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**STUDY OF ICE FORMATION PROCESSES ON OVERHEAD POWER LINES AND  
DEVELOPMENT OF SYSTEMS TO COMBAT THIS PHENOMENON**

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*Icing on the wires of overhead power lines is a big problem to maintain their integrity. The process of icing wires leads to a significant increase in their mass and, accordingly, to large overloads on the wire and electric supports. Exceeding the loads above the permissible ones can cause great damage to power lines. Wires, cables can break, fittings can be damaged and even lead to collapse of electrical poles. At the same time, damage is caused from the undersupply of electricity. This damage may exceed the damage from damage to the elements of power lines.*

*Ice on the wires usually appear in winter, especially when the warming is going to be replaced by a cold snap and the temperature fluctuates around zero. The problem can be exacerbated by strong wind loads. An increase in air humidity also accelerates the formation of an ice "coat" on wires and electrical poles. Under the most unfavorable conditions, the wall thickness of the "fur coat" of ice on the wire can reach more than 70 mm. Such an ice coat can lead to exceeding the maximum permissible loads and damage to the power line, as well as damage from a power outage.*

*The mechanism of ice formation on overhead power lines, as well as negative damage to power lines and high-voltage pylons under the action of ice load, has been studied. An analysis of the known methods of dealing with ice on power lines has been carried out. An innovative device for combating icing formations is proposed. The advantage of the proposed device is the ability to operate in two modes: vibrating and shock-shaking, which expands its functionality.*

*In preventive mode, the device operates continuously due to the interaction with alternating current flowing through the wires of power lines in the normal mode of their operation, without the need for shutdown for maintenance, which gives the electromechanical interactions of devices with the wire of the power line a vibrational character and ensures the continuity of the process of removing water drops from the wires at an early stage before ice formation.*

*Thus, in the preventive mode of operation of the power line, the causes of icing of the wires are eliminated, and not its consequences, which eliminates the need to shut down for maintenance, and reduces the required costs of resources and energy.*

**Key words:** power transmission, power support, overhead power lines, icing, ice removal.

**Fig. 11. Table. 1. Ref. 10**

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**1. Problem formulation**

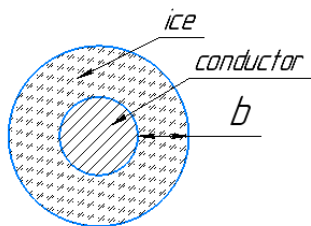
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The formation of ice formations on the wires of overhead power lines is a serious problem for power grid companies. Ice deposits can cause great damage to power lines and can lead to breakage of wires, cables, damage to fittings and even collapse of poles. In addition, there is damage from undersupply of electricity, which often exceeds the damage from damage to line elements.

Ice deposits appear directly in winter, more often when warming is replaced by cooling and the temperature passes through zero. The problem is exacerbated by strong wind loads and high humidity. Under such conditions, the wall thickness of ice on the wire can reach more than 70 mm, which can lead to damage to the line and damage from a power outage.

Sensors of the state of overhead power lines can greatly facilitate the process of their diagnosis, inspection and repair. This development can be applied in areas with adverse climatic conditions (large ice wall thickness).

The ice detection sensor, together with other electronic devices, can be part of smart grids and active-adaptive communication. Communication between the sensor and the control system can be organized using any of the known data transfer protocols.



**Fig. 1. Idealized representation of ice on wires.**

Icy frost deposits on the wires and cables of overhead power lines occur at an air temperature of about  $-5^{\circ}\text{C}$  and a wind speed of  $5 \dots 10 \text{ m/s}$ . The total mass of ice-frost deposits is reduced to the shape of a hollow ice cylinder with a wall thickness equal to  $b$  (Fig. 1).

The thickness of the ice wall with a repeatability of 1 time in 25 years can reach 25 mm.

## 2. Analysis of last researches and publications

There are several types of ice formations, namely:

1) Ice - growing precipitation in the form of a layer of dense ice formed as a result of desublimation of atmospheric vapor on surfaces cooled to a negative temperature.

2) Frost.

a) Granular hoarfrost - snow-like sediment in the form of loose, granular ice. The average density of such formations is  $0.1\text{-}0.4 \text{ g/cm}^3$ . It is formed as a result of freezing of droplets of supercooled fog on the object at a temperature of  $-4$  to  $-8^{\circ}\text{C}$ .

b) Crystalline hoarfrost - a white precipitate consisting of individual crystals with an average density of  $0.01\text{-}0.05 \text{ g/cm}^3$ . It is formed as a result of the process of sublimation of water vapor during haze or fog in the temperature range from  $-11$  to  $-25^{\circ}\text{C}$ . In Siberia, the formation of crystalline frost is also possible at temperatures below  $-25^{\circ}\text{C}$ , when the air is close to saturation.

3) Icy sleet - an ice mass that looks like very dense frost. It occurs as a result of rapid freezing of wet snow falling at temperatures from  $0$  to  $+2^{\circ}\text{C}$  and wind speeds of more than  $6 \text{ m/s}$ . The size of deposits can exceed ordinary ice, therefore it is a very dangerous weather phenomenon.

Wind plays an important role in the shape and structure of ice deposits. Under certain conditions, it can contribute to the association of small drops into large ones, and under other conditions, it can contribute to the crushing of large drops. The wind affects the intensity of ice formation on the wire due to the convection phenomenon.

Also, the intensity of the electric field of the wire has a significant effect on the process of icing. Studies have shown that under the influence of an electric field, the weight of ice on the wire increases [1]. This is explained by the fact that in an electric field, fog and water drops are polarized, creating a negative dipole charge when the wire is positively charged, which creates conditions for attracting the drop to the wire. Table 1 shows the classification of wire icing by groups.

**Table 1**

**Classification of wire icing by groups**

Group	Type of deposit	Icing conditions	Density sediments $\text{kg/m}^3$
I	Crystal frost, frost	Desublimation of water vapor	10 - 50
II	Granular hoarfrost, ice	Precipitation and freezing of supercooled water	100 - 900
III	Wet snow deposits	Wet snow precipitation and freezing	200 - 600
IV	Grainy frost on ice, alternating layers of ice and frost	Complex ice deposits	250 - 500

Figure 2 shows the actual formation of ice on the wire.



**Fig. 2. Ice on the wire**



**Fig. 3. Consequences of icing on a high-voltage overhead power line**



The above conditions lead to the formation of icy growths on the wires. The mass of ice deposits can reach large values. The wall thickness of dense ice on wires can reach 40-50 mm, and loose ice 90-100 mm. At the same time, calculations show that for a wire of the AS - 500 brand with an ice wall thickness of 50 mm and a wire length of 1 km, the mass of the wire increases from 1,85 tons to 12,5 tons, that is, 7 times, and with an ice thickness of 70 mm - 11 times. Such an increase in the mass of the wire leads to mechanical overloads, and, as a result, to the breakage of wires, lightning protection cables, damage to the reinforcement and even complete collapse of the supporting supports of the line, which is shown in Fig. 3.

Ice with wind is one of the main causes of accidents in high-voltage power lines. Over the past decades, these accidents have caused serious damage to power systems. According to Ukrenergo, ice with wind caused up to 37% of falls of reinforced concrete poles of voltage class 35-110 kV, and on lines of 330-750 kV, ice with wind caused up to 12% of the total number of wire breaks, up to 42% of lightning wire breaks and up to 8 % of damages and breaks of garlands of insulators. Despite a relatively small percentage of failures of overhead lines due to ice (from 2.9 to 8.1% according to Ukrenergo), these damages cause great damage to the national economy and are much more difficult to eliminate. So, if in case of failure for other reasons, the recovery time after damage does not exceed 1 day, then the restoration of the line after ice-wind accidents can take 7 days or more. Emergency undersupply of electricity due to such accidents is more than 50% of the total annual emergency undersupply.

Based on the foregoing, the urgency of the problem becomes obvious. Timely detection of ice on the wires of overhead lines and taking measures to eliminate it will help to avoid damage from damage to line elements and from interruption in the power supply to consumers.

The problem of ice on wires appeared simultaneously with the advent of the first high-voltage lines, but there are still no effective and economically sound methods to most effectively determine the presence of ice on wires and deal with this ice. When developing a device, researchers are faced with the task of creating a universal device that meets modern requirements, these are: reliability, durability, ease of execution, no need for maintenance, low cost. Over the past decades, patents have been divided into two groups:

- analysis of attenuation of high-frequency (HF) oscillations of probing pulses passed through the phase wires of overhead lines.
- analysis of the weight load of ice on the wires of overhead lines using strain gauge load sensors.

Consider the works based on the analysis of the weight load using load cells.

A known method of measuring ice and wind loads on overhead power lines [2].

According to this method, ice and wind loads are measured using a weight sensor that measures the forces arising under the action of ice and wind loads on the wires and power line supports (Fig. 5), while the support on which the wires are suspended is used as the elastic element of the weight sensor. overhead power line, while to determine the ice loads, the elastic deformation of the support along the vertical axis of symmetry of the support is measured, and to determine the wind loads, the elastic bending deformations of the support are measured, which occur when the vertical axis of symmetry of the support deviates from the vertical line.

A known method of detecting the appearance of ice on the wires of the power line [3].

The method includes the transmission of a high-frequency signal along the power line from the beginning of the line to the end of the line and the control of a parameter associated with a change in the conditions for the propagation of a high-frequency signal along the wire section when ice appears (Fig. 6). The difference between the method is that the wire section is limited by two PLC modems, the time of propagation of the high-frequency signal from the beginning of the limited section of the wire to its end is taken as a control parameter, the average temperature of this section of the wire is determined, and the appearance of ice is judged by the change in the propagation time of the high-frequency signal, caused by the appearance of ice, taking into account the effect on the controlled parameter of the temperature change in the length of the wire section.

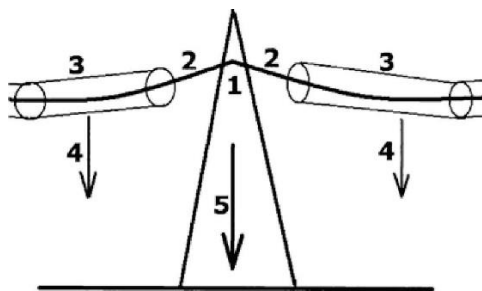


Fig. 5. Load diagram

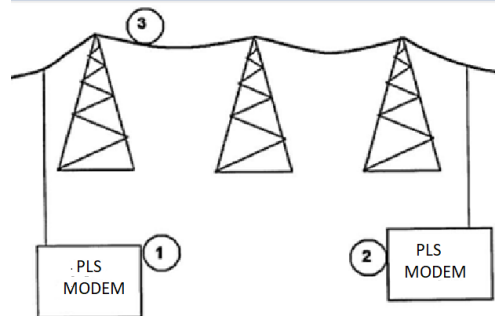
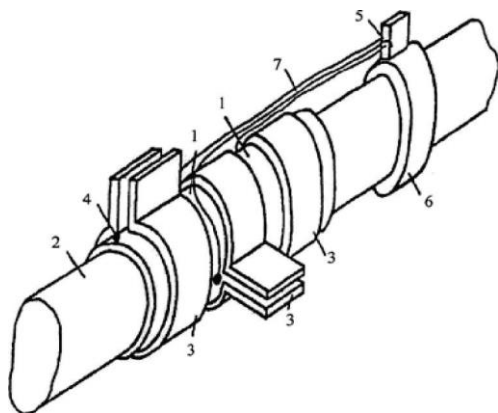


Fig. 6. High-frequency signal transmission scheme



Next, we consider technical solutions based on the idea of transmitting probing RF signals through the phase wires of the line and monitoring the parameters of this signal.

Consider an ice warning device on wires [5].



**Fig. 7. Ice warning device on wires**

The ice deposit detector (Fig. 7) contains a transmitting device, a housing in the form of a sleeve 1 made of a heat-conducting diamagnetic material, put on a linear wire 2, ferromagnetic clamp-like plates 3, rigidly fixed to the housing at a calculated distance from each other and rotated through an angle of  $360^\circ$ , microphones 4, power source, connecting wires 7, through which the microphones and the transmitter are connected to the power source, while the ferromagnetic clamp-like plates 3 are made with inserts of a soft magnetic material with a lower saturation induction. The second variant - the signaling device of ice deposits contains a transmitting device from ferromagnetic clamp-shaped plates, each of the plates additionally has a measuring winding.

The icing detector according to the first variant works as follows. In the absence of ice deposits, the alternating current in the linear wire 2 creates an alternating magnetic field of the same frequency in the ferromagnetic plates. The magnetic forces that arise in this case attract the elastic, parallel, ends of the plates 3 to each other with a doubled frequency. At an industrial frequency, for example 50 Hz, the movement of the ends of the plates 3 creates air vibrations in the sound range, perceived by human hearing. The sound signal, the strength of which is determined by the amplitude of the vibrations of the plates 3, is converted by microphones 4 into an electromagnetic signal. The signal is broadcast by the transmitter 5 and registered by the receiver. When ice is deposited on the surface of the sensor, the oscillation amplitude of the ends of the plates 3 decreases, the sound intensity and, accordingly, the power of the emitted signal for a given current load decrease, which makes it possible to determine the presence of deposits.

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### 3. Aim of the researches

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The purpose of this work is to study the processes of icing on overhead power lines and the development of systems to combat this phenomenon.

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### 4. Results of the researches

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Currently, all methods of dealing with ice buildup on wires of overhead lines are divided into 5 large groups:

- Passive
- Mechanical
- Electrothermal
- Physical and chemical
- Electromechanical

The category of passive methods includes the use of rings or spirals fixed on wires, the presence of which contributes to the discharge of wet snow when it slides along the outer contour of the wire, which, in combination with wire torsion limiters, reduces the size and mass of ice, and also leads to an accelerated discharge of deposits into form of wet snow, ice or hoarfrost.

Among the active methods of dealing with icing can be attributed dielectric coatings of current-carrying wires, which belong to the category of ferromagnetic and are subject to heating due to magnetization reversal losses in the coating material. The specified heating of the coating under certain meteorological conditions (low wind speed, relatively low intensity of the ice-bearing flow) can help prevent the deposition of ice by maintaining the temperature of the coating above the freezing point of drops that settle on the wires of moisture.

Most often, in the practice of combating ice formations, a mechanical method is used. Its essence lies in the use of special devices that ensure the knocking of ice from the wires [6].

The easiest way to mechanically remove ice from the wires is to knock them off the ground with long



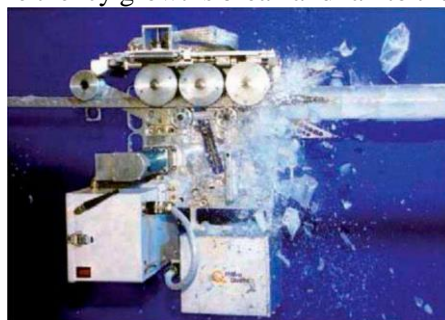


poles or with the help of an aerial platform basket (Fig. 8).

For upholstery, mainly wooden, fiberglass or bamboo poles are used. The pole for upholstery from the ground has a length of 5 to 9 meters, for upholstery from mechanisms - 1.5-2 m. The upholstery is done by side impacts, which cause a wave-like vibration of the wire, while the icy growths break and fall to the ground.



**Fig. 8. Mechanical removal of ice from the wires of overhead power lines.**



**Fig. 9. Mechanical removal of ice from the wires of overhead power lines**

The technology of mechanical removal methods is based on the use of one of two known alternative approaches.

The first involves the removal of ice by cutting it. A device of this type is shown in Fig. 9 and is a battery-powered carriage moving along the wire, equipped with high-strength cutting devices that break through the ice coat due to the pushing forces of the carriage, freeing the wire from the ice coat.

The second approach is based on the removal of deposits by excitation of shock waves of bending or twisting of the wire or cable, in order to destroy and throw off the ice coat in this way.

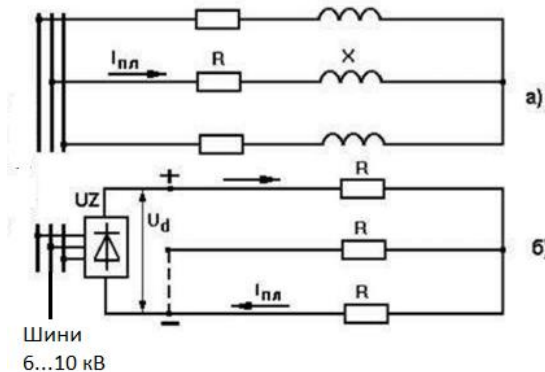
The advantages of mechanical methods lie in the relative simplicity of their implementation in comparison with ice melting methods.

Mechanical methods are also preferred in terms of speed of their implementation in cases where it is necessary to remove ice on relatively short sections of overhead power lines.

Electrothermal methods include heating the wires of the line with electric current to the required temperature, which prevents further formation of ice on the wire, or ensures the melting of ice [7].

During preventive heating, the wire is heated to a temperature above  $0^{\circ}\text{C}$ , at which ice is not deposited on the wire. In this case, disconnection of consumers on the line is not required. Melting of ice is carried out with an already formed crust of ice on the wire. The wire is heated to the design temperature, which ensures the elimination of ice with a given wall thickness under given ambient temperature conditions. Most often, the wire is heated to a temperature of  $100-130^{\circ}\text{C}$  with direct or alternating current with a frequency of 50 Hz using special short circuit mode circuits.

The industry produces unregulated and adjustable rectifiers for melting ice. Ice melting can be carried out both from a stationary ice melting system and from a mobile mobile one. Currently, current melting is the most common method of dealing with ice deposits on wires of high-voltage power lines. Fig. 10 shows the circuit diagrams for melting ice with alternating and rectified current.



**Fig. 10. Schematic diagrams of melting ice with alternating (a) and rectified (b) current**

Recently, physical and chemical methods have been actively used to combat icing. They consist in applying to the wire special substances that freeze at temperatures much lower than water.

The result is coatings with a low degree of adhesion to the aquatic environment, snow and ice.



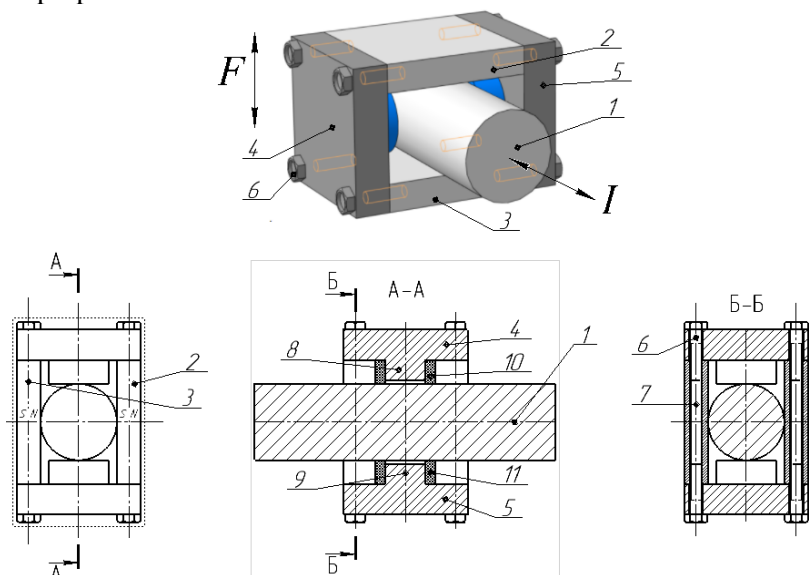
Active work is underway to create superhydrophobic coatings for wires [8]. These substances prevent the formation of ice deposits on the wires of the line and solve the problem of icing. The disadvantage of the method is the partial applicability and high cost of the substance. In addition, the effect of these substances is short-lived and must be reapplied.

One of the developed technologies, CVD plasma spraying (Plasma Chemical Vapor Deposition Technology), provides the possibility of creating a diamond-like coating that is dense, hard, durable and has a high level of adhesion to the coated object. The conducted studies have shown that the developed superhydrophobic nanotextured coating based on aluminum oxide nanofibers withstands up to 100 freeze/thaw cycles without significant texture degradation and superhydrophobic state. Tests of superhydrophobic coatings in a water aerosol flow were carried out at a temperature of  $-5^{\circ}\text{C}$  and a wind speed of 10 m/s.

After a minute, a layer of ice already appears on the uncoated aluminum sample, but not on the superhydrophobic coated aluminum sample.

The electromechanical method of removing ice from wires, along with physical and chemical methods, is the most exotic. According to this method, the removal of ice should be carried out not by thermal heating of the wire with electric current, but by means of electromagnetic action on the ice. The principle of operation is as follows: an electric current of a certain frequency and shape is passed through the wires of the line. When current flows, the Ampere force acts on the wires, as a result of which mechanical vibrations of the wires occur, which prevent the formation of ice and ensure the elimination of the ice crust on the wire.

As a result, since a mechanical rather than thermal effect is applied to the wire, a significant reduction in the time and energy spent on cleaning is predicted [9, 10]. A new design of a mechanical shock vibrating device shown in Fig. 11 is proposed.



**Fig. 11. Electromechanical impact element.**

The device contains a shock element elastically connected to the wire, which is a rectangular frame put on the wire 1, two opposite sides 2, 3 of which are made in the form of plate magnets, magnetized axially and opposite poles facing each other and freely enclosing the wire with the possibility of relative displacements.

The other two sides of the rectangular frame are made in the form of plates 2 and 3 connecting the magnets made of non-ferromagnetic material, in particular, duralumin, and attached to the magnets with screws 6 screwed into threaded bushings 7 reinforced with magnets. In this case, each of the plates 2 and 3 with the side facing the magnets in its central part is equipped with a protruding cylindrical striker 8 and 9 and a bushing 10 and 11 freely put on it from an elastic elastic material, brought into contact with its outer end with the surface of the wire 1.

The operation of this device is as follows. Permanent magnets 4 and 5 are pressed close to wire 1, and a constant magnetic field is created in the working gap between the poles, equal to the diameter of the wire. When an alternating current flows through the wire, an alternating electromagnetic force of interaction of the wire 1 and the magnetic field of the permanent magnets 4 and 5 arises, causing the cylindrical strikers 8 and 9 to shift relative to the wire, that is, the strikers oscillate relative to the wire.



The strikers automatically and continuously work in a vibration mode, which gives the electromechanical effects on the wire a vibrational character and ensures the continuity of the process of removing water drops from the wires at an early stage before ice formation.

The proposed device can operate in two modes: vibrating and shock-shaking, which expands its scope and functionality.

For the purpose of prevention, the device can operate continuously during periods of possible icing due to interaction with alternating current, without the need to turn it off for maintenance, which ensures the vibrational nature of the device's impact on the wire and leads to the continuity of the process of removing water drops from the wires at an early stage before ice formation.

## 5. Conclusions

The mechanism of ice formation on overhead power lines, as well as negative damage to power lines and high-voltage pylons under the action of ice load, has been studied. An analysis of the known methods of dealing with ice on power lines has been carried out. An innovative device for combating icing formations is proposed. The advantage of the proposed device is the ability to operate in two modes: vibrating and shock-shaking, which expands its functionality.

In preventive mode, the device operates continuously due to the interaction with alternating current flowing through the wires of power lines in the normal mode of their operation, without the need for shutdown for maintenance, which gives the electromechanical interactions of devices with the wire of the power line a vibrational character and ensures the continuity of the process of removing water drops from the wires at an early stage before ice formation.

Thus, in the preventive mode of operation of the power line, the causes of icing of the wires are eliminated, and not its consequences, which eliminates the need to shut down for maintenance, and reduces the required costs of resources and energy.

In the preventive mode, the device allows you to prevent the appearance of ice on the wires, and not start fighting it after the ice "coat" envelops them.

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## ДОСЛІДЖЕННЯ ПРОЦЕСІВ ЗЛЕДЕНІННЯ НА ПОВІТРЯНИХ ЛІНІЯХ ЕЛЕКТРОПЕРЕДАЧ І РОЗРОБКА СИСТЕМ БОРОТЬБИ З ЦИМ ЯВИЩЕМ

Зледеніння на проводах повітряних ліній електропередач є великою проблемою підтримки їхньої цілісності. Процес зледеніння проводів призводить до значного збільшення їх маси і відповідно до великих перевантажень на проводі та електроопорах. Перевищення навантажень вище допустимих може завдати великої шкоди лініям електропередач. Можуть обриватися дроти, троси, пошкоджуватися арматура і навіть призводити до обвалення електроопор. Одночасно з цим завдається шкода від недовідпуску електроенергії. Ця шкода може перевищувати шкоду від пошкодження елементів ліній електропередач.

Ожеледиця на проводах з'являється як правило в зимовий час, особливо тоді, коли потепління йде на зміну похолодання і температура коливається біля нульової позначки. Проблема може посилюватись сильними вітровими навантаженнями. Підвищення вологості повітря також прискорює процес утворення крижаної «шуби» на проводах та електроопорах. За найнесприятливіших умов, товщина стінки «шуби» ожеледиці на дроті може досягати більше 70 мм. Така крижана «шуба» може призвести до перевищення гранично допустимих навантажень та пошкодження лінії електропередач, а також збитків від перерви в електропостачанні.

Досліджено механізм виникнення ожеледиці на повітряних лініях електропередач, а також негативних руйнувань ліній електропередач та високовольтних опор під дією льодового навантаження. Проведено аналіз відомих методів боротьби з ожеледицею на лініях електропередач. Запропоновано інноваційний пристрій боротьби з зледенінням. Перевагою нового пристрою є можливість працювати у двох режимах: в ударно-струсувальному та вібраційному, що суттєво розширює його експлуатаційні можливості.

Як профілактика пристрій працює постійно за рахунок взаємодії зі змінним струмом, який протікає по проводах ліній електропередач у нормальному режимі їх роботи і не вимагає відключення на обслуговування, що надає електромеханічну взаємодію, запропонованого пристрою, з проводом лінії електропередач і викликає вібраційний характер взаємодії, що забезпечує безперервність процесу видалення з дротів крапель води до льодоутворення.

Таким чином, у профілактичному режимі роботи лінії електропередач ліквідуються причини зледеніння проводів, а не його наслідки, що позбавляє необхідності відключення на обслуговування, знижує необхідні витрати ресурсів та енергії.

**Ключові слова:** електропередача, електроопора, повітряні лінії електропередач, зледеніння, видалення голольоду.

**Рис. 11. Табл. 1. Літ. 10.**

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