Methods for dealing with icing of power line wires

V G Kul'kov¹, V N Kuryanov and R A Fokin

Department of Fundamental Disciplines, Volzhsky branch of National Research University «Moscow Power Engineering Institute», 69 Lenina Avenue, Volzhsky 404110, Russia

¹Corresponding author: vikulkov@yandex.ru

Abstract. This article describes the types of ice and snow deposits on metal wires of overhead power lines. It has a harmful effect on the functional state of power lines. Under the influence of the force of resistance to air flows in the wind and the gravity of the wires with an increased mass, accidents are possible. These include breaks, wire interconnections, and short circuits in the line. Here we give a brief overview of existing methods for preventing the formation of ice on the line wires and fighting icing by removing the ice shell. This article describes a combined method for breaking the ice coating on the wires. For this purpose, we propose a combination of two methods. One of them is to load the wires with high-frequency current. Due to the skin effect, the inner surface of the ice heats up, and a thin layer melts. This significantly reduces the adhesion of the ice to the metal. Simultaneously, low-frequency current of the order of one Hertz flows through the wires. This current causes the wire to resonance oscillations, which destroy the ice covering. The article provides an estimate of the duration of the high-frequency current exposure time, its value, and the frequency of the second current.

1. Introduction

The icing of power line wires is a very harmful phenomenon [1]. The presence of an ice shell on a metal wire leads to an increase in mass, a decrease in its strength and service life. It also changes the drag of the wind. All these can lead to broken wires and damaged supports. Effective control of wire icing is a relevant task.

The process of the appearance of the ice shell is associated with such atmospheric influences as sleet, frost, ice, and their combination [2]. Wet snow has a high degree of adhesion to metal, has a mass density of 0.12–0.3 g/cm³. Frost is a white, crystalline, opaque precipitate, with a density of 0.02-0.3 g/cm³. It is formed at a temperature of -10 – -40 °C. Ice is a solid, continuous translucent sediment with a density of 0.6-0.9 g/cm³, often formed during rains and fogs. The thickness of ice on the wires and lightning protection cables can reach 60 – 70 mm, significantly weighing them down. The essence of the phenomenon of icing is the deposition and subsequent freezing of water droplets on the surface of the wires or the sticking of wet snow at a wind speed not exceeding 10 – 20 m/s. Icing occurs on the windward side of the wires if the wind is perpendicular to the transmission line, and evenly along the entire length if the wind is directed parallel to the wire. In the latter case, the ice is less dangerous for the line, since it has a more porous structure and lower density. Usually, the ice layer is not uniform in thickness. The SAG of icy wires can increase by several meters.

In the process of mathematical modeling of ice formation, it is represented as a hollow cylinder with the same wall thickness on all sides. AC-185/43 wire with a diameter of 19.6 mm and a kilometer length has a mass of 846 kg. The weight of a wire with a thickness of ice deposits of 20 mm increases
by 3.7 times, with a thickness of 40 mm – by 9 times, with a thickness of 60 mm – by 17 times. The total weight of the transmission line of eight-kilometer-long wires increases to 25, 60 and 115 tons, respectively, which leads to the breakage of the wires and metal supports.

The icing of wires causes chaotic vibrations with two degrees of freedom under the influence of air flows. This leads to a violation of the adjustment of wires and cables, their breakage, and the overlap of the linear insulation of the high-voltage line. These effects also cause the pillars to collapse. Such accidents lead to significant economic damage. Repairs to the line involve disconnecting it for a period of several hours to several days.

2. Methods for removing ice from wires

The fight against icing of wires is a complex problem and includes a complex of technical means [3]. These include mechanical, electrothermal, physical and chemical, thermodynamic, and electromechanical methods.

The simplest mechanical method is the destruction of ice deposits using long poles from the car or from the ground surface. It is used on fairly short sections of power lines. This method can be used without disconnecting the line using electrical insulation tools. The disadvantages of the method are related to its long duration, the need to be present in difficult-to-reach locations of the line, and the possibility to damage it. It is assumed to use manual physical labor and attract a large number of people, which is not effective. This method is used on short-distance lines.

The mechanical method can be attributed to the effect on the deposits of ice moving along the wires of cutting devices that use the energy of permanent magnets, wind or electromagnetic field of the electric current of the line. There is a variation of the method in which rollers move along the wires, lifting and bending the wires. In these places, the ice is breaking down. Usually, the rollers are mounted on rods attached to special machines moving along the line. In this case, there is always some probability of damage to the line elements. The cutting tool has a limited service life. There are inconveniences of its placement on the wires. This method also includes the use of various pneumatic devices and robotic systems. Their work is based on the impact on the ice cover. Robots are used that are installed on a wire. They are controlled remotely from the ground. Their application was quite effective. They allow one to carry out some repairs. The disadvantages of such devices include the need to control the operator, as well as the high cost of the robot itself.

In the electromechanical method, the ice removal occurs by passing periodic current pulses through the wires. The ampere force acts between the wires. In this case, the impact occurs. There are fluctuations and further destruction of the icing when mechanical resonance appears. Various forms of current pulses and duty cycle are used. The main advantage of the method is its ability to work in a preventive mode. In this case, you do not need to destroy the formed ice. It will not appear on the wires.

The electrothermal method consists in heating the wires and melting the ice on them [4]. Various types of current are used to achieve this goal. It can be alternating or direct current. The frequency of the alternating current can be different: infra-low, industrial, or high. It can be tens or hundreds of megahertz. The current value usually exceeds the nominal value by 1.5-2 times. The duration of exposure varies. The disadvantages of this method include the need to disable the line. The operating mode of the line is close to a short circuit. This may not reflect well on the technical condition of the line. In addition, you must use separate generators, rectifiers, and electronic devices.

The physical and chemical method consists in applying special solutions to the wires that prevent water crystallization on the wires [5]. The method is based on the use of coatings with low adhesion to snow, ice, and water. Such coatings are called hydrophobic. The peculiarity of the method is not the destruction of the ice shell but the prevention of its formation [6]. The general property of such coatings is that the more effective it is, the shorter its service life. Fluoropolymer coatings have good prospects.

The intensity of icing depends on both the height of the overhead line wires and the diameter of the power line wire. As the height of the wire increases, so does the thickness of the resulting ice. When
increasing the overall thickness of the wire, it twists less. Each of these methods has its advantages and disadvantages. Combined methods are more effective for dealing with wire icing. They combine the simultaneous impact of different processes on the ice shell, which increases the probability of its destruction. Some physical aspects of one of these methods are discussed below. It consists of simultaneous action of high-frequency current and low-frequency alternating or pulsed current on the ice cover. The first factor melts the ice layer. The second method of shock loading [7] destroys the ice shell.

3. Mathematical model of the current effect on the ice shell
In the case of mechanical failure, one of these methods must be used to separate the ice layer from the metal wire. To increase the efficiency of this process, it is enough to create a liquid layer at the interface between them. This can be done by melting the layer of ice directly adjacent to the bound.

The actual situation must take into account many factors, such as the heterogeneity of ice thickness along and across the wire, its loose structure, heat exchange conditions on the inner and outer surfaces of the ice shell, the movement of the ice-water interface during the phase transition, the state of the environment, etc. Here is an estimated calculation of the melting time by passing high-frequency current till the appearance of a water layer.

It is known that at high frequencies, there is a surface effect (skin effect). It consists in the fact that high-frequency current is displaced to the surface of the wire. In fact, it flows in a certain surface layer with an effective thickness that depends on the frequency. The effective cross-section of the conductor decreases, and its resistance increases. As a result, it can be many times higher than the value determined for direct current. The ratio of resistances, in this case, is equal to

\[
\frac{R}{R_0} = \frac{r_0 \sqrt{\omega \mu \gamma}}{2 \sqrt{2}},
\]

where \(R\) and \(R_0\) are the AC and DC resistances, \(r_0\) is the wire radius, \(\omega\) is the frequency, \(\mu\) is the magnetic permeability of the wire material, and \(\gamma\) is its specific conductivity.

First, let us estimate the required amount of current in the wire. The heat output in the wire is used to heat the wire and inhomogeneous heating of the ice shell. Some of this power is lost by heat exchange with the environment. The wire temperature in steady mode must be higher than the melting point of ice \(T_0\). Otherwise, the ice layer will not melt. Consider the limit stationary mode when the wire temperature is equal to \(T_0\). In this case, all the allocated power is equal to the loss of power. The value of this current is called critical. For a unit of wire length, the heat balance equation looks like

\[
q = \Delta T \left( \frac{1}{2 \pi k} \ln \frac{r_1}{r_0} + \frac{1}{2 \pi \alpha} \right) = \frac{I_c^2 R}{l}.
\]

Here \(q\) is the linear density of heat flow through the ice wall, \(\Delta T\) is the difference in melting temperatures of ice and ambient air, \(k\) is the coefficient of thermal conductivity of ice, \(\alpha\) is the coefficient of heat exchange between the outer surface of the ice shell and the surrounding air, \(r_0\) and \(r_1\) are the radii of the wire and the shell, \(I_c\) is the effective value of the critical current, \(l\) is the length of the wire. Note that

\[
R_0/l = \left( \pi r_0^2 \gamma \right)^{-1}
\]

and express from (2) the critical current strength.

\[
I_c = \left( \frac{32 \gamma}{\omega \mu} \right) \frac{r_0 r_1 \alpha}{r_1 r_0 / r_0 + k} \Delta T \right)^{1/2}
\]
In order to get a layer of water, it is necessary to pass a current greater than the critical value of \( I = nI_{I} \), \( n > 1 \) through the wire. The greater the multiplier \( n \), the faster the layer will appear.

Now let us estimate \( \tau \) – the required time of current passage. The amount of heat released in the wire goes to the following processes. 1 - inhomogeneous heating of the ice shell. 2 - melting of the cylindrical layer of thickness \( b \). 3 - heating of the formed water layer. The specific heat capacities of ice and water are \( 2.1 \cdot 10^3 \) and \( 4.2 \cdot 10^3 \) J/kg·K, respectively. The specific heat of melting ice is \( 3.35 \cdot 10^5 \) J/kg.

Non-uniform heating of ice requires an amount of heat

\[
Q_1 = Km_1c_1\Delta T.
\]  

(5)

Here \( m_1 \) is the initial mass of the ice shell, \( c_1 \) is the specific heat capacity of the ice, and \( K << 1 \) is the coefficient that takes into account the uneven radial heating. The internal temperature of the shell reaches a value of \( T_0 \), and the external temperature reaches a value close to the ambient temperature. Heating the resulting amount of water requires energy, which is calculated using a similar (5) formula with \( K = 1 \). The amount of heat required to melt the ice layer is equal to

\[
Q_2 = \lambda m_2,
\]  

(6)

where \( \lambda \) is the specific heat of melting ice, \( m_2 \) is the mass of the molten ice layer.

Based on the given ratio of energy values, for a rough estimate, we can neglect the values (5) for the water layer and the ice shell in comparison with (6). Then the energy consumption for obtaining the water layer and heating the wire to the melting point of ice is

\[
Q = \rho_1l\left((r_0 + b)^2 - r_0^2\right) + \pi r_0^2l\rho_1c_1\Delta T,
\]  

(7)

where \( \rho_1 \) is the mass density of ice and \( b \) is the thickness of the water layer. The second term refers to the metal of the wires. It has high thermal conductivity. Therefore, we can assume that its heating also occurs uniformly from the ambient air temperature to a temperature slightly higher than \( T_0 \). The amount of heat released by the current \( I \) in the wire during the time \( \tau \) is

\[
Q = I^2R\tau.
\]  

Equating it to (6) and counting \( b << r_0 \), we get the required warm-up time

\[
\tau = \sqrt{\frac{8\lambda}{\rho_1}} \frac{\pi^2r_0^2(2\lambda\rho_1b + r_0\rho_1c_1\Delta T)}{I^2}.
\]  

(8)

Further destruction of the ice shell can be carried out by passing a low-frequency sinusoidal or pulsed current along the wires. A wire with an ice shell, located between two adjacent poles of a power line, is like a stretched string with fixed ends. The lowest natural frequency of string vibrations is defined by the expression

\[
\omega_0 = 2\pi\sqrt{\frac{F}{l^2\rho_1}},
\]  

(9)

where \( F \) is the tension force of the wire, and \( \rho_1' \) is the effective linear mass density of the iced wire, taking into account the water layer. After simple transformations taking into account the ratio \( b << r_0 \), we find the frequency of the supplied current for dropping the ice shell

\[
f = \frac{\omega_0}{2\pi} = \left(\frac{F}{\pi l^2\left(r_1^2\rho_1 + 2r_0b(\rho_2 - \rho_1) + r_0^2\rho_1\right)}\right)^{1/2}.
\]  

(10)

Theoretical estimates of the natural frequency of vibrations of the wire can not be made with an acceptable degree of accuracy. The fact is that the thickness of the ice layer and its density are not the same along the wire. In addition, the shape of the shell is not cylindrical. The vibrations of the wire
have components in two planes. The process is significantly affected by the surrounding air masses. In [8], it is proposed to introduce a coefficient that takes into account the change in the natural frequency of vibrations of a wire with ice frozen on it relative to the natural frequency of vibrations of a wire without ice. According to this work, the calculated value of this coefficient is of the order of one. More reliable is the experimental determination of the natural frequency. According to [9], the experimentally determined value is 0.65 – 1 Hz.

In order to perform an effective effect on the ice shell of the wire, it is recommended to use a generator with a smoothly varying frequency within 0.2 – 3 Hz and select the frequency directly on this section of the line. At the same time, you can judge the effectiveness of the impact visually. For resonance oscillations, it is necessary to close the end of the line and two wires formed a circuit consisting of two parallel conductors, of sufficient size to skip current with a frequency equal to half the natural frequencies of the system. In this case, under the influence of the ampere force that occurs when the interaction of opposite-directed currents, the wires will repel at a frequency twice the current frequency.

4. Conclusions
The icing of power lines is a dangerous and harmful phenomenon. There are several methods of dealing with it. However, a universal effective method has not yet been developed. Pre-separation of solid ice from the wire metal can contribute to the ice destruction. Melting of the ice layer significantly reduces its adhesion to the wire metal, which facilitates its subsequent separation after mechanical action. For this purpose, the wire is loaded with high-frequency current. The current value must exceed the critical value. We made estimates of the critical current value and its transmission time.

Acknowledgements
The work was carried out with the financial support of the state task of the Russian Federation no. 0720-2020-0025 “Development of methods and analysis of ways to achieve a high level of safety and competitiveness of energy systems based on digital technologies”.

References
[1] Wang Z 2017 Recent progress on ultrasonic de-icing technique used for wind power generation, high-voltage transmission line and aircraft Energy and Buildings 140 P 42-49
[2] Tomaszewski M, Ruszczak B, Michalski P and Zator S 2019 The study of weather conditions favourable to the accretion of icing that pose a threat to transmission power lines International Journal of Critical Infrastructure Protection 25 P 139-151
[3] 2008 Atmospheric Icing of Power Networks (Farzaneh, Masoud, Springer) p 381
[4] Levchenko I I, Zasyypkin A S, Alliluyev A A and Satusk E I 2007 Diagnostics, Reconstruction and Operation of Overhead Power Lines in Icy Areas (Moscow: National Research University "Moscow Power Engineering Institute") p 494
[5] Wang Y 2020 Numerical study of a droplet impact on cylindrical objects: Towards the anti-icing property of power transmission lines Applied Surface Science 516 146155
[6] Wen S F, Wang Y M, Zhang Z M and Liu Y L 2019 Application of anti-icing coating based on adsorption of functional substances by microporous sphere Progress in Organic Coatings 137 105320
[7] Ji K, Liu B, Cheng Y, Zhan X and McClure G 2019 Evaluation and optimization of a shock load de-icing method for transmission lines with combined ice failure criteria Cold Regions Science and Technology 165 102818
[8] Sukhorukov S I, Soloviev V A, Cherniy S P and Savelyev D O 2014 Russian Internet Journal of Electrical Engineering 1(2) 10–12
[9] Mikheev V P 2003 Contact Networks and Power Lines (Moscow: Marshrut) p 416