IJE TRANSACTIONS A: Basics Vol. 38 No. 07, (July 2025) 1621-1630

International Journal of Engineering

Journal Homepage: www.ije.ir

Estimation of Lightning Performance of Double-Circuit Overhead Power Lines without an Overhead Ground Wire using Line Lightning Protection Devices of Enhanced Quenching Capability

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PAPER INFO

Paper history:
Received 28 August 2024
Received in revised form 16 November 2024
Accepted 18 November 2024

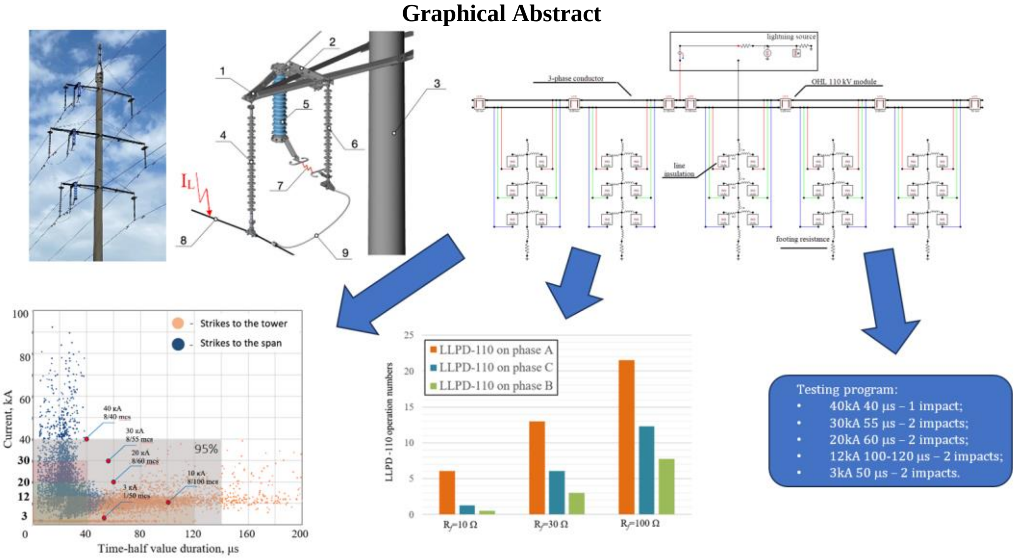
Keywords:
Arresters
Emergency Outages
Impulse Quenching
Lightning Protection
Overhead Power Lines

ABSTRACT

A new type of closed-type lightning protection multi-chamber arrester named impulse quenching line lightning protection device (LLPD) used for protection of overhead power lines is described. After the passing of lightning current, the multi-chamber system of the arrester prevents the occurrence of a network short-circuit current due to the total voltage drop across several thousand series-connected spark gaps that significantly exceeds the applied network voltage in magnitude. The total operating time of the LLPD is less than 1 ms which is not sensitive for microprocessor and relay protection of overhead lines. A computational estimation of the emergency outage rate of double-circuit overhead power lines without an overhead ground wire resulting from lightning overvoltage was carried out. Number of current impulses used when arresters are tested for quenching capacity as well as their parameters were determined by the mathematical modeling using the statistical Monte Carlo method. Results of calculation that make it possible to determine the efficiency of lightning protection of double-circuit overhead lines with various placement schemes of the line lightning protection device LLPD-110 of the company Streamer Electric AG are presented in the conclusion.

***doi**: 10.5829/ije.2025.38.07a.14*

Graphical Abstract



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Please cite this article as: Enkin EY, Zaretskiy ND, Frolov VY, Belko DO, Sivaev AD, Ivanov DV. Estimation of Lightning Performance of Double-Circuit Overhead Power Lines without an Overhead Ground Wire using Line Lightning Protection Devices of Enhanced Quenching Capability. International Journal of Engineering, Transactions A: Basics. 2025;38(07):1621-30.

NOMENCLATURE

b	Line width (m)	n_{tr}	Number of the arrester triggerings
h	Average height of phase conductor suspension (m)	P_{tw}	Probability of lightning strike to the tower
h_{tw}	Transmission tower height (m)	P_{sp}	Probability of lightning strike to the span
$\bar{I}$	Median value of maximum lightning current (A)	R_f	Footing resistance (Ohm)
l_{sp}	Span length (m)	$U_{50\%}$	Fifty percent discharge voltage of the spark gap arrester
N_{DLS}	Number of lightning strikes	**Greek Symbols**	
N_g	Number of lightning strikes into the ground	σ_I	Standard deviation of maximum lightning current

1. INTRODUCTION

The growing demand for electric power leads to the systematic development and modernization of electric networks (1-5). The transmission of electricity to consumers by 110 kV lines is often carried out using double-circuit transmission towers to reduce the size of the overhead line. To ensure reliable power supply, 110 kV overhead lines must be equipped with overhead ground wires (OHGW). However, in Russia a large percentage of OHGW has already exhausted its service life which significantly reduces the reliability of its operation. The problem is also increased by additional negative factors such as an ice formation and corrosion which often lead to OHGW breaks and their fall onto phase wires. Due to the above facts, in some regions of Russia, a broken OHGW is not restored preferring the application of additional lightning protection devices on the opened sections of overhead lines.

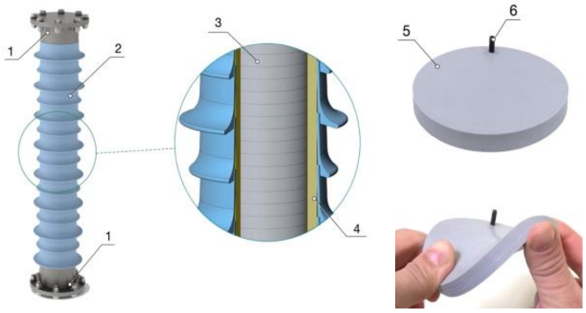
Devices that provide protection for overhead lines without OHGW are subject to high requirements in terms of their ability to withstand currents of direct lightning strikes (DLS). If we consider the protection of overhead lines based on surge arresters (SA), then a parameter so called lightning discharge capability has been introduced in their classification, and devices for DLS protection must have one of its highest classes (4, 5).

If we consider the protection of overhead lines based on multi-chamber arresters (MCA) (6-10), then the main parameter characterizing their ability to withstand DLS currents is the ability to withstand the pressure that arises in the chambers during the passing of lightning current. A lightning current generator is used for testing, the parameters and quantity of current pulses are selected according to the calculation model (11-18).

Company Streamer Electric AG has developed a new type of closed-type lightning protection multi-chamber arrester – impulse quenching line lightning protection device (IQ LLPD-110, see Figure 1a). The design and characteristics of LLPD-110 are described in more detail in literature (19). Here we should focus only on its differences from surge arresters. Despite the similarity in appearance, the operating principles of LLPD and surge arresters are different. Unlike metal-oxide varistors, the main working elements of LLPD are discharge modules (see Figure 1b) which do not contain materials with nonlinear characteristics in their design.

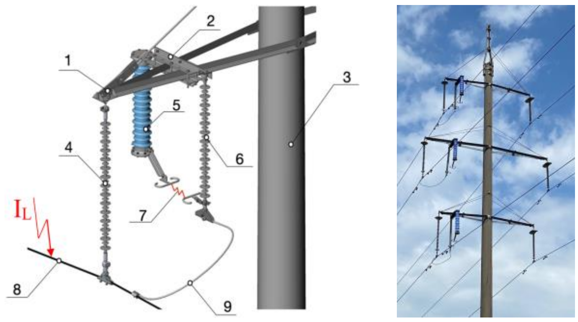
Brief description of the principle of operation is following. Lightning overvoltage causes the LLPD triggering (Figure 2a). After the passing of lightning current, the multi-chamber system of the arrester prevents the occurrence of a network short-circuit current.

Arc quenching takes place due to the total voltage drop across several thousand series-connected spark gaps that significantly exceeds the applied network voltage in magnitude. The total operating time of the LLPD is less than 1 ms which is not sensitive for microprocessor and relay protection of overhead lines. There is no emergency outage.



(a) (b)

Figure 1. Design of the impulse quenching line lightning protection device LLPD-110: (a) LLPD general view and a cross section; (b) single discharge module; 1. upper and lower ends; 2. shell; 3. column of discharge modules; 4. fiberglass pipe; 5. body of the discharge module; 6. supply end electrode



(a) (b)

Figure 2. LLPD-110 on overhead power line: (a) schematic view; (b) photo; 1. crossarm of the tower; 2. additional crossarm; 3. tower body; 4. line insulator; 5. LLPD-110; 6. additional insulator; 7. spark air gap; 8. phase wire; 9. cable for LLPD-110 connection; IL is lightning current

In terms of lightning discharge capability, LLPD-110 is a competitor to the surge arrester of the highest class 5 according to Russian Institute of Standards withstanding a twenty-fold current pulse with a charge of 2.4 C (see Table 1).

The installation of LLPD on a 110 kV overhead line is electrically carried out in parallel to any type of line insulation with a spark air gap between the high-voltage electrode of LLPD and the electrode of the additional insulator connected to the phase wire (Figure 2a). The presence of a spark gap isolates the LLPD from the continuous influence of the operating network voltage and excludes triggering due to internal network overvoltage which has a beneficial effect on the reliability and durability of the device. The LLPD is switched on only when the spark gap breaks through due to a lightning overvoltage.

The installation of the arrester must be carried out for the voltage class for which it is intended to protect, which is the main criterion when choosing a protective device. To determine the required service lifetime of LLPD-110 as well as to select an effective scheme of placement of arresters on a tower, a computational estimation was carried out using the ATP-EMTP software (20, 21).

2. MATERIALS AND METHODS

2. 1. Calculating Method for Determining the Number of Lightning Outages of a 110 kV Overhead Power Line and for Estimation the Impacts on Lightning Protection Devices

The task of determining the number of lightning outages of overhead lines includes the following steps:

- calculation of the number of lightning strikes depending on thunderstorm activity in the region under consideration and the height of towers. It is determined by the following expression:

$$N_{DLS} = 0.2 \cdot N_g \cdot \left(\frac{b}{2} + 5h - \frac{h^2}{15}\right), \quad (1)$$

where N_g is the number of lightning strikes into the ground, strikes/km^2/year; b is line width, m; h is the average height of phase conductor suspension, m.

TABLE 1. Classification of line surge arresters intended for lightning protection

Class designation	Rated discharge current 8/20 (kA)	Charge transfer rating, Qth, (C)
5	20	>2.4
4	10	>1.6
3	10	>1.0
2	10	>0.4
1	5	>0.2

- calculation of lightning parameters;
- calculation of the probability of insulation overlapping or arrester triggering;
- calculation of the probability of arc establishment.

Each calculation is controlled by regulatory documents (22). They provide generalized cases for 110 kV overhead lines. However, each overhead line has different features, therefore it is necessary to take theirs into account and make calculations for each line separately. To determine the number of annual overhead line (OHL) lightning outages of a 110 kV line, the calculation of the probability of insulation overlapping or arrester triggering will be considered in detail. This task will be resolved through mathematical modelling of a 110 kV overhead line unprotected by OHGW.

To calculate the probability of insulation overlapping/arrester triggering during a lightning strike to a line, the ATP-EMTP software is used which allows ones to create a model of an overhead line based on its equivalent circuit (Figure 3) (23-30).

The elements of the equivalent circuit are:

- Model of a transmission line using an LCC block with defined position of phase conductors on the tower and the height of their suspension as well as conductor parameters such as DC resistance, radius (31-35);
- Crossarms and tower bodies are presented in the form of concentrated inductance taking into account the dimensions of the tower;
- Insulation is a controlled switch that closes when the impulse strength of the insulation corresponding to the voltage class is exceeded. When the electrical strength of the insulation is exceeded, the switch closes and current begins to flow through the insulator. In normal mode, the switch is open and there is no path for current to flow;
- The arrester model used for simulation in the ATP-EMTP software package is a nonlinear element. The main parameters that define nonlinearity are current and voltage. The volt-ampere characteristic (VAC) is determined using experimental oscillograms obtained during testing of samples for quenching capacity in the laboratory.

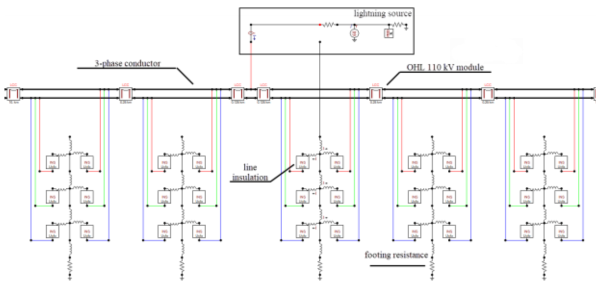


Figure 3. Calculation scheme for the Monte Carlo method implementation

The essence of the Monte Carlo method (36, 37) is to repeatedly calculate the original overhead line model using a random variable generator according to a given distribution. An analysis of probabilistic characteristics is carried out based on the data obtained. To implement it, a statistical element is added to the calculation scheme which makes it possible to obtain the parameters of the generated lightning pulses using the lognormal distribution (38, 39). A lightning strike is characterized at each calculation step by its own parameters: the amplitude value of the lightning current, the front time and the front duration. Lightning parameters are set according to IEEE recommendations (22). The magnitude of the current passing through the insulation or the arrester is registered. The model set the quantity of numerical experiments: 5000 lightning strikes in the tower-span section. Some of the lightning strikes hit the tower, some of them hit the middle of the span (on the OHGW in the case of its presence, on the phase conductor in the case without OHGW). The number of lightning strikes that caused insulation overlapping/arrester triggering is registered to calculate the number of lightning outages on overhead lines. Next, the parameters are analyzed and the level of current passing through the nearest arrester that 95% of all lightning striking the overhead line led to is estimated.

2. 2. Determination of the Number of the Arrester Triggerings over the Service Life After a quantitative estimation of the impacts on the arrester, it is necessary to determine the number of the arrester triggering on a 110 kV overhead line without OHGW by calculations in order to formulate a test program.

The number of the arrester triggering n_{tr} is determined by the sum of the number of triggerings due to lightning strikes into the tower and the number of triggering due to lightning strikes into the span. When lightning strikes a span, an electromagnetic voltage wave propagates on both sides of the strike location and is necessarily trigger arresters on nearby towers. When lightning strikes the tower, the arrester is triggered because of back flashovers (BFO) on this tower. Line lightning protection devices LLPD-110 with impulse arc quenching have a distinctive feature compared to arresters with current zero quenching. It is necessary to consider not only the LLPD closest to the location of the lightning strike but also the LLPD on the next towers because the lightning strike can also trigger them. The number of towers with triggered arresters increases as the footing resistance increases. Thus, the total number of one arrester triggering will be added up as the number of triggering from lightning strikes in the location closest to the place where the arrester installed as well as the number of triggering caused by the propagation of the current wave from the strike on distant towers.

Solving the task of determination, the number of arrester triggering is similar to solving the task of determination the number of annual OHL outages. In this case, it is necessary to consider the service life of the lightning protection device. According to the operating manual, the service life of the LLPD-110 device is 30 years. When solving this task, it is necessary to understand what reason will cause most of the arrester triggering.

2. 3. Schemes of the Placement of Protection Devices on Double-circuit 110 kV Overhead Lines in the Sections without OHGW The following input parameters are used to analyze the effectiveness of various schemes of arrester placement:

- Double-circuit 110 kV overhead lines (see Figure 4);
- P110-4v transmission tower with height h_{tw}=31 m and standard span length l_{sp}=250 m;
- Impulse electric strength of a garland of insulators 8xPS70E $U_{50\%}$=600 kV;
- Impulse electric strength of the arrester $U_{50\%}$=550 kV;
- Median value of maximum lightning current and standard deviation $\bar{I}$ = 31 kA, σ_I =0.29;
- The tower-span strikes distribution was determined based on the span length and tower height using the following expression:

$$P_{tw} = \frac{4 \cdot h_{tw}}{l_{sp}}, \quad P_{sp} = 1 - P_{tw} \qquad (2)$$

where h_{tw} is the tower height, l_{sp} is the span length.

- Footing resistance of towers is 5…50 Ohm.

There are two approaches to the protective devices placement schemes for overhead lines mounted on double-circuit towers. The first approach involves

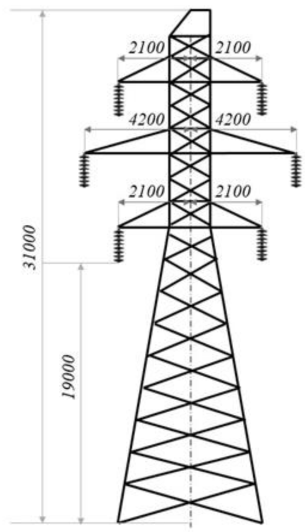


Figure 4. Typical 110 kV overhead line tower

installing arresters on a phase of each circuit. The effectiveness of installing of lightning protection devices estimated by reducing the number of lightning outages of overhead lines depends on the number of protective devices on the tower. In this case, the level of lightning performance with the same number of arresters will be determined by the footing resistance of towers. The following schemes for the placement of arresters are proposed for a section of a double-circuit overhead line without OHGW (Figure 5a):

1. 2 arresters per tower on the upper phase;
2. 4 arresters per tower for the upper and lower phases;
3. 6 arresters per tower for all phases.

Besides double circuit protection scheme, it is also permitted to protect only single circuit with sets of arresters (Figure 5b).

This option reduces the cost of lightning protection activities and is also relevant in the case when overhead line outages are most often takes place on the single circuit or at high footing resistances, when the probability of phase-to-phase overlaps increases.

This approach reduces the number of outages not only on the protected circuit but also on the second circuit without arresters. Here we consider one variant for the arrester's placement scheme – the one with full protection of single circuit.

In this approach, it is interesting to analyze the outages of each circuit separately to estimate the effectiveness of lightning protection devices installing.

3. RESULTS AND DISSCUSSION

3. 1. Results of the Number of Annual OHL Outages on a Double-circuit 110 kV Overhead Line without OHGW

Figure 6 shows the number of annual OHL outages (40) of a 110 kV line without OHGW per 100 km of length with a lightning activity of 100 lightning hours (l.h.) as function of footing resistance in the presence of lightning protection devices using double circuit protection scheme. Presented results show that installing of 2 arresters on the upper phase of a tower makes it possible to achieve the same level of lightning performance as in the case with OHGW. However, the effectiveness of this approach is confirmed at low footing resistances. As the footing resistance increases, the probability of phase-to-phase overlaps increases, and protection with 2 arresters becomes less effective. Particular attention should be paid to protection by 4 arresters on the tower. Research has demonstrated that this variant will be effective when installing arresters on the upper and lower phases of each circuit. The order of phase overlap depends on the capacitive coupling between the conductors.

When the insulation on the upper phase overlaps, the next overlapping will be for insulator installed on the far phase i.e. lower one. Thus, installation of arresters on the upper and middle phases does not protect the lower phase which will lead to line outage.

When protection by 4 or 6 arresters for the entire overhead line takes place, the number of outages is reduced by more than 10 times and is practically independent of footing resistance.

Let's consider the single circuit protection scheme. Figure 7 shows the number of outages of each circuit in the case of absence of the arresters as well as in the case of their presence. As one can see, this variant reduces the number of outages of the protected circuit by more than 15 times. It is necessary to notice that the presence of arresters at one circuit reduces the number of outages on another circuit that does not have protection. This is explained by the fact that the breakdown voltage of LLPD-110 is approximately 15% lower than the breakdown voltage of line insulation. Thus, the pulse overvoltage formed on the tower body is cut off by the operating of the lower phase arrester which prevents the back flashovers of the line insulation on the unprotected circuit.

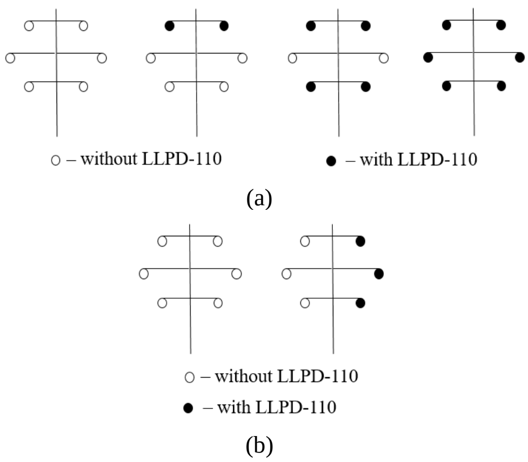


Figure 5. Schemes for the placement of protection devices on double-circuit 110 kV overhead lines: (a) double circuit protection scheme; (b) single circuit protection scheme

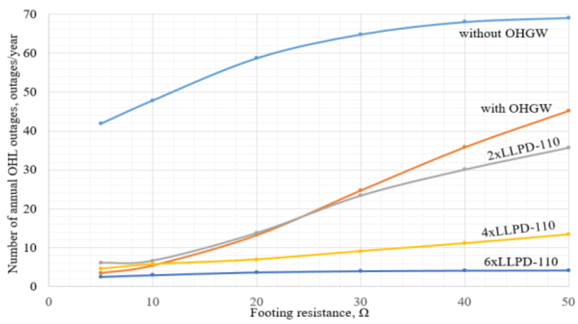


Figure 6. Number of annual OHL outages of 110 kV line depending on the footing resistance of the towers with double circuits protection scheme

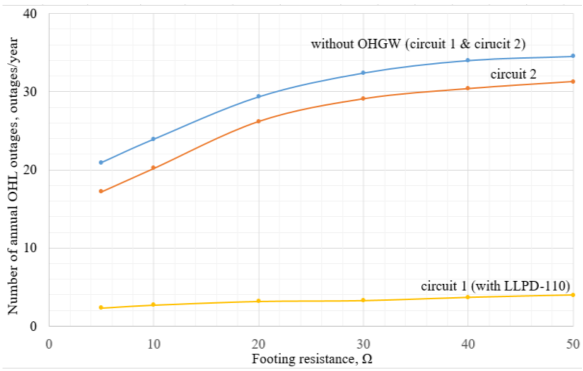


Figure 7. Number of annual OHL outages of 110 kV line depending on the footing resistance of the towers with single circuit protection scheme

3. 2. Results of Quantitative Estimation of the Effects of Pulses on Protective Devices Let's consider the quantitative estimation of the impacts on the LLPD-110 arrester designed for lightning overvoltage protection on lines without OHGW. Analysis of calculations to determine the parameters of impacts on protective devices shows that current through the upper phase arrester is larger during a direct lightning strike to the span in comparison to current through middle and lower phases arresters during a lightning strike to the tower. This is explained by the fact that the lightning current flows into the ground without alternative through the upper phase arresters in the case of a lightning strike to a span.

In another case, when lightning strikes a tower, one part of the lightning current is directly flows into the ground, and the other part passes through the arresters due to the occurrence of back flashovers.

In addition, it is necessary to noting that the current passing directly through any arrester is significantly less than the initial lightning current both in amplitude and in the time-half value duration which is explained by the increase of the nonlinear resistance of the arrester during its triggering. It should also be added that when lightning strikes a tower, the magnitude of current through the protective device depends on the value of the footing resistance. As it increases, the magnitude of current directly flowing into the ground decreases, and most of the current flows through the device. Figure 8 shows dependences of the current passing through the arrester during a lightning strike to the tower and to the span for different footing resistance, a lightning current was 100 kA.

Figure 9 shows the point distribution of current pulses through the arrester closest to the location of the lightning strike. From a series of impacts, all lightning strikes into the span and into the tower which led to the triggering of the arrester with the footing resistance of 100 Ohms were registered.

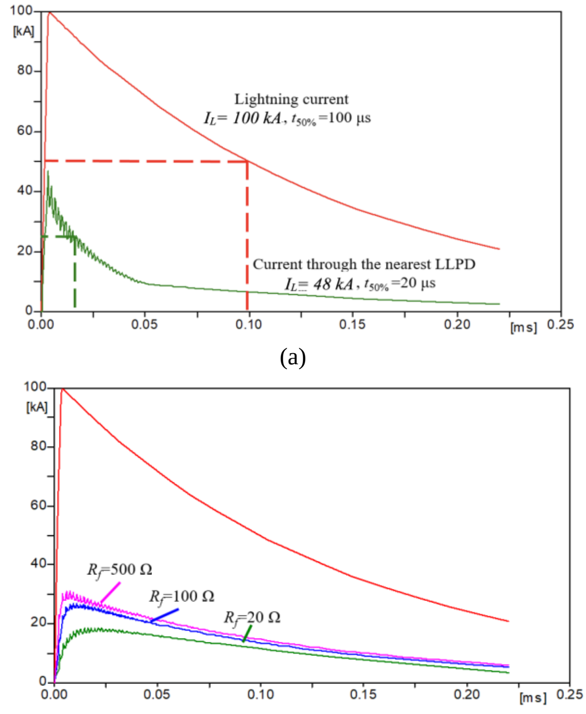


Figure 8. Dependence of the current passing through the arrester during a lightning strike: (a) into the span; (b) into the tower

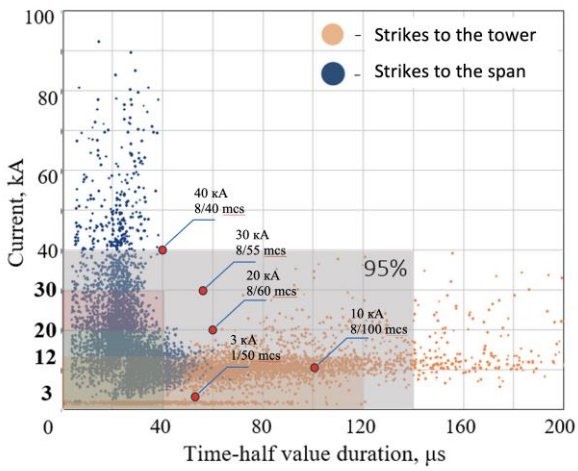


Figure 9. Point distribution of the parameters of the pulse current passing through the arrester, i.e. pulse current (Y-axis) and time-half value duration (X-axis) with the tower footing resistance of 100 Ohms. Red point are experimental data

To formulate a test methodology, it is necessary to consider the most severe case of operation. That is why the paper presents analysis of the impacts with a tower footing resistance of 100 Ohms.

The graph shows an area of strikes to the span that characterized by significant magnitudes of current passing through the arrester and by quite short time-half value durations. Strikes to the tower, on the contrary, have a smaller current magnitude but a significant pulse duration. This feature is because when lightning strikes a tower, all arresters are in the same conditions as a result of back flashovers, and the change in the pulse waveform is insignificant.

Strikes into the arrester installed on the upper phase will have parameters up to 40 kA and a half-life duration of 150 μs in 95% of cases. However, to formulate a test program this area can be divided into several areas, i.e. strikes to the tower and strikes to the span as shown in Figure 9.

3. 3. Results of the Number of Triggerings of Lightning Protection Devices Installed on a 110 kV Overhead Line without OHGW and the Formation of a Testing Program for Arresters

The number of lightning strikes per 100 km during the service life of the arresters (30 years) is estimated using formula 1. With a lightning activity of 100 l.h. which is equal to 5 strikes/km^2/year, the number of lightning strikes in the tower-span section for 30 years is N_{DLS} = 5.4 strikes for the considered tower. Thus, over the entire service life, about 2000-2200 lightning strikes the entire 100 km long overhead line with a span length of 250 m. Some of them are characterized by significant currents and long durations which can lead to the operating of arresters. It was determined what fraction of all lightning strikes will trigger the arresters using the Monte Carlo method in the ATP-EMTP software.

The arresters installed on the upper phase are found in the most difficult conditions, since they pass through themselves the maximum impulse current when lightning strikes the phase wire. Let's consider for these devices what fraction of the current from the magnitude value of the lightning current flows through the nearest and distant arresters.

Figure 10 shows a diagram with the calculation results of the number of LLPD-110 triggering for each phase of the tower over a service life of 30 years with lightning activity of 100 l.h. for three tower footing resistances: 10, 30 and 100 Ohms.

For all cases the predominant triggering of the upper phase arrester A is observed since each DLS into the phase wire is accompanied by the triggering of the nearest upper phase arrester. The arresters on the lower phases B and C have a lower probability of triggering since it depends on both the lightning current and the footing resistance of the towers. The number of arrester triggering increases with an increase in the footing resistance of the towers since the probability of lightning strike with low critical current increases which leads to the triggering of the lightning protection device.

Considering the most dangerous case when the footing resistance of the towers is 100 Ohms for the upper arrester, the maximum number of triggering of the LLPD-110 arrester is about 20 times over a service life of 30 years at 100 l.h.

Additionally, an analysis of the current impacts and the percentage of the magnitudes of the pulse currents passing through the upper phase arrester was carried out for the case of a tower footing resistance of 100 Ohms. The results of this analysis are presented in Table 2.

In most cases triggering is caused by current passing through the upper phase arrester that not exceeds the value of 12 kA. Taking into account the abilities of the existing testing laboratory and the calculations performed, the following program for testing of protective devices for quenching capacity to protect lines without OHGW is proposed:

- 40 kA 40 μs – 1 impact;
- 30 kA 55 μs – 2 impacts;
- 20 kA 60 μs – 2 impacts;
- 12 kA 100-120 μs – 2 impacts;
- 3 kA 50 μs – 2 impacts.

The LLPD-110 arrester designed to protect 110 kV overhead lines without OHGW has successfully passed the quenching capacity test according to the program presented in this paper.

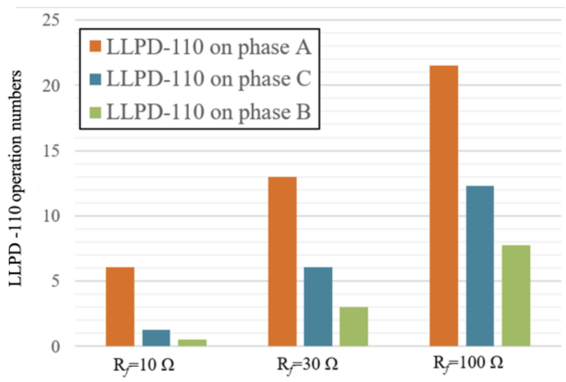


Figure 10. The number of operating of LLPD-110 arresters on a 110 kV overhead line without OHGW depending on the footing resistance of the towers (phase A is upper wire, phase B is middle wire, phase C is lower wire)

TABLE 2. Percentage of pulse currents passing through the LLPD-110 arrester in phase A (tower footing resistance is 100 Ohms)

Magnitude of current through the LLPD -110	% of total number of operatings
Up to 12 kA	84%
12-20 kA	10%
Over 20 kA	6%

4. CONCLUSIONS

Sections of overhead lines without OHGW are subject to frequent lightning strikes on phase wires which causes emergency outages. To provide the required level of lightning protection of overhead lines, it is necessary to use special devices. To increase the lightning performance of 110 kV overhead lines operated without OHGW, the company Streamer Electric AG has developed a new type of arresters i.e. impulse quenching line lightning protection device LLPD-110.

The estimation of the annual OHL outages in the case of the installation of lightning protection devices presented in the paper demonstrates the effectiveness of lightning protection activities up to 90% when all operating requirements are performed depending on the number of arresters installed on the tower.

There are various approaches to protecting the line from lightning surges for double-circuit power lines. Analysis of the results showed that the protection with 2 sets of arresters on the tower is effective at low footing resistances of the towers. As the resistance increases, the probability of phase-to-phase overlaps increases, and it is necessary to install a larger number of arresters per tower. One of the methods for lightning protection of a 110 kV line is the installation of arresters on only single circuit which reduces the number of outages of the protected circuit by more than 15 times, and also reduces the number of outages of the unprotected circuit as well as the total number of outages.

When creating new lightning protection devices, it is necessary to determine the requirements for withstand capability to repeated passing of DLS currents (lightning discharge capability). For this purpose, a computational analysis of the characteristics of pulse currents passing through the arrester was carried out in this paper. The magnitude of the pulse currents passing through the arrester is not exceed 40 kA, and the time-half value duration is not exceeding 150 μs in 95% of cases. Moreover, the graph of the point distribution of lightning currents shows that the currents are distributed not evenly (see Figure 9). Currents with large magnitudes are concentrated in an area with short durations, and currents with long durations are concentrated in an area with small magnitudes. Therefore, the paper proposes a program for arresters testing with pulsed currents, grouped according to the principle of the probability of their occurrence.

An estimation of the number of arrester triggering indicates that the arrester will operate about 20 times over the entire period of operation in the most severe conditions (R_f = 100 Ohm). In this case, most of the strikes will be caused by currents up to 12 kA. Calculation of the triggering number and estimation of pulse parameters provided an opportunity to formulate a testing program for quenching capacity for new lightning protection devices being developed to protect 110 kV overhead lines in the absence of OHGW.

5. ACKNOWLEDGMENTS

Present research was carried out within the state assignment of Ministry of Science and Higher Education of the Russian Federation (Theme No. FSEG-2023-0012).

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Persian Abstract

چکیده

یک نوع جدید از دستگاه حفاظت از خطوط هوایی در برابر صاعقه با چند محفظه بسته به نام دستگاه حفاظت از خطوط هوایی در برابر صاعقه با خاموش‌کننده پالس (LLPD) معرفی شده است. پس از عبور جریان صاعقه، سیستم چند محفظه این دستگاه از بروز جریان اتصال کوتاه شبکه جلوگیری می‌کند، زیرا افت ولتاژ کل در چند هزار جرقه‌زن متصل به صورت سری، به طور قابل‌توجهی از ولتاژ شبکه اعمال شده بیشتر است. زمان کل عملکرد LLPD کمتر از ۱ میلی‌ثانیه است که برای میکروپروسسور و حفاظت رله‌ای خطوط هوایی حساس نیست. تخمین محاسباتی نرخ قطع اضطراری خطوط هوایی دو مداره بدون سیم زمین هوایی به دلیل اضافه ولتاژ صاعقه انجام شد. تعداد پالس‌های جریان مورد استفاده در هنگام آزمایش خاموش‌کنندگی دستگاه‌های حفاظت از صاعقه و پارامترهای آن‌ها با استفاده از روش شبیه‌سازی آماری مونت کارلو تعیین شد. نتایج محاسبات که امکان تعیین کارایی حفاظت از صاعقه خطوط هوایی دو مداره با طرح‌های مختلف قرارگیری دستگاه حفاظت از خطوط هوایی در برابر صاعقه LLPD-110 شرکت Streamer Electric AG را فراهم می‌کند، در نتیجه‌گیری ارائه شده است.