De-icing/Anti-icing Techniques for Power Lines: Current Methods and Future Direction

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Abstract—**Atmospheric icing may be problematic for many industries, including electric utilities. The combination of wind and ice could cause damages, sometimes leading to power outages. The January 1998 ice storm has led to the development of several de-icing methods destined to overhead power lines. These techniques are the subject of several technical reports and publications. Furthermore, in the past five years, advances in ice adhesion, surface, and interface science have led to the development of new de-icing and anti-icing techniques. After a brief review of the most notable de-icing and anti-icing methods developed during the last decade, and which could be applied to power lines, this paper presents a review of some interesting de-icing methods under consideration for use by Hydro-Québec. Also, the potentiality of the new developments in the field of ice adhesion and their application to power-line and conductor de-icing and anti-icing will be discussed.**

I. INTRODUCTION

Adhesion of ice to surfaces causes problems for many industries, including aviation, telecommunication, navigation, power network equipment, and transportation. In the case of overhead electrical lines, the combination of wind and ice could cause damages, sometimes leading to power outages and dire socio-economic consequences. The January 1998 ice storm in North of America is a good example of such consequences [1]. Subsequently, the need for new solutions led to the development of several de-icing and anti-icing methods destined to overhead power lines, which were the subject of several technical reports and publications [2-3], resulting in an exhaustive and detailed review of the different de-icing and anti-icing techniques, already available and in development.

Based on the above, while some of the methods in development or in a conceptual or prototyping state seem to be very promising, if only from the point of view of ice removal, some parameters were not taken into account in the evaluation. Despite all the factors considered, no parameters relative to mechanical, thermal, or electrical constraints were mentioned.

Finally, a review of patents shows that new methods have been proposed since the state-of-the-art report [3]. The latter are principally based on recent developments in the ice adhesion field and represent some new directions for future anti-icing and de-icing techniques, primarily for power line equipment and other surfaces that need protection from ice accretion.

After reviewing some classification of different anti-icing and de-icing methods and some of the major constraints related to their applicability, this paper will present briefly some recently developed methods under consideration for use by Hydro-Québec and future directions in ice prevention.

II. BRIEF REVIEW OF ANTI-ICING AND DE-ICING METHOD CLASSIFICATION

Historically, to the best of our knowledge, the first review dedicated to anti-icing and de-icing methods applicable to overhead power lines was presented by [4]. A few years later, another paper presented a detailed review of two methods, rolling and heating by short-circuit current, which are used on the Manitoba Hydro electrical network [5]. However, these reviews present only some ad-hoc techniques and consequently were not exhaustive or complete.

A detailed classification of de-icing and anti-icing methods was done by [6] in a Hydro-Québec technical report, in which all methods inventoried were classified in four (4) categories: passive, thermal, mechanical, and miscellaneous. This simple classification of the twenty-eight (28) methods identified was based on the physical principle used in the method to remove the ice from a defined surface. This classification was also used in [2] in a state-of-the-art report presented after the January 1998 ice storm in the Northeast of North America. The methods identified include eight (8) thermal, eight (8) mechanical, eight (8) passive, and four (4) miscellaneous. Finally, a recent state-of-the-art study on power line de-icing techniques was presented [3]. The forty-one (41) methods listed were classified in six categories; passive techniques (13), active coatings and sheathings (6), active methods on bare conductors (7), methods using external thermal energy (5), methods using external mechanical energy (6), and finally, miscellaneous methods (4), with less potential for application for ground wire and energized conductor de-icing.

As previously mentioned, different classifications can be used according to various criteria. An interesting criterion that can be used is the applicability of the method to only ground wires, only energized conductors, or both. Thus, twenty-seven (27) methods can be used both on conductors and ground wires, nine (9) on conductors only, and one (1) to ground wires only. Some of the methods dedicated to energized conductors only are based on current line Joule effect. Some of them have been developed or improved by Hydro-Québec and are currently in use on several critical portions of the Hydro-Québec network. Some of these methods will be described in a next chapter.

Another classification can be proposed to illustrate the permanent or temporary character of the method, the need for line modification, and whether it is automated or manual. Thus, the thirty-seven (37) potential methods can be divided into inline (9), punctual (9), and permanent (19). Inline methods refer to those using Joule effect to melt the ice, using the line's own energy or an external source with no device or coating added to the energized conductor or ground wire. Punctual methods regroup all methods that are not permanently installed on the lines, but are used at specific locations, primarily for de-icing, or that can be used only once. Finally, permanent methods include all methods permanently installed on the conductors or ground wires.

Also, in greater detail, among the thirty-seven (37) methods inventoried, eleven (11) are preventive, thirteen (13) are for de-icing, and thirteen (13) for mitigation. In addition, fifteen (15) are operational, four (4) have already been tested, thirteen (13) are at a conceptual or in development stage, and three (3) are at the prototype stage. However, among the fifteen (15) operational methods, only seven (7), or 19%, are effective and two (2) were proof-tested for ice prevention or de-icing. Finally, among the seven (7) effective methods, four (4) are thermal methods and the others are mechanical. The four (4) thermal and three (3) mechanical methods are inline and punctual methods, respectively.

It appears that no permanent method, as defined previously, is presently in use. Most of them are in fact in development or at the conceptual stage, or refer to specific coatings or devices that must be added to the energized conductors or ground wires. In this context, the development of such methods becomes more complex as they have to meet some specific requirements to ensure good performance and life expectancy. This consideration is developed in detail in the following section.

III. CONSTRAINTS OF APPLICABILITY FOR DE-ICING AND ANTI-ICING METHODS

As mentioned previously, these methods have to respect some specific electrical, mechanical, and thermal constraints relative to power line operation. Also, some environmental constraints like U.V. radiation can decrease the life expectancy of certain devices. These parameters should generally be taken into account in the development of a method, as they serve to define its application field, particularly in the case of permanent methods for energized conductors and ground wires.

A. Electrical Constraints

The presence of high electric and magnetic fields, as well as electrical discharges and the impact of lightning should normally be taken into account in the development of de-icing and anti-icing methods. Also, electromagnetic perturbations, caused by the high-frequency electric fields emitted by some devices, can interfere with civil or military apparatus and must be considered in design.

As concerns lightning, it induces very high impulse currents in connection with high voltages, along with large mechanically induced forces and high temperatures [4-5]. Depending on the type of strike (direct or indirect), currents between 30 and 60 kA can be generated, and can sometimes reach as high as 200 kA in the worst cases [4]. Theses high currents are accompanied by voltages higher than 1 MV, which are generally sufficient to induce flashover on or between overhead line equipment. In fact, lightning can breakdown the electrical insulation of dielectric coatings or electrical tracing of such methods as electromagnetic expulsive sheathings and vibrating devices. Consequently, lightning can directly affect active de-icing or anti-icing methods, implying that the devices used should be electrically insulated from live conductors or ground wires.

B. Mechanical Constraints

Permanent methods used on live conductors and ground wires are also subjected to different types of mechanical constraints.

If a coating is already on the conductor or ground wire before installation, it must support all the mechanical stresses caused by the rolling for transportation, the unrolling and stretching during the assembly on the tower, and the bending of the span [6]. All permanent coatings are concerned by these constraints if they cannot be deposited on the conductor or ground wire after its installation on the tower. This is true for future icephobic, low adhesion, or dielectric coatings. However, some of these coatings could be deposited on the conductor or ground wire during the unrolling process, but they would still have to support the mechanical stress induced by the pulley used to put the conductor or ground wire under tension and adjust the span. Once ground wires and conductors are installed on towers, they undergo bending under their own weight caused by their elasticity. For this reason, conductor or ground wire coatings must preferably have the same or higher elasticity coefficient as its corresponding substrate.

On the other hand, all methods have to support mechanical online stresses (stretching and torsion) caused by the low-frequency vibration of large amplitude, called galloping, of energized conductors or ground wires, created by wind, ice shedding [10-12], or electrodynamic stresses induced by high current pulses [13]. Under galloping, conductors or ground wires oscillate to a frequency close to the span's fundamental, low-order harmonics (0.5 to 3 Hz), but with amplitudes that may range from 1 m to 10 m or more, depending on span length. Subjected to this solicitation, rigid coatings can undergo crack ignitions. Also, any apparatus mechanically attached to the conductor, such as vibrating devices and ferromagnetic heating rings or envelopes, could be subjected to high acceleration forces generated by Aeolian vibrations or galloping oscillations.

In the same way, under very high impulse current, parallel live conductors are subjected to electrodynamic strains resulting in high velocity mechanical shocks between them [13]. High current pulses can be induced by short-circuits on active conductors, due to different causes like trees, galloping, or lightning. In this situation, any apparatus or coating on live conductors can undergo very large mechanical shocks.

Hence, the mechanical constraints that are inherent to the installation and the dynamic behavior of conductors and ground wires must be taken into account in the applicability of the new prevention and de-icing methods currently in development. This will also contribute to decrease the potential of some new concepts based on rigid dielectric coatings [3]. Preferably, coatings will have to be more flexible, but with the same equivalent mechanical coefficient as that of the conductor or ground wire on which they are installed.

Of course, methods based on Joule effect melting are not affected by these considerations as no apparatus needs to be added on the conductors or ground wires.

C. Thermal Constraints

One of the major aspects that should be considered is the thermal energy released by the high current pulse of lightning. In fact, because of the short duration of the pulse (a few tens to hundreds of μs), this is equivalent to high frequency leakage current (from hundreds kHz to MHz) flowing mainly to the surface of the conductor due to the skin effect. In this situation, most of the thermal Joule energy generated by the strike is dissipated at the surface of the conductor. In some cases, thermal energy is sufficient to melt the surface aluminum conductor fibers [5], and could consequently melt material on the surface of the energized conductors or ground wires. For this reason, any coating or apparatus installed on the surface of live conductors or ground wires, or fixed to towers, can be subjected to this kind of thermal shock, which can cause permanent damage and drastically reduce their life expectancy and performance.

The second aspect deals with the thermal limitation of energized conductors. Normally, conductors, under service current, can support a steady-state temperature, which depends on weather conditions, conductor characteristics, and conductor electrical current [14-15]. Conductors can generally support a maximum allowable temperature, above which a loss of strength, sag, line losses, or a combination of these can occur. Normally, for a given conductor type and a steady-state service current line, the temperature depends mainly on ambient temperature, as well as wind speed and direction. During winter, these conditions are not critical because conductor temperature is low enough to allow ice to accrete on it. This however becomes critical during summer, when high ambient temperatures, solar radiation, and low wind conditions prevail. In this situation, temperature is only limited by current intensity.

Now, if we take into account the presence of special coatings for ice prevention or removal, the thermal limitation of energized conductors must be considered. With these coatings, values of convection heat loss and the total heat capacity of the conductor have to be taken into consideration in the maximum allowed temperature calculation [15]. As these coatings are permanently installed on the conductors, particular attention will be paid to the thermal conductivity of the coating and the different current values (steady-state and short-circuit) acceptable for the conductor and its prevention or de-icing coating.

IV. NOTABLE DE-ICING METHODS

This section presents a brief review of the most notable de-icing methods developed so far, which could be applied to conductors or ground wires. This review is not exhaustive but presents some interesting methods under consideration for use by Hydro-Québec.

A. Conductor De-Icing

Heating of ice-covered line conductors by electrical current is recognized worldwide as the most efficient engineering approach to minimize the consequences of severe ice storms on overhead lines [16]. De-icing time is a function of air temperature, ice thickness, wind speed and conductor diameter. Both AC and DC have been used in different countries to melt ice [3]. Technologies for both types of currents are available, the methodology has been developed, and decades of operational experience with ice melting systems has been gained around the world. A variety of conceptual electrical schemes has been considered for ice melting technologies. Some of them are reviewed in the following sections.

A.1 Load Shifting Method

The load shifting method consists in using the heating effect of load currents to prevent conductor icing or to remove ice form conductors. However, high-voltage lines carry limited current and do not generally produce enough heat to prevent or melt ice. Normal operating conditions must be modified in order to force more load current through a particular circuit by transferring or shifting loads from other circuits linking the same two substations [4].

In 1998, Hydro-Québec completed an inventory of circuits, conductor load capacities, and seasonal load variations of its transmission network. The task was enormous, but finally, 120 circuits from 69 kV up to 315 kV were identified as potential candidates for load transfer de-icing [3].

A.2 Reduced-Voltage Short-Circuit Method

Many electric power utilities around the world have some experience with short-circuit heating. For instance, in the early 1970's Manitoba Hydro began using 3-phase short-circuits to melt ice as an experimental procedure [17]. Today, they have the capability to melt ice off several thousand kilometers of lines with conductors ranging in size from 2/0 to 336.4 kcmil ACSR. Currently, 90 substations, at 33, 66, and 115 kV, are equipped for short-circuiting. Ice melting is routinely carried out by Manitoba Hydro, not only during severe widespread ice storms, but also during less severe weather conditions, as a preventive measure against the slow build-up of ice on conductors.

Current intensity is a function of the applied voltage, circuit length, and the electrical characteristics of the conductor. As an approximate rule, for applied voltages of 12, 25, or 69 kV, it is possible to get the required current intensity for circuit lengths of 12, 25, or 69 km respectively on Hydro-Québec's transmission lines with single conductor per phase, within a margin of 15% [18].

A.3 High-Voltage Short-Circuit Method

Joule Effect de-icing cannot be easily applied to lines with bundled conductors at rated voltages of 315 & 735 kV. To protect these lines against severe ice loads, a new de-icing method was tested at Institut de Recherche d'Hydro-Québec (IREQ) [19].

This method involves circulating short-circuit current (I_{SC}) at the rated voltage of the transmission lines and the subsequent action of electromagnetic forces that allow conductors to knock against each other to de-ice, as shown in Fig. 1. Tests were carried out on a sample overhead transmission lines with twin (315 kV) and quad (735 kV) bundles installed in the switchyard at IREQ's high-power laboratory [20]. In order to reduce the amplitude and duration of the short-circuit currents as much as possible, asymmetrical I_{SC} and appropriate reclosing sequences are necessary. Conductors have to be excited at a frequency close to their fundamental subspan frequency to get a maximum dynamic motion synchronized with the reclosing sequences.

Impact studies on Hydro-Québec power's system reveal that this method could hardly be used for 315-kV lines because the voltage drops are significant and a number of industrial customers would be affected [19]. For 735-kV lines, the required short-circuit currents and reclosing sequences are too detrimental to network stability and, therefore, the method would not be applied.

A.4 DC Current

Both AC and DC can be used to heat line conductors. Using AC does not involve high additional costs, since the melting current is supplied directly from the existing network. However, to obtain the necessary value of melting current, the melting voltage and corresponding total melting power must be sufficiently high, especially with long transmission lines. If the length of the line being heated and the required melting current and voltage are relatively small, AC can be successfully used, but DC is more advantageous for long high power lines with large cross-section conductors because reactive losses are eliminated.

Fig. 1. De-icing a twin bundle using 10 kA and an appropriate reclosing sequence. Reference [19].

This technology has been developed, installed, and successfully used on a large scale in the former USSR to melt ice on long 500 kV lines with large bundled phase conductors [16]. For the main 735-kV corridor, Hydro-Québec plans to use this method based on the use of DC rectifiers at strategically selected substations in order to de-ice quad bundles [18].

B. Ground Wire De-Icing

Besides mechanical reinforcement of transmission lines, ground wire de-icing can be useful as part of a global approach to avoid major breakdown of transmission networks during severe ice storms.

B.1 Joule Effect De-Icing

Ground wire de-icing by Joule effect [21] requires a current source as well as the electrical insulation of ground wire at towers, as shown in Fig. 2. A medium voltage AC transformer (25 kV) supplied by the main AC circuit could be used as the current source.

This method is very useful to de-ice many kilometers of ground wires. The range of de-icing is limited only by the withstand voltage of insulators and arcing horns covered with ice. Cost associated with the insulation of ground wires are partly compensated by the elimination of the annual induction losses (2 kW/km for a 735 kV line and 1 kA).

In remote areas, it is possible to use an auxiliary diesel-generator to de-ice the ground wires on strategic line sections, such as river crossings.

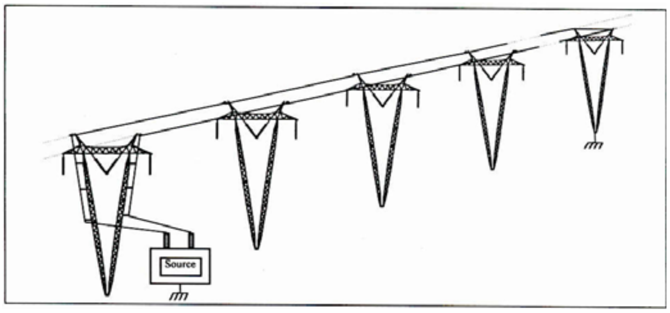

Fig. 2. Simultaneous de-icing of two ground wires (loop configuration). Reference [21].

B.2 Remotely Operated Vehicle

A Remotely Operated Vehicle (ROV) has been developed at IREQ [22-24]. Hydro-Québec TransÉnergie was looking for a mechanical device for de-icing overhead ground wires on its transmission network. The development of a method allowing for gradual de-icing of the cables, without dynamic stress on structures, was the main objective.

Robust, lightweight, and compact, the device has high traction force, which allows it to perform demanding tasks. The ROV was successfully tested on live-line conductors (315 kV lines). Its electronic circuitry is protected against electromagnetic interference and it has an operational range of 1 km. The de-icing tool, based on a set of steel blades, is mounted on the ROV (Fig. 3).

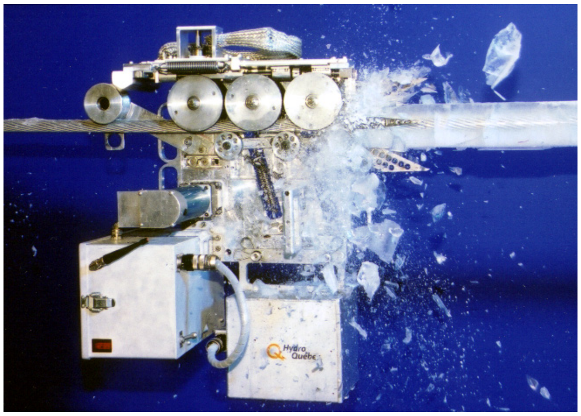

Fig. 3. Prototype of the ROV de-icer. Reference [24].

The automated prototype (3rd generation) is ready to be tested in field conditions following an icing event. The ROV will probably have to be installed from a helicopter or an insulated boom truck, since the icy structures prevent linemen from reaching the ground wires.

B.3 De-Icer Actuated by Cartridge (DAC)

A mechanical de-icing device, called DAC, aims at de-icing GW and OPGW span by span, is shown in Fig. 4. This mechanical method consists of using a portable cylinder-piston system that creates shock waves to de-ice the cable [24, 25]. The device is designed to take advantage of the brittleness of ice at high strain rates to create shock waves that propagate along the span and break the ice. The DAC is a portable, robust, effective, and simple device that can easily be used after a line fault due to clearance violation between GWs and phase conductors. The de-icing operation is carried out entirely from the ground, which represents a major advantage.

First, a commercially available line-thrower is used to throw a projectile which tows a line that passes over the cable to be de-iced. Next, the DAC is pulled up to the cable and held in place by a taut rope. The DAC is equipped with a revolver barrel that stocks 6 blank cartridges that can be remotely fired from the ground. Numerous tests have been carried out to assess the efficiency of the method and to optimize its physical parameters [26].

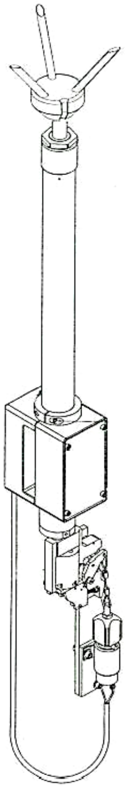

Fig. 4. Drawing of the DAC prototype. Reference [26].

V. FUTURE DEVELOPMENTS IN PREVENTION METHODS

In addition to the need to respond to severe constraints of different natures, methods in development must primarily demonstrate their effectiveness in removing ice accreted on energized conductors and ground wires.

While efforts to develop different active ice removal techniques have received the most attention [3], few studies have focused on understanding the basic mechanisms of ice adhesion and the development of icephobic surfaces from the very fundamental standpoints [27-30]. However, recent advances in ice adhesion mechanisms have led to new developments in prevention methods based on passive and active icephobic coatings.

A. Passive Icephobic Coatings

Atmospheric ice is generally formed from supercooled water droplets. To adhere to a surface, in the first stage of ice formation, these droplets wet the surface, thus replacing the existing surface–air interface with a surface–water interface. This wetting condition has attracted attention to low-surface-energy or hydrophobic materials as potential icephobic materials, or materials that allow for the ice to detach itself under the effect of gravity or wind. Teflon is a good example, as it has very low surface energy, as well as the lowest ice adhesion force among solid materials [31]. But ice adhesion forces obtained with Teflon demonstrated that it cannot be considered an icephobic material as it cannot completely prevent or drastically decrease atmospheric ice adhesion. Some efforts were made in order to develop other solid materials with low ice adhesion. Such materials have actually not been developed for supercooled droplets, but some of them yielded good results for wet snow flakes [32], for which the adhesion process is quite different.

However, advance in material and surface science, such as ice adhesion research, has recently reinitiated interest for passive icephobic materials. Recent studies have established a strong correlation between hydrophobicity and the ice adhesion strength of a surface [29-30]. These studies showed that an increase in the hydrophobicity of a surface leads to a decrease of its ice adhesion strength. In other words, the strong correlation between the work on water adhesion and the strength of ice adhesion reveals that the degree of hydrogen bonding seems to be a major factor controlling ice adhesion strength.

In this context, by increasing the hydrophobicity of the material surface, it could be possible to reduce drastically the ice adhesion strength. This is an interesting research direction that has not been really explored in the field of icephobic materials. Over the past few years, new technologies have been developed in order to create high hydrophobicity with high water contact angle (CA), and more recently very high hydrophobicity with CA greater than 150° [29-30]. These specific surfaces have attracted much interest because of potential practical applications as self-cleaning or anti-soiling materials [29-33].

Conventionally, highly hydrophobic surfaces have been produced mainly in two ways. One is to cover a rough surface with a low-surface-energy material (CA > 90°), and the other is to roughen the surface of hydrophobic materials [33-35]. Relative to the studies done on highly hydrophobic materials, the contact angle or hydrophobic properties of a surface increase with an increase of surface roughness. In fact, rough surfaces allow for the creation of a texture in which air is likely to remain trapped when it comes into contact with water. In this context, the drop is then partially sitting on air and it behaves much like a fakir on a bed of nails: it sits comfortably on top of the posts, as illustrated by Fig. 5-a. Thus, the substrate supporting the water drop consists mainly of air, as the drop is in contact with a very small percentage of the hydrophobic material represented by the tip of the posts. This phenomenon, which uses a textured surface called "fakir regime", is particularly interesting in view of developing some new icephobic coatings. In that case, it should become very difficult for supercooled water droplets-coming from freezing rain for example-to wet totally the textured surface. Thus intermolecular interactions at the ice/solid interface could be considerably reduced as most of the substrate if formed by air. As a consequence, a drastic reduction of the ice adhesion strength could be obtained.

However, this ideal icephobic material should be able to function in the ideal case of a single water drop smoothly deposited on the surface. If other water drops add weight to initial drop, or if the water drop strikes the surface with a certain velocity, it can be impaled on the posts, as shown in Fig. 5-b. In this situation, the solid surface looses its hydrophobicity, in which case supercooled water drops can easily wet the entire surface, at the same time increasing the anchorage or interlocking mechanical effect as intermolecular interactions. The consequence could be a drastic increase in ice adhesion strength.

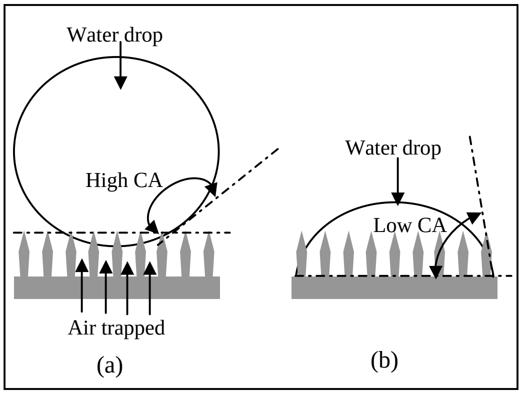

Fig. 5. Behavior of a water drop on a solid textured surface. (a) the drop can sit on the top of these posts and the space between the posts is filled with air. (b) the water drop is impaled on the posts due to its own weight or high velocity impact.

In order to avoid this problem, another parameter must be taken into account in the characterization of textured surfaces. While the water CA has been commonly used as a criterion to evaluate the hydrophobicity of a solid surface, this alone is insufficient to assess the sliding properties of a water droplet on the surface [33]. This sliding property can be quantified by the sliding angle (α), which is the critical angle at which a water drop begins to slide down an inclined plane. It reflects the dewetting property of a surface [33, 35]. A fully superhydrophobic surface like that of natural lotus leaves should exhibit both high CA (around 160°) and low sliding angle (around 2º) [33]. Low α means a high rolling capacity of water drops on the surface of a horizontal plan. With this new property of textured surface, supercooled water drops could be easily evacuated from the solid surface before freezing, thus preventing ice accumulation. Studies of lotus leaves showed that the topology the superhydrophobic surfaces is quite similar to highly hydrophobic surfaces, but with both micro- and nanoscale hierarchical roughness structure [33]. In fact, it is like the microscale posts shown in Fig. 5, but with nanoscale roughness in the same time.

Up to now, many methods have been developed to produce high or super hydrophobic surfaces, but our interest is turned towards methods that can be applied on a large scale to materials which can be found on aerial power lines. These methods deal with ultrathin film deposition based on self-assembled monolayers (SAM's) and diamond-like carbon (DLC).

SAM's are attractive as a potential icephobic material for various reasons. First, recent theoretical and experimental studies have demonstrated the potentiality of SAM's as a highly hydrophobic surface [29-30, 36-38]. In particular, theoretical studies have demonstrated the possibility of combining high CA and low sliding angle with SAM's [36-38]. Also, from a practical point of view, SAM's can be chemically deposited at relatively low cost by simply dipping the substrate in specific solutions, which adhere well to the substrate. And finally, SAMs, formed on aluminum substrates, have been reported to reduce ice adhesion strength [29-30]. However, the results obtained for ice adhesion reduction were performed with non-exotic SAM's, in order to make the surface hydrophobic. No particular attention was paid to optimize the assembly of SAM's in order to create a very highly hydrophobic surface and to study its effects on ice adhesion strength. It may be expected that further improvement in this direction can be achieved, along with a better understanding of the mechanisms of SAM formation and ice adhesion to them. It may also be expected that the proper choice of SAM molecules with optimal chain length and chemical composition could also yield some positive result. In the same context, the mechanical and environmental behavior of SAM's should be of great interest as they are organic substances and remain fragile.

DLC is generally advantaged by its high mechanical hardness, chemical inertness [30, 36-38], and better life expectancy, as compared to SAM's. Generally, DLC is not used alone because it is not a hydrophobic material (CA > 90°), but it can be used to create a rough surface and an adherence layer on which is deposed the hydrophobic material. Recent studies have demonstrated the potentiality of ultrathin films based on DLC associated with fluorocarbon (CF_x) [36-38]. Obtained by common PECVD technology, these coatings exhibit high hydrophobicity with high adhesion to aluminum and porcelain, and good mechanical properties. However, no ice adhesion tests were done with these films. More recent studies showed than adding suitable hydrophobic polymers (PTFE or PDMS) during DLC deposition can considerably enhance DLC hydrophobic properties and produce a novel diamond-like-carbon-polymer-hybrid (DLC-p-h) [24]. This novel structure has the great advantage of exhibiting a high CA and a very low sliding angle (around 0.15º), and can lead to a new type of hybrid DLC coating.

B. Active Icephobic Coating

As developments in nanotechnology seem to open up a new direction for research in passive icephobic coatings, recent discoveries in ice adhesion have led to new developments in active icephobic coatings. But active icephobic coatings need energy to be effective. In general, this energy comes from an electrical source. Like passive icephobic ones, active coatings must prevent or reduce considerably ice adhesion strength on surfaces by breaking the chemical bonding involved in ice adhesion and/or intercalating air or other gases between the solid surface and the ice.

One of the most interesting methods proposed is the application of a DC voltage on ice adhesion strength [41]. Results of tests showed that two different mechanisms dominate in the reduction of ice adhesion strength: reduction of the electrostatic interactions, and electrolysis of ice. However, ice electrolysis seems to be dominant in the case of an ice/solid metal interface, as proposed in [41]. In fact, the ice electrolysis method acts as a passive icephobic material; electrolysis gases are intercalated between the ice and the solid surface and behave like air trapped in a textured surface, as discussed previously. Also, gas accumulates in the form of bubbles, which contribute to produce interfacial cracks. The other advantage of this method is that it requires little electrical energy. Fig. 6 illustrates the principle of this method [41]. DC voltage is applied between the grid-electrode and a conductive surface. The grid-electrode is insulated from the conductive surface (Fig. 6-a), which is the surface to be protected and must be conductive, as its acts as the second electrode of the circuit. When ice forms on the surface, it bridges the circuit and the DC voltage is applied to the interface between the conductive surface and the ice. The grid-electrode can have different configurations, as shown in Figs. 6-b and 6-c. As the grid-electrode and its insulating layer can be as thick as 1 mm, this method can be considered to be a very light-weight active coating.

This method is well suited to conductive surfaces and for application to insulating surfaces, these should be made conductive. Also, this method requires a minimum of ice conductivity to ensure electrical current conduction, which completes the electrical circuit formed by the electrodes and the ice layer. This is not really a problem, as atmospheric ice is generally conductive due to the fact that it carries various contaminants [42]. However, if the ice is not conductive enough, grid-electrode spacing must be reduced considerably or the applied voltage increased in a same manner.

The configuration shown in Fig. 7 was proposed for energized conductors [41]. However, it seems more convenient to use it on ground wires, as the conductive surface could be the wire itself. With this configuration, an axial grid-electrode surrounding the wire must be used. This seems to be difficult to set up and install as the grid-electrode must be electrically insulated from the wire. Also, more studies and experiments will be carried out, under different icing conditions and using different electrode size and material, in order to optimize method efficiency.

Another method was proposed recently to avoid ice adhesion on surfaces [43]. This method, which can be considered as an active icephobic material, is based on the assumption of ice surface electrical properties caused by the presence of a liquid-like layer. Present at temperatures below -20ºC and with a thickness of a few nanometers, the liquid-like layer can provide an ordered orientation of the randomness of the water molecules. This results in a high density of electrical charges at the ice surface interface, either positive or negative, dependently of the exposed surface charge. In this context, if a charge is generated on the surface coming in contact with the ice, it is possible to modify the adhesion between the two surfaces. As like charges of same polarity repel, DC voltage from an external source that matches that of the charge occurring in the liquid-like layer is applied to the surface, which reduces the adhesion between the ice and the surface.

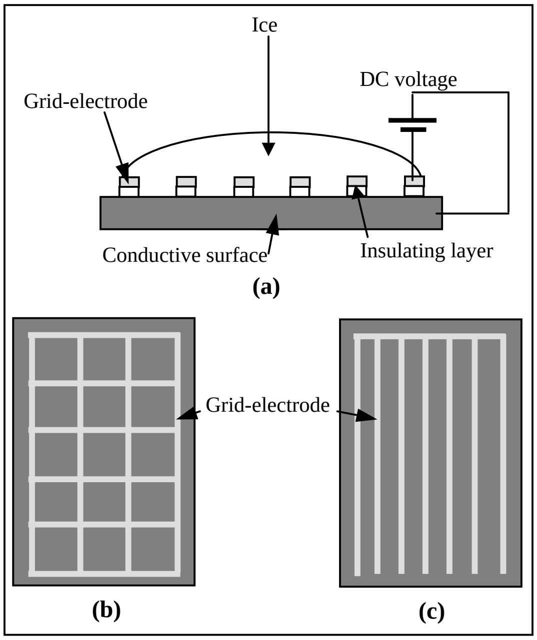

Fig. 6. Principle of generation of ice electrolysis by application of a DC voltage between ice/solid interface [41].

As this method aims to break intermolecular forces between the ice layer and the exposed surface, the principle is quite different from the electrolysis method described previously. Here, the exposed surface, which must be conductive, is coated with a dielectric layer. The DC voltage of negative or positive polarity is applied to the conductive surface. By polarization, the dielectric surface, exposed to ice accumulation, acquires a charge of the same polarity as the conductive surface. If this charge is of the same polarity as that of the ice, then the substrate becomes an icephobic surface as it and the ice repel each other.

The advantage of this method is that no grid-electrode insulated from exposed conductive surface is needed since the DC voltage is only applied to the conductive surface. Also, the amount of electrical energy required is small and the dielectric surface can be a very thin coating, like paint, applied on the conductive surface. Finally, the ice must not necessarily be electrical conductive.

However, much like ice electrolysis, this method is better adapted to ground wires than bare conductors, as the wire can act as the conductive surface. Also, the disadvantage of this method is that the dielectric coating must cover the entire conductive surface to be protected, thus the entire ground wire surface. Also, as mentioned in [43], this method needs an ice detection system and inverse the polarity of the dielectric coating by changing the polarity of the conductive surface. However, the efficiency of the method on a cylindrical surface has not been experimentally demonstrated. Finally, as mentioned previously, the addition of an active coating on a wire must satisfy some specific constraints, which could affect the applicability of such method for ground wires.

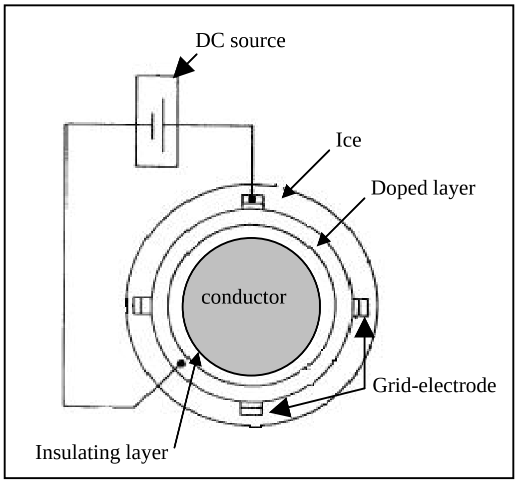

Fig. 7. Ice electrolysis method for bare conductor application (figure based on [41]).

Finally, a general remark can be made concerning the efficiency of these active coatings, particularly in the case where the operation starts late. In this situation, if the ice layer is cylindrical, as illustrated in Fig. 7, it will not adhere to the wire but, due to its cylindrical shape, will not shed by natural forces.

C. *Active Ice Shedding Methods*

As active and passive icephobic coating seem to be attractive for ground wires, active ice shedding methods can be used on both ground wires and bare conductors. Since the last review presented in [3], only two new methods dedicated to aerial line de-icing have been identified. Both methods are active mechanical techniques that induce mechanical ice shedding by different ways (involve different ways of mechanically breaking the ice away from the conductors.)

The first method uses an apparatus which is similar to the Protura vibrating device presented in [3]. This apparatus, called ice-shedder device, shown in Fig. 8, is attached to conductors and uses a motor to move an unbalanced weight, which causes the device to vibrate. However, the vibration frequency generated by the ice-shedder is in the range of the natural frequency of the span and not in the range of ultrasounds, like the Protura device. These vibrations are then transmitted to the wire [44], which causes an oscillation of the wire that is sufficient to substantially shed ice. The output of the motor can be regulated so that the wire may be ramped through several frequencies of oscillation, thereby improving its ice-shedding ability. Some preliminary tests were conducted on power lines with a span of about 500 feet and a diameter of 1.2 inches [44]. By operating the ice-shedder device within a frequency range of approximately 1.5-8.0 Hz, power line displacements of between about 4-13 inches were observed, with power line accelerations of between approximately 0.5-14 g. Accumulated ice was adequately shed from the power lines within these ranges, with hanging ice being the most easily shed and tubular type ice being the most difficult to shed.

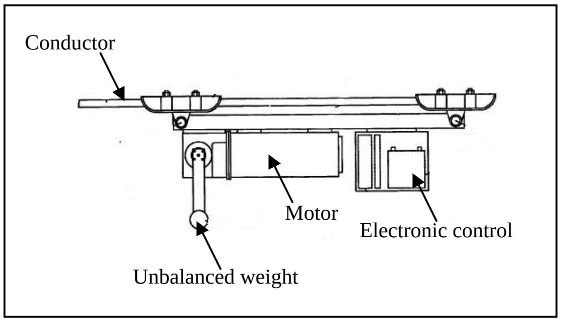

Fig. 8. Ice-shedder apparatus (figure based on [44]).

The main advantages of this technique are that it can be installed easily on existing bare conductors and ground wires, and that it is manufactured to support high mechanical constraints and can be easily automated. Moreover, the ice-shedder device can be directly driven by power from the bare conductor line to which it is attached and can consequently function online. For ground wires, an external power supply must be added. Finally, this technique could be applied to bundle conductors with minor modifications. However, this application has not yet been tested.

The main disadvantages of this method could be the long term mechanical damage to the power lines or support insulators generated by the high oscillation magnitude. Also, the de-icing capacity of this method and particularly the maximum radial thickness of ice and the maximum span length than can be deiced are presently unknown.

The second technique consists of using a specifically designed apparatus to slowly twist the wire or the conductor around its longitudinal axis and then release suddenly the elastic mechanical energy accumulated by torsion [45]. The rotation can be achieved in the direction of the whorl of the outside stranding or in the opposite direction. In this situation, the outer diameter of the ground wire or conductor decreases or increases, respectively, which induces the ice to crack at the ice/wire interface and facilitates shedding. When the wire is suddenly released, the accumulated elastic energy breaks and expels the ice deposit, which was previously weakened by the twisting phase.

The main advantages of this twisting de-icing system are that it is effective for all types of ice accretion and can be easily automated for ground wires and bare conductors. In the last case, it does not require that power be interrupted so that service to customers is maintained during the de-icing procedure. The system can also be powered directly by line current. Moreover, this technique requires very low energy consumption, around 0.05 W/m of wire. Also, because the deformation is below the elastic shear limit of the wire material, the twisting does not damage it by fatigue.

The main disadvantages are that the apparatus is quite complex as it needs an electric motor mounted on a rigid attachment at the height of the wire; a reduction gear box and a magnetic clutch coupled at the motor; a control module; and an ice detection unit. Also, its installation is not easy as some modifications of the ground wire or conductor attachments are required. Finally, this technique cannot be used for bundle conductors.

The same general remark as made for active ice coatings can be made for active ice shedding methods. It seems to be more difficult to remove a cylindrical ice layer than an asymmetrical one with both apparatii.

VI. CONCLUSIONS

The review of literature shows that all the methods can be classified into three groups: (i) added permanent methods; (ii) punctual methods; (iii) inline methods. Also, this review reveals that only 19% of all the inventoried methods are efficient and currently in use, and that none of these methods are permanent. From a technical point of view, all theses methods, and especially the added permanent methods, permanently installed on bare conductors or ground wires must satisfy electrical, mechanical, and thermal constraints generated during the normal operating conditions or during specific defaults like a short-circuit or lightning strike, for example. Some of these constraints are generally not taken into account in the development or the applicability of a method. In the same context, most permanent methods do not meet all the constraints, especially those thermal, which require particular attention. All the methods based on coatings are particularly concerned by thermal constraints, which can affect the coating and the normal operation of the line during the warm seasons.

Some very interesting de-icing methods under consideration for use by Hydro-Québec have been presented. The applicability of a given method for a particular line or network depends on many factors, such as the degree to which the method can be applied to power lines, the basic energy requirements, the approach, the efficiency level, and the cost of infrastructure and operation. These methods could be applied to bare conductors or ground wires.

On the other hand, new developments in materials science and ice adhesion have reinitiated interest in icephobic materials. Advances in nanotechnology have allowed for the development of some new highly- and super-hydrophobic materials, which show good potential as icephobic coatings. Low sliding angle (α) combined with high CA could improve the dewetting of supercooled water droplets during the ice accretion process and avoid adhesion of these on exposed surfaces. It could be possible to treat ground wires as well as bare conductors with these icephobic coatings. This technique not only modifies the surface properties of the material to be protected and, being in the nano- or microscale, this passive and inert coating would be less prone to thermal, electrical, and mechanical constraints than other thicker coatings. However, to the best of our knowledge, no systematic research has yet been carried out on the relation between superhydrophobic textured surfaces and atmospheric ice adhesion strength. Particular attention must be paid to the role of sliding angle and high surface roughness to the process of anchorage of supercooled water droplets on exposed superhydrophobic surfaces.

Similarly, active coatings seem to be another attractive way to prevent ice accretion. As automated active coatings, the two low-power-consumption methods proposed can be applied to ground wires, but their application to bare conductors seems to be very difficult. For the polarization method, experiments need to be carried out with cylindrical shapes. Moreover, more studies and experiments must be carried out under different icing conditions and using different electrode shapes, material, and dielectric material in order to optimize the method efficiency and life expectancy. However, these methods will not be efficient in the case of a cylindrical ice layer accumulated on the entire surface of a ground wire. In order to increase their efficiency, theses methods will have to be coupled with adequate ice detection allowing to distinguish the ice geometry accumulated on a cylindrical surface, such as a ground wire.

Finally, active ice shedding methods have the main advantages of being usable on both bare conductors and ground wires. They also do not require line shutdown during de-icing. As for mechanical methods, they have low power consumption and can be fully automated. Also, they seem more efficient in the case of a cylindrical ice accumulation than active coatings. However, as mentioned previously, it could be interesting to use adequate ice detection in order to optimize these methods.

In brief, some efforts must be made in order to finalize the understanding of all ice adhesion phenomena. As many de-icing and prevention techniques are currently available, additional efforts in coordination and collaboration between developers and users have to be improved in order to make methods operational on the short term.

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