Study of Influencing Factors on Ice Shedding from Power Transmission Lines

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***Abstract*- Ice shedding or sudden dropping off of atmospheric ice from cables is a source of serious problems for power transmission and distribution networks. It is influenced by some direct factors such as wind force, ice load and others, and indirect factors such as the constitutive behaviour of ice, cable torsional stiffness, cable tension and ice shape. Wind force creates three types of oscillations in power transmission lines, which are galloping (high amplitude, low frequency), Aeolian vibration (low amplitude, high frequency) and wake-induced oscillation. The results of investigation on the effects of galloping on ice shedding show that wind velocities below 4.5 m/s (under studied conditions) do not cause ice shedding, while wind velocities above 5.2 m/s break the atmospheric ice on cables. This study also revealed that Aeolian vibration cannot cause ice shedding. The ice load may cause ice shedding by applying the force of ice weight and the ice mass inertia. The mechanical properties of atmospheric ice as indirect factors in ice shedding are greatly dependent on temperature, wind velocity, liquid water content of air, and droplet size during ice accretion. Some mechanical properties of this ice also depend on the load rate and temperature during ice shedding. Cables with higher torsional stiffness or higher tension are more susceptible to ice shedding. The atmospheric ice shapes that surround the cable and create less air drag show more resistance against ice shedding. The results of two laboratory tests revealed that the thermal gradient between the external surface of the ice and the surface of the cable does not cause ice shedding from power transmission lines, neither does the Joule effect nor the thermal shock caused by varying temperatures due to weather conditions.**

***Index Terms*—Atmospheric ice, shedding, galloping, cyclic load, Finite element, model, stress.**

I. INTRODUCTION

The accumulation of atmospheric ice on power transmission lines is a source of tremendous damage to power networks. It is common knowledge that in cold regions significant ice layers may accumulate on cables and conductors. Such accumulations can produce major problems such as overloading the conductors and towers, galloping in high wind conditions, ice shedding, short-circuiting due to wire sag, etc. Ice shedding is the name given to the physical phenomenon that occurs when the accreted ice suddenly drops off the cables, either naturally or as a result of some form of intervention. The dynamic effect of ice shedding on transmission lines creates two major categories of concern: electrical and mechanical. The main electrical concerns are lack of clearance between adjacent conductors, conductors and towers, and conductors and the ground that may lead to flashover or electrical shock. From a mechanical point of view, high-amplitude vibrations due to ice shedding may cause suspension strings on towers to come into contact, which may break the insulators; whereas the associated excessive tension generated in the conductors may result in large unbalanced loads on towers. As these problems can pose a major threat to the operational safety of a grid system, recognizing the influencing factors of ice shedding is essential.

Many factors influence ice shedding and most of them issue from weather changes. One can divide these factors into two categories: Direct factors which are the applying forces and create loads on atmospheric ice such as wind force (i.e. galloping, Aeolian vibration and wake-induced oscillations), ice loads (gravity and ice mass inertia), impact of flying objects, impact resulting from ice shedding in adjacent conductors, etc.; Indirect factors such as the constitutive behaviour of atmospheric ice (including ice type and structure which are affected by the atmospheric conditions during ice accumulation, mechanical properties of ice that depend on air temperature during ice shedding as well as load rate, and ice behaviour in crack nucleation and propagation), ice shape, cable torsional stiffness and cable tension. This paper aims to shed light on the effects of these factors on ice shedding. As well, the possibility of ice shedding due to temperature gradient resulting from Joule effect and variation of ambient temperature are also examined.

II. DIRECT INFLUENCING FACTORS (NATURAL LOADS)

II.A. Wind effects

The interaction of natural wind with the surface roughness of the earth produces a wind character that is gusty or turbulent, as opposed to being smooth and uniform. Turbulence or gusts produce velocity fluctuations that are spatial and temporal in character. Therefore, the wind force acting on a cable will vary in direction as well as magnitude, vertically and horizontally, at any point in time. Static wind loads are derived from an assumption of a steady, uniform wind and are the lift, drag and moment as shown in Fig. 1. The magnitude of these forces will vary with changes in the angle of attack and with cross-sectional shape.

When ice or wet snow accretion builds up on conductors and a wind force acts across the resulting profile, the conductors can rotate, move and vibrate at high amplitude low frequency (galloping) or low amplitude high frequency

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(Aeolian vibration) mode. In this study, all these wind induced motions are called cable dynamics.

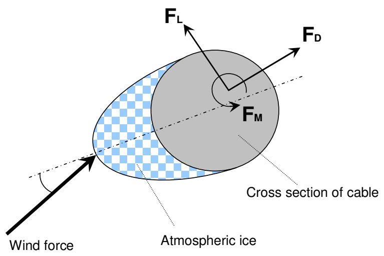


Fig. 1. Drag, lift and moment on cable.

Energy absorbed by a cable loaded with atmospheric ice may be dissipated by internal friction at the molecular level; inter-strand friction; transference to clamps; dampers, spacers and suspension assemblies; crack nucleation, crack propagation and consequently fracture of atmospheric ice; b transference to adjoining wires (in the case of bundled conductors); or the return of the energy to the wind. The relative magnitudes of these dissipations, and their phase positions within each motion cycle determine whether the conductor motion will be suppressed, sustained, or accelerated (EPRI, 1979).

The intensive wind loads have two effects on ice breaking. Firstly, they can break the ice by inducing a load beyond the ultimate strength of atmospheric ice. Secondly, they have a tremendous effect on the fatigue life of ice because of their influence on the damage created by smaller wind loads and vibration. Small amplitude wind loads can break the ice by enhancing the propagation of the cracks initially created by loads at a higher amplitude range.

The most important types of cable dynamic that can cause the ice shedding will be discussed in the following paragraphs.

Conductor galloping

Galloping of ice-coated conductors consists of low frequency, high amplitude, wind-induced vibrations associated with the effect of atmospheric ice deposits on the conductors. This phenomenon occurs when the aerodynamic lift can be modulated by the periodic motion of the conductor in such a way that the variations in lift act to augment or at least sustain that periodic motion. Galloping usually requires moderate to strong winds at an angle greater than about 45^o to the line, a deposit of atmospheric ice on the conductor lending it suitable aerodynamic characteristics, and positioning of the ice deposit (angle of attack) so as to increase aerodynamic instability. Galloping is enhanced if the ice shape is uniform and the angle of attack along the span is constant. In long single-conductor spans, the eccentric weight of the accreted ice may be great enough to significantly twist the conductor. Since the conductor span is fixed against rotation at the ends, this eccentric ice load will twist the conductor most at mid-span and the angle of twist will decrease progressively from that point toward the supports. The angle of attack will thus vary along the span.

Galloping is one of the major phenomena inducing stresses in the accreted atmospheric ice. The significant deformation of the iced conductor during these high-amplitude vibrations induces stresses in the atmospheric ice. This deformation can be estimated by modeling the motion of conductor during galloping to obtain the position of each point along the conductor.

Galloping of suspended conductors has been studied by many researchers [2]-[10]-[16]-[17]. Irvine and Caughey (1974) developed a linear theory for free vibration of a uniformly suspended conductor in which both in-plane and out-of-plane motions were considered. The results of this theory have been used by many researchers to model galloping behaviour. Yu *et al.* (1993) developed a three-degree-of-freedom model to describe and predict different galloping behaviours of a single iced electrical transmission line. Ohkuma *et al.* (1998) focused on the effects of wind turbulence on galloping, and tried to explore the galloping behaviour of a four-bundle overhead transmission line in gusty winds. Luongo and Piccardo (1998) derived a two-degree-of-freedom model to examine the aeroelastic behaviour of a flexible elastic suspended conductor driven by the mean wind speed blowing perpendicularly to the plane of the conductor. Abdel-Rohman and Spencer (2004) used the results of Luongo and Piccardo (1998) to study the along-wind and across-wind response motion of a suspended conductor. They also examined the effect of a vertical viscous damper at a certain location of the conductor.

Kermani (2007) applied the calculation of conductor galloping motion, developed by Abdel-Rohman and Spencer (2004) and Luongo and Piccardo (1998), to a conductor covered with atmospheric ice. The problem was solved assuming certain cable and ice characteristics, span lengths and various wind velocities. The results of the computations yielded the displacements of each point along the conductor in vertical and transverse directions, as well as the aerodynamic forces and other loads on the ice. These results were used in a new model constructed using the ABAQUS finite element software. This model provides an estimation of the stress levels in different parts of atmospheric ice on the conductor and its variation through a galloping cycle.

The trajectory of the mid-point of the conductor is shown in Fig. 2, and it is clear that the amplitude of the vertical motion is significantly greater than that of the transverse motion.

According to Fig. 3, the Von Mises stresses in an element located at the external layer of the ice at the bottom of the conductor reach their maximum values at around 1.2 s and 2.8 s, when the mid-point of the conductor is at the highest and lowest position of its trajectory, respectively. Numerically, these maximum values at a wind speed of 6 m/s are 7.33 MPa and 4.54 MPa. As shown in Fig. 3, the vertical displacement of the conductor reaches its limits twice in one cycle: first when the mid-point of the conductor is at the highest position of its trajectory (at 1.2 s), and second when this point reaches the lowest position (at 2.8 s). The stress is greater in the first case, because in this situation, the transverse position of the mid-point of the conductor is the farthest from its location in static equilibrium, while it is the nearest when the mid-point is at the lowest position.

As shown in Fig. 2, when wind speed increases from 3 to 6 m/s galloping amplitude increases from 0.5 to 2 m while the galloping frequency decreases from 0.324 to 0.3 Hz. The significant increase in stress levels in atmospheric ice due to varying wind speeds (Fig. 3), clearly demonstrates that variations of stresses in atmospheric ice are more directly related to amplitude rather than to galloping frequency.

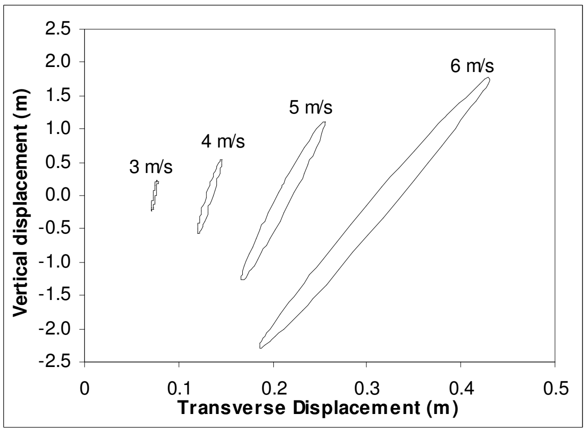


Fig. 2. The trajectory of mid-point of conductor during galloping at various wind speeds.

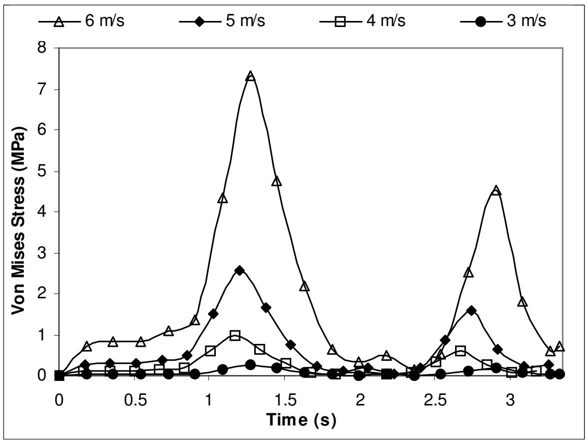


Fig. 3. Cyclic stresses at various wind speeds in the external layer of atmospheric ice.

The bending strength of atmospheric ice was measured in a parallel research, the results of which were published in Kermani *et al.* (2008a). Those observations ascertained that the bending strength of atmospheric ice at -10° C varied with strain rate. According to the guidelines recommended by the IAHR (International Association of Hydraulic Engineering and Research) working group on test methods (Schwarz *et at.*, 1981), experiments with loading times to failure on the order of 1 second yield satisfactory results for bending strength of ice. In Kermani *et al. (2008a)* this load rate corresponds to the strain rate of 2 x10 s yielding a value of approximately 2.73 MPa for bending strength of atmospheric ice, which gives a reasonable value for tensile strength and can be used here as failure limit of atmospheric ice. Therefore, since the von Mises stress is significantly greater for some ice elements than the bending strength of ice, the model predicts ice fracture from the part of the cable under examination. Ice failure is initiated at the top and bottom sides of the accreted ice sheath, because stresses are higher at these locations, whereas stress levels do not exceed the bending strength for the lateral elements on the left and right sides of the cable.

Readers are referred to Kermani (2007) for more information about displacement calculation, the ABAQUS model and stress distribution in atmospheric ice on the conductors during galloping.

- *Aeolian vibration*

The primary cause of aeolian vibration is the alternate shedding of wind-induced vortices from the top and bottom sides of the conductor. This action creates an alternating pressure imbalance, inducing the conductor to move up and down at right angles to the direction of airflow. When the cable is covered with ice, stresses develop in both the cable and the ice. The three primary variables involved in vortex shedding from a circular cylinder are the cylinder diameter, fluid velocity, and kinematic viscosity of the particular fluid. The wind power, p, transferred from the wind to a vibrating conductor may be expressed in the following general form:

$$p = d_c^{\,4} f_v^{\,3} fnc\left(\frac{y}{d_c}\right) \qquad (1)$$

where d_c is the outside diameter of the bare or iced cable, f_v is the vortex shedding frequency in units of Hz, and y is the vibration amplitude (Blevins, 1990).

The vibration amplitude is determined by a power balance between what is provided by the wind and what is dissipated by the cable self-damping and installed dampers. Ice and/or snow precipitations affect Aeolian vibration through different mechanisms. A snow cover may smooth terrain obstacles that would normally contribute to wind velocity fluctuations. More constant wind velocity and azimuth are more propitious to severe Aeolian vibration (Van Dyke and Havard, 2005).

When conductors are covered with ice, other factors will also contribute to increasing the severity of Aeolian vibration. For example, an iced conductor may lock cable strands together so that cable internal damping through strand slippage decreases. Moreover, it is well known that internal cable damping depends heavily on the mechanical tension of the cable. The weight of ice will increase cable tension, which will also reduce conductor self-damping.

Equation 1 shows that when ice accretion increases, assuming the cable diameter and frequency remain constant, Aeolian power increases to about the fourth power of the outside diameter of the iced cable (EPRI, 1979).

Aeolian vibration have been studied by other researchers (e.g. [4], [5]). In order to simulate Aeolian vibration and estimate the stresses generated in atmospheric ice, it was necessary to model cable motion and obtain the position of each point along the cable. To do so, the equation of motion describing cable vibration was studied and Aeolian vibration were simulated. The equations of cable motion were obtained from the basic equations of motion of a suspended cable. A MATLAB code was developed to calculate the time histories of cable motion, aerodynamic forces, additional horizontal tension acting in the cable, and torque generated by springback. The study considered a 10 cm-long sample of iced cable at mid-span and the input data were determined at the two end points of the sample. A finite element model was constructed using ABAQUS to calculate the stresses in the atmospheric ice accreted on the cable.

The MATLAB code showed that the amplitude of Aeolian vibration for the BERSIMIS cable covered with 2.5 cm of accreted ice subjected to 4 m/s wind velocity is 58.1 mm. EPRI (1979) reported that the amplitude of Aeolian vibration in field measurements varied within the range of 0.01 to 1 cable diameter. Considering the ice load on the cable, the corresponding interval occurs between 0.85 mm and 85 mm in the specific example of this study, so that the value of vibration amplitude calculated by the MATLAB code falls within that range.

The cable displacement in the middle of the span in vertical direction is shown in Fig. 4. A full cycle of Aeolian vibration lasts 0.12 s.

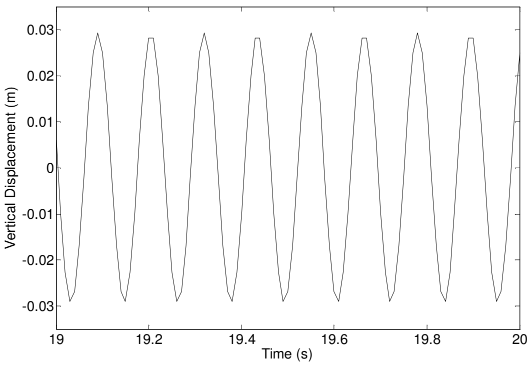


Fig. 4. Cable displacement in the middle of the span in vertical direction.

The Von Mises stresses in the elements at the top and the bottom of the conductor during a 0.3-second interval of Aeolian vibration are shown in Figs. 5. According to the ABAQUS model, the Von Mises stresses reach their maximum values when the mid-point of the cable is at the highest and lowest positions of its trajectory. Numerically, these maximum values are 6210 Pa for the elements in the external layer, and 4056 Pa for the elements in the internal layer.

Comparing the stress levels in atmospheric ice during Aeolian vibration and the bending strength of atmospheric ice, it was observed that no ice failure occurs under the conditions of this study. Since the vibration amplitude, and consequently the stress in the ice are at least one order of magnitude lower than during galloping, ice failure during Aeolian vibration may occur due to fatigue rather than stress peaks exceeding the bending strength. However, the results of low-cycle fatigue tests of atmospheric ice (Kermani, 2008b) show that no ice failure occurs due to cyclic loads and fatigue during low-amplitude vibrations.

Readers are referred to Kermani (2007) for more information about displacement calculation, the ABAQUS model and stress distribution in atmospheric ice on the conductor during Aeolian vibration.

Another form of wind induced cable vibration is wake-induced oscillation that occurs only in only in bundled conductors . The effects of this type of cable vibration on ice shedding are beyond the scope of this paper.

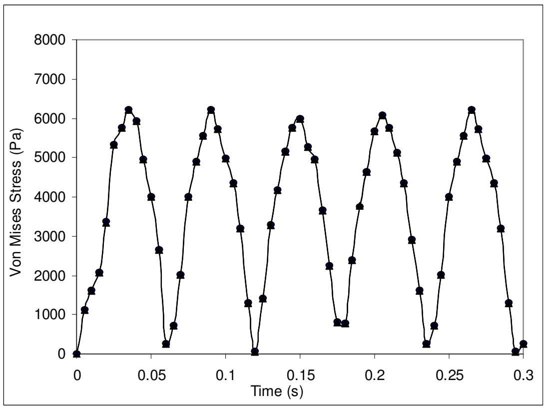


Fig. 5. Von Mises stresses in 4 elements in the external layer of atmospheric ice during Aeolian vibration.

II.B. Ice load

The other important influencing factor in ice shedding is the mass of ice accreted on the cable. The ice load may break ice or accelerate its breaking by several mechanisms:

- If the adhesive force between atmospheric ice and the cable is eliminated by Joule effect or the ambient temperature, the ice will drop due to its weight.
- The ice load during ice accretion (especially at a higher icing rates) can prevail over the adhesive force between ice and cable and cause ice shedding.
- The ice load can propagate cracks in atmospheric ice.
- Ice mass inertia can break the ice during cable motion and vibration.
- During ice accretion, the ice load can rotate and bend the cable and create tension and bending stress in accreted ice.
- It is well known that internal cable damping depends heavily on the mechanical tension of the cable. The ice load increases cable tension, which also reduces conductor self-damping. Thus, a heavier ice load causes more cable tension and ice shedding.

II.C. Other loads

Other events can influence ice shedding when a load or impact is suddenly applied to transmission lines, such as the rupture of an adjacent cable, ice shedding in an adjacent cable, flashover and the impact of flying objects. These events are not controllable and their prediction and investigation are beyond the scope of this study.

III. INDIRECT INFLUENCING FACTORS

III.A. Constitutive behaviour of ice

The constitutive behaviour and mechanical properties of atmospheric ice have been studied by many researchers (e.g. Druez *et al.,*1986, Druez *et al.,* 1989, Kermani *et al.* 2007, Kermani *et al.,* 2008a, Kermani *et al.,* 2008c). Some results of these investigations are summarized as follows:

- These studies have shown that compressive and tensile strengths are greatly dependent on temperature, wind velocity, load rate, liquid water content of air and the mass mean diameter of super-cooled droplets during accretion.
- The mechanical properties of atmospheric ice vary considerably according to the type of ice, which in turn

depends mainly on the meteorological conditions prevailing during ice formation.

- The compressive, tensile and adhesive strengths of atmospheric ice increase with increasing values of liquid water content of air and mean volume droplet diameter during ice accretion.
- The compressive, tensile and adhesive strengths of atmospheric ice increase with decreasing test temperature.
- The compressive strength of atmospheric ice increases with increasing strain rate up to $10^{-3}s^{-1}$, and then decreases at higher strain rates.
- At the lower strain rates the bending strength of atmospheric ice increases with decreasing test temperatures but no temperature effect is seen at the higher strain rates.
- At colder temperatures, the bending strength of atmospheric ice under cyclic loads is lower than that under static loads.
- The bending strength of atmospheric ice under cyclic loads decreases with decreasing test temperatures.
- The fracture toughness of atmospheric ice decreases with decreasing accumulation temperatures.

With these considerations in mind, one can conclude that each factor that causes a reduction in strength and adhesion of atmospheric ice to the cable can pave the way for ice shedding.

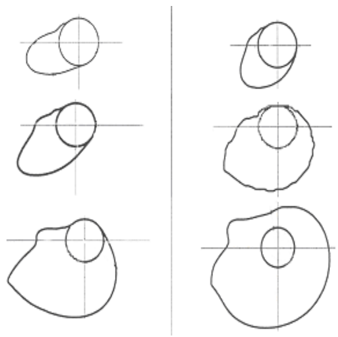
III.B. Cable torsional stiffness and tension

Cable torsional stiffness influences ice accretion and ice shedding. In the case of two similar cables with different torsional stiffness, the ice accretion on the soft cable exhibits a perceivably circular shape, while ice on the rigid cable is asymmetrically distributed underneath. Ice on a rigid cable tends to shed from the cable due to aerodynamic or gravitational forces (Fig. 6) (Fu, 2004).

Internal cable damping depends heavily on the mechanical tension of the cable. Therefore, vibration and motion in a cable with more tension can shed more ice. The ice weight will increase cable tension, which will also reduce conductor self-damping. Thus more ice causes more cable tension and more ice shedding.

III.C. Ice shape

Another factor that influences ice shedding is ice shape. It has two different effects on ice shedding. Firstly, its form can change the aerodynamic forces on itself as well as on the cable, and therefore change the oscillation amplitudes. Secondly, its shape determines the difficulty of its shedding. Ice shape varies along the span. Near the span extremities, ice deposited on the top windward surface will progressively thicken with the continued impingement of freezing droplets. Ice deposited on that quadrant remains in that quadrant. Near mid-span, however, continued deposition of ice causes progressive rotation of the conductor, so that the ice coating is "wrapped on". Due to this rotation, the first film of ice, which is initially in the upper windward quadrant, may ultimately face directly windward, or down, or even directly leeward, depending upon the torsional stiffness of the span and the duration of icing conditions. The shape of this "wrapped on" ice is different from the ice deposited near the span ends, where little rotation occurs. The shapes that surround the cable and have less air drag show more resistance to ice shedding. The most characteristic forms of glaze ice and sleet accretion are presented in Figure 2.13 (Kazakevitch and Grafsky, 1998).



Rigid cable soft cable

Fig. 6. Ice shape for rigid and soft cable (Fu, 2004).

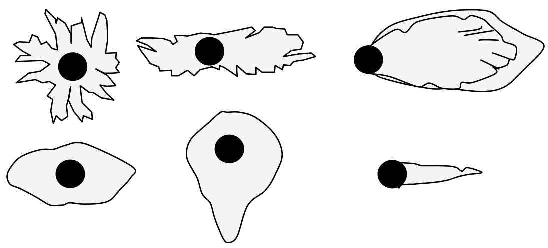


Fig. 7. The characteristic forms of glaze ice and sleet accretion on round structure elements (Kazakevitch and Grafsky, 1998).

III.D. Thermal shock

One of the factors thought to influence ice shedding is ice fracturing due to thermal shock created by variations in ambient temperature or Joule effect in the cable. To study the effect of air temperature variation and the Joule effect in ice fracture, two tests were conducted.

To study the Joule effect, a minimum electrical current was applied in the cable. The value of the current intensity was calculated from Zsolts (2006).

$$I = \sqrt{\frac{T_{ca} - T_{am}}{R\ .K_s}\left(\frac{1}{\frac{1}{2.K_i.\pi}\ln(\frac{r_i}{r_c}) + \frac{1}{2r_i\pi.h_t}}\right)} \tag{2.4}$$

where R is the electrical resistance of the cable, K_s is the skin effect factor, K_i is the thermal conductivity of ice , r_i is the radius of the ice around the cable (ice thickness plus cable radius) , r_c is the radius of cable, T_{ca} is cable temperature, T_{am} is ambient temperature and h_t is the heat transfer coefficient, which can be calculated as follows:

$$h = k_a \sqrt{\frac{U}{2\nu_{air}.r_i}} \tag{2.5}$$

where U is air velocity , K_a is the thermal conductivity of air , ν_{air} is the kinematic viscosity of air.

To obtain the values of h and I, the characteristics of the cable and the atmospheric ice were selected as the data, as shown in Table 2.2.

The heat transfer coefficient h_t and the required current intensity to increase the cable temperature to -2^o C were obtained 79.1 $w/m^{2o}C$ and 2165.6 A, respectively.

Parameter	Value	Unit
Skin effect factor	1.07	---
Electrical resistance of cable	4.22x 10^{-5}	Ω / m
Thermal conductivity of ice	2.2	W/m.K
Radius of ice around the cable	37.55	mm
Cable radius	17.55	mm
Cable temperature	-2	^{o}C
Ambient temperature	-25	^{o}C
Kinematic viscosity of air	1.368 x10^{-5}	m^2/s
Thermal conductivity of air	0.025	W/m.K
Air velocity	10	m/s

Table 2.2. Cable and atmospheric ice characteristics.

A one-meter-long BERSIMIS cable was prepared for this test. The liquid water content of atmospheric ice was set at 2.5 g/m^3; air velocity during accumulation was 10 m/s; and the ice accumulation temperature was -10^o C. After the ice was allowed to accumulate in a wind tunnel, the temperature of the ice was reset to -25^o C. The ice remained at this temperature for one hour. Then, a current intensity of 2150 A was applied to the cable. After 45 minutes the cable temperature reached -2^o C and the atmospheric ice was carefully scanned. No sign of cracking due to thermal shock was observed.

The current was then disconnected and the atmospheric ice was allowed to cool down to -25^o C, where it was kept for one hour. Finally, it was removed from the wind tunnel and exposed to a 20^o C air flow at a velocity of 5 m/s. Of course, these conditions never happen in nature, but the worst condition was chosen to investigate the effect of temperature variation on atmospheric ice. After 10 minutes, the ice was scanned and again no cracks were observed.

The results of these tests show that ice shedding from power transmission lines never occurs owing to a thermal gradient between ice and cable, and that the thermal shock due to temperature variation created by meteorological conditions does not cause ice shedding either. Nevertheless, a full-scale test in more realistic conditions is required to entirely exclude these two factors from those influencing ice shedding.

IV. CONCLUSION

Ice shedding is influenced by some direct and indirect factors. The direct influencing factors act as a source of energy for ice breaking and ice shedding. Wind force and ice load are the most influential ones. Wind force creates three types of oscillations in power transmission lines: galloping (high amplitude, low frequency), Aeolian vibration (low amplitude, high frequency) and wake-induced oscillation.

In galloping, altered aerodynamic characteristics of the cable cause oscillation. Based on the results of a model developed to simulate conductor galloping, wind velocities below 4.5 m/s (under studied conditions) cannot increase stresses in atmospheric ice to its failure limits. Wind velocities above 5.2 m/s however, break the atmospheric ice on cables.

In Aeolian vibration, alternate shedding of wind-induced vortices from the top and the bottom of the cable cause conductor vibration. The action creates an alternating pressure imbalance, inducing the conductor to move up and down at right angles in the direction of airflow. The results of another finite element model simulating Aeolian vibration in conductors showed that this type of vibration cannot create sufficient stresses in atmospheric ice to cause ice shedding.

The ice load may break the ice or accelerate its fracture by applying the weight force, the ice mass inertia and so on.

The indirect factors provide suitable conditions for ice breaking by reducing the ice strength or eliminating its adhesion to the cable. One of these factors is the constitutive behaviour of atmospheric ice. The compressive, tensile and adhesive strengths of atmospheric ice are greatly dependent on temperature, wind velocity, liquid water content of air and mean diameter of supercooled droplets during ice accretion. The strength of atmospheric ice also depends on the load rate and temperature during ice shedding. The other influencing factors on ice shedding are cable torsional stiffness, cable tension and ice shape. Ice sheds more readily from cables with higher torsional stiffness or higher tension. The atmospheric ice shapes that surround the cable and create less air drag are less susceptible to ice shedding. Under certain circumstances, all of the above-mentioned factors can work together and cause ice shedding.

Two tests showed that the thermal gradient between the external surface of the ice and the surface of the cable does not cause ice to shed from power transmission lines, neither due to the Joule effect nor to thermal shock caused by natural temperature variations.

V. ACKNOWLEDGEMENTS

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