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Study of the influence of the parameters of modern grounding wires on the value of power losses in them for overhead power lines of 330-750 kV

***Introduction**. The problem of estimating power losses in grounding wires with built-in fiber optic cable for overhead power lines of voltage class 330-750 kV is relevant, while it is obvious that the amount of losses depends on the chosen brand of wire. **Problem**. In the article, an analysis of the influence of the parameters of grounding wires on the amount of losses that occur in them in the normal mode of operation of the overhead power lines is carried out. **Goal**. The purpose of the work is to determine the criterion for the selection of grounding wires with a built-in optical fiber cable under the condition of increasing the energy efficiency of electricity transmission. **Methodology**. To calculate power losses in grounding wires, the methods of electromagnetic field theory were used, while taking into account the location of phase conductors on various types of towers of operating 330-750 kV overhead power lines and the possible current load of such lines. **Results**. The paper analyzed the dependence of losses in the grounding wires of the overhead power lines on the ratio of its active and reactive resistances, determined in which range of this ratio the losses will be close to the maximum. It is shown that the amount of specific power losses in the grounding wires of 330-750 kV overhead power lines in its normal operating modes can range from 1.6 kW/km for the 750 kV lines to hundreds of W/km for the 330 kV power lines. **Originality**. For the first time, it is recommended to use grounding wires with built-in fiber optic cable with running active resistance in the range of no more than 0.25 Ohm/km, which will minimize power losses and increase the energy efficiency of the 330-750 kV overhead power lines. **Practical value.** The obtained results can be applied at the stage of designing new or modernizing existing overhead power lines in order to reduce losses and increase the energy efficiency of lines.* References 27, tables 1, figures 5.

Key words: **overhead power line, lightning protection system, grounding wire, electricity losses, running active resistance.**

Досліджено втрати електроенергії в грозозахисних системах повітряних ліній електропередавання напругою 330-750 kV з грозозахисними тросами, що містять вбудований оптоволоконний кабель. Показано, що ці втрати є значними, залежать від взаємного розташування фаз та тросу, навантаження лінії за струмом та параметрів самого тросу (співвідношення його активного та реактивного опорів) і можуть становити від 1,6 kW/km для ліній 750 kV до сотень W/km для ліній 330 kV. Визначено, що грозозахисні троси з погонним активним опором в діапазоні від 0,32 Ω/km до 1,5 Ω/km будуть мати втрати, близькі до максимальних. Вперше рекомендовано використовувати грозозахисні троси, які містять вбудований оптоволоконний кабель, з погонним активним опором не більше 0,25 Ω/km, що дозволить зменшити втрати потужності та підвищити енергоефективність повітряних ліній електропередавання 330-750 kV. Бібл. 27, табл. 1, рис. 5.

Ключові слова: **повітряна лінія електропередавання, грозозахисна система, грозозахисний трос, втрати електроенергії, погонний активний опір.**

Introduction. In the modern world, overhead power lines (PLs) are increasingly equipped with lightning protection cables (LPCs) with built-in fiber optic cable (cables of the OPGW type). Such cables not only protect the PL phases from direct lightning strikes, but at the same time have built-in channels for transmitting information. The process of equipping PLs with such cables continues in Ukraine, primarily these are main PLs of the 220-400 kV voltage class. It should be noted that the lightning protection system of the PLs of the above voltage classes most often consists of two LPCs.

According to the requirements of the Electrical installation regulations [1], OPGW-type LPCs must be connected to each PL support, which, in turn, is grounded. Here, additional losses of electrical energy will occur in the PL lightning protection system in normal operation mode. The magnetic field of the PL phase wires forms an alternating magnetic flux coupled to the PL lightning protection system. This flow leads to the appearance of induced currents in the LPC and, as a result, energy losses for heating the LPCs themselves, which have a certain active resistance.

Review of publications. In [2], the approach to calculating power losses in the lightning protection system of the 330 kV PL, which has one LPC and is made on poles of the PS330-2 brand with a vertical arrangement of phases, is considered. The authors show that in the case of the use of the LPC of the OPGW type, the induced current in the LPC can lead to significant power losses. However, the majority of 330-750 kV PLs have horizontal wiring and two LPCs. It should be noted that most often in the course of the modernization of the mentioned PLs in Ukraine, only one of the two LPCs is replaced with OPGW: the other remains divided into segments by a steel rope, and each of the segments, in accordance with the Electrical installation regulations, is grounded at one point in order to prevent the flow of the induced current in such a LPC.

Studies of the modes of operation of high and ultra-high voltage lightning protection systems have a long history [3, 4]. However, the never-ending interest in these issues is due to both the use of new materials and the development of new types of PL supports, changes in the parameters of the LPCs themselves, changes in the PL load, etc. Issues of arrangement and modes of operation of lightning protection systems are considered in [5-7]. However, in them, attention is paid to multi-circuit PLs with one or two lightning protection cables [5] and vertical arrangement of phases. Here, the optimal mutual location of the phases of different circuits of such a PL is chosen in order to reduce power losses in its lightning protection system.

PLs of voltage classes 330-750 kV found on the territory of our country have horizontal arrangement of phases and are mostly single-circuit. A characteristic feature of Ukrainian PLs is the significant size of the supports and the distances between the phases and the LPC, therefore, the methods of reducing power losses in the lightning protection system given in [5-7] cannot be applied to them.

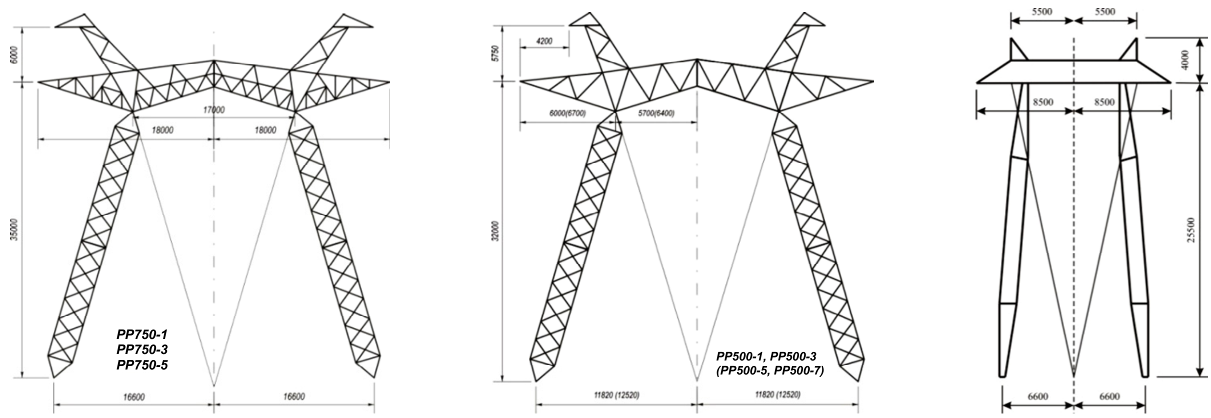
Many works, in particular [8-13], are dedicated to the reduction of power losses in electrical networks. However, most of these works are aimed at solving the problem of reducing technological losses of electrical energy in phase conductors of the electrical network and power transformers.

The issue of reducing losses is also relevant for cable lines, where currents are induced in the shields of single-core cables according to a similar mechanism of influence (if there are conditions for their flow) [1, 14-17].

The analysis of regulatory documents regarding the installation of fiber-optic communication lines (FOCL) on PLs showed that when choosing OPGW, their mechanical strength and resistance to lightning and short-circuit currents are taken into account, and power losses that occur in them in normal PL operation mode are not taken into account[1]. It is obvious that it is worth proposing additional criteria for the selection of LPC in order to reduce these losses.

The goal of the article is to find and justify the selection criterion for the OPGW for 330, 400, 500 and 750 kV PLs, which will ensure the reduction of power losses in the lightning protection systems of such PLs.

The main research materials. Below are the calculation method and numerical values of power losses in the lightning protection system of the 330-750 kV PLs using the example of supports of the PP-750, PP-500 and P330-9 brands (Fig. 1).



a *b* *c*

Fig. 1. External view and geometric dimensions of high-voltage PL supports: *a*) PP-750; *b*) PP-500; *c*) P330-9

For 750 kV PLs, which are built on supports of the PP-750 type (Fig. 1,*a*) [18], there will be the largest distances between the phases and the LPCs, which form the lightning protection system of the PL. Such PLs are designed to transport up to 2.25 GW of power (the current in a phase is approximately equal to 1.7 kA), and the load of PLs during the day, as a rule, changes insignificantly. In Ukraine, the indicated PLs most often have a load of up to 1 GW (the current in a phase is approximately equal to 770 A). All this means that it is in such PLs significant losses in the lightning protection system can occur. For example, the maximum annual losses in one LPC of the 750 kV PL with maximum load of 2,000 MW and the number of hours of use of the maximum load of 6,000 hours/year can reach 50,000 kW·h/km [4].

Let's find out for which LPCs the greatest losses will occur in the PL lightning protection system.

The currents induced in adjacent circuits from the OPGW grounded on each support, the body of the supports, and the ground, flow through the supports of the PL in opposite directions and compensate each other in the case of equality of the run lengths. It should also be noted that the resistance of one cable run is significantly lower than the grounding resistance of one PL support. Under such conditions, the currents from OPGW to the ground flow only from the terminal supports of the PL, the resistance of which is normalized in Table 2.5.29 of the Electrical installation regulations [1]. The circuit for the flow of this current has a certain active resistance R_{GW} and inductive resistance X_{GW}, which are determined by the parameters of the OPGW (provided that the grounding resistances of the terminal supports of the PL are small relative to R_{GW} and X_{GW} of the OPGW along the length of the PL).

Knowing the induced voltage U_{GW}, we can determine the induced current of I_{GW} by the formula:

$$I_{GW} = \frac{U_{GW}}{\sqrt{R_{GW}^2 + X_{GW}^2}}. \tag{1}$$

Losses of active power in the lightning protection system can be determined by the formula:

$$P_{GW} = I_{GW}^2 \cdot R_{GW} = U_{GW}^2 \cdot \frac{R_{GW}}{R_{GW}^2 + X_{GW}^2}. \tag{2}$$

The condition of maximum active losses can be found by determining the extremum of (2):

$$\frac{dP_{GW}}{dR_{GW}} = U_{GW}^2 \cdot \frac{\left(R_{GW}^2 + X_{GW}^2\right) - 2 \cdot R_{GW}^2}{\left(R_{GW}^2 + X_{GW}^2\right)^2} = 0. \tag{3}$$

It follows from (3) that the condition for maximum active losses in the LPC has the following form:

$$R_{GW} = X_{GW}. \tag{4}$$

It is obvious that the maximum power losses will be equal to:

$$P_{GW\max} == \frac{U_{GW}^2 \cdot X_{GW}}{X_{GW}^2 + X_{GW}^2} = U_{GW}^2 \cdot \frac{1}{2 \cdot X_{GW}}. \quad (5)$$

Let's determine the value of reduced losses in the form of the ratio of P_{GW} to $P_{GW\max}$:

$$\frac{P_{GW}}{P_{GW\max}} = \frac{2 \cdot R_{GW} \cdot X_{GW}}{R_{GW}^2 + X_{GW}^2}. \quad (6)$$

By dividing the numerator and denominator of (6) by the square of the reactive resistance, it is possible to obtain the value of the reduced losses in the lightning protection system as a function of the ratio of its active and reactive resistances:

$$\frac{P_{GW}}{P_{GW\max}} = f\left(\frac{R_{GW}}{X_{GW}}\right) = \frac{2 \cdot \frac{R_{GW}}{X_{GW}}}{1 + \left(\frac{R_{GW}}{X_{GW}}\right)^2}. \quad (7)$$

The dependence constructed according to (7) is shown in Fig. 2.

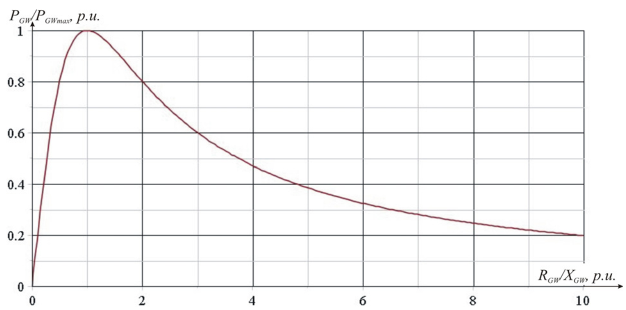


Fig. 2. Dependence of reduced losses of active power in the lightning protective cable of the PL on the ratio of its active and reactive resistances

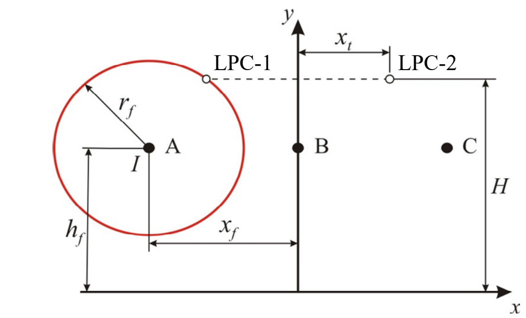
It is obvious that in order to avoid maximum losses in the lightning protection system, one should choose such OPGW for which the ratio R_{GW}/X_{GW} will be either less than 1 or greater than one. So, in Fig. 2 it can be seen that under the condition of choosing OPGW, for which R_{GW}/X_{GW} = 0.5 or 2 p.u., we have a value of specific losses of 0.8 p.u., which means a reduction of losses relative to the maximum by only 20 %. Provided that $R_{GW}/X_{GW} \leq 0.4$ or $R_{GW}/X_{GW} \geq 2.5$, we have a reduction in losses in the lightning protection system by more than 30 % in any operating mode of the PL. It is obvious that this criterion of the ratio R_{GW}/X_{GW} should be guided by the choice of OPGW for PL. Here, economic considerations should also be taken into account, because cables with a small ratio of active and reactive resistance have a larger diameter and mass per kilometer of length, as well as a higher price, but at the same time they will provide a better level of lightning protection and have greater resistance to lightning currents and short circuit (SC).

It should be noted that the above considerations are valid for the case when the resistance of the OPGW along the length of the entire PL is significantly greater than the resistances of the grounders of the terminal supports of the PL, which is actually performed for PLs of considerable length (in the case of short PLs, the above-mentioned resistances of the grounders should be taken into account).

Let's calculate the lossyi of active power in the lightning protection system of the PL under the condition of using different brands of OPGW. The mutual location of the phase conductors of the PL and the lightning protection cables with all the necessary distances is shown in Fig. 3.

Figure 3 shows the distance r_f between the phase and LPC1, as well as other distances necessary for the calculation. In cases where PLs are built on supports of the type:

- PP-750 (Fig. 1,*a*) – x_f = 18 m, x_t = 16.75 m, h_f = 15.9 m, H = 27.75 m;
- PP-500 (Fig. 1,*b*) – x_f = 11.7 m, x_t = 7.5 m, h_f = 17 m, H = 26.5 *m*;
- P330-9 (Fig. 1,*c*): x_f = 8.5 m, x_t = 5.5 m, h_f = 13.8 m, H = 20.25 m [18].



h_f – the height of the location of the phase conductors;
H – the height of the LPC location;
x_f – the distance from the vertical axis of symmetry of the support to the phases;
x_t – the corresponding distance to the LPC

Fig. 3. Geometric model of the PL for calculation

We assume that in Fig. 3 LPC1 is of the OPGW type, in which power losses should be determined. A steel rope divided into single-sided grounded segments is assumed as the LPC2.

It is also worth noting that the flow of current I in the PL phase will lead to the formation of the electromagnetic field around the conductor and, in the case of the passage of the PL along a residential building, create a harmful effect on the human body [19-23].

In Fig. 3 it can be seen that the distance between the PL phase and OPGW can be calculated by the formula:

$$r_f = \sqrt{(x_f - x_t)^2 + (H - h_f)^2}. \quad (8)$$

The depth of the current flow in the ground and the running voltage, in V/km, induced on the LPC1 of the OPGW type from the current of one phase of the PL, can be determined according to [4, 24] as:

$$D_{gr} = \frac{2{,}1}{\sqrt{f \cdot \gamma \cdot 10^{-5}}}; \quad (9)$$

$$U_{GW1P} = 0{,}1447 \cdot I \cdot \lg\left(D_{gr}/r_f\right), \quad (10)$$

where f is the current frequency; γ is the specific electrical conductivity of the soil (taken as equal to 0.01 S/m); I is the effective value of the current of one phase of the PL.

The running voltage from all phases of the PL induced on the OPGW will be determined as:

$$\dot{U}_{GW1} = U_{GW1A} \cdot e^{j \cdot 0} + U_{GW1B} \cdot e^{-j \cdot \frac{2 \cdot \pi}{3}} + U_{GW1C} \cdot e^{j \cdot \frac{2 \cdot \pi}{3}} . \quad (11)$$

The active and reactive resistances of one kilometer of the OPGW, taking into account the current in the ground, are equal to [4]:

$$R_{GW} = R_p + 0{,}05 ; \quad (12)$$

$$X_{GW} = 0{,}1447 \cdot \lg\left(\frac{D_{gr}}{d/2}\right), \quad (13)$$

where R_p is the running active resistance of the OPGW of a certain brand; d is its diameter.

The current induced in the lightning protection system is calculated according to (1). Based on the known effective value of this current, losses in the lightning protection system of the PL can be found according to (2).

The passport parameters of OPGW of various brands, as well as the calculated running active and reactive resistances of lightning protection systems of PL 330, 500 and 750 kV and their ratios are given in Table 1 [25]. As can be seen in Table 1, the active resistance of the lightning protection system depends very much on the selected brand of OPGW, while the reactive resistance changes much less. Therefore, when choosing a brand of LPC, we need to focus, first of all, on its running active resistance.

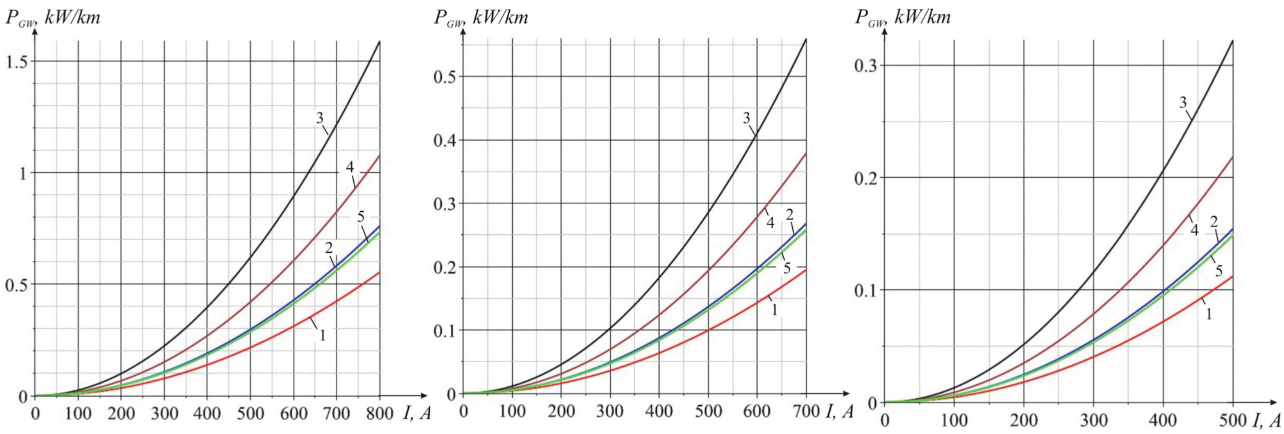
Table 1

OPGW parameters for PL 330-750 kV

LPC brand	OPGW parameters		Running active and reactive resistances of OPGW of PL voltage 330-750 kV		R_{GW} / X_{GW}, p.u. for PL voltage 330-750 kV
	d, mm	R_p, Ω/km	R_{GW}, Ω/km	X_{GW}, Ω/km	
OPGW 426-AL1/56-A20SA	28,8	0,065	0,115	0,697	0,165
OPGW 264-AL3/29-A20SA	22,5	0,12	0,17	0,712	0,239
OPGW 34-AL3/34-A20SA	11,4	0,681	0,731	0,755	0,969
OPGW 11-AL3/15-A20SA	7,3	1,856	1,906	0,783	2,435
OPGW 27-A20SA	7,3	3,022	3,072	0,783	3,925

According to (1), (2), (8) – (13) for all cables specified in Table 1, the dependencies of the specific losses of active power in the lightning protection system on the current in the PL phase are plotted, shown in Fig. 4.

It is easy to see that the OPGW 34-AL3/34-A20SA type cable (curve 3 in Fig. 4) provides a significantly higher level of losses than other brands of OPGW. If the current value of the 750 kV PL phase is 770 A when using the OPGW 34-AL3/34-A20SA cable, the power losses in the 750 kV PL lightning protection system will be about 1.472 kW/km (see Fig. 4,*a*). With PL length of 500 km, the losses of active power over the entire length of the LPC will amount to 0.736 MW. The cost of such losses per year, under the condition of operation of the PL with constant load at the existing tariff for the transmission of electricity through main networks (397.85 UAH per MW·h. as of December 2022), will amount to 2.565 million UAH/year. It is obvious that the use of cables of other brands will allow to significantly save electricity, especially if we take into account the standard operating life of the PL, which according to current legislation is 40 years, as well as the fact that electricity prices are constantly increasing. For example, for the OPGW 426-AL1/56-A20SA brand cable with the same value of current, the power losses are 0.513 kW/km, while the cost of such losses during the year will be 0.893 million UAH/year.



a) for PL 750 kV *b*) for PL 500 kV *c*) for PL 330 kV

Fig. 4. Dependencies of power losses in the 330-750 kV PL lightning protection system on the phase current for different brands of LPC:
1 – OPGW 426-AL1/56-A20SA; 2 – OPGW 264-AL3/29-A20SA; 3 – OPGW 34-AL3/34-A20SA;
4 – OPGW 11-AL3/15-A20SA; 5 – OPGW 27-A20SA

Figure 4,*b* shows that the power losses in the lightning protection system of the 500 kV PL can amount to hundreds of Watts per 1 km of its length. Such losses are also significant, especially considering the total length of the PL (for current of 500 A, losses in the lightning protection system of the PL with OPGW 34-AL3/34-A20SA brand cable can reach 0.285 kW/km). The correct choice of the LPC brand allows to reduce the value, and therefore the cost of such losses several times.

330 kV voltage class PLs are also of interest in the amount of losses in the lightning protection system. Such PLs also operate for a long time with significant current load. In Fig. 4,*c* it can be seen that the use of certain brands of OPGW allows to reduce losses to the value of tens of Watts per km of the length of the 330 kV PL (at current of 300 A, the losses in the lightning protection system of the PL with OPGW 34-AL3/34-A20SA cable can reach 116 W/km, and with OPGW 426-AL1/56-A20SA cable – only 40.5 W/km).

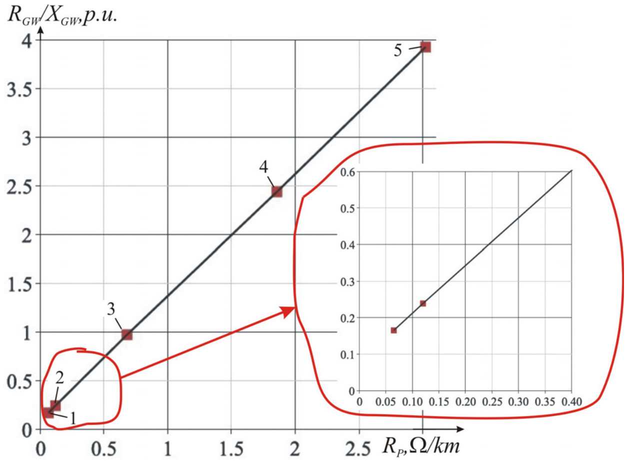
It should also be noted that when changing the OPGW brand, the reactive resistance of the lightning protection system changes significantly less than the active resistance (see Table 1), therefore, the value of the running active resistance of the OPGW should be the selection criterion in order to minimize power and electrical energy losses.

Analysis of the curves in Fig. 4 shows that cables with both low and high running active resistance on 330-750 kV PLs allow for a significant reduction in power losses in the lightning protection system, but at the same time, OPGWs with significant running active resistance have a smaller diameter, lower strength and thermal resistance to lightning currents and SC [26, 27].

According to Table 1 plots the dependencies of the ratio of active and reactive resistances R_{GW}/X_{GW} of the lightning protection system on the running active resistance R_p of the LPC are plotted (Fig. 5).

In Fig. 5 it can be seen that when using OPGW with running active resistance of 0.25 Ω/km, we have the value of R_{GW} / X_{GW} approximately equal to 0.4 p.u., which according to the curve in Fig. 2 provides a reduction of losses by 30 % from their maximum possible value. When choosing a LPC with lower values of the running active resistance, the losses in the lightning protection system of the 330-750 kV PL will be even smaller. Thus, when choosing an OPGW-type LPC for the considered PLs, it is worth choosing cables with running active resistance of no more than 0.25 Ω/km. Loss reduction can also be achieved by choosing cables with running active resistance greater than 1.85 Ω/km, corresponding to R_{GW} / X_{GW} of at least 2.45 p.u., which also provides a loss reduction of 30 % or more. However, such cables have a smaller cross-section, less mechanical strength and thermal resistance to lightning currents and SC, so it is not recommended to choose them.

It should also be noted that LPCs with running active resistance in the range from 0.32 Ω/km to 1.5 Ω/km are better not to be chosen at all, because it is for them that the R_{GW} / X_{GW} ratio varies from 0.5 to 2 p.u., that in accordance with Fig. 3 will ensure losses in the lightning protection system within 80-100 % of the maximum possible.



1 – OPGW 426-AL1/56-A20SA, 2 – OPGW 264-AL3/29-A20SA, 3 – OPGW 34-AL3/34-A20SA,
4 – OPGW 11-AL3/15-A20SA, 5 – OPGW 27-A20SA

Fig. 5. Dependencies of the R_{GW} / X_{GW} ratio on the running active resistance *Rp* of the LPC for lightning protection systems of the PL 330-750 kV

Conclusions.

It is shown that the value of specific power losses in lightning protection systems of 330-750 kV PLs in their normal modes of operation can range from 1.6 kW/km for 750 kV PLs to hundreds of W/km for 330 kV PLs and significantly depends on the mutual location of the phase wires and OPGW, PL load current and OPGW characteristics.

It has been determined that lightning protection cables with running active resistance in the range of 0.32 Ω/km to 1.5 Ω/km will have losses close to the maximum and should therefore be avoided. Smaller losses will be in the case of using OPGW with running active resistance of less than 0.25 Ω/km (usually of considerable value) or more than 1.85 Ω/km (usually of insufficient mechanical strength and thermal resistance to lightning currents and short circuit).

For the first time, it is recommended to use OPGW with running active resistance of no more than 0.25 Ω/km, which will allow to minimize power losses and increase the energy efficiency of 330-750 kV PLs at the stage of their design.

Conflict of interest. The authors declare no conflict of interest.

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