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EFFECT OF DISCHARGE CURRENT MAGNITUDE ON EFFECTIVENESS OF OVERHEAD POWER LINE PROTECTION AGAINST DIRECT LIGHTNING STROKES

In this paper the efficiency of lightning shielding provided by single overhead ground wire mounted atop of a double circuit self-supported 220 kV lattice power transmission line tower with a total height of 37.115 m was examined. According to the electro-geometric concept, each phase conductor of a power transmission line has an area where the overhead ground wire does not provide full protection against a direct lightning strike. The width of this unprotected area depends on the design and dimensions of overhead power line tower, the expected magnitude of the lightning current and decreases with increasing magnitude of the discharge current. The lightning protection effectiveness of upper and middle phase conductors was studied. The values of the minimum lightning current, capable of causing an insulation flashover in case of the lightning shielding failure were calculated. The minimum values of the lightning current at which complete shielding is achieved have also been determined. It was found that for upper phase conductor the minimum current at which a complete lightning shielding is achieved is 7.597 kA, and it is smaller than minimum current of 8.604 kA capable to cause an electrical flashover of the transmission line insulation. For middle phase conductor the lowest current at which a complete lightning shielding is achieved is 5.976 kA, that is much smaller than minimum current of 9.206 kA leading to an insulation flashover. The results show that the specified overhead power line is protected from dangerous lightning currents. However, computations show that downward lightning flashes having a smaller current magnitude are able to bypass the shield wire and hit the phase conductors. In this regard, due to unpredictable nature of lightning, to improve the lightning protection of power lines, other measures can be applied, including the use transmission line arresters mounted on or near towers at individual points of the power line. When thunderstorm activity increases due to global warming, strengthening of lightning protection measures is justified.

Keywords: *lightning, minimum shielding failure current, overhead ground wire, electro-geometric model.*

Introduction.

Lightning events occurs in all regions around the globe, including Antarctica and Arctic [1], but lightning strikes more frequently when air temperature (and humidity) is higher than when it is lower. Studies have been underway for a long time to determine how much more lightning should be expected as a result of global warming and an increase in global temperature [2, 3]. Modern lightning detection networks detect almost all lightning flashes over land and sea. In some regions, lightning activity increases, in others, on the contrary, it may decrease, but in general, the number of lightning flashes around the globe tends to increase. In perspective, the growth of lightning activity will lead to the need to strengthen the lightning protection of electric power facilities. Already, there are reports of lightning strikes at electrical facilities outside the typical season with the highest thunderstorm activity. Lightning is seasonal, for example, in Europe it most occurs the summer. However, there are recent shut-downs of 220 kV and 400 kV overhead transmission lines in Poland which occurred in January due to strike of winter lightning [4]. Previously, information about winter lightning concerned only several countries, for example, Japan [5, 6]. Above examples confirm that climate change could alter lightning patterns across the planet and show that lightning protection has to play an important role for providing the resilient and reliable electricity transmission by overhead power lines. Lightning can hit different elements of overhead power line structure. In case of a direct lightning strike to a phase conductor, overhead power line may be disconnected by automatic circuit breakers for a while, which will cause economic losses. Overhead power lines are usually protected against direct lightning strike by one or two overhead ground wires, fixed above phase conductors. If a direct lightning strike to phase conductor does occur, when it is said that lightning shielding failure took place. That means the occurrence of a lightning stroke capable to bypass the shield wire and terminate on the phase conductor. To estimate the possibility of lightning shielding failure, the electro-geometric model (or rolling sphere model) is widely used [7, 8]. One of a key principles of the electro-geometric model is that there is a mathematical relation between peak value of lightning current and a final striking distance of lightning flash (rolling sphere radius). This means that the interception effectiveness of the lightning protection system varies depending on the amplitude of the lightning current. Electro-geometric model allows one to evaluate how effectively specific overhead power lines are protected from direct lightning strikes.

Purpose of work:

The aim of the research is to study how lightning current magnitude affect the effectiveness of overhead power line protection against direct lightning strokes.

Research material.

It is believed that negative cloud-to-ground lightning flashes account for about 90% or more of global downward lightning flashes [9]. Therefore, in most cases, calculations are carried out only for the negative lightning currents. According to [7], the cumulative probability of first return stroke current I_f in negative lightning flash to exceed the given value I is approximated by the expression:

$$P\left(I_f > I\right) = \frac{1}{1 + \left(\dfrac{I}{31}\right)^{2.6}} \quad (1)$$

The median value of first return stroke current in (1) is 31 kA. Expression (1) is applied for negative lightning with first return stroke current magnitude varying from 2 kA and 200 kA [7]. This approximate cumulative distribution of lightning peak currents is shown in Fig. 1.

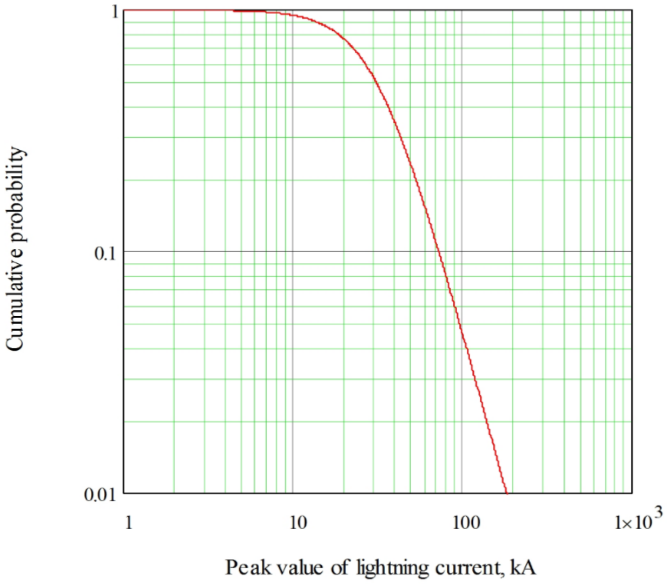

Figure 1 – Cumulative probability distribution of return stroke current magnitude in negative lightning flashes shown on a logarithmic scale

According to expression (1), the cumulative probability that the magnitude of the lightning current during a lightning stroke will exceed 2 kA is 99.92%, the cumulative probability of a stroke current exceeding 200 kA is 0.78%.

Impulse flashover of insulation poses a great danger for overhead power lines. Impulse flashover of the suspension insulator strings occurs due to severe overvoltage that caused by lightning strikes to overhead ground wires, phase conductors or a lightning strike at the top of the electricity pylon. The probability of an impulse flashover of electrical insulation increases significantly when lightning strikes directly to the phase conductor of an overhead power transmission line. Even at relatively low lightning currents, this can lead to occurrence of a voltage that exceeds the impulse withstand voltage of the insulation.

The shield wire (overhead ground wire) reduces the number of power lines outages, but it does not provide full protection against direct lightning strike to a phase conductor. In this paper a conventional 220 kV transmission line tower [10] with a height of 37.115 m is considered. A graphical explanation of the shielding failure mechanism according to conventional electro-geometric model [13] is shown in Fig. 2.

Among three lightning leaders approaching to the overhead power line in Fig. 2, the overhead ground wire will only intercept the downward leader #1. According to electro-geometric model any downward lightning leader reaching the arc *AB* can make its final jump only to the overhead ground wire. Any lightning leader reaching the straight line *CD* can make its final jump only to the earth. Lightning flash #3 is depicted for such cases. Eventually, lightning flash #2 indicates a case where the lightning protection can fail and the shield wire does not intercept the approaching leader. Any downward lightning leader reaching the arc *BC* will result in direct strike to an upper phase conductor. The horizontal distance, D_c, is called exposure width and it denotes the area unprotected by overhead ground wire. It depends on design and dimensions of overhead power line tower, as well as, lightning current magnitude.

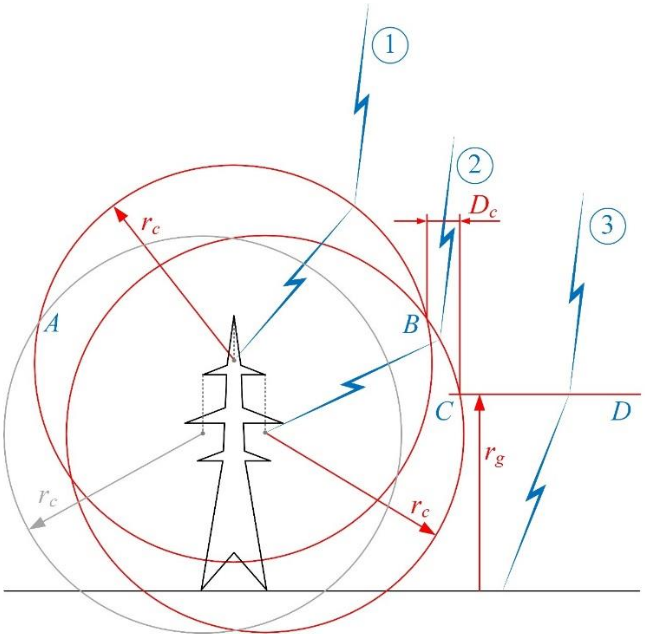

Figure 2 – Incomplete shielding provided by overhead ground wire.

The striking distance of the lightning flash depends on lightning current magnitude:

$$r_c = 10 \cdot I^{0.65}, \tag{4}$$

where: r_c is the striking distance to phase conductors, m; I is the expected lightning current magnitude, kA. In simplified electro-geometric model the striking distances to the shield wire, to the phase conductor and to the earth can be assumed equal.

Obviously, that for power engineers it is preferable to achieve complete shielding (refer to Fig. 3), when possibility of direct lightning strike to any phases is eliminated. However, it is achievable only starting from some lightning current magnitude.

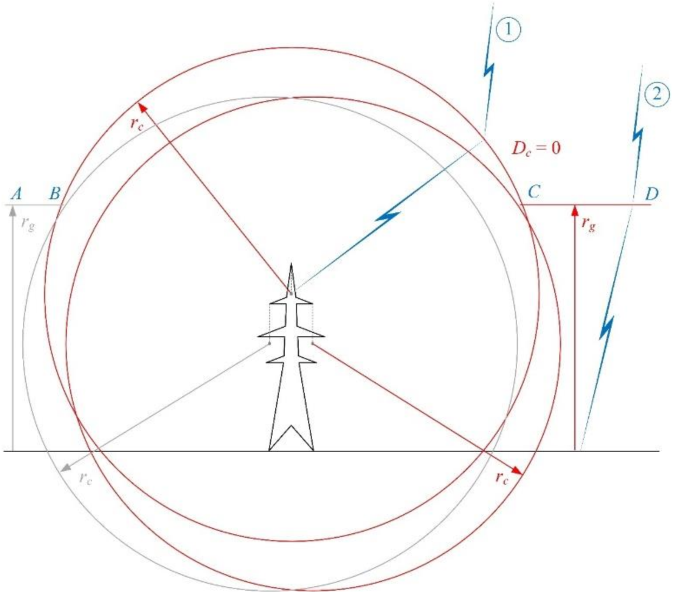

Figure 3 – Complete shielding provided by overhead ground wire.

According to electro-geometric model, in Fig. 3 all downward leaders reaching the arc *BC* can make their final strike only to the overhead ground wire (alike lightning flash #1). Outside this arc, the rest of lightning leaders after reaching straight line *CD* or *AB* would strike the earth (alike lightning flash #2).

As mentioned above, some lightning shielding failures may lead to a back flashover, when a voltage difference between phase conductor and tower exceeds an impulse withstand voltage of the insulation.

Assuming, that the length of insulation string is 2.879 m [10], the critical flashover voltage (kV) of given insulator string can be roughly estimated as [7]:

$$U_c = \left(400 + \frac{710}{t^{0.75}}\right)\cdot l_s = \left(400 + \frac{710}{6^{0.75}}\right)\cdot 2.879 = 1684.80\ \text{kV}, \qquad (5)$$

For the direct stroke to the phase conductor, the critical flashover voltage of insulation in (5) is calculated at $t = 6$ μs according to [7, 11].

Knowing the height of insulation string attachment point (29.170 m), the length of insulation string (2.879 m) and conductor midspan clearance to ground (19.200 m), one can calculate the mean height of the upper phase conductor:

$$y_{cm} = y_{ct} - \frac{2}{3}\cdot(y_{ct} - y_{cs}) = (29.170 - 2.879) - \frac{2}{3}\cdot(29.170 - 2.879 - 19.200) = 21.564\ \text{m}. \qquad (6)$$

In (6): y_{cm} is the mean height of the phase conductor, m; y_{ct} is the height of the phase conductor at power line tower, m; y_{cs} is the conductor clearance to ground in the middle of the span, m.

The corona discharge forms on the surface of the phase conductor when downward lightning leader reaching it. Because the presence of corona may help to limit overvoltage, it must be considered. The radius of corona sheath around the phase conductor can be determined from the following equation [7, 11]:

$$R_c \cdot \ln\left(\frac{2\cdot y_{cm}}{R_c}\right) = \frac{U_c}{E_0}, \qquad (7)$$

where: R_c is the radius of corona sheath, m; y_{cm} is defined by (6); U_c is defined by (5); $E_0 = 1500$ kV/m is the critical gradient for the phase conductor. Substituting these vales into (7), one can obtain the equation for the given tower:

$$R_c \cdot \ln\left(\frac{43.128}{R_c}\right) = 1.123. \qquad (8)$$

A plot of corona envelope radius as a function of critical flashover voltage and critical corona gradient relation for specific mean height of the phase conductor (21.564 m) is shown in Fig. 4.

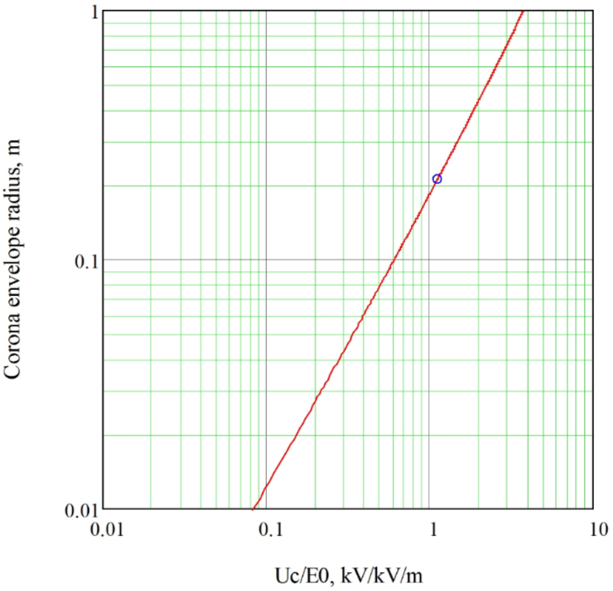

Figure 4 – Calculated corona sheath radius as a function of conductor voltage, corona extinction gradient and conductor height.

The solution of equation (8) is $R_c = 0.211$ m (denoted in Fig. 4 as a blue circle).

Knowing the conductor radius (1.4355 cm according to [10]), one can calculate a self-surge impedance of a phase conductor under presence of corona [11]: Knowing the conductor radius (R = 1.4355 cm according to [10]), one can calculate a self-surge impedance of a phase conductor under presence of heavy corona [11]:

$$Z_s = 60\cdot\sqrt{\ln\left(\frac{2\cdot y_{cm}}{R}\right)\cdot\ln\left(\frac{2\cdot y_{cm}}{R_c}\right)} = 60\cdot\sqrt{\ln\left(\frac{2\cdot 21.564}{0.014355}\right)\cdot\ln\left(\frac{2\cdot 21.564}{0.2110}\right)} = 391.622\ \Omega. \qquad (9)$$

The magnitude of minimum shielding failure current required for flashover occurrence would be

$$I_c = \frac{2 \cdot U_c}{Z_s} = \frac{2 \cdot 1684.80}{391.622} = 8.604\,\text{kA}. \tag{10}$$

For comparison, in [12] for 275 kV overhead transmission line with 3.3 m long insulation string using similar calculation procedure [7] the obtained magnitude of minimum shielding failure current is equal to close value about 8 kA.

Knowing the position of shield wire in the midspan (horizontal coordinate assumed zero, vertical coordinate assumed 31.208 m) and the upper phase conductor (horizontal coordinate assumed 4.20 m, vertical coordinate assumed 19.20 m) allows determining the unprotected width D_c values for various lightning current magnitudes. According to [11], the unprotected area, where downward lightning leader can strike the phase conductor (refer to Fig. 2) is calculated through the steps: (4), (11)-(14):

$$\alpha_1 = \arcsin\left(\frac{r_g - y_c}{r_c}\right). \tag{11}$$

$$\alpha_2 = \arctan\left(\frac{x_c - x_{gw}}{y_{gw} - y_c}\right). \tag{12}$$

$$\alpha_3 = \arccos\left(\frac{\sqrt{(x_c - x_{gw})^2 + (y_{gw} - y_c)^2}}{2 \cdot r_c}\right). \tag{13}$$

$$D_c = r_c \cdot (\cos(\alpha_1) + \sin(\alpha_2 - \alpha_3)), \tag{14}$$

where: r_c is the striking distance to phase conductors (4); r_g is the striking distance to ground surface (4); x_c and y_c are the coordinates of a phase conductor; x_{gw} and y_{gw} are the coordinates of the shield wire. All striking distances are considered equal, that is used in simplified electro-geometric model. Below is the example of calculations for downward lightning with peak current value of 3 kA.

$$r_c = r_g = 10 \cdot I^{0.65} = 10 \cdot 3^{0.65} = 20.423\,\text{m}.\ \ \alpha_1 = \arcsin\left(\frac{r_g - y_c}{r_c}\right) = \arcsin\left(\frac{20.423 - 19.20}{20.423}\right) = 0.059\ \text{rad}.$$

$$\alpha_2 = \arctan\left(\frac{x_c - x_{gw}}{y_{gw} - y_c}\right) = \arctan\left(\frac{4.2 - 0}{31.208 - 19.2}\right) = 0.336\,\text{rad}.$$

$$\alpha_3 = \arccos\left(\frac{\sqrt{(x_c - x_{gw})^2 + (y_{gw} - y_c)^2}}{2 \cdot r_c}\right) = \arccos\left(\frac{\sqrt{(4.2 - 0)^2 + (31.208 - 19.2)^2}}{2 \cdot 20.423}\right) = 1.254\,\text{rad}.$$

$$D_c = r_c \cdot (\cos(\alpha_1) + \sin(\alpha_2 - \alpha_3)) = 20.423 \cdot [\cos(0.059) + \sin(0.336 - 1.254)] = 4.167\,\text{m}.$$

All the results of calculations are shown in Table I. Calculations performed starting from 3 kA lightning current magnitude corresponding to the minimum value for first lightning protection level (LPL I) [13].

Table I. Examining the upper phase shielding provided by overhead ground wire

Lightning current magnitude *I*	Probability of exceeding lightning current magnitude *P*(*I*) according to (1)	Striking distance of lightning flash *S* according to (4)	Exposure width D_C, unprotected by shield wire according to (11)-(14)	Effectiveness of shielding
3.0 kA	99.77%	20.423 m	4.167 m	Incomplete shielding
4.0 kA	99.52%	24.623 m	3.665 m	Incomplete shielding
5.0 kA	99.14%	28.466 m	2.825 m	Incomplete shielding
6.0 kA	98.62%	32.048 m	1.811 m	Incomplete shielding
7.0 kA	97.95%	35.425 m	0.696 m	Incomplete shielding
7.597 kA	97.48%	37.361 m	0 m	Complete shielding achieved
8.604 kA (minimum shielding failure current)	96.55%	40.509 m	0 m	Complete shielding

The minimum value of lightning current resulting in complete shielding is 7.597 kA, and it is smaller than value of minimum current capable to cause flashover of the transmission line insulation (8.604 kA).

Knowing the position of the middle phase conductor (horizontal coordinate assumed 6.50 m, vertical coordinate assumed 12.63 m) allows repeating above procedure (5)-(14) for examining the lightning shielding efficiency. The final results are given in Table II.

Table II. Examining the middle phase shielding provided by overhead ground wire

Lightning current magnitude *I*	Probability of exceeding lightning current magnitude *P*(*I*) according to (1)	Striking distance of lightning flash *S* according to (4)	Exposure width D_C, unprotected by shield wire according to (11)-(14)	Effectiveness of shielding
3.0 kA	99.77%	20.423 m	5.236 m	Incomplete shielding
4.0 kA	99.52%	24.623 m	3.450 m	Incomplete shielding
5.0 kA	99.14%	28.466 m	1.692 m	Incomplete shielding
5.976 kA	98.63%	31.964 m	0 m	Complete shielding achieved
9.206 kA (minimum shielding failure current)	95.92%	42.330 m	0 m	Complete shielding

For this conductor, the minimum value of lightning current when complete shielding is achieved is 5.976 kA, that is much smaller the value of minimum shielding failure current that would cause an electrical flashover (9.206 kA).

Conclusions. In this work the efficiency of lightning shielding provided by single overhead ground wire was examined. According to the electro-geometric model, each phase conductor of a power transmission line has an area where the overhead ground wire does not provide full protection against a direct lightning strike. The width of this unprotected area depends on the design and dimensions of overhead power line tower, the expected magnitude of the lightning current and decreases with increasing magnitude of the discharge current. A double circuit self-supported 220 kV lattice power transmission line tower with a total height of 37.115 m was considered in the paper. The lightning protection of the line is provided with a single overhead ground wire. The upper and middle phase shielding provided by overhead ground wire was studied. The values of the minimum lightning current, capable of causing an insulation flashover in case of the lightning shielding failure were calculated. The minimum values of the lightning current at which complete shielding is achieved have also been determined. It was found that for upper phase conductor the minimum current at which a complete lightning shielding is achieved is 7.597 kA, and it is smaller than minimum current of 8.604 kA capable to cause an electrical flashover of the transmission line insulation. For middle phase conductor the lowest current at which a complete lightning shielding is achieved is 5.976 kA, that is much smaller than minimum current of 9.206 kA leading to an insulation flashover. The results show that the specified overhead power line is protected from dangerous lightning currents. However, calculations show that downward lightning flashes having a smaller current magnitude are able to bypass the shield wire and hit the phase conductors. Therefore, due to unpredictable nature of lightning, to improve the lightning protection of power lines, other measures can be applied, including the use transmission line arresters mounted on or near towers at individual points of the power line. In conditions of increased thunderstorm activity, strengthening of lightning protection measures is justified.

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ВПЛИВ АМПЛІТУДИ РОЗРЯДНОГО СТРУМУ НА ЕФЕКТИВНІСТЬ ЗАХИСТУ ПОВІТРЯНОЇ ЛІНІЇ ЕЛЕКТРОПЕРЕДАЧІ ВІД ПРЯМИХ УДАРІВ БЛИСКАВКИ

У даній статті досліджено ефективність захисту від блискавки, що забезпечується одним грозозахисним тросом, встановленим на вершині дволанцюгової ґратчастої опори лінії електропередачі класу 220 кВ загальною висотою 37,115 м. Згідно з електрогеометричною концепцією кожен фазний провідник лінії електропередачі має ділянку, де грозозахистний трос не забезпечує повного захисту від прямого удару блискавки. Ширина цієї незахищеної зони залежить від конструкції та розмірів опори повітряної лінії електропередачі, очікуваної величини струму блискавки та зменшується зі збільшенням амплітуди розрядного струму. Досліджено ефективність блискавкозахисту провідників верхньої та середньої фази. Розраховано значення мінімального струму блискавки, здатного спричинити перекриття ізоляції у разі відмови блискавкозахисту. Також визначено мінімальні значення струму блискавки, при яких досягається повний блискавкозахист. Було встановлено, що для провідника верхньої фази мінімальний струм, при якому досягається повний захист від блискавки, становить 7,597 кА, що менше, ніж мінімальний струм 8,604 кА, здатний спричинити електричне перекриття ізоляції лінії електропередачі. Для провідника середньої фази, найменший струм, при якому досягається повне захист від блискавки, становить 5,976 кА, що набагато менше, ніж мінімальний струм 9,206 кА, що призводить до перекриття ізоляції. Результати показують, що зазначена повітряна лінія електропередачі захищена від небезпечних струмів блискавки. Однак обчислення показують, що спрямовані донизу спалахи блискавки з меншою амплітудою струму здатні оминути грозозахисний трос і влучити у фазні провідники. У зв'язку з цим, через непередбачуваний характер блискавки, для покращення блискавкозахисту ліній електропередачі можуть бути застосовані інші заходи, у тому числі використання підвісних нелінійних обмежувачів перенапруги, встановлених на опорах або поблизу них в окремих точках лінії електропередачі. При збільшенні грозової активності внаслідок глобального потепління, посилення заходів блискавкозахисту є виправданим.

Ключові слова: *блискавка, мінімальний струм відмови блискавкозахисту, грозозахисний трос, електрогеометрична модель.*

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