. All power transmission lines with a voltage of 110 kV and higher are equipped with ground wire with a small suspension angle to prevent lightning breakthroughs through the grounded wire, as one of the methods of lightning protection for power lines. The effectiveness of ground wire protection is confirmed at low footing resistance of poles and low thunderstorm activity in the region. In areas of the extreme north and mountainous terrain, the soil categories along the entire power line route may vary. High specific resistance of soils increases the probability of insulation flashover even when struck by lightning with low current amplitudes, which, in turn, increases the number of outages caused by lightning strikes. Therefore, the task is to reduce of annual outages of power 110 kV lines with a ground wire, the route of which passes through areas with poorly conductive soils.

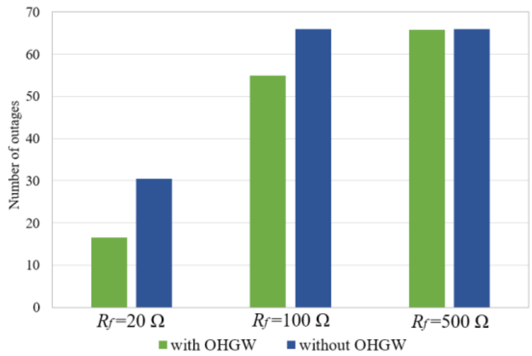

Fig. 1. The total number of outages of OHL 110 kV for the footing resistance value 20, 100, 500 Ω

In industrial operation, protective devices – multi-chamber LLPD (Line Lightning Protection Devices) – are used to protect the line from lightning overvoltages [1, 2]. The protection of overhead lines with overhead ground wire with LLPD is necessary, in the first term, for enterprises with continuous production processes. It is important to understand the demand LLPDs are subjected to throughout the entire operating period to determine the switching capacity, throughput, and mechanical strength limits, when design new lightning protection device. At high footing resistances, the lightning performance of the line with a ground wire becomes comparable to the lightning performance for a line without ground wire protection (Fig. 1) [3]. However, protective devices are subjected to lower current pulse impacts, and therefore, there is no need to install and develop devices with throughput capacity comparable to that of a line without a ground wire.

II. Open Type LLPD

The next-generation multi-chamber arrester Enclosed Type Line Lightning Protection Device dH110i developed by Streamer Electric Company is used to protect 110 kV overhead lines from the outages caused by lightning strikes. One of the advantages of the LLPD dH110i is its ability to withstand multiple currents of direct lightning strikes, achieved due to a durable fiberglass body, providing protection for the arrester element against mechanical damage and adverse environmental factors. Furthermore, the device implements a new principle for quenching the electric arc named Impulse Quenching. This mode implies the absence of accompanying network current flow after the device operating from the lightning current. The absence of an accompanying network current allows for a significant reduction in electrode erosion volume, thereby increasing the lifespan and reliability of the device, as well as expanding its application area in terms of short-circuit currents. The full operating time of the arrester is no more than 0.5 ms, so the relay protection at the supplying substation does not have time to react, and the overhead line continues its uninterrupted operation. The lack of a need to disconnect short-circuit currents and use automatic reclosing saves the switching resource of substation circuit breakers and reduces the cost of their maintenance.

Most 110 kV overhead lines in Russia are equipped with overhead ground wires (OHGW). With a standardized protective angle, the probability of a lightning shielding failure through the wire is less than 1%. Therefore, the installation of LLPDs capable of withstanding direct lightning currents in these conditions will be inefficient due to excessive strength and throughput reserves, and as a result, high cost. Streamer Electric Company offers an innovative solution in the form of a multi-chamber Open Type lightning protection device – LLPD b0110i (Fig. 2a). The new device operates on the same principle as the LLPD dH110i (Fig. 2b), however, its design does not involve a casing and is only intended to protect 110 kV overhead lines from outages under the influence of back flashover lightning currents.

LLPD b0110i consists of many quenching modules made of rubber and includes brand new multi-chamber with patented technology (Fig. 3). This solution helps to significantly reduce the cost of lightning protection of overhead lines compared to using the LLPD dH110i.

Fig. 2. Configuration of a) LLPD b0110i b) LLPD dH110i

III. Calculation method

The analysis of lightning performance of the overhead power lines with or without lightning protection devices involves defining the following parts:

- the total number of lightning strikes in the line
- the distribution of lightning parameters
- the probability of insulation flashovers or LLPD operation
- the probability of lightning breakthrough
- the arcing probability or arc quenching by the LLPD.

Each of these parts is regulated by the international standard IEEE 1410 [4], the data of which is overly generalized and cannot be applied to all calculation cases. The most time consuming task is determining the probability of insulation flashover or the operation of the lightning protection device. This parameter determination will be implemented using the Monte Carlo method or Analytical Simplified Method (ASM) [6].

ASM let determine the insulation flashovers or LLPD operation probability for each phase taking into account coupling effect of the conductors on each other. Accomplish that, an equivalent replacement circuit is drawn up, which allows consider the decrease in the lightning current upon impact into the span or into the span and including active and inductive resistance of the pole, pole footing resistance, impedance of OHL and lightning channel parameters. Then, value of critical current for flashover the phase is calculated. The final value of the insulation flashover probability is primarily affected by the chosen distribution of lightning current that may be determined by equation from [4].

The Monte Carlo statistical method, implemented in the ATP-EMTP software suite, allows for the description of the process occurring on the overhead power line during a lightning strike [5, 6]. To achieve this, a mathematical model of the line is created in the form of long-line blocks with the geometric arrangement of wires on poles, which are represented as concentrated inductance depending on the material of the structure. Using a lightning source that takes into account the parameters of the lightning current pulse, considering the log-normal distribution of parameters, and a random number generator, the model is calculated repeatedly. From the obtained data, probability characteristics are calculated.

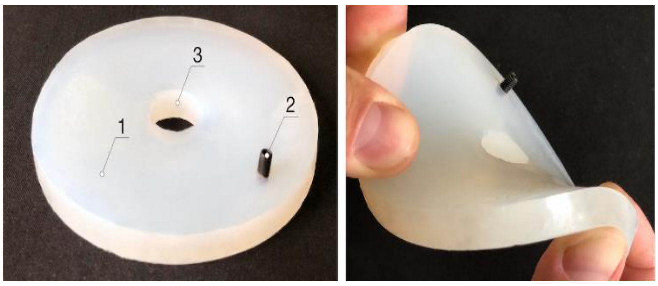

Fig. 3. One quenching module of LLPD b0110i
1 – rubber with electrodes inside, 2 – feeding electrod
3 – the hole for the central rod

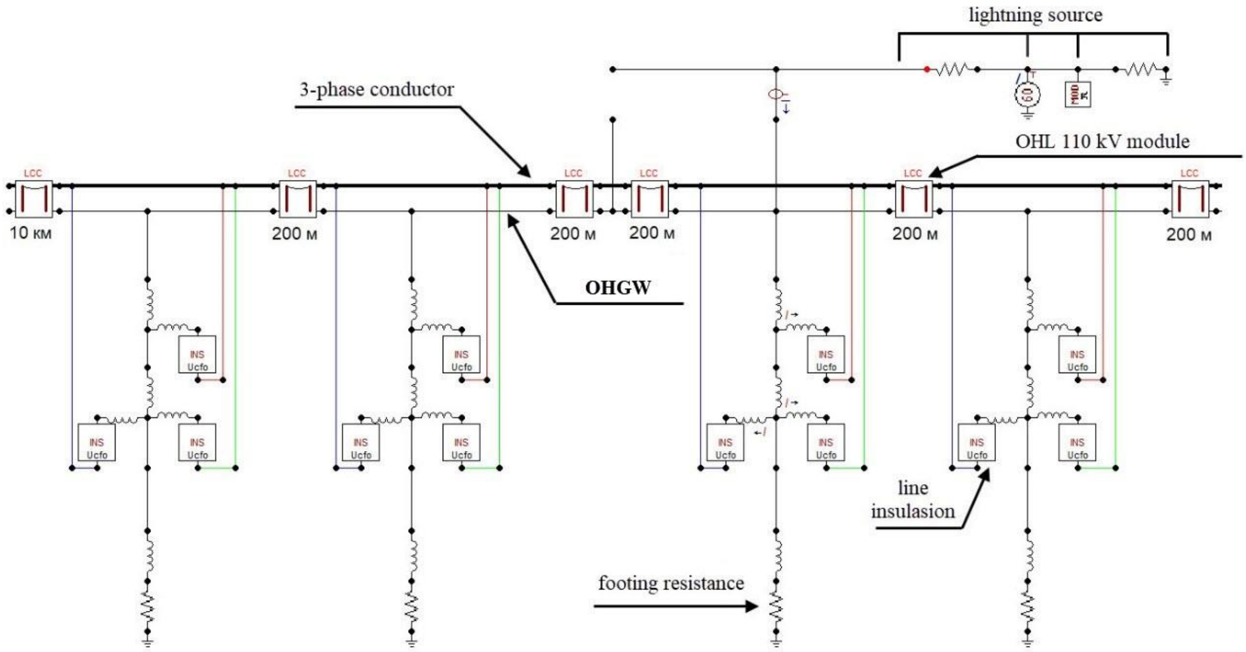

Fig. 4. The calculation scheme in ATP-EMTP for Monte-Carlo method implementation

Each lightning strike is characterized by its amplitude value of lightning current, pulse durability, and front time, with the pulse shape taken in accordance with [4]. The model sets the number of numerical experiments – 5,000 lightning strikes to a pole-span section. Some strikes hit the pole, while others strike the middle of the span (into the OHGW when present, or into the phase conductor when there is no OHGW). From the total number of strikes, the number of lightning strikes causing flashover or LLPD operating is recorded.

The assessment of impulse effects is carried out through a series of calculations. The calculation scheme is evaluated with 10,000 lightning strikes to the midpoint of the span and to the pole. Lightning parameters lightning current amplitude and time to half-value have been recorded in each case. Further, the parameters are analyzed, and the level of current flowing through the nearest LLPD, which will be affected by 95% of all lightning strikes hitting the power line, have been estimated. The calculated model for Monte Carlo method implementation, is represented on Fig.4 [5, 6].

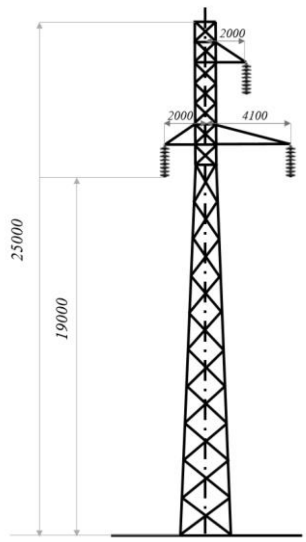

Fig. 5. Typical OHL 110 kV pole design

IV. Lightning performance with LLPDs

A. Input data

To determine the number of lightning outages for the 110 kV power line, the following input parameters are used:

- 110 kV overhead power line (Fig.5);
- Single-circuit poles with a height of h=25 m and a standard span length of l=200 m;
- Critical flashover voltage of the insulator string U_{CFO}=600 kV;
- LLPD b0110i represents an element with non-linear resistance, determined by the experimental current-voltage characteristic;
- The distribution of lightning current parameters is determined according to [4]. The median value of the maximum lightning current and the standard deviation $\bar{I}$ = 31 kA, σ_I = 0.29;
- The distribution of pole-span strikes is determined based on the span length and pole height [3].

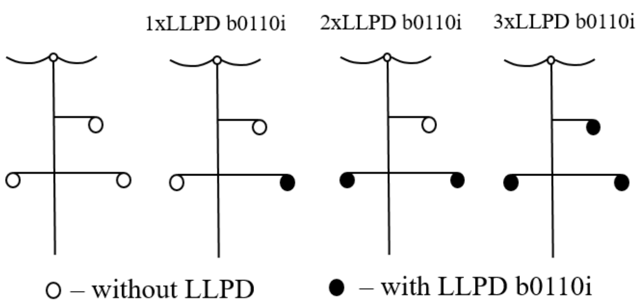

Fig. 6. Technical lighting protection decisions for OHL 110 kV with OHGW

B. *LLPD placement schemes*

For power lines built on single-circuit poles, the effectiveness of lightning protection devices in reducing the number of lightning outages is determined by the number of protective devices on the pole (Fig. 6). At the same time, the number of annual outages with the same number of LLPDs will depend on the footing resistance of the poles. The probability of occurrence of two- and three-phase flashovers is low with sufficiently low footing resistance of the poles (up to 10 Ohm), therefore, a cost-effective option is to install the 1xLLPD on the pole. With the growth of the footing resistance, the number of phase-to-phase flashovers increases and, in this case, it is necessary to protect the pole with 2 or 3 LLPDs. The following technical solutions for LLPD placement schemes are proposed:

1. 1xLLPD per pole for the most remote phase from OHGW;
2. 2xLLPDs per pole for the lower phases;
3. 3xLLPDs per pole for all phases.

C. *Calculation results*

In Fig. 7, the number of outages for the overhead power line with an OHGW is shown for a range of pole grounding resistances from 20 to 500 Ω, both with and without line protection. The results have been calculates by Simplified Analytical Method [3, 6]

In the absence of lightning protection devices on the power line, the number of outages increases with the increase in pole footing resistance. Furthermore, with grounding resistance above 100 Ω, practically any lightning with a small current impulse will lead to insulation flashover. With standardized values (up to 20 Ω), the number of outages is significantly reduced when installing one LLPD on the pole. The effectiveness of installing two or more LLPDs on the pole is confirmed with high grounding resistances.

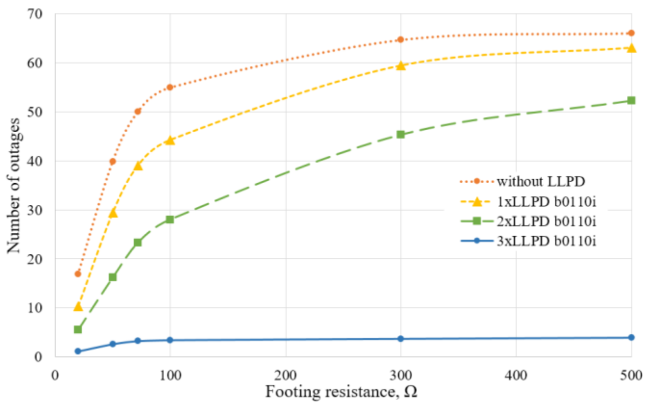

Fig. 7. Number of outages of OHL 110 kV with OHGW in depence of the footing resistance with LLPD (per 100 km per year)

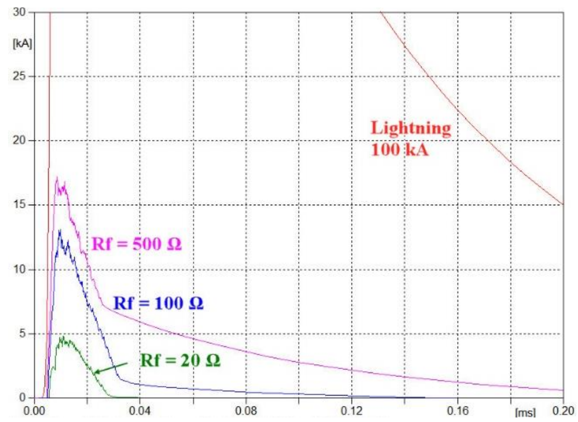

Fig. 8. Current value through the LLPD for the footing resistance 20, 100, 500 Ω.

In this case, the probability of flashover in two unprotected phases increases. It should be noted that for such cases, the most optimal lightning protection option is to install three LLPDs on the pole, as the number of outages changes significantly with the increase in *Rf*. This approach provides the best line protection option.

The analysis of calculations for determining the parameters of the impact on protective devices - opened-type multi-chamber LLPDs b0110i, demonstrates that during back flashovers, the current impulse flowing through the nearest LLPD is significantly lower than the lightning current. This is due to the fact that most of the current flows through the pole into the ground. The greatest impact is on the LLPD closest to the point of lightning strike. The proportion of current from the lightning impulse flowing through the LLPD strongly depends on the pole grounding resistance. As it increases, so does the current magnitude, since the current diversion through the pole is hindered.

The graph in Figure 8 shows the dependence of the current flowing through the arrester on the footing resistance 20, 100 and 500 Ω for a lightning current amplitude of 100 kA.

Figure 9 shows the point distribution of current pulses through the nearest lightning protection device. From a series of 10,000 lightning strikes, all strikes on the OHGW and the pole are recorded, varying the amplitude of the lightning current and the duration to half-value for the footing resistances under consideration. The front duration is estimated similarly for the footing resistances under consideration (Fig. 10). Like the time to half-value, the front time depends on the pole footing resistance.

The average front duration values are predominantly in the range of 1-5 µs. With significantly high footing resistances (*Rf* =500 Ω), time to half-value is maintained up to 20 µs, but on closer examination, a tail pulse is observed (Fig. 8), which increases the total charge flow. These results confirm the need to create a less demanding lightning protection device for protecting overhead lines from back flashovers, compared to devices that provide protection from direct lightning strikes. In addition, these devices can be used on lines without an OHGW to protect the lower phases on the pole.

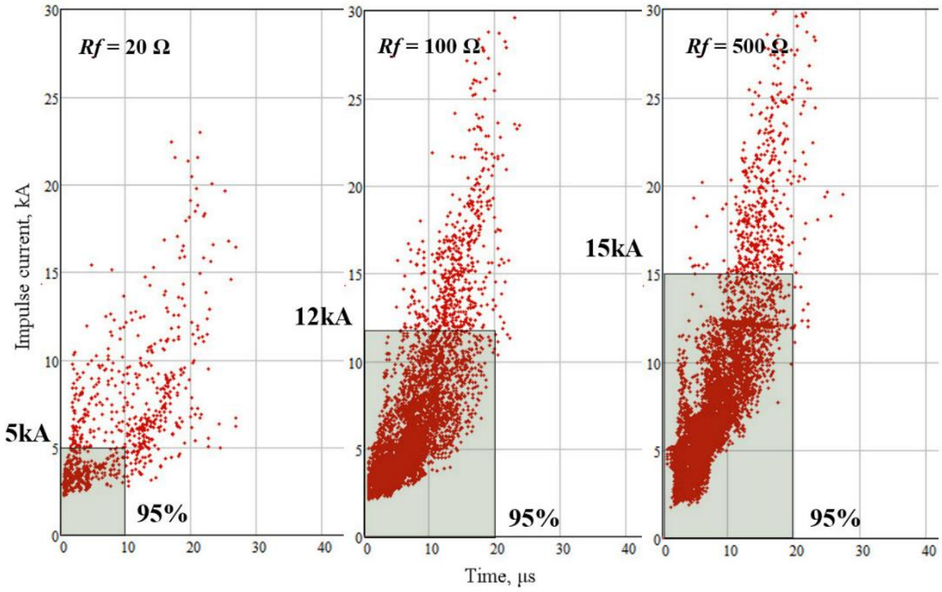

Fig. 9. Point distribution of values of the current impulses throught the LLPD for the footing resistance of 20, 100, 500 Ω. Y-axis – the maximum of the impulse current and X-axis – half-value time

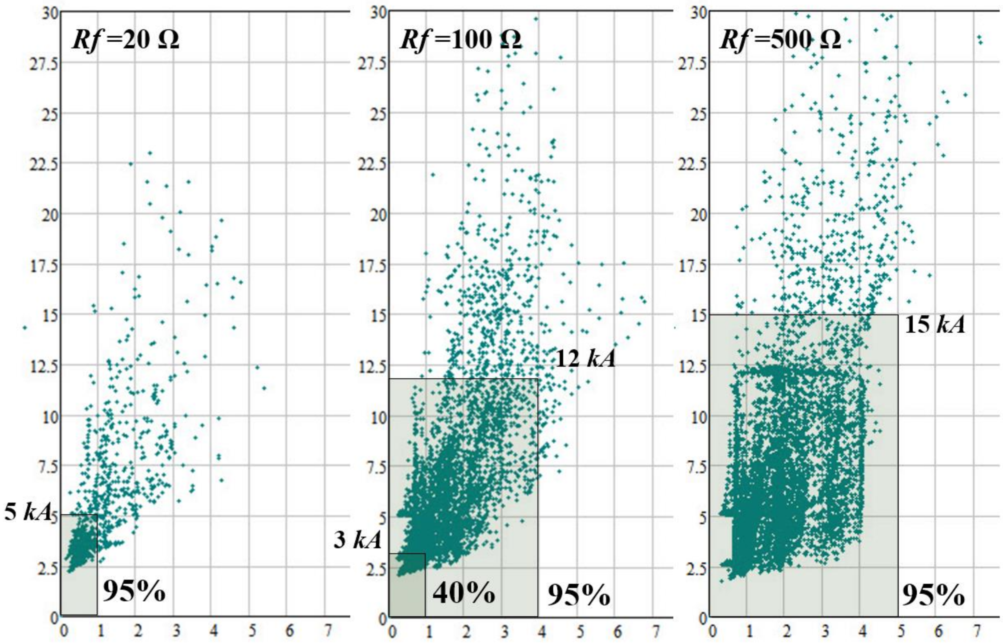

Fig. 10. Point distribution of values of the current impulses – the maximum of the ligthning current (Y-axis) and time to half-value (X-axis) – for the nearest LLPD for the footing resistance of 20, 100, 500 Ohm

V. LLPD QUENCHING CAPABILITY TEST

The most critical tests that determine the operation of LLPDs are quenching capability tests. The test setup consists of two components: a Marx generator that generates lightning current, and a RLC circuit that simulates the effect of industrial frequency voltage (Fig. 11).

During the tests, a current pulse from the Marx generator passes through the device simultaneously with the network voltage effect from the RLC circuit. If the LLPD operates successfully, it prevents the flow of the accompanying network current, providing pulse quenching. The setup is arranged so that pulse impacts coincide with the voltage peaks for both polarities of the first half waves.

For checking the operation of the LLPD b0110i, it is essential to define the test impacts correctly, namely the parameters of the back flashover pulse currents. Based on the calculations conducted, the following test program was proposed:

- 4 impacts of 3 kA 1/50 µs;
- 10 impacts of 12 kA 4/20 µs.

It should be noted that the maximum charging voltage of the RLC circuit in testing laboratory is 28 kV. Thus, the number of discharge modules of LLPD in the test sample is reduced proportionally to the decrease in the applied voltage:

$$k = \frac{U_{\max}}{U_c},$$

where

k – the ratio of the number of discharge modules of the test sample to the actual LLPD b0110i,

U_{max}– the max operating phase voltage of 110 kV OHL,

U_c – the charging voltage of the lab RLC circuit.

The test sample of LLPD b0110i underwent a complete program of quenching capability tests. An example of an oscillogram is presented in Fig. 12.

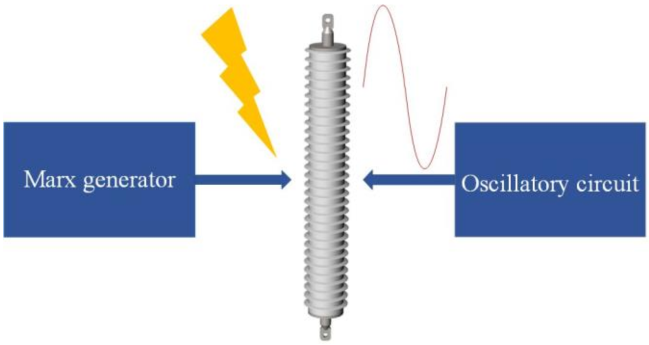

Fig. 11. Test device flow diagram

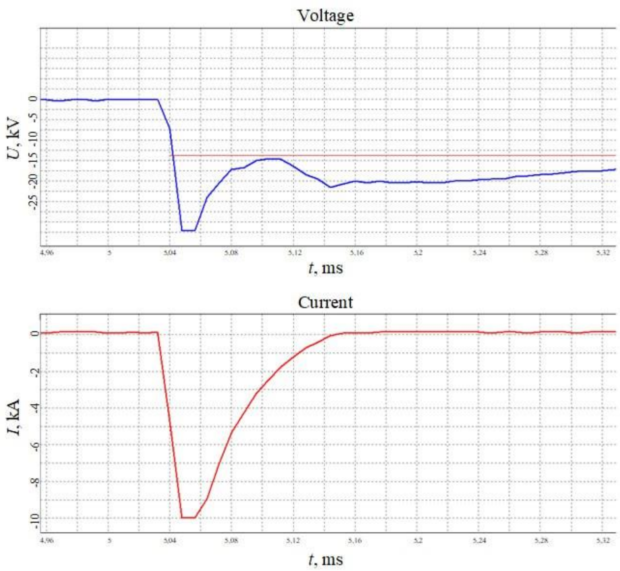

Fig. 12. The oscillograms of experimetal current and voltage values of LLPD during the test with impulse 12 kA 4/20 μs .

VI. Conclusions

1. An analytical calculation to determine the number of outages on a 110 kV line protected by an OHGW demonstrates that the OHGW does not provide complete line protection from lightning overvoltages, and at elevated pole footing resistances, its protective role is entirely excluded.
2. To solve the issue of line outages due to atmospheric overvoltages with OHGW and high pole footing resistance, Streamer Electric Company proposes a new generation of lightning protection devices an open type multi-chamber LLPD b0110i.
3. The quantitative assessment of impacts on protective devices determines the parameters of the current pulse - lightning current amplitude, pulse front, time to half-value. This allows the estimation of the pulse parameters that apply to the LLPD and defines the test program for research. As a standard program was proposed:
   - 4 impacts of 3 kA 1/50 μs
   - 10 impacts of 12 kA 4/20 μs
4. The developed multi-chamber arrester LLPD b0110i has successfully passed the quenching tests according to the proposed program. This type of LLPD can be recommended for the lightning protection of 110 kV overhead lines operated with an OHGW.

References

[1] G.V. Podporkin, E.Yu. Enkin, V.V. Zhitenev, R.I. Zainalov, V.E. Pilshchikov, D.O. Belko, Development of shield-type multi-chamber lightning arrester for 35kV OHL, XIII SIPDA, 2015

[2] Podporkin G.V., Enkin E.Y., Belko D.O., Pilschikov V.E., Multi-chamber Disc-Type Lightning Arrester for 13.8 kV Overhead Lines Protection, 11th APL, 2019

[3] Belko D., Zhitenev M., Implementation of the Analytical Method for the Lightning Performance Assessment of Power Line with Line Lightning Protection Devices, XV SIPDA, 2019

[4] IEEE Guide for Improving the Lightning Performance of Electric Power Overhead Distribution Lines, IEEE Std. 1410-2010.

[5] D. O. Belko, G. V. Podporkin, Analysis of current distribution among long-flashover arresters for 10 kV overhead line protection against direct lightning strikes, 33rd ICLP, 2016

[6] D. Belko, N.Zaretskiy. Comparison of the Analytical Simplified Method of the OHL Lightning Performance Assessment with Monte Carlo Method in ATP-EMTP using Line Lightning Protection Devices, 36th ICLP, 2022.