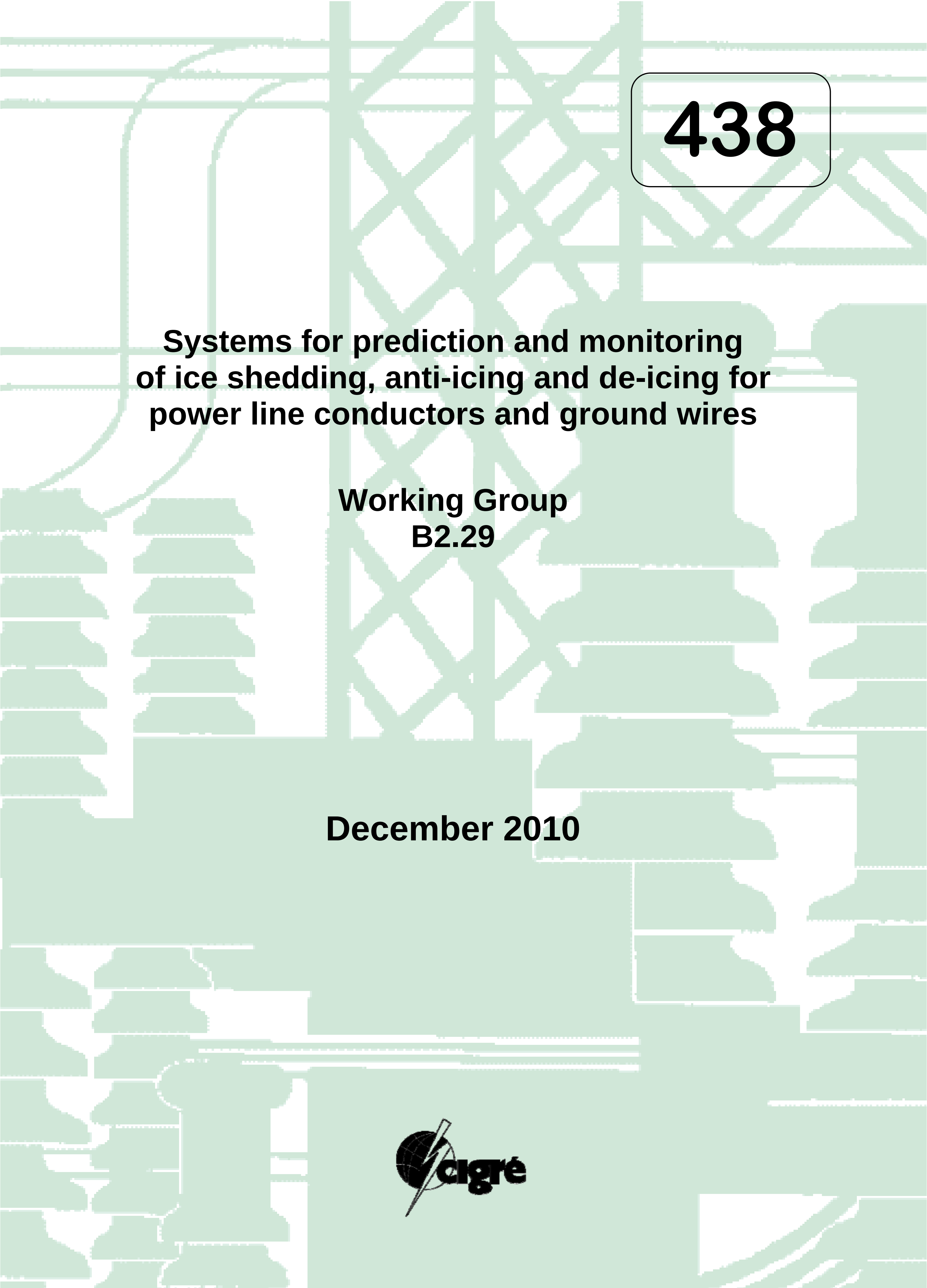

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Systems for prediction and monitoring of ice shedding, anti-icing and de-icing for power line conductors and ground wires

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Terms and definitions

Active coatings de-icing methods: *De-icing techniques* which require electrical energy to activate heating effects of the coating material, but much less so than *thermal methods*. For example, some of these methods use the heat losses from dielectric materials covering a conductor or are based on the use of ferromagnetic coatings to heat the conductor surface.

Anti-icing techniques: Techniques used to prevent or reduce ice and snow from accumulating on *phase conductors* or *ground wires* by weakening *ice adhesion* strength or by preventing freezing of *supercooled water droplets* on impact, particularly by the use of *icephobic coating techniques*.

Atmospheric icing: The expression "atmospheric icing" comprises all processes where drifting or falling water droplets, rain, drizzle, or wet snow in the atmosphere freeze or stick to any object exposed to the weather.

Bending strength: The ability of a structural member to resist breakage when subject to an internal bending moment.

Brittleness: Character of a material mechanical behavior involving no visible deformations prior to fracture.

Compressive strength: The capacity of a material to withstand normal compressive stresses. When the limit of compressive strength is reached, materials are crushed or yield.

Contact angle: The value of the angle a drop of water makes with the surface.

Creep: The inelastic, continuing deformation of a solid material beyond the instantaneous deformation, when a load is applied and sustained.

De-icing techniques: Techniques used to remove or reduce ice accretion on *phase conductors* and *ground wires*. Contrarily to anti-icing techniques, they are activated late during or sometimes after the ice storm. They comprise *passive methods, active coating methods, mechanical methods, and thermal methods.*

Dielectric material: A material that acts as an electrical insulator that may be polarized by the action of an applied electric field.

Dielectric permittivity: A measure of how an electric field affects, and is affected by, a dielectric medium.

Dry snow: A type of *precipitation icing* that accretes at sub-freezing temperatures. This type of accretion has low density and low adhesion, and appears rarely and when the wind speed is very low, i.e. below 2 m/s.

Ductility: Character of a material mechanical behavior involving substantial inelastic deformation and visible deformations at stresses well below fracture.

Freezing rain: A type of *precipitation icing* that falls in liquid form but freezes on impact to form a coating of glaze upon the ground and on exposed objects.

Glaze ice: A type of *precipitation icing* resulting in transparent ice accretion of density 700 kg/m^3 to 900 kg/m^3, sometimes with the presence of icicles underneath the wires. It very strongly adheres to objects, and is difficult to knock off.

Ground wire: A conductor having grounding connections at intervals and that is suspended usually above but not necessarily above the line conductor to provide protection against lightning discharges.

Icephobic coatings: *Anti-icing method* used to reduce or eliminate ice adhesion force on coated equipment such as *phase conductors* or *ground wires*.

Icephobic surface: A surface on which ice adhesion is low.

Interphase spacers: Composite rod insulators of suitable length to keeping conductors separated during icing events or ice un-loading, thus reducing the potential adverse effect of ice build up on electrical clearances.

Joule effect: A physical phenomenon by which heat is generated by the electrical current flowing through a conductor.

Liquid water content (LWC): The mass of water per unit volume of air, typically expressed in g/m3.

Mechanical de-icing methods: Methods involving ice breaking in order to accelerate *ice shedding*. Generally, most of the mechanical methods are based on two strategies. One strategy consists in breaking the ice by *scraping methods* and the second by *shock waves methods*.

Natural ice or snow shedding: The process of reduction of the accumulated ice and snow on ground wires and phase conductors as it occurs naturally, without human intervention.

Passive de-icing methods: *De-icing techniques* which do not require any external energy input other than from natural forces: wind, gravity, incident radiation and temperature variations.

Phase conductor: Any conductor other than the neutral conductor.

Precipitation icing: A type of *atmospheric icing* which is caused by rain droplets or snowflakes that freeze or stick to the icing body.

Quasi-liquid layer: This is a water film which is generally present at the surface of ice as well as at the ice-solid interface.

Rime icing (in-cloud icing) : A porous, opaque ice deposit which is formed by the impaction and freezing of *supercooled water droplets* on a substrate.

Scraping methods: A *mechanical de-icing technique* consisting in removing accreted ice by using scrapers, rollers or cutters attached to a rope which is pulled by linemen.

Shock wave methods: A *mechanical de-icing technique* consisting in creating a shock wave which is propagated along the conductor to induce ice shedding.

Sublimation: The release of vapour molecules to the ambient air from the ice surface.

Supercooled water droplets: Water droplets whose temperature is below 0 °C, but which are still in the liquid state.

Superhydrophobic surface: A surface whose *contact angle* is greater than 150°. Such a surface has a repelling effect on water droplets.

Tensile strength: Ratio of the maximum load a material can support without fracture when being stretched to the original area of a cross section of the material.

Thermal de-icing methods: These are *de-icing techniques* based on Joule effect by which line conductors are heated by the passage of electrical current, AC or DC, in order to melt the ice deposits and hence cause ice shedding.

Wet snow : A type of *precipitation icing* which is observed when the air temperature is just above freezing point, usually between 0.5 °C and 2 °C. The density of wet snow varies in a wide range, but is normally significantly higher than that of snow on the ground.

1 Executive Summary

1.1 Introduction

Heavy ice or wet snow accretion on ground wires and phase conductors of overhead lines may lead to major service outages. One of the most practical solutions to combat icing problems is a procedure for monitoring ice and snow accumulation before its load reaches a dangerous level, allowing time to remove the accreted ice or snow or adjust system operations.

From the point of view of power line maintenance, it would be difficult to develop a common strategy to protect all overhead power lines against the damage caused by severe ice and snow accretion. The initial approach is to consider expected ice loads from available data bases. Several methods then exist to reduce or prevent icing on conductors and ground wires. Many utilities in cold climate regions have developed and used methods and strategies to reduce ice loads using anti-icing (AI) and/or de-icing (DI) methods. Generally, AI methods are employed before or early during ice accumulation, whereas DI methods are activated during, and sometimes after ice has accumulated.

This technical brochure, resulting from the work of Working Group B2.29, essentially aims at presenting and discussing some operational or potential AI/DI systems. However, for a better understanding and appropriate application of the AI/DI techniques, some fundamental aspects of icing are also provided in the brochure. Moreover, the promising potential of new materials as AI coatings, as well as the role of modern meteorological forecasting models for reliable use of AI/DI techniques are also discussed. This brochure has been presented in such a way as to raise the level of understanding of the subject matter, including a thorough referencing to allow for deeper information and study.

1.2 Process of natural ice and snow shedding and prediction models

Ice shedding from ground wires and phase conductors, that is any phenomenon of ice mass reduction, may occur through the following mechanisms:

Ice melting starts on the external part of the ice at air temperature above 0°C. This stage is associated with a low shedding rate which is mainly influenced by air temperature, solar radiation and wind velocity. Then after a short period, melting occurs at the ground wire/conductor-ice interface resulting in ice chunks dropping off under the effect of wind and gravity.

Ice sublimation consists of the release of vapour molecules from the ice surface to the ambient air. The process depends on the gradient between the water vapour concentration for saturated conditions and that of moist air. The most important atmospheric parameters influencing sublimation are the relative humidity of air, air temperature, and wind velocity.

Ice mechanical breaking is a consequence of adhesive or cohesive failure of the accretion. Sudden ice shedding can cause the conductors to jump sometimes leading to flashovers especially when they are vertically arranged. It can also cause damage to the line and supporting structure.

Snow shedding from ground wires and phase conductors differs from ice shedding mainly because the process and structure of ice and snow accretion are different. The principal condition of snow growth is that adhesive forces between the snow and ground wire/conductor surface as well as cohesive forces between the snow flakes are high enough to keep the snow flakes together on the ground wire/conductor. Snow sheds from the ground wire/conductor when aerodynamic and gravitational forces exceed these adhesive and cohesive forces.

1.3 Mechanisms of ice adhesion

Research so far shows that the two main influences on ice adhesion are the electrostatic forces present at the ice-solid interface and the surface roughness of the substrate.

As concerns the electrostatic forces, materials or coatings with very low dielectric permittivity such as fluoropolymers exhibit low ice adhesion strengths. As for substrate roughness, it plays a crucial and complex role in ice adhesion strength. In the presence of strong mechanical interlocking, ice cracking and even ice de-bonding can be observed due to excessive pressure build-up resulting from air trapped in closed pores. Therefore, the engineering of an optimum surface roughness, with superhydrophobic properties for instance, can create enough internal stress to de-bond ice, particularly when the texture is composed of a low dielectric material.

Other parameters should also be taken into account to fully understand the ice adhesion mechanism: temperature and the type of precipitation (e.g. impact velocities of supercooled water droplets) that influence water penetration within a 3-dimensional surface structure, as well as the shape and size of the ice crystal grains affecting ice adhesion strength.

1.4 Operative and design systems for anti-icing and de-icing

In general, AI and DI techniques belong to one of the following four categories:

i) Passive methods based on natural forces or physical geometry;
ii) Active coatings and devices;
iii) Mechanical methods based on breaking down the ice;
iv) Thermal methods based on ice melting.

In what follows, a brief overview of these method categories is presented. However, this section constitutes the bulk of the Technical Brochure where most methods in each category are described in detail.

Passive methods are ones which do not require an external source of energy but rather use natural forces such as wind, gravity or solar radiation, or phase/circuit geometry. Consequently, they can function on both energized and non-energized conductors as well as ground wires. Passive methods include most of the anti-icing methods used to prevent or reduce the formation or development of wet snow and ice on conductors or ground wires. To achieve this, different strategies are used: (i) weakening ice adhesion strength, (ii) preventing freezing of supercooled water droplets on impact, (iii) using a combination of specific devices for limiting the impact of ice overload on conductors, and (iv) exploiting natural forces such as wind, gravity or solar radiation in order to limit the adverse effects of ice loads on overhead lines. Some of these methods are already effective for wet snow but their efficiency for ice needs to be studied.

Active coating method s require some electrical energy to be effective. One of the proposed methods makes use of losses in a specific dielectric coating covering the entire surface of the conductor. By choosing an adequate dielectric coating among ferroelectric materials, it is possible to maintain the surface conductor temperature above the freezing point in order to melt the ice/substrate interface. However, this would require the use of a higher frequency, 60 kHz, instead of the normal 50 or 60 Hz service voltage frequency. This condition is problematic as the use of such high frequencies can lead to electromagnetic perturbations and other problems, and needs additional investigation. However, most of the proposed methods are not available commercially. In the same area, other methods are based on the use of a ferromagnetic coating for the purpose of sustaining a positive temperature of the energized conductor surface. Instead of absorbing energy from the electric field, the ferromagnetic coating absorbs energy from the magnetic field, which is at a maximum at the surface of the conductor.

Mechanical methods refer to any method involving ice breaking in order to accelerate ice shedding. In most cases, they can be considered as DI methods as they are used to speed the shedding process after snow packs or ice have formed on conductors or ground wires. It has been demonstrated that mechanical methods require around 100,000 times less energy than thermal methods to force ice shedding. Generally, most of the mechanical methods are based on two strategies. One strategy consists in breaking the ice by scraping it and the second in releasing energy from shock waves, vibrations or ground wire/conductor twisting to pull or fling off the ice. One of the main advantages of mechanical methods is their ease of application compared to thermal methods. In fact, mechanical methods are preferred for timely and fast intervention to de-ice short critical sections of a power network. However, in the absence of any precise instructions, mechanical methods involving significant bending of ground wires/conductors should be avoided for optical ground wires to prevent damage to the optical fibers.

Thermal methods include all non-natural methods causing the ice to melt in order to force shedding. They consist in the heating of line conductors or ground wires to prevent ice accretion or for de-icing purposes. It is recognized worldwide as the most efficient engineering approach to minimize the consequences of severe ice storms on overhead lines. Some of these methods can be used for anti-icing purposes in order to prevent supercooled water droplets from freezing during their impact on the conductor surface. In that case, less energy is required for anti-icing than for de-icing. Thermal methods can be divided in two categories: (i) methods based on pure Joule effect, and (ii) methods based on dielectric losses, radiative waves and external heat sources, which are discussed in detail in the Technical Brochure.

1.5 New materials

Recent advances in ice adhesion physics, materials science and in analytical tools have spurred new interest in developing materials having enhanced specific properties. Icephobic materials are no strangers to such developments. It would be extremely difficult, if ever possible, to formulate a truly icephobic material (ice adhesion strength = 0). However, by drastically reducing its adhesion strength, ice may be subsequently removed using a minimum amount of work or heat or could even detach itself under its own weight. Such strategies, which are described in detail in the Technical Brochure, have great potential as efficient AI techniques.

1.6 Modern meteorological model systems

In recent years the development of meteorological weather forecasting models of the atmosphere has reached a level of accuracy and details that makes it possible to estimate the amount of ice already accreted, or to forecast the expected ice build-up on standard objects. As discussed in the TB, the most important aspect with this technique is to insert local scale models into a global weather forecasting model by nesting. Since it is not possible to insert abrupt changes in model scale from several tens of kilometres (global models) to the order of hundreds of metres (local scale models) in one step because of stability in the models, such transitions are made by nesting of intermediate models.

1.7 Conclusion

In this report, the most promising methods to combat ice accumulation on overhead line ground wires and phase conductors are discussed. However, in order to understand these methods, some fundamental aspects and processes of ice adhesion and accretion, as well as the mechanical and thermodynamic behaviour of ice and snow, including the shedding process, are covered.

A review of the existing de-icing and anti-icing technology showed interesting non-thermal methods, including passive methods, active coatings and devices and mechanical methods, but their scope is generally limited to local intervention. On the other hand, a survey of anti- and de-icing methods showed that the heating of ice-covered line conductors by electrical current has been accepted worldwide as the most efficient engineering approach to minimize the sometimes catastrophic consequences of severe ice events, thus increasing power system reliability. Either AC or DC has been used for ice melting. The technologies for both types of current are available, the methodology has been developed, and operational experience with ice melting systems has been acquired for several decades.

Furthermore, new technologies based on the use of icephobic materials are discussed. This approach is promising, and could present a good potential for future applications. Also, as any anti-icing and de-icing techniques depend on reliable monitoring and predicting icing events, the important role of modern meteorological forecasting systems is briefly discussed.

2 Introduction

When atmospheric ice accretes on overhead line conductors, different phenomena can be observed which can lead to small perturbations or catastrophic damage depending on the severity of the ice storm and the intensity of the coincident wind speed. These phenomena can be divided in two categories: moderate and severe icing events.

In some moderate icing events affecting lines in open terrain and exposed to transverse winds, ice deposits may not be large enough to pose an immediate risk of damage to the conductor. However, under specific conditions which mainly depend on the type, direction and speed of the wind, as well as the shape and dimensions of the ice sleeve, an aerodynamic instability can be created. Depending on the magnitude of the forces involved, conductor galloping can occur [1]. This is characterized by large oscillatory movements generally in an elliptical trajectory in the cable transverse plane. Under conductor galloping, phase-to-phase or ground wire - phase flashovers may occur, leading to widespread power outages and potential physical damage to conductors. The resulting conductor motions may also lead to high stresses on towers, with possible damage to hardware, tower steelwork and insulator tension strings, as well as conductor fatigue.

During severe icing events, glaze ice deposited on conductors increases their weight resulting in heavy loads on the structural components of power lines with possible conductor breakages and tower collapses or phase clashing causing outages and conductor damage. A recent example of the catastrophic consequences of a severe ice storm is the one that struck a relatively narrow swath of land from Eastern Ontario to southern Quebec to Nova Scotia in Canada, and bordering areas from Northern New York to Southeast Maine in the United States, in January 1998. With up to 100 mm of ice on the ground in the Montreal area, this extreme ice storm exceeded the design limits of the Hydro-Quebec electrical line system [2]. These limits had been raised after 1961 when a storm in the same region deposited 30 to 40 mm of ice on the OHL system. Nevertheless, many power lines broke and over 600 towers collapsed in chain reactions under the weight of the ice and the effects of conductor failure, leaving more than 1.5 million people without electricity for up to a month [2].

In the past, utilities have adopted two different philosophies regarding ice accretion on power lines. Some have accepted the necessity to build strong lines that are capable of withstanding the largest ever recorded ice/wind load and have sufficient phase spacing [3]. This philosophy required the use of passive methods like vibration dampers, anti-galloping devices, and changes in geometry, dimension, structural and mechanical strength of line components, etc. Other utilities have chosen to develop and use methods which prevent ice-induced damages on overhead lines [3]. This latter philosophy is based on the use of active methods to reduce the ice loads on conductors. From their own experience, these electric utilities have developed methods and strategies for reducing ice problems. These strategies can be divided into two main families commonly identified as anti-icing methods and de-icing methods. Generally, anti-icing methods are employed before or early during an ice storm whereas de-icing methods are activated late during or after the ice storm when on-site interventions are required.

However, the severe ice storms in North America, Europe and China in recent years highlighted the fact that de-icing approaches and strategies are difficult to implement when a large zone is affected, and that new strategies based on the combination of active and passive methods had to be developed. This renewed awareness has thus allowed the emergence of new anti-icing and de-icing methods as well as questions concerning the standards used in the construction of overhead electrical lines in critical areas with high severe ice storm recurrence. Another related issue concerns the climate changes that increase the likelihood of ice storms in regions where they were not expected when the power grid was designed.

In general, de-icing techniques belong to one of the following four categories:

- Passive methods based on natural forces
- Active coatings and devices
- Mechanical methods based on breaking down the ice
- Thermal methods based on ice melting.

The feasibility of the most suitable method for a particular line or network has to be evaluated. This evaluation is done by considering the following factors:

- the performance requirements of the line in the power grid
- the degree to which the method can be applied to a given line
- the basic energy requirements
- the efficiency/risk and security level
- the cost of the associated infrastructure and operation.

The passive methods do not require any external energy other than from natural sources: wind, gravity, solar radiation and temperature variations. As such, passive techniques do not hinder ice formation directly, but help to limit its problematic effects. For example, the technique using counterweights blocking the rotation of the conductors (see Section 7.2), and that allowing the conductors to slide in their suspension clamps or be dropped for a given overload do not prevent ice deposition. The former helps only to reduce to some extent the quantity of ice that is deposited, while the latter helps to eliminate or reduce the loads transferred to adjacent supports.

Active coating methods require electrical energy to be effective. For example, some of them use the heat losses from dielectric materials covering a conductor or are based on the use of ferromagnetic coatings to heat the conductor surface. The goal of these methods is to prevent significant ice accretion on conductors.

The mechanical methods are aimed at removing accreted ice by mechanical means. These are *ad-hoc* methods applied locally in specific spans and terrain conditions. They include methods like rolling, scraping, induced shocks. These methods are automated, or manual where iced spans are accessible, and require the use of helicopters where spans are less accessible. Because of their makeshift character, the safety and efficiency of these techniques are not proven, and therefore none are presently recommended as an effective de-icing method on a large scale. They are used typically in emergency situations and with limited success, to de-ice the lines where accretions are significant and there is a risk of a second icing event occurring before the ice is shed.

The thermal methods are based on the concept of heating line conductors by electrical current to force ice melting and shedding. Some of these methods can also be used for preventing ice accretion by maintaining the external conductor surface at a temperature above 0 °C during the icing event.

In general, the mechanical and passive de-icing methods are less efficient than thermal ones as they can only be applied locally to a few spans or line sections while the ice storm footprint is typically much larger. In contrast, thermal de-icing techniques can be used on larger segments of power grids, typically on high priority lines, and they are effective if triggered in sufficient time before the ice accretion becomes too large. Moreover, suitable thermal de-icing technologies have been developed in the last few years [4].

Icephobic coating techniques are intended to reduce or eliminate ice adhesion forces on coated equipment such as phase conductors or ground wires. Many research efforts have been deployed to use design and test new materials to reach this performance objective.

This technical brochure aims at presenting some operational de-icing systems, and at recommending the most appropriate ones applicable to overhead power lines with any voltage including HV and UHV. However, in order to reach these objectives, some fundamental aspects and processes of ice and snow adhesion and accretion on OHL conductors as well as the prediction of their occurrence and severity are reviewed. Also, aspects of the mechanical and thermodynamic behaviour of ice, as well as the process of ice shedding, are presented, as their knowledge is required to understand de-icing and anti-icing methods. Finally, some potential promising methods based on the use of new icephobic materials are described.

3 Ice and snow accretion processes

In order to understand anti- and de-icing methods and apply them to OHL power networks, it is important to have a good knowledge of the different types and processes of ice and snow accretion on ground wires and conductors. These types and processes are described in the CIGRÉ TB 291 “Guidelines for meteorological icing models, statistical methods and topographic effects”, issued by CIGRÉ SCB2 WG16 “Meteorology for overhead lines” [5]. Other references are [6,7,8,9,10]. Some excerpts from these sources are used for clarification of physical processes, definitions and terminology in this report.

The formation of ice and snow on overhead power lines may come from cloud droplets, rain drops, snow or water vapour. Cloud droplets are a constitutive part of fog, while rain drops and snowflakes are associated with freezing rain and snow falls, respectively. Accordingly, icing is classified into two main types:

(i) *in-cloud icing (or rime icing),* which is caused by supercooled, suspended cloud water droplets, and

(ii) *precipitation icing,* which is caused by rain drops or snowflakes that freeze or stick to the icing body.

The accretion types which occur during in-cloud icing are soft rime, hard rime and glaze due to supercooled cloud droplets. Glaze due to freezing rain, wet snow and dry snow are the accretion types which occur during precipitation icing. These icing types are principally governed by atmospheric parameters such as air temperature, wind speed, precipitation rate, relative humidity of the air, liquid water content (LWC) of the air or snowflakes, and size of water droplets or snow flakes [5,11,12,13].

(a) (b)

Figure 3.1 (a) Rime ice accretion, (b) glaze ice accretion

Rime is formed by the impaction and freezing of supercooled droplets on a substrate. When air temperature is well below $0^{\circ}C$, supercooled droplets possess small momentum and air pockets are created between the freezing droplets. This type of deposit is known as *soft rime,* and has low density and weak adhesion. When the droplets possess greater momentum, or the contact and freezing time is greater, a denser structure with stronger adhesion, known as *hard rime,* is formed. In these cases, the released latent heat of fusion is ventilated away before new droplets impinge on the same area, thus maintaining the surface temperature below the freezing point; the ice growth is therefore classed as *dry*.

Glaze ice is formed when the released heat of fusion is not dissipated before the next impingement and is therefore raising the substrate's surface temperature up to 0 °C, so that the droplet contact and freezing time is sufficiently long for a water film to form on the accreting surface, resulting in *wet* ice growth. This type of ice accretion has the greatest density and the strongest adherence to conductors. Figure 3.1 shows the visible difference between dry rime (left) and wet glaze ice (right).

Frost, or hoar frost, is a deposit of ice crystals formed when water vapour in the air condenses on a substrate of temperature below 0 °C. Increase in gravity load due to frost is normally small but the effective wind area can be increased significantly and cause adverse effects if the accumulation persist. Frost can also cause high energy losses due to corona effects on HV and UHV lines.

Dry snow accretes at sub-freezing temperatures. It has low density and low adhesion on OHL conductors. Therefore, it appears rarely and when the wind speed is very low, i.e. below 2 m/s; it sheds naturally as the wind speed increases.

Wet snow accretion is observed when the air temperature is slightly above the freezing point, usually between 0.5 °C and 2 °C, and may occur under any wind speed. The density of wet snow varies in a wide range (see Table 3.1), but is normally significantly higher than that of fresh snow on the ground, mainly due to wind pressure effects and LWC. The adhesion of wet snow to conductors is relatively poor at air temperature above the freezing point; it may become very strong, however, if the temperature drops below 0 °C after the accretion, which is quite common.

Table 3.1 summarizes, in general terms, the main characteristics of the accretion types described in this paragraph [5].

Table 3.1 The main characteristics of different icing accretion types [5]

Ice and snow type	**Density (kg/m^3)**	**Description**
Glaze ice	700-900	Translucid solid ice, sometimes with icicles underneath the ground wires/conductors. The density may vary with the content of air bubbles. Adhesion is very strong and difficult to knock off.
Hard rime	300-700	Homogenous opaque structure with inclusions of air bubbles. Pennant shaped against the wind on stiff objects, more or less circular on flexible wires and conductors. Adhesion is strong and more or less difficult to knock off, even with a hammer.
Soft rime	150-300	Granular structure, “feather-like” or “cauliflower-like”. Pennant-shaped also on flexible ground wires/conductors. Can be removed by hand.
Wet snow	100-850	Various shapes and structures are possible, mainly dependent on wind speed and torsional stiffness of conductor. When the temperature is close to zero it may have a high liquid water content, slide to bottom side of the object and slip off easily. If the temperature drops below zero after the accretion, the adhesive strength may be very high.
Dry snow	50-100	Very light pack of regular snow. Various shapes and structures are possible, very easy to remove by shaking of ground wires/conductors.
Hoar frost	<100	Crystal structure (needle-like). Low adhesion, easily blown off.

4 Mechanical and thermodynamic properties of ice and snow

Atmospheric icing and its accretion on power transmission lines may cause considerable damage to power networks in cold climate regions. In this chapter, some of the fundamental mechanical and thermodynamic properties of ice and snow are presented, which will help understanding the process of AI/DI methods.

4.1 Mechanical properties of ice

The mechanical properties of atmospheric ice depend mainly on temperature, wind velocity, the liquid water content (LWC) of the air and the volume mean diameter (vmd) of the supercooled droplets during ice accretion. These parameters also depend on the ambient temperature, ice structure, density, grain size, specimen size, loading rate and failure mode.

Solid ice is a polycrystalline material. Depending on the ambient temperature, loading conditions, and strain level, ice can be interpreted either as elastic, inelastic and ductile or as almost linear elastic until brittle fracture. At temperatures closer to the melting point, ice undergoes creep deformation, which is divided into four stages: instantaneous deformation, primary creep (transient), secondary creep deformation (steady-state), and tertiary creep resulting in failure [14]. When ice is subjected to large and sudden loads, its brittle behaviour dominates its ability to creep. The maximum tensile strength occurs in the ductile to brittle transient regime. Ice strength greatly depends on the load type and failure mode. Anyhow, failure of ice in all load types proceeds in three distinctive stages: (1) crack nucleation, (2) crack propagation, and (3) ice fracture. Crack nucleation without pre-existing flaws requires that stresses be locally concentrated at levels matching the theoretical cleavage or cohesive strength. There are several candidate mechanisms for this concentration of stress: dislocation pile up, grain boundary sliding, thermal expansion of extraneous inclusions and elastic anisotropy of the ice crystals [15].

According to the results of compressive strength [16] and bending strength tests [17], atmospheric ice shows higher strength under compressive loads, and increases with decreasing temperature. It also increases and then decreases with increasing strain rate. The bending strength of atmospheric ice has approximately the same value as tensile strength, since tensile failure will govern. At the lower strain rates, the bending strength of the ice increases with decreasing temperature while no temperature effect is observed at the higher strain rates. It is also observed that, depending on the temperature, increasing the strain rate can increase or decrease the ice strength. Ice failure in brittle regime is dominated by crack nucleation and propagation. That is why the de-icing methods require comprehensive information about the fracture toughness of atmospheric ice. The results of fracture toughness of atmospheric ice [18] showed that at very cold temperatures (around -20 ^{o}C), the fracture toughness of atmospheric ice increases owing to higher strength as demonstrated for fresh water [19].

In light of the above discussion on the mechanical properties of atmospheric ice, one can conclude that de-icing methods by mechanical breaking of the accreted ice will be more effective when the ice failure occurs under tensile stresses in fracture classical opening mode I, in the brittle region of the stress-strain rate curve, at strain rates greater than 10^{-5} s^{-1}. A temperature range between -5 °C and -10 °C will also allow better results for de-icing because in this range, the ice shows neither ductile behaviour (due to warm temperatures) nor high strength (due to cold temperatures) [18].

In short, the mechanical properties of atmospheric ice and its failure modes under various loading conditions are of interest in many projects including de-icing by mechanical breaking and ice shedding (modelling, prediction, prevention). It should be taken into account that ice shows higher strength at colder temperatures and that de-icing techniques with rapid loading producing high strain rates yield better results in ice removal projects. This information may improve the precision of ice shedding models.

4.2 General heat balance

The thermal behaviour of overhead conductors is described in [20], taking into account the Joule, magnetic, solar and corona effects as heat gains, and convective, radiative and evaporative cooling as heat losses. However, this heat balance has to be extended to account for icing conditions: the general heat balance equation is reported in [21]. More precisely, its form applied to a power line conductor exposed to a two-phase air/water spray flow is as follows:

$$Q_j + Q_f + Q_k = Q_c + Q_e + Q_w + Q_r \tag{4.1}$$

where Q_j is the rate of heat generation, in watts, by Joule effect, Q_f is the combined heat flow rate due to stagnation and friction effects in the boundary layer, Q_k is the kinetic energy rate of the impinging water droplets, Q_c , Q_e and Q_w are the heat loss rates due to convection, evaporation and due to impinging water droplets respectively, and Q_r is the rate of radiative heat exchange. The terms in Equation 4.1 can be parameterized as presented in [21].

The convective term is expressed by:

$$Q_c = hA(T_s - T_a) \tag{4.2}$$

where h is the overall heat transfer coefficient (W/m^{2}K), T_s (°C) is the conductor surface temperature, T_a (°C) is the air temperature, and A (m^2) is the exposed conductor surface. The heat loss rate due to water layer evaporation from the conductor surface is expressed in Equation 4.3.

$$Q_e = 0.622 \cdot h \cdot l_e \cdot A_w \cdot (p_{sat,s} - p_{sat,a})/(c_p \cdot p_a) \tag{4.3}$$

where l_e (J/kg) is the latent heat of evaporation, A_w (m^2) is the wetted surface of the conductor, $p_{sat,s}$ (Pa), $p_{sat,a}$ (Pa), and cp are the saturation vapour pressures at the surface, air temperature over water and specific heat of air, respectively, and where p_a (Pa) is the atmospheric pressure. The wetted surface is estimated as equal to half of the total surface area in the calculations.

The rate of heat taken away by the impinging water droplets is formulated as

$$Q_w = \kappa_1 \cdot \kappa_2 \cdot W \cdot v \cdot E \cdot D_c \cdot L \cdot c_w \cdot (T_s - T_a) \tag{4.4}$$

where κ_1 and κ_2 are correction factors, W (kg/m^3) is the liquid water content (LWC) of air, v (m/s) is the air velocity of the free stream, E is the collection efficiency, D_c (m) is the conductor external diameter, and c_w (J/kg·K) is the specific heat of liquid water. In Equation 4.4, the water droplet temperature may be assumed to be the same as air, because of their small impact velocity [13]. However, some larger water droplets could be supercooled. Furthermore, it is assumed in Equation 4.4 that the air water droplet collection area is equal to the longitudinal projected area ($D_c \cdot L$) of the conductor. The collection efficiency, E, is the ratio of the water content in the free stream to the water content collected after impinging on the conductor surface. E is always smaller than unity because the small water droplets following air streamlines may bypass the conductor [13]. The leeward side of the conductor, though less exposed to droplet strikes, nevertheless gets wetted by runback water from the front side. The influence of the runback water flow toward the leeward surface of the conductor, as well the effect of supercooled water droplets are taken into consideration with coefficient κ_1. As it means additional heat loss, this coefficient should be set to $\kappa_1 \geq 1$ [21].

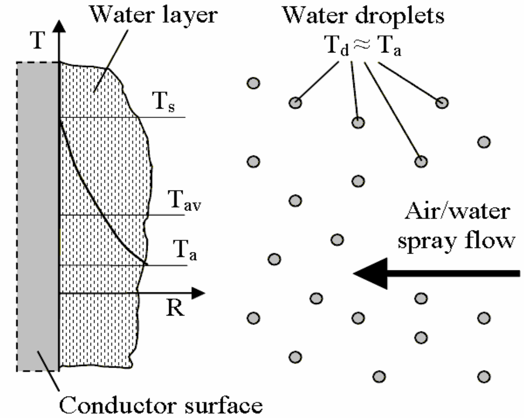


Figure 4.1 Schematic temperature distribution through water layer [22]

The non-uniform water film formed on the stranded surface by the impinging droplets cannot reach a perfect thermal equilibrium with the conductor. Let T_s be the water film temperature near to the conductor surface, and T_a be a good approximation of the temperature at the water-air interface (see Fig. 4.1). In theory, the average water film temperature, T_{av}, should be used instead of T_s in Equation 4.4. However, since the calculation of T_{av} is not feasible due to strong variations in water layer thickness, it is assumed to be the same as the surface temperature of the conductor. This effect is taken into account in the correction factor κ_2, which should be set less than unity ($\kappa_2 \leq 1$) [21]. In the setting of this term, the following factors are also taken into consideration: a slightly higher conductor temperature than 0 °C, the displacement of the water layer separation point, as well as the fact that the leeward side of the conductor is sometimes exposed to impinging water droplets in the turbulent wake.

It is a challenge to find the appropriate values of the collection efficiency, E, the overall heat transfer coefficient, h, as well as the κ_1 and κ_2 correction factors for stranded conductors. The relevant literature offers several methods to calculate the collection efficiency [22,13,23]. As for the overall heat transfer coefficient, as well as the κ_1 and κ_2 correction factors, they can be estimated from the experimental results obtained in [22]. Other related references are [24,25,26,27].

5 Process of natural ice and snow shedding and prediction models

In this chapter, the process of reduction of the accumulated ice and snow on ground wires and phase conductors is described as it occurs naturally, without human intervention. Understanding natural ice shedding processes may help improve shedding efficiency when using or designing de-icing methods.

5.1 Mechanisms of ice shedding

Ice shedding from ground wires and phase conductors, i.e. any phenomenon resulting in ice mass reduction, may occur through the following mechanisms: melting, sublimation, mechanical breaking, or any combination of them. These mechanisms are characterized by the prevailing atmospheric conditions, shedding rates, duration of ice shedding, variations of ice load, and ice strength. They are discussed next.

5.1.1 Melting

Ice mass reduction by melting consists of two phases under the condition that air temperature remains above 0°C. In the first phase, characterized by low shedding rates, melting is limited to the external part of the ice deposit, as it is affected by air temperature, solar radiation and wind velocity. When the air temperature is above 0°C, this phase usually does not last long before being replaced by the second phase. The short duration of this initial phase partly explains its lack of field observation. In the second phase, melting also occurs at the ground wire/conductor-ice interface resulting in ice chunks dropping off under the effect of wind and gravity. Shedding occurs when adhesive forces on fractured ice deposits are overcome by the aerodynamic and gravitational forces involved. This process is hastened by the fact that ice-free sections of the ground wire/conductor will heat up faster. The second phase may last a few hours, and is associated with a significantly higher shedding rate than the first, typically about 0.3 kg/m/h, but it may exceed 1 kg/m/h in some cases [28,29].

5.1.2 Sublimation

During sublimation, vapour molecules are released to the ambient air from the ice surface. The process depends on the vapour concentration gradient between the water vapour concentration for saturated conditions and that of moist air. The most important atmospheric parameters influencing sublimation are the relative humidity of air, air temperature, and wind velocity. Since sublimation occurs at the ice surface, its rate increases with the external surface area of the accretion, and consequently, with the ice mass and ice porosity. The shedding rate is always low during sublimation, in the order of 0.01 kg/m/h only [29]. The sublimation process, however, may last up to several days, in which case the mass reduction may become significant. Therefore, ice sublimation does not generally cause ice chunks falling from the ground wires and phase conductors.

Lambrinos *et al.* [30] examined the effect of atmospheric parameters on the ice mass loss during sublimation and on the sublimation flux, defined as the mass flow rate divided by the corresponding area of the ice sample. They undertook wind tunnel experiments on a cylindrical ice sample by varying air temperature, T_a, air velocity, V_a, and relative humidity of air, φ_a, in the following ranges: 243 K < T_a < 270 K, 0.5 m/s < V_a < 4 m/s, and 40% < φ_a < 90%. Experimental observations are summarized as follows.

- The mass loss increased linearly with time in the range of the conditions examined.
- The sublimation flux increased with air temperature. The dependence was found linear for low temperatures and became exponential as the temperature approached the freezing point of water. This result is explained by the significant change in the partial vapour pressure gradient, and by the dependence of diffusion on temperature.
- The sublimation flux increased linearly with air velocity due to the linear dependence of the convective mass transfer coefficient on air velocity. The slope of this linear relationship was steeper for higher air temperatures and for lower relative humidity values.
- The sublimation flux decreased with relative humidity of air. This dependence may be realized by nonlinear steeply decreasing curves for low relative humidity values, while these curves tended to become linear for higher values of humidity.

5.1.3 Mechanical ice breaking

Ice shedding by mechanical breaking is a consequence of adhesive or cohesive failure of the accretion. Sudden ice shedding can cause the conductors to jump sometimes leading to flashovers especially when they vertically arranged [31]. In turn, conductor jumps and flashover-induced shocks may cause more subsequent shedding. Since both static and dynamic loads may induce mechanical ice breaking, the following factors exert an influence on this mass reduction mechanism: wind velocity, air temperature, ice mass and strength. Ice shedding by mechanical breaking usually occurs at temperatures below 0°C. The most important factor in the breaking of the ice at such temperatures is the large displacements of the ground wire/conductor due to aerodynamic forces. Galloping conductors undergo very high-amplitude vibrations, usually resulting in fast ice breaking. Low-amplitude, high-frequency wind-induced vibrations may also remove ice from the ground wire/conductor due to fatigue type failure. Thus, the meteorological factor which has the greatest influence on natural mechanical ice breaking is wind velocity.; this has been confirmed by observations on test lines [29,32], showing that the decrease in ice mass was proportional to the square of the wind velocity. It was also observed that the slope of this relationship increased with the elevation of ground wire/conductor above ground level, which correlates with the increase of wind velocity with elevation as predicted by the classical boundary layer wind model.

Druez *et al.* [29] examined the effects of some parameters on the rate of ice shedding from mechanical ice breaking, or more precisely, on shedding rate. They found that the second important factor after wind velocity during shedding, $V_{a,s}$, was the mass of accreted ice at the beginning of shedding, P_0. These two factors are related to aerodynamic forces and thus to ground wire/conductor vibration. Other important parameters are air temperature during shedding, $T_{a,s}$, and during accretion, $T_{a,a}$, and wind velocity during accretion, $V_{a,a}$, all of them affecting the mechanical properties of ice. The authors warned, however, that the assessment of the relative importance of the aerodynamic forces and mechanical properties of ice requires further investigation, since the type of ice observed was limited to rime ice. The five variables study examination varied in the following ranges: 1.0 m/s < $V_{a,s}$ < 8.2 m/s, 0.5 kg/m < P_0 < 5.5 kg/m, -21.3 °C < $T_{a,s}$ < -6.0 °C, -20.9 °C < $T_{a,a}$ < -4.5 °C, and 1.9 m/s < $V_{a,a}$ < 4.4 m/s. The shedding rate during mechanical ice breaking may vary within a wide range, from below 0.1 kg/m/h to around 0.5-0.6 kg/m/h. The duration of such shedding events may also vary from a few hours to a few days [28,29].

Of the three mass reduction processes, mechanical breaking is the most potentially damaging for transmission lines because it is generally associated with a high shedding rate and it involves the sudden fall of ice chunks. The main characteristics of the different ice shedding mechanisms are summarized in Table 5.1..

Table 5.1. Mechanisms of ice shedding (T_a - air temperature, V_a - air velocity, φ_a - relative humidity of air, P_0 - ice load)

Mechanism	Process	Main influencing parameters	Place of appearance	Duration	Shedding rate
melting, 1st phase	simple melting due to $T_a > 0^\circ\mathrm{C}$	T_a, V_a, solar radiation	external part of ice	Short (minutes), depending on T_a	low (lack of data from field observation)
melting, 2nd phase	Ice drop off under wind and gravity	V_a, P_0	cable-ice interface	few hours	high (0.1 – 1 kg/m/h)
sublimation	vapour molecules released to ambient air	φ_a, T_a, V_a, ice surface area	ice-air interface	several days	low (ca. 0.01 kg/m/h)
mechanical ice breaking	adhesive or cohesive failure of accretion	V_a, T_a, P_0, ice strength	ice deposit structure	variable (from few hours to few days)	variable (below 0.1 to ca. 0.5 kg/m/h)

5.2 Snow shedding

The shedding of snow accretion from ground wires and phase conductors differs from ice shedding mainly because the process and structure of ice and snow accretion are different. The principal condition of snow growth is that adhesive forces between the snow and ground wire/conductor surface as well as cohesive forces between the snow flakes are high enough to keep the snow flakes together on the ground wire/conductor. Snow sheds from the ground wire/conductor when aerodynamic and gravitational forces exceed these adhesion forces.

5.2.1 Adhesion forces in snow accretion

The most important parameters governing the processes of snow accretion and snow shedding are air temperature, wind velocity and precipitation intensity. As mentioned in section 3 and summarized in Table 3.1, the two main types of snow accretion are dry snow and wet snow. Dry snow accretion occurs below freezing temperature and involves low adhesive forces; dry snow will be blown off the cable or conductor if the wind velocity reaches about 2 m/s. Thus, dry snow may only accumulate under calm conditions and usually does not give rise to significant overload since it is likely to fall due to gravity, especially if the conductor is small in diameter and has low torsional rigidity. The adhesive forces are significantly larger between the snowflakes in wet snow accretion above 0.5°C. Wet snow may not shed even if exposed to high wind speed, thus promoting the growth of heavy loads. If ambient conditions change during snow accretion such that the air temperature drops below freezing point, the wet snow will freeze in place, thus causing the adhesive forces to increase and leading to further snow growth.

Adhesive forces during snow accretion have different sources depending if the process is dry (at low air temperature) or wet (when air temperature is higher) [12]. Since overload due to wet snow accretions is more frequently observed, the factors associated with that process are of greater interest and are discussed next. The liquid water content (LWC) of snow was especially scrutinized in related research studies as it proved to be the main variable which determines whether wet snow accretes on conductors and whether it sheds.

5.2.2 Cohesive limit

The LWC of snow controls the mechanical cohesion in the snow matrix formed during wet snow accretion. Increasing the LWC of the snow matrix weakens the internal cohesive forces which keep snow particles together. Above a maximum diameter of snow deposit, aerodynamic and gravitational forces overcome the cohesive forces, the snow sleeve breaks up and the snow deposit drops off. This maximum diameter decreases rapidly with LWC as illustrated in Figure 5.1. Wind-tunnel experiments were carried out by Sakamoto *et al.* [33] to simulate wet snow accretion, and to study the conditions of wet snow accretion and shedding. Although the authors proposed an empirical relationship between initial snow water content and air temperature, they concluded that it was not possible to obtain a clear relationship between the snow sleeve water content and the cohesion of the sleeve. However, they proposed the critical LWC value of 40 % when the maximum snow sleeve diameter is around 5 cm. Above this LWC level, the snow sleeve breaks up before its diameter reaches 5 cm, meaning it will fall off the transmission line. At this critical LWC level, wet snow accretion continues if the ambient conditions remain favourable, but wet snow always sheds, at least partially, before the sleeve diameter reaches 5 cm [34]. The existence of this critical LWC threshold was also verified experimentally by Roberge *et al.* [35,36,37].

The LWC of snow sleeves was reported to be in the range of 20 to 30 % during natural events in France, and between 10 and 50 % in Japan [38]. In both countries, snow sleeves of large diameter may grow when LWC approaches the lower limit of the ranges observed, so that the resulting overload may be significant and cause damage to transmission lines.

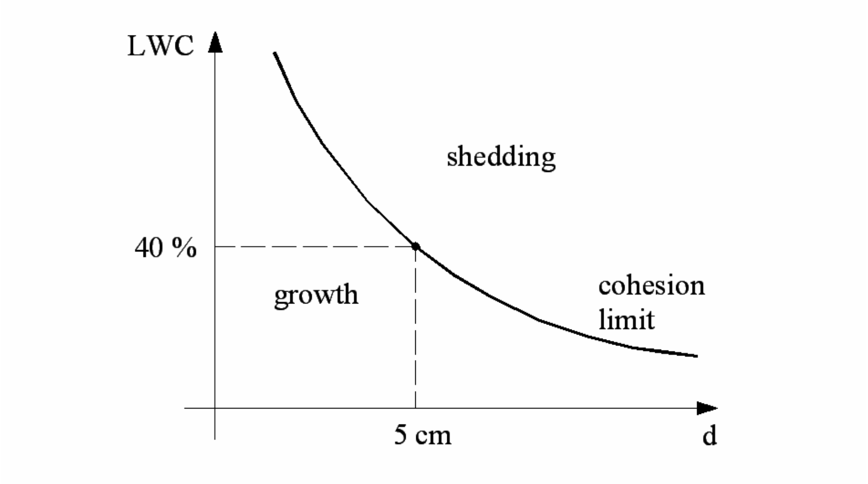


Figure 5.1 Qualitative relationship between LWC of snow sleeve and its maximum diameter

5.2.3 Factors influencing LWC

The LWC of snow accretion is the result of thermodynamic exchanges between air and the snow sleeve. The most important parameters influencing LWC are air temperature, relative humidity of air, wind velocity and precipitation intensity. Admirat presented a thermodynamic model to calculate the mean LWC of a snow sleeve as a function of sleeve growth, air temperature, differential vapour pressure (defined from the relative humidity of air), wind velocity, vertical snowflake velocity, precipitation intensity and initial snow water content which is proportional to the square of the air temperature [34]. An alternate model was developed by Poots and Skelton [39] to calculate LWC during axial growth of wet snow on a fixed cylinder. This model considered more parameters than those listed above, and the authors provided a critical precipitation rate which corresponded to the cohesive limit. The critical value depends on air temperature and wind velocity, and if the precipitation rate is less than this critical value, then LWC exceeds 40 % and the snow deposit will shed

6 Mechanisms of ice adhesion

Ice adheres to virtually any solid material. It is necessary to understand, from a theoretical point of view, what are the physico-chemical mechanisms responsible for its adhesion on a given substrate in order to study and find the proper strategies to remove or melt ice and snow from a given substrate, to prevent its formation or to reduce its adhesion strength.

Adhesion is an important and complex physical concept [40,41]. In fact, three different types of adhesion can be identified depending on the problem scale:

1. “Thermodynamic adhesion” or “ideal adhesion” defined by the reversible work needed to separate two surfaces bonded by molecular interaction forces across the interface (van der Waals and hydrogen type bonding), which are long range interactions (> 0.3 nm).
2. “Chemical adhesion” which involves the covalent, electrostatic or metallic atomic bonding across a given interface, and which are short range interactions (0.15 to 0.3 nm).
3. “Mechanical adhesion” which involves the mechanical interlocking of microscopic asperities at the interface between the two materials.

In the case of ice-solid interactions, the various factors involved are:

i. Thermodynamics related to surface tension;
ii. Influence of intermolecular forces: electrostatic, van der Waals and hydrogen bonding;
iii. Topographic influence, also referred to as roughness, that ranges from atomic roughness (vacancies, terrace, steps or ad-atom), to nano-roughness and macroscopic roughness (several micrometers);
iv. Influence of the water Quasi Liquid Layer (QLL) at the interface;
v. Influence of the chemical heterogeneity of the solid surface;
vi. Other factors such as type and conditions of precipitation.

6.1 Surface tension

Adhesion strength between two materials is referred to as adhesion work, W_a, which corresponds to the change in free energy when two separated surfaces are created for a given system. The liquid-solid-vapour system is schematically represented in Fig. 6.1 where γ_{sv} γ_{lv} and γ_{sl} are the surface energies of the solid, the liquid, and the solid/liquid interface, respectively. The angle Θ is the contact angle between the liquid and vapour phases.

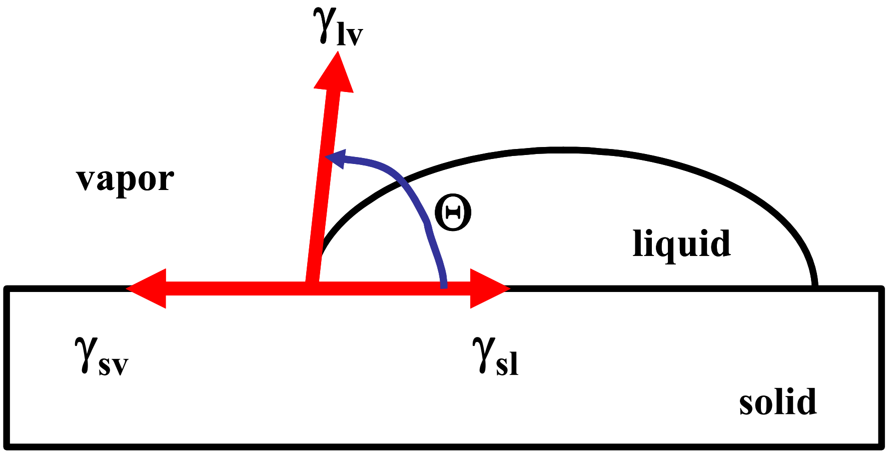


Figure 6.1 Schematic representation of free surface energies at a triple phase system.

Adhesion work is given by Equations (6.1) and (6.2). It can be seen from Equation 6.2 that the adhesion work can be determined from contact angle measurements. The binding energies of H_2O molecules to different solids are expected to be similar for water and ice [42], and it can be assumed that the W_a values on different ice-solid interfaces are correlated with the contact angle of liquid water. In fact, some authors [47,48,49] have measured the shear strength of ice at the contact interface on different materials and compared their results with the corresponding water contact angles. The results compiled by [42] are displayed in Fig. 6.2. The correlation is somewhat weak, but this may be attributed to the fact the surfaces are not equivalently smooth and that the mechanism of failure is not taken into account in the measurement of W_a. The Young equation (6.3) corresponds to another way of expressing Equation 6.2.

$$W_A = \gamma_{sv} + \gamma_{lv} - \gamma_{sl} \tag{6.1}$$

$$W_A = \gamma_{lv}(1 + \cos\Theta) \tag{6.2}$$

$$\gamma_{lv}\cos\Theta = \gamma_{sv} - \gamma_{sl} \tag{6.3}$$

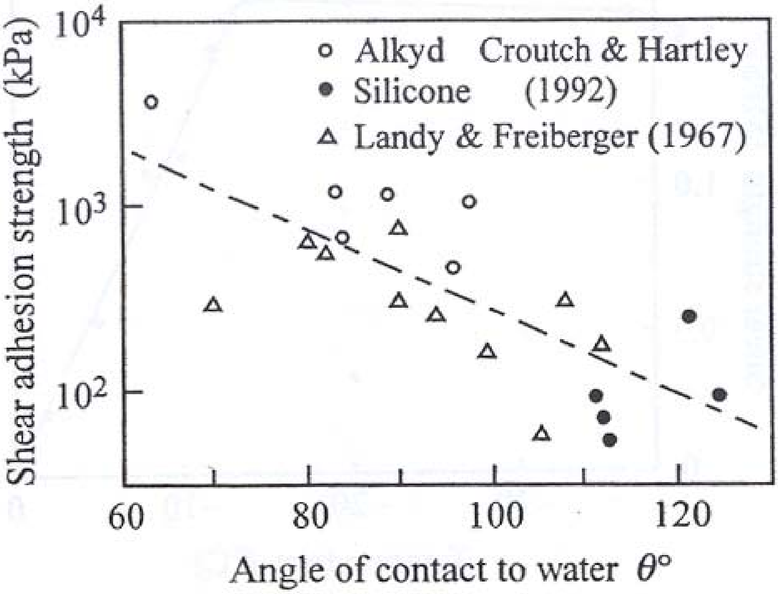


Figure 6.2 Correlation between shear strength of ice adhesion and contact angle for various plastics [42]

Table 6.1 - Surface free energies for different substrates [50]

Material	Surface free surface energy ($mN.m^{-1}$)
Poly(tetrafluoroethylene) or PTFE	20
Poly(dimethylsiloxane) or PDMS	22
PVDF	25
Polystyrene	33
Nylon 6,6	46
Copper	60
Liquid water	**72**
Silica (dehydrated)	78
Anatase (TiO_2)	92
Iron oxide (Fe_2O_3)	107
Aluminium	>100
Steel	>100
Rutile (TiO_2)	143

In the literature, many calculations of the surface free energies can be found (Table 6.1). Considering the values displayed in this table, materials of surface energy lower than 72 $mN.m^{-1}$ should exhibit low ice adhesion strengths. For instance, PTFE (or Teflon®) and PDMS would appear to be the best candidates to counter ice adhesion. However, it must be emphasized that surface energy measurements must be performed on ultra clean and very flat surfaces. While the first requirement can be achieved relatively easily, a given material such as industrial surfaces or coatings such as those of OHL conductors may have a degree of roughness large enough to affect contact angle measurements. Also, very rough surfaces may exhibit superhydrophobicity or ultrahydrophobicity ($\Theta > 150^o$), as will be discussed in Section 6.3.

6.2 Intermolecular forces

6.2.1 Electrostatic forces

Electrostatic interactions occur at material/substrate interfaces when they have different electronic bond structures [43], and both materials gain charge through an in-balance of charges. Electrostatic attraction theory is based on Coulomb's law and receptor-donor interactions. Petrenko and Ryzhkin [44] theoretically studied in depth the electrostatic interaction taking place at ice/metal or ice/dielectric interfaces. Their theory, summarized next, is based on the Jaccard theory stating that the electrical charge in ice is transferred by protonic point defects, L, D, H_3O^+ and OH^-, as shown in Fig. 6.3, and which play a role similar to electrons and holes in electronic semiconductors. The empty bond is an L-defect and the bond with two protons is a D-defect (doubly occupied). The other two defects correspond to ionic defects resulting from the water ionization reaction (6.4).

$$2H_2O \leftrightarrow H_3O^+ + OH^- \tag{6.4}$$

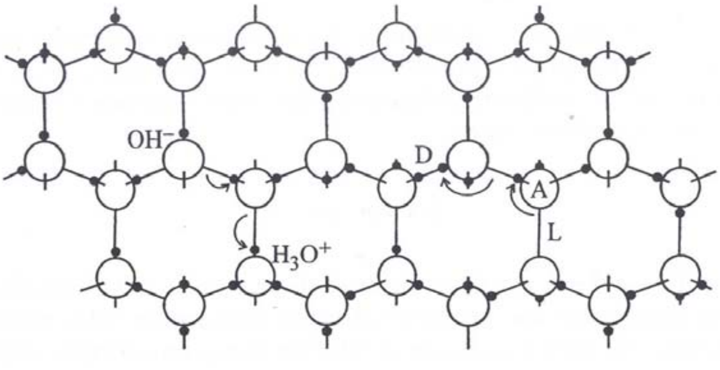


Figure 6.3 Ionic and Bjerrum defects in ice structure [42].

At an ice crystal surface, some of the protonic defects may be captured in the surface states, which have energies lower than those in the bulk of the ice. The capture of charged protonic defects in the surface states will result in a surface charge build-up, and therefore in the creation of a surface electric field. Additionally, at the metal or dielectric surface, a surface charge is created. The force of this charge is described in Equation (6.5), where the solid has an effective dielectric constant (ε) larger than that of ice (ε_{ice}). The image force F is inversely proportional to the square of the distance to the interface r, q is the charge and ε_0 the absolute permittivity in vacuum.

$$F = \frac{q^2}{16\pi\varepsilon_0\varepsilon r^2}\frac{\varepsilon_{ice} - \varepsilon}{\varepsilon_{ice} + \varepsilon} \tag{6.5}$$

Considering the energies of these different defects, it was evaluated theoretically that the adhesive energies for an ice/metal interface were between 0.08 and 1.3 $J.m^{-2}$. These values were comparable or even higher than those experimentally found at -20 ^oC. However, these authors did not consider the surface oxide or hydroxide layer which, in the case of non-noble metals or industrial metals or alloys, is always present at the surface. In fact, the thickness of such a layer can have either a very low conductivity (e.g. TiO_2), or be very thick in the case of anodized aluminium (Al_2O_3).

They assumed that the very same mechanism is applicable to the ice/insulator interface, but no evaluation of the corresponding energy of adhesion was performed [44]. A charge q_{ice} on the ice surface induces the “image charge” in a metal, while the very same charge q_{ice} will induce a smaller “image charge” , q_{diel}, in the insulator, as shown in Equation (6.6), where $\varepsilon_{\text{diel}}$ is the dielectric permittivity of the insulator. In most solid dielectrics, $\varepsilon_{\text{diel}}$ is much larger than 1, and the induced charges are comparable with ones induced in metals. The lower ε is, the lower is the electrostatic related adhesion. For instance, Teflon®, which has a very low ε (~ 2.1), exhibits icephobic properties.

$$q_{diel} = q_{ice}\left(\frac{\varepsilon_{diel} - 1}{\varepsilon_{diel} + 1}\right) \tag{6.6}$$

6.2.2 Acid-base hydrogen bonding forces

Hydrogen bonding, which can also be regarded as an electrostatic interaction, results from the distribution of a proton (hydrogen atom) between two electronegative atoms such as oxygen, nitrogen or fluorine. In fact, these attractions are responsible for the cohesion of solid ice and are also present in liquid water (H_2O). Therefore, this type of bonding plays an important role because oxides, $-CH_n$ or $–CF_n$ ($n = 1$ to 3) types of radicals are often present on the solid side. Chemical bonding between ice and other solids is largely hydrogen bonding but it has not been studied and quantified in detail yet. Van Oss *et al.* [45] measured the contact angles of a flat, polycrystalline ice surface with a number of liquids. They concluded that the contribution of the Lifshitz–van der Waals non-polar component to the ice surface tension (26.9 $mJ.m^{-2}$) was less than that of the polar Lewis acid–base component (39.6 $mJ.m^{-2}$), which in the case of ice is due to hydrogen bonding.

6.2.3 Lifshitz - van der Waals forces

The Lifshitz - van der Waals interaction forces are always present. It is the most common interfacial force, resulting from a temporary dipole-dipole interaction. The Lifshitz–van der Waals interaction between ice and several metals and insulators was calculated by Wilen *et al.*[46] and they concluded that this mechanism is not a dominant factor for ice adhesion. This was confirmed by Van Oss as mentioned in the previous paragraph.

6.3 Influence of surface roughness on ice adhesion

Industrial or functionalized surfaces are never perfectly plane. Aluminium and stainless steel based alloys always exhibit a certain surface roughness or even porosity. Water can penetrate into their three-dimensionnal surface structure, and subsequently solidify. Strong joints are created through enhanced mechanical interlocking resulting from the unique property of solid water to expand during the freezing process; as shown in Fig. 6.4(a). A comprehensive review of the ice adhesion due to mechanical interlocking can be found in [43]. The degree of surface roughness therefore affects the strength of the joint. The expansion coefficient of water around 0°C is greater than those of metals and oxides: water expands upon freezing, whereas metals and the oxides contract. On the other hand, air may be entrapped in some pores and the resulting pressure build-up can be significant, and may lead to crack initiation and propagation as well as ice de-bonding, as shown in Fig. 6.4(b) [52]. Therefore, internal pressure build-up or residual stress can result in ice de-bonding.

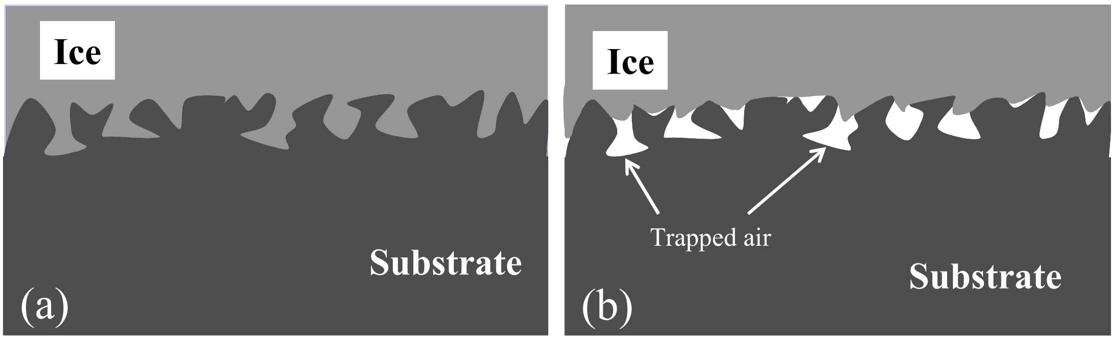


Figure 6.4 Schematic representation of ice adhesion on a rough substrate. (a) Mechanical interlocking and (b) low adhesion strength due to air entrapment.

Recently, the CIGELE team at University of Quebec at Chicoutimi discovered that certain superhydrophobic ($\Theta > 150^o$) surfaces can drastically reduce ice adhesion strength [53,54]. More details on the theoretical approach of superhydrophobicity can be found in [55,56,57] and only a condensed presentation is presented here.

Surface nano- and micro-asperities are usually responsible for the superhydrophobic phenomenon. The value of the contact angle measured on a rough surface corresponds in reality to an apparent contact angle (Θ_r), which depends on both the surface roughness and the behaviour of the liquid drop at the interface. Two different models were proposed to describe this phenomenon, known as the Wenzel [58] and the Cassie & Baxter [59] models, represented schematically in Fig. 6.5.

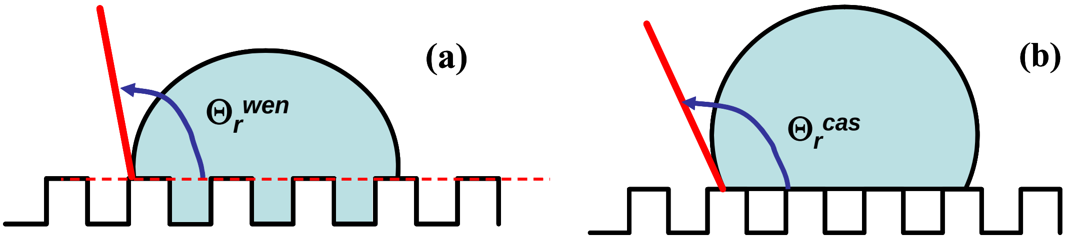


Figure 6.5 – Wenzel (a) and Cassie (b) models for a water droplet deposited on a rough surface

These models suggest that contact angle measurements alone (obtained by the sessile drop method) are not sufficient to characterize properly superhydrophobic surfaces, and that the evaluation of contact angle hysteresis, as shown in Fig. 6.6 and Equation (6.7), is necessary. The contact angle hysteresis can be evaluated when a liquid droplet is allowed to slide on a given surface. Advancing and receding angles, Θ_{adv} and Θ_{rec}, are measured on the distorted liquid droplet, and $\Delta\Theta$ is computed. If $\Delta\Theta \rightarrow 0$, the surface exhibits high superhydrophobicity. It has been demonstrated that superhydrophobic surfaces with $\Delta\Theta < 5^o$ are icephobic [60].

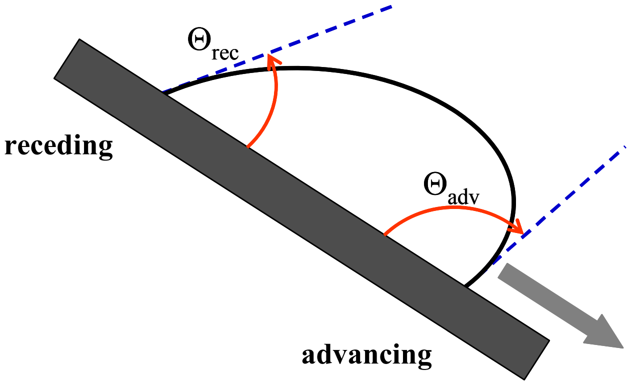


Figure 6.6 Schematic representation of a sliding water droplet for contact angle hysteresis evaluation.

$$\Delta\Theta = \Theta_{adv} - \Theta_{rec} \tag{6.7}$$

6.4 Influence of the quasi-liquid layer

Since ice frequently exists at ambient temperatures very close to the melting point, a quasi-liquid layer (QLL) is present at its surface as well as at the ice-solid interface, which constitutes an influential parameter on ice adhesion strength. Early studies by Jellinek [61] have been devoted to the behaviour of an ice surface and its interaction with solid surfaces, accounting for the existence of a QLL relative to temperature. It was estimated that the thickness of the QLL can extend from 100 Å to 1000 Å at -4.5° C, which corresponds to a 30 to 300 water molecule depth layer. A recent review by Dash *et al.* [62] cited many laboratory studies that have explored the interfacial fusion of ice with various substrates such as quartz, metals, graphite, glass, silica, polystyrene and PVC. A variety of techniques have been used for that purpose, namely, atomic force microscopy, mercury porosimetry, quartz micro-balance and X-ray scattering. Many of these cited studies noted that interfacial fusion starts at temperatures much lower than that of surface fusion. For example, in the case of graphite, interfacial fusion is detected as low as -30° C. The presence of QLL is clearly a factor to be taken into account, since it wets the surface of the solid and therefore increases the contact surface area between the ice and the solid, which promotes ice adherence.

6.5 Heterogeneous surface

In 1994 and 1997, Murase *et al.* [63,64] published their research results on heterogeneous polymer coatings aimed at decreasing ice adhesion These studies involved coatings with organopolysiloxane chains (presence of -CH_3 radicals) grafted with fluoro-polymer chains (presence of -CF_2): such coatings were found to drastically reduced ice and snow accretion. To explain their findings, Murase performed molecular orbital energy calculations for three molecules: ethane (C_2H_6), dimethylesiloxane (DMS) and hexafluoroethane (C_2F_6). The hydrogen bond length (O---H and F---H) as well as the various interaction energies were evaluated, and the former were found to differ widely depending on the molecular group examined. In fact, there was a slight repulsion between a water molecule and a siloxane group, while a strong attraction was observed for the fluorocarbon group and H_2O molecules. It is worth mentioning also that the water molecule orientations at the surface of the fluorocarbon group and the polysiloxane group were completely different. This work shows that by creating at the molecular level various disparities in terms of energy bonding and water molecule orientation, the ice-material interface can be weakened with the probable creation of a wide range of dislocations and slips in the ice structure immediately adjacent to the solid.

6.6 Influence of ice structure on its adhesion

The ice structure at the ice-metal or ice-metal oxides interface usually evolves from the presence of large polygonal crystals or grains to the formation of smaller ones with similar shape due to recrystallization. The overall process occurs within a few hours after initial freezing [47,48,65]. This process leads to the accumulation of dislocations at ice surfaces, and occurs in any polycrystalline material subject to a steady stress. This stress is induced by differences in thermal coefficients of expansion and contraction of the ice and the solid. There are also volume changes as the ice forms and cools [48].

As a rule of thumb, the greater the grain size, the lower the ice adhesion. Druez *et al.* [51] performed wind tunnel studies on ice microstructure for water droplets having variable speed and temperature during their impacts on aluminum conductors. It was found that the adhesion strength decreased with increasing ice grain size, which was in turn dependent on temperature and air velocity. In fact, ice grain size decreased as wind velocity increased, and decreased as temperature decreased.

Another study [52] has shown that the ice crystals (or grains) not directly attached onto steel, cement concrete, asphalt concrete and glass substrates were randomly oriented polygons, while the crystals directly attached to the substrate surfaces were air bubble-free, with a much smaller polygon structure (or needles, in the case of steel). The layer formed by these crystals can be assumed to be stronger than bulk ice, this added strength being derived from the small size of the crystals in the absence of visible flaws. The presence of such a strong layer would explain the high adhesion strength of ice on these materials. It would also suggest that mechanical ice removal procedures are likely to leave a thin layer of adhered ice behind. The study also addressed the appearance of ice crystals on polystyrene and found that the ice interference fringes on this material were significant. Interference fringes are an indication of mechanical stress within the ice crystals themselves. This stress was attributed to the low thermal conductivity and the high coefficient of thermal expansion of polystyrene.

6.7 Concluding remarks

The rigorous scientific process of linking experimental results to the corresponding theoretical developments is a difficult task in the case of ice-solid interfaces. Firstly, on the ice side, many types of ice are encountered in nature: wet and dry snow, rime and glaze ice. Moreover, contaminants and air bubbles may be present at the ice-material interface, and this is almost the case in OHL conductor icing. Secondly, on the materials side and from an engineering point of view, the presence of atomically clean and flat surfaces is never achieved, which makes experimental work on adhesion very difficult to compare with theory. Nevertheless, it can be clearly stated that the two main influences on ice adhesion strength are:

i. the electrostatic forces present at the ice-solid interface
ii. the surface roughness of the substrate.

Concerning the electrostatic forces, materials or coatings with very low dielectric permittivity such as fluoropolymers generally exhibit low ice adhesion strengths. As for substrate roughness, this undoubtedly plays a crucial and complex role in ice adhesion strength. In the presence of strong mechanical interlocking, ice cracking and even ice de-bonding can be observed due to excessive pressure build-up resulting from air trapped in closed pores. Therefore, the engineering of an optimum surface roughness, having superhydrophobic properties for instance, may create internal stresses large enough to de-bond ice, particularly when the substrate is composed of a low dielectric material.

Other parameters should also be taken into account to fully understand the ice adhesion mechanism: temperature (as it affects the QLL) and the type of precipitation (e.g. impact velocities of supercooled water droplets) that influence water penetration within a 3-dimensional surface structure, as well as the shape and size of the ice crystal grains affecting ice adhesion strength. Furthermore, factors usually leading to poor ice adhesion strength include substrate low thermal conductivity, relatively large differences between ice and substrate thermal expansion coefficients, as well as some heterogeneous materials.

In addition to the above concerns, the use of hydrophobic coatings to reduce ice adhesion on OHL conductors has raised some other operational concerns such as the audible noise from the protected conductors. Furthermore, the influence of such coatings on corona noise levels and related interferences is not well understood and should be investigated.

7 Operative and design systems for anti-icing and de-icing

7.1 Background

Ice deposits on overhead power networks, and particularly on ground wires and phase conductors have always been a major challenge in cold climate regions [10]. Considerable research and development have been carried out until now, and large-scale successful technologies have been developed to address this challenge. The first review devoted to anti-icing and de-icing methods for overhead power lines was presented by Pohlman and Landers in 1982 [66]. A few years later, Hesse [67] presented a comprehensive description of two methods used by Manitoba Hydro, namely ice breaking by rolling and ice melting by short-circuit current. However, these reviews presented only *ad-hoc* techniques and, consequently, were not exhaustive or complete enough to apply on large scale. A first classification of these methods in four categories was proposed: passive, thermal, mechanical and "miscellaneous", reflecting the physical principles used for ice removal [68]. A more recent report proposed a six-category classification: passive techniques, active coatings and sheathings, active methods on bare conductors, thermal methods, mechanical methods, and miscellaneous methods [69].

Another classification can be used which takes into consideration the permanent or temporary character of the method, the need for line modification, and whether or not it is automated [70]. With this classification system, the existing potential methods can be categorized into inline, limited-use and permanent methods. Inline methods are those using Joule effect, with energy from or external to the line, with no extra device or coating attached to the energized conductor or ground wire. Limited-use methods are those which are used only at specific locations and are not permanently installed on the line. Finally, permanent methods are those which are permanently installed on the conductors or ground wires.

No permanent method is currently used widely, as most of them are under development. Developing and validating such methods, like coatings, is a complex task, as they have to perform successfully and have a relatively long life expectancy.

It is important to mention that in some countries, restrictions may exist with regards to de-icing of overhead power lines. So, eventual users of these methods should be aware of such restrictions, if applicable.

In the following sections of this chapter, anti-icing and de-icing methods are classified in the four following categories for simplicity and practicality:

- i) passive methods
- ii) active coatings and devices
- iii) mechanical methods
- iv) thermal methods.

The new materials and their potential as icephobic coatings are discussed in Chapter 8.

7.2 Passive methods

Passive methods are ones which do not require an external source of energy but use only natural forces such as wind, gravity or solar radiation. Consequently, they can function on both energized and non-energized phase conductors as well as ground wires. This group includes most of the anti-icing methods used to prevent or reduce the accretion of wet snow and ice on conductors. To achieve this, different strategies are used:

i) weakening ice adhesion strength,
ii) preventing freezing of supercooled water droplets on impact, and
iii) using a combination of specific devices for limiting the impact of ice overload on conductors.

The first two strategies, defined as anti-icing strategies, were described in more detail in Chapter 6.

The third strategy is based on passive methods, which exploit natural forces such as wind, gravity or solar radiation in order to limit the adverse effects of ice loads on overhead lines. Some of these methods are already effective for wet snow but their efficiency for ice needs to be studied. A well-known method among these consists in using counterweights (Figure 7.1a) to increase the torsional stiffness of conductor spans. Field observations in Japan, Iceland and France on wet snow have shown that this device can limit the formation of cylindrical deposits of wet snow by limiting the rotation of a conductor resulting from eccentric snow loading on its windward side. With highly eccentric snow loadings, shedding caused by gravity and wind forces is facilitated. Based on these observations on wet snow, numerical and experimental studies were conducted on atmospheric ice [71,72]. The results showed that limiting the rotation of a ground wire under icing conditions can effectively reduce ice load as well as shedding time under natural warming conditions.

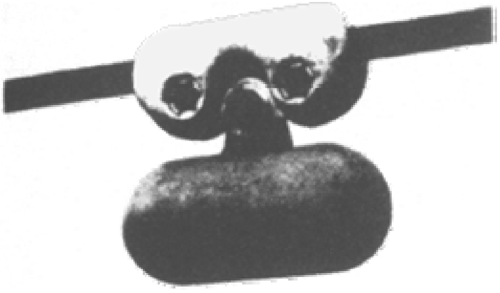


Figure 7.1a Illustration of a counterweight

Bundled conductors have higher rotational stiffness than single conductors which leads to differences in ice accumulation and shedding. Field measurements on two parallel 400 kV lines in heavy in-cloud icing area have shown that a sub-conductor in a duplex bundle accumulates more elongated ice shapes that tend to fall off before the semi-circular accretions on a single conductor [73]. Other field measurements of ice shedding on a 80-m long test span exposed to heavy in-cloud icing have revealed that ice shedding tends to occur first on conductors of larger diameter [73] and those with smoother surface (trapezoidal strands vs. circular) at the same diameter [74]. This last observation was confirmed on a natural site on a 200m-long segment of a conductor line with trapezoidal strands compared to ACSS and ACSR round-stranded conductors [75].

Another interesting passive method to reduce wet snow accumulation is the use of snow rings around the conductors [76,77]. The snow tends to accumulate on the top of the conductor and slide down along the direction of the strands, as shown in Figure 7.1b (top). Adding rings (Figure 7.1b, middle) or wires in opposite direction to the strands (Figure 7.1b, bottom) causes the sliding wet snow to shed by breaking the surface tension as it impacts the obstacle at the bottom of the conductor.

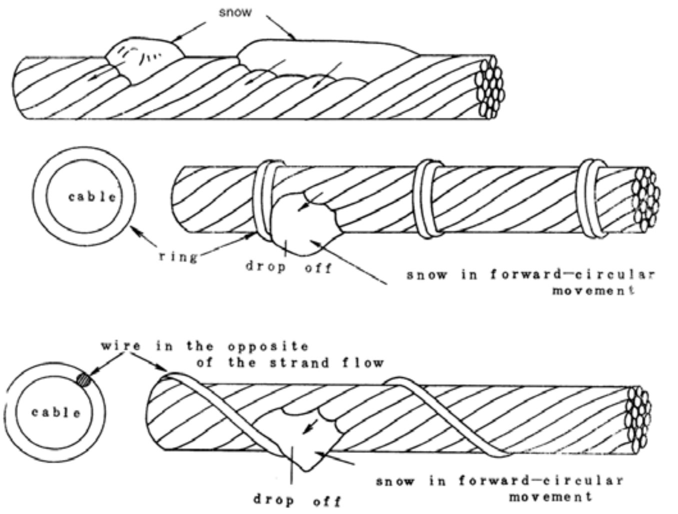


Figure 7.1b Top: Path of wet snow accretion sliding in strand direction. Middle: Snow rings. Bottom: Wire wound in opposite direction of strand to facilitate shedding [76].

All overhead lines in Japan, except for the Okinawa region where there is no snow in winter, are equipped with snow rings. The overhead lines with single conductors are also fitted with counterweights, as shown in Figure 7.1c.

The effectiveness of these prevention systems has been determined by sophisticated automatic monitoring equipment which confirmed a significant reduction in accreted snow after the installation of these devices [77].

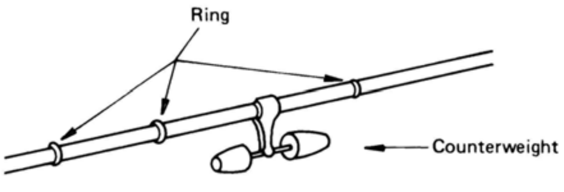


Figure 7.1c Combination of rings and counterweights for wet snow removal from conductors [77].

In some other countries, including New Zealand whose experience is described below, where only a relatively small number or sections of lines (generally double circuit lines) are affected by atmospheric icing, a number of other passive methods are used to minimize the impact of icing and shedding events, including:

- Install longer middle crossarms;
- Modify the crossarm or circuit spacing;
- Install inter-phase spacers;
- Modify phase sub-conductor bundling;

- Install separate structures for each phase; and/or,
- Rearrange the phasing configuration between circuits.

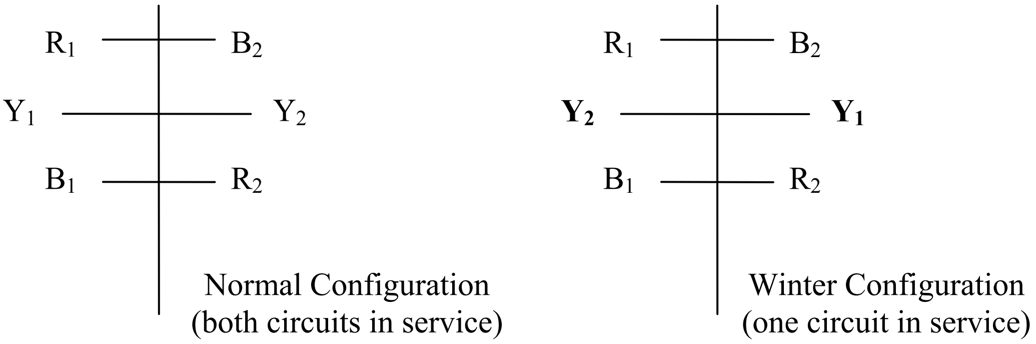
In some cases, a combination of these methods has been used. It should be noted that some of these options may involve increased right-of-way, tower modification and strengthening, operational guidelines and limits etc.

The biggest impact of icing in New Zealand for example, is that of increased conductor sag or in some cases ice dropping resulting in unwanted phase clashing causing outages. An obvious method for double circuit lines, and most appropriately initiated before the line is built, involves creating a horizontal separation between the phases within a circuit by using longer middle crossarms. This allows uneven sags of iced/un-iced conductors in the phases to be accommodated. It should be remarked that, in some countries, like Austria, some regulations for overhead lines require a horizontal rather than vertical circuit configuration to provide this mitigation.

A similar method has also been used on existing lines where there was provision to use a redundant ground wire peak or similarly add an upper section to the tower to increase the separation between the top and middle crossarms to again accommodate uneven conductor sag profiles. The towers would either need to have additional capacity or utilisation available, or sufficiently strengthened to accommodate increasing the tower loading.

Another form of passive anti-icing technique is the use of interphase spacers (stiff rod insulators) which reduce the potential effect of ice build up by keeping conductors suitably separated during icing events or ice un-loading. These are usually composite long rod insulators of suitable length to match the dimensions of the phases, and electrically to accommodate the phase-to-phase voltage. The disadvantage with this method is that it introduces another location for possible conductor fretting under the many clamps involved. It also requires inspection and maintenance of the insulators themselves, and will only provide mitigation if installed in the spans where icing is most likely to occur. However interphase spacers do provide a very positive method of ensuring conductor separation. There are presently just under 500 such units installed on four affected lines in New Zealand. A further 40 units are installed on specific spans to mitigate against similar clearance issues related to high winds.

Another passive method that has been used successfully to limit the impact of conductor icing is that of phase rearrangement. Generally the circuit arrangement of double circuit lines is a complete circuit on each side of the tower. But, provided the system can accommodate only one of the two circuits being in-service at the time during the icing-prone season, the phases can be rearranged to place the middle phase in each circuit, on the opposite side of the tower to the other two phases in the circuit (Fig. 7.1d). This again allows the top phase to unevenly sag under ice and not clash with its adjacent phase, although it may still come close to the out of service phase of the other circuit.



Normal Configuration (both circuits in service)

Winter Configuration (one circuit in service)

Figure 7.1d Alternative phasing configuration for anti-icing

This phase rearrangement method is put in place just before winter by rearranging the phase connections at the substations at each end or special towers at either side of the higher altitude line section. If an icing event is forecast, one of the circuits is switched out of service and the situation monitored. Normal phasing is returned during the summer months to allow for safe operation and maintenance opportunity on the individual circuits. Care and suitable communication is needed during these temporary phase rearrangement periods to ensure safety of operational and maintenance staff, as normal phase markings on affected structures could not be readily changed or modified.

7.3 Active coatings and devices

Methods based on active coatings are active methods requiring some electrical energy to be effective. One of the proposed methods makes use of losses in a specific dielectric coating covering the entire surface of the conductor [78]. By choosing an adequate dielectric coating among ferroelectric materials, it would be possible to maintain the surface conductor temperature above the freezing point to melt the ice/substrate interface. However, these coatings would need to be applied in a factory, and it is unlikely they would survive the environment of an overhead line for more than 5 years. Moreover, this method would require the use of a higher AC frequency of 60 kHz, instead of the 50 or 60 Hz service voltage frequency. This condition is problematic as the use of such high frequencies can lead to electromagnetic perturbations and interference. Also, high frequency generation would require addition of an external source in order to superimpose a 60 kHz electric field to the 50/60 Hz one. The use of high frequency could also affect ACSR conductors differently than AAAC ones as most energy loss (and so heat gain) would be in the zinc layer on the galvanised steel core strands. However, it should be noted that most of the active coating methods are neither available commercially nor widely in use.

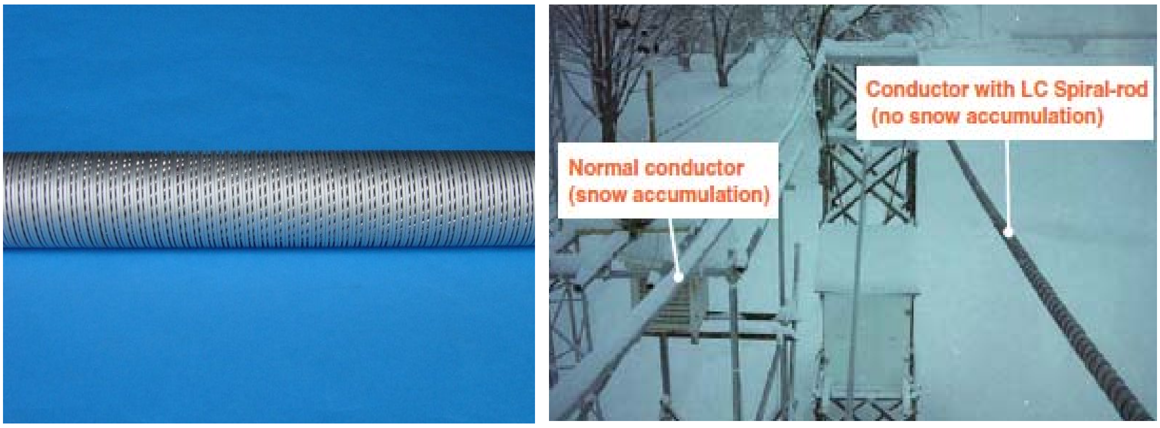


Figure.7.2a: Snow-melting magnetic wire used in Japan [79]

Other such methods are based on the use of a ferromagnetic coating for the purpose of sustaining a positive temperature of the energized conductor surface [69]. Instead of absorbing energy from the electric field, the ferromagnetic coating absorbs energy from the magnetic field, which is at a maximum intensity at the conductor surface. Ferromagnetic coating heating is based on hysteresis and the induced eddy current loss generated by the AC magnetic field. Thus, such methods do not require any external source of energy.

This method, known as LC-Spiral Rod method, has been implemented successfully in Japan. These spiral rods have been manufactured and installed for more than 20 years to prevent accidents caused by the sudden fall of large chunks of snow. Figure 7.2a shows a typical installation of LC-Spiral Rods on a conductor and their relative performance to prevent snow accretion. In Japan, LC-Spiral Rods have been satisfactorily used under wet snow conditions and are installed on more than 100 spans (50 transmission lines). According to the observation results at the Mont Bélair icing test site (Canada) by Hydro-Québec, LC-Spiral Rods are also effective under natural icing conditions (freezing rain and in-cloud icing) under favourable weather and conductor current conditions [80]. Figure 7.2b shows an example of the good anti-icing performance of LC-Spiral Rods at Mont Bélair. It is noteworthy that such techniques were used successfully on high altitude line sites at Tomintoul in Scotland over 50 years ago [81] but were discontinued due to metallurgical limitations in shaping the material.

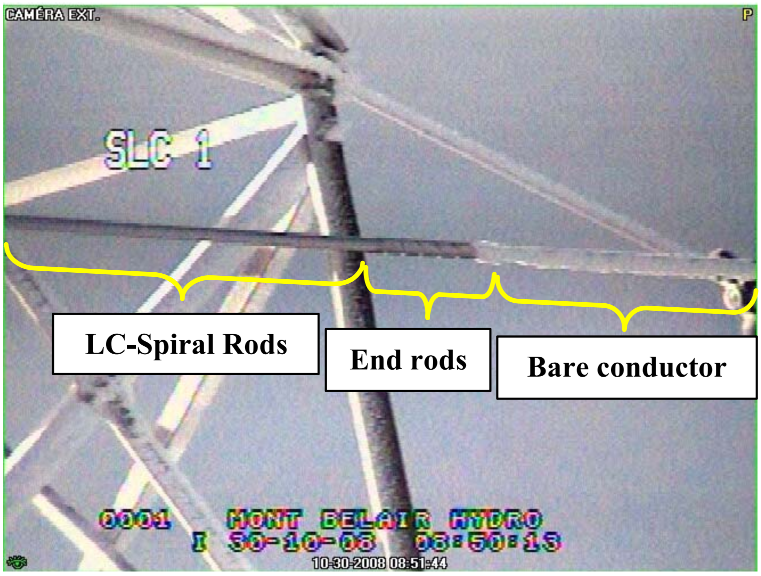


Figure 7.2b: Anti-icing performance of LC Spiral-Rods at Mont Bélair icing test site [80]

Another proposed passive solution resides in using electrical tracers actually used in chemical plant for heating pipes [69]. Electrical tracers are electrically insulated resistive heating wires which are wound around conductors or ground wires to heat their surface. Although it is a mature technology in the chemical industry, it would still need to be adapted to power lines.

More recently, thanks to new developments in ice adhesion, a method based on ice electrolysis was proposed [82]. Ice electrolysis is produced via a small DC voltage applied between a grid electrode and the surface to be protected. It should be mentioned that compared to thermal methods, which require a considerable amount of input energy, this method requires low external energy. The grid electrode is insulated from the conductive surface (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. This leads to the accumulation of gas bubbles between the ice and the solid surface which contributes to loosening the ice layer’s bond onto the surface. As presented in Figure 7.3, a configuration was proposed for energized conductors [82]. However, it seems more convenient to use it on ground wires, as the conductive surface could be the wire itself and the energy required is very small. More studies and experiments need to be carried out under different icing conditions and using different electrode sizes and materials in order to optimize the efficiency of this method for ground wires. In its present state, however, this method seems to be impractical as it has not been manufactured and tested on a large scale.

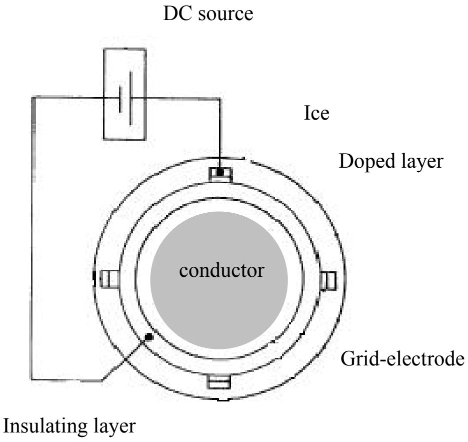


Figure 7.3: Ice electrolysis method applied to a bare conductor [82].

7.4 Mechanical methods

In most cases, mechanical methods can be considered as de-icing methods as they are used to speed the shedding process after snow packs or ice have formed on conductors and ground wires. It has been demonstrated [83] that mechanical methods require around 100,000 times less energy than thermal methods to force ice shedding. Generally, most of the mechanical methods are based on two strategies. One strategy consists in breaking the ice by scraping it and the second in releasing energy from shock waves, vibrations or ground wire/conductor twisting to break and pull off the ice. One of the main advantages of mechanical methods is their relative ease of application compared to thermal methods. In fact, mechanical methods are those preferred for timely and fast intervention to de-ice short critical sections of a power network. However, in the absence of any precise operational instructions, methods involving significant bending of ground wires/conductors should be avoided for OPGW to prevent damage to the optical fibers.

7.4.1 Scraping methods

The simplest scraping methods are manual and use scrapers, rollers or cutters attached to a rope which is pulled by linemen to release the ice. These methods can only be used when lines are accessible from the ground [84,69]. For example, Manitoba Hydro uses an aluminium roller wheel to de-ice energized distribution lines up to 12 kV and 25 kV [84]. More recently, this method has been upgraded by using automatic robots. One such robot, the Remotely Operated Vehicle (ROV), has been developed at Hydro-Quebec’s Research Institute (IREQ) [85,86]. Robust, lightweight, and compact, the ROV device has high traction force, which allows it to perform demanding tasks. It has been successfully tested on 315 kV energized line conductors. Its electronic circuitry is protected against electromagnetic interference and it has an operational range of 1 km. The ice-scraping tool comprises a set of steel blades mounted on the ROV (Figure 7.4). The automated prototype (3rd generation) is ready to be tested in field conditions. The ROV will probably have to be installed from a helicopter or an insulated boom truck, since the icy tower structures prevent linemen from climbing them to reach the wires.

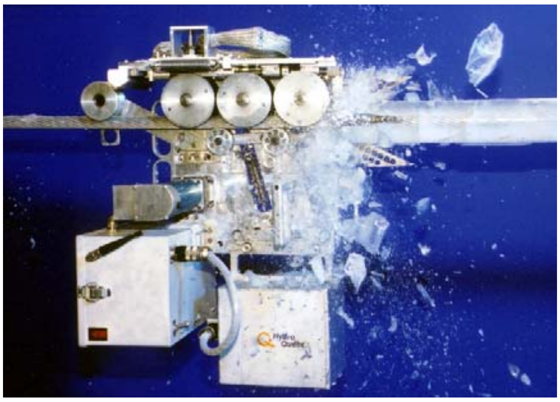
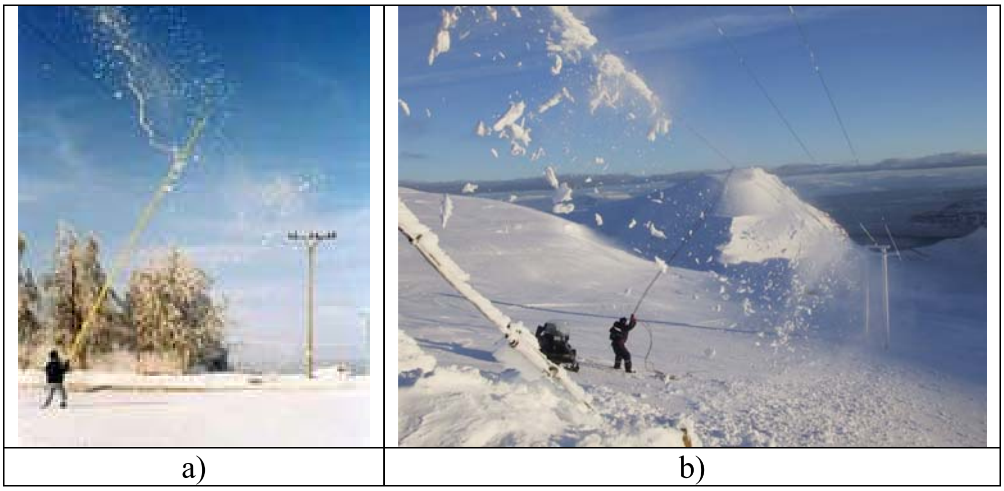


Figure 7.4: Prototype of the ROV de-icer [86].

7.4.2 Shock wave methods

Energy releasing methods use conductor or ground wires for transmitting mechanical energy to induce ice shedding. One way to mechanically induce ice shedding is to create a shock wave which is propagated along the conductor. As ice is a very brittle material at high strain rates (>10^{-3} s^{-1}) [87], relatively little mechanical energy is required for breaking the ice by mechanical shocks because energy is not dissipated in plastic deformation. The first method that has been used to create a shock wave was to manually hit the conductor with an insulated pole, as illustrated in Figure 7.5a. An alternative way is to pull a rope looped over a de-energized conductor, as shown in Figure 7.5b This method is effective for de-icing one span at a time but it requires that the conductor be easily accessible from the ground. An improvement of the rope method was proposed by [88]. As illustrated in Figure 7.6, the rope is equipped with a hammer/hook head activated by a pneumatic piston charged with compressed air. This rope can be used from ground by linemen or mounted on a telescopic lift. These methods require accessibility of the iced lines by linemen, and consequently, are not efficient to de-ice lines over rough terrain or crossing rivers. In such special cases, the rope may be activated directly from the tower or from a helicopter [69].



a)

b)

Figure 7.5 : De-icing of a conductor line using a) an insulated pole (from www.lopour.cz) a) or b) a rope

More recently, Hydro-Québec has developed a new device to de-ice ground wires by shockwaves. This is a portable cylinder-piston system called De-icer Actuated by Cartridge (DAC) (Figure 7.7). [86,89]. The high velocity piston impact is activated by firing blank cartridges. The de-icing operation with the DAC 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 rope that passes over the ground wire/conductor to be de-iced. Next, the DAC is pulled up to the ground wire/conductor and held in place by a taut rope. The DAC is equipped with a revolver barrel that stocks 6 blank cartridges that can be fired remotely from the ground. Numerous tests have been carried out to assess the efficiency of the method and to optimize its physical parameters [89]. For example, a series of trials on a ground wire 100-m test span indicated that one firing only could de-ice the full span with eccentric accretions, but multiple firings were necessary for an equivalent concentric ice accretion.

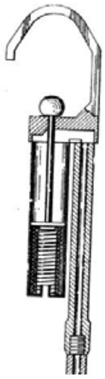


Figure 7.6 : Pneumatic hammer/hook for de-icing overhead conductors [88]

Figure 7.7. DAC prototype held in place by a taut rope and ready to be fired [89]

Electro-impulse methods have also been proposed for de-icing conductors and ground wires by shock waves. One of these methods initially developed for de-icing aircraft wings (EIDI), was tested on electric lines [90]. The EIDI technique adapted to power line de-icing consists of stacking two insulated strips of copper ribbon together and winding them around the full conductor span. When energized by a current pulse, the two copper strips repel one another and exert forces outward from the conductor which breaks and sheds the ice. Some successful laboratory tests were undertaken on short conductor segments covered with 12 mm of ice. However, it was not possible to test the method on a natural site due to the difficulty to wrap the actuator tightly enough around the conductor. An improvement of the EIDI method was proposed by [68], where the shock wave actuator is formed by a pair of wire strands of the external layer of the conductor which are isolated and connected at one extremity, while the other ends are connected to the impulse current generator. Tests conducted *in situ* with this improved method have permitted de-icing of a 260-m OPGW span. Even if this technology appears effective, further investigations are necessary before going onto prototype installations on ground wires [69]. A practical operational issue is the insulation degradation of the EIDI actuator when the ground wire is hit by lightning strokes.

Based on the same EIDI principle, a method was developed and tested at the High Power Laboratory of IREQ in order to de-ice lines with twin or quad conductors at rated voltages of 315 and 735 kV respectively [91,92]. In this case, the EIDI actuator is formed by the bundled conductors. The high current impulse is generated by a short-circuit current (I_{SC}) at the rated voltage of the line and by the subsequent action of the electromagnetic forces forcing the conductors to knock against each other and de-ice the span, as shown in Figure 7.8. Asymmetrical I_{SC} and reclosing sequences are necessary in order to reduce the amplitude and duration of the short-circuit currents as much as possible. The conductors have to be excited at a frequency close to their fundamental subspan frequency to get a maximum dynamic motion which is synchronized with the reclosing sequences. Impact studies on the Hydro-Québec power system indicated that this method could be applied on 315 kV lines, but only for emergencies during severe ice storms. For 735 kV lines, however, the required short-circuit currents and reclosing sequences are unacceptable for network stability and, therefore, the method was rejected.

Figure 7.8: EIDI of twin bundle using 10 kA and appropriate reclosing sequence [91]

7.4.3 Vibrating devices

Another set of mechanical methods use specific devices attached to the conductors or ground wires to induce sustained vibrations to shed ice. Two devices, similar in principle, have been proposed. The first device, Automatic Ice Control (AIC), has been reported in [93]. It comprises a current transformer for power supply, a camera, different sensors for ice detection, a control box with a HF emitter/receiver, and a commercial electromagnetic vibrator. All these elements are encapsulated in a rigid protective housing directly mounted on the conductor (Figure 7.9). The AIC is permanently installed at the mid span and is completely autonomous. Due to its ice detector and HF communication capabilities, de-icing sequences can be fully automated or controlled by signal order transmitted through HF. The AIC was installed on a 230 kV line located near St. John's, Newfoundland in 2004-2006 and the test was not successful. The system experienced major problems ranging from repeated sensor malfunction to communication failure, and was never operational during the two winter seasons [94].

The second vibrating apparatus is called ice-shedder (Figure 7.10). It is mounted on the conductor and comprises a motor activating an unbalanced weight whose imbalanced motion is tuned to the natural frequency of the span. Some preliminary tests were conducted on power lines with a span of about 152 m long and 3 cm diameter [95]. By operating the ice-shedder device within a frequency range of approximately 1.5-8.0 Hz, conductor displacements of 10 to 33 cm (4 to 13 inches) were observed, with accelerations between 0.5 and 14g. Accumulated ice on power lines can be adequately shed within these ranges of forced motion. The ice-shedder can be installed easily on bare conductors and ground wires. Moreover, it can easily be automated and driven by power from the bare conductor line or from an external power supply. It could also be used with bundled conductors, with minor modifications, but this has not been tested yet. In fact, the de-icing capacity of this method has not been quantified yet, in terms of maximum radial ice thickness and maximum span length. It is also possible that these large oscillations of conductors or ground wires could eventually cause long-term mechanical damage to the power lines or support insulators.

Most of the mechanical methods proposed here work by inducing waves that propagate along the conductor. A recent method proposed by [96] consists in using an apparatus to slowly twist the ground wire or the conductor around its longitudinal axis and then suddenly release the elastic strain energy accumulated by torsion [97]. The application of the torque can be achieved by hand or by a motor depending of the torsional stiffness of the conductor span. The efficiency of this method was demonstrated on a 15-m-long ground wire span was entirely de-iced using a manual twisting device (Figure 7.11) installed at mid-span [96]. The main advantages of this twisting de-icing system are its simplicity and efficiency for all types of ice accretion and conductors. The method requires very low mechanical energy and can be operated safely and quickly by linemen to de-ice strategic ground wire spans or non-energized conductors. The main disadvantages are that the automation of this de-icing process may be quite complex as it requires an electric motor mounted on a rigid attachment at the height of the conductor, a reduction gear box and a magnetic clutch coupled at the motor, a control module, and an ice detection unit. Finally, this technique cannot be applied to bundled conductors.

Figure 7.9 : Automatic Ice Control [93]

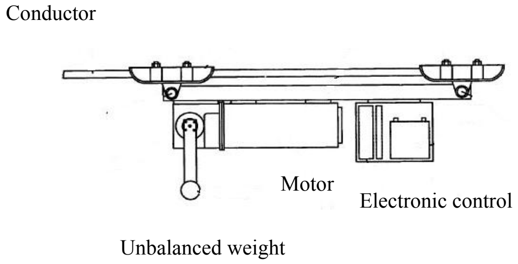


Figure 7.10: Ice-shedder apparatus [95]

Figure 7.11: Twisting device installed at mid-span of a ground wire [96]

In higher altitude regions only accessible by helicopter, British Columbia Hydro crews have used a 90-kg weight attached to a 30-m rope with a series of large knots at about 0.5 m spacing (Fig. 7.12) to force conductor motion and shed accreted wet snow. Initially, the bottom part of the knotted rope is set vertically below the conductor and the top part of the rope is pulled up at a 30 degree angle against the conductor causing the knots to catch (impact, lift and drop) the conductor as they are pulled across. However, one must make sure that the suspended weight does not touch the ground, which could cause an outage. Typically, fifty percent of the sticky wet snow of a 500-m span can be removed in less than half an hour resulting from about 30 multiple knot pulls per half hour along the length of the span. This is much more effective than simply impacting the conductors with insulated poles from a helicopter [10].

Figure 7.12: Helicopter use of 90-kg weight with large knotted rope

7.5 Thermal methods

Heating of line conductors or ground wires to prevent ice accretion or for de-icing purposes is recognized worldwide as the most efficient engineering approach to minimize the consequences of severe ice storms on overhead lines [3]. Thermal methods include all methods causing the ice to melt in order to force shedding. Some of these methods can be used for anti-icing purposes in order to prevent supercooled water droplets from freezing during their impact on the conductor surface. In that case, less energy is required for anti-icing than for de-icing [98]. Thermal methods can be divided in two categories: (i) methods based on pure Joule effect, and (ii) methods based on dielectric losses, radiative waves and external heat sources.

7.5.1 Joule-effect methods

Using Joule-effect heating for de-icing is without any doubt the oldest method. It was successfully used by the New England Company during the storm of 1920 [99]. For years, in USA, Canada and the former USSR, thermal de-icing and anti-icing methods based on Joule effect have been developed and implemented in the field. However, with an ever increasing demand for energy, transmission lines became longer and more effective with the use of higher voltages. As a result, using the Joule effect for de-icing has become a challenging task considering the minimization of electric losses in the process.

Both AC and DC have been used in different countries to melt ice [69], and effective technologies for both types of current are now available. Generally, using AC does not involve costly equipment, since the required current is supplied directly from the power network. However, under certain atmospheric conditions, the melting power must be sufficiently high, especially with long transmission lines, to obtain the right melting current. A variety of conceptual electrical schemes have been considered for ice melting technologies. Some of the main Joule-effect based methods are reviewed in the following sections. For a comprehensive coverage of Joule effect de-icing, the reader is referred to the Appendix I of this report, which is an adaptation of the late Dr Yakov Motlis' draft document [3]. However, one must bear in mind that much development in ice melting technology has occurred since, which is covered in the present chapter.

7.5.1.1 Equations relative to Joule-effect de-icing and anti-icing

The heating energy required by thermal methods depends principally on whether the application is for anti-icing or de-icing. In both cases, the nominal current in the overhead conductor must be increased in order for the conductor surface to reach a temperature greater than 0 °C. The required current depends on many parameters, and particularly upon ambient temperature, wind velocity, and heat exchanges involving wind and droplets, as well as ice thickness in the case of de-icing.

Historically, the first study on the current required to prevent ice formation on overhead line conductors was performed by J.E. Clem [100]. Taking into account the heat lost by convection, Clem proposed Equation (7.1) for calculating the temperature rise of a bare conductor surface above ambient air for wind speeds greater than 1 m/s in order to prevent ice accumulation.

$$\Delta T = 4.43 \cdot 10^{-4} \frac{I^2 R_{AC}}{\sqrt{dv}} \tag{7.1}$$

where: ΔT is the temperature rise (in °C)
R_{AC} is the conductor AC resistance (in Ω/km)
I is the conductor current (in A)
d is the conductor diameter (in mm)
v is the wind speed (in m/s)

Clem also proposed Equation (7.2), to determine the current required to melt the ice already accumulated on the conductor.

$$I = 1772.5\sqrt{\frac{(w_i + w_c)d}{R_{AC}}} \tag{7.2}$$

where: R_{AC} is the conductor AC resistance (in Ω/km)
w_i is the melt-through power (in W/mm^2)
w_c is the power required to maintain temperature rise (in W/mm^2)
d is the conductor diameter (in mm)

The model proposed by Clem has served as the basis for different improved models used by various utilities in order to determine the current required to improve de-icing efficiency. One of theses models is actually used by Manitoba Hydro [67] which has accumulated considerable experience on conductor de-icing for the last twenty-five years [84]. In the latter model, heat loss due to radiation and heat gain due to solar radiation, which were neglected by Clem, are taken into account, as presented by Equation (7.3). This equation provides the current required to melt the volume of ice V_{MELT} within a time Δt. The general validity of this simple equation was verified experimentally.

$$I = \sqrt{\frac{1}{R_{AC}}\left(P_c + P_S - P_{SOL} + \frac{\rho_I\left(L_F + C_{pI}\left(T_F - T_A\right)\right)}{\Delta t}\right)V_{MELT}} \tag{7.3}$$

where: R_{AC} is the conductor AC resistance (in Ω/km)

P_C is the convective heat transfer (in W)

P_S is the radiative heat transfer (in W)

P_{SOL} is the solar heat transfer (in W)

ρ_I is the ice density in kg/m^3)

L_F is the latent heat of fusion (in J/kg)

C_{pI} is the specific heat of ice (in J/kg/°C)

T_F is the fusion temperature of ice (in °C)

T_A is the ambient temperature (in °C)

Δt is the required time for a melt (in s)

V_{MELT} is the volume of ice sector to be melted above the conductor (m^3)

However, the Manitoba Hydro model makes some limiting assumptions. In particular, it works well for dry-grown ice because all impinging precipitation is assumed to be captured and frozen, and because heat transfers associated with the impinging precipitation are ignored. However, it is not adapted for mild temperatures when ice accumulates in a wet regime and when some impinging precipitation drips off the ice surface and contributes or extracts heat energy to or from the iced conductor [101].

In order to take into account the wet-grown ice regime as well as the heat transfer associated with impinging supercooled droplets, new melting models were developed and tested by Hydro-Quebec to evaluate and manage the required current during ice storms [101,102]. One model has been tested at length and provides good results under typical ice storm conditions, but overestimates the melt energy in colder conditions. This model was then improved with the consideration of the trapped water and ice, elements that are also missing in the Manitoba Hydro model [101]. This new model has been formulated but has not been validated yet. The general current equation is given by Equation (7.4).

$$I = \sqrt{\frac{r_C}{r_I}\frac{\rho_I\left(L_F + C_{pI}\left(T_I - T_A\right)\right)}{R_{AC}\Delta t}V_{MELT}} \tag{7.4}$$

where: R_{AC} is the conductor AC resistance (in Ω/km)

L_F is the latent heat of fusion (in J/kg)

ρ_I is the ice density in kg/m^3)

r_C is the radius of the conductor (in m)

r_I is the outer radius of the ice sleeve (in m)

C_{pI} is the specific heat of ice (in J/kg/°C)

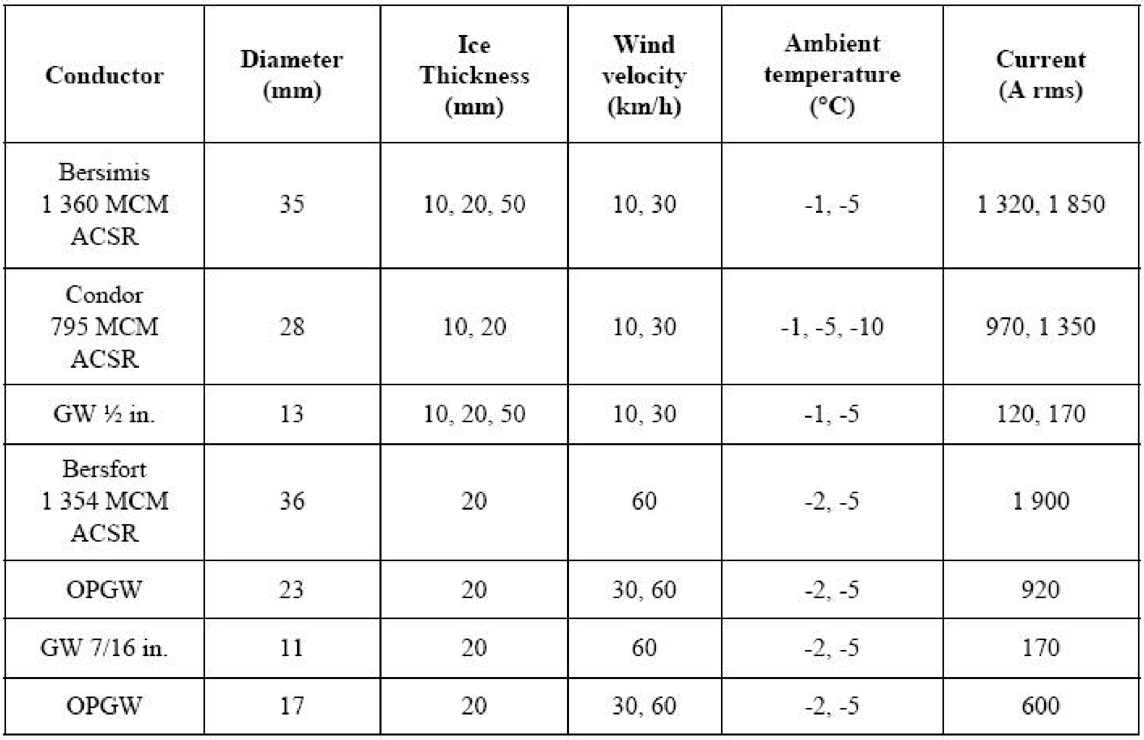
T_I is the temperature of the ice (in °C)

T_A is the ambient temperature (in °C)

Δt is the required time for a melt (in s)
V_{MELT} is the volume of ice sector to be melted above the conductor (m^3)

Table 7.1 provides some values of de-icing current obtained for different types of conductors and different environmental conditions [98].

Table 7.1 De-icing current required for various types of conductors



Conductor	Diameter (mm)	Ice Thickness (mm)	Wind velocity (km/h)	Ambient temperature (°C)	Current (A rms)
Bersimis 1 360 MCM ACSR	35	10, 20, 50	10, 30	-1, -5	1 320, 1 850
Condor 795 MCM ACSR	28	10, 20	10, 30	-1, -5, -10	970, 1 350
GW ½ in.	13	10, 20, 50	10, 30	-1, -5	120, 170
Bersfort 1 354 MCM ACSR	36	20	60	-2, -5	1 900
OPGW	23	20	30, 60	-2, -5	920
GW 7/16 in.	11	20	60	-2, -5	170
OPGW	17	20	30, 60	-2, -5	600

7.5.1.2 Conductor de-icing

a) Load shifting method

The load shifting method requires no additional equipment on the system, and consists of using the heating effect of load currents to prevent conductor icing or to remove ice from conductors. However, the current carried by HV lines is generally not sufficient to 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 [66,98]. Hence, if the load is high enough, depending on the ambient temperature and wind speed, the current in the remaining circuit will induce ice melting. This method is suitable for single-conductor lines as bundled conductors require too much current. One problem with this method resides in the difficulty of controlling the current flow during the de-icing period which is mainly determined by the power load demand of customers. Loss of power load could lead to de-icing failure whereas too much power load could lead to the overheating of conductors. Moreover, the power load available must be in accordance with the climatic conditions in the area where de-icing must take place. For these reasons and considering the large number of parameters to take into account, to be efficient, the load shifting method requires a well-defined de-icing strategy and decision tools [102,103].

b) Reduced voltage short-circuit method

Many electric power utilities in 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 [104]. Today, they have the capability to de-ice several thousands of kilometers of lines with conductors ranging in size up to 218 mm^2 (336.4 kcmil) ACSR. Currently, 90 stations, 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 conductor electrical characteristics. 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 single conductor lines, within a margin of 15% [105]. This de-icing method requires some equipment to be added like switches on the short-circuit side which is normally open in order to produce a three-phase fault. On the source side, switches and connections are required to power the lines to be de-iced. Also, the overload capability of existing equipment like system protection devices must be increased to support the de-icing current.

c) DC Current

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 required melting current and voltage are relatively small, AC can be used successfully. DC is more advantageous for long high-voltage power lines with large cross-section conductors because reactive losses are eliminated.

The DC-current technology has been developed, implemented, and successfully used on a large scale in the former USSR to melt ice along long 500 kV lines with large bundled phase conductors [3]. Following the January 1998 ice storm, Hydro-Quebec carried out digital simulations to determine the minimum network backbone needed to ensure the supply of a minimum load to guarantee electricity for essential services. Hydro-Québec uses a system incorporating a 250 MW rectifier at the Lévis substation near Québec City to de-ice four lines at 735 kV and one double circuit line at 315 kV [105,106]. One of the 735 kV lines has a length of 242 km, and consequently, short-circuit methods with AC sources would require too much reactive power and excessive voltage magnitude. The rectifier's power rating has been determined on the basis of its capacity to de-ice a 242-km long 735 kV transmission line consisting of 1354 MCM quad bundles. The rectifier is capable of supplying a 7960 A current at a voltage level of ±22 kV.

The basic principle of the DC current method is simple, as illustrated in Figure 7.13a. The longest 735 kV line will be de-iced one phase at a time using a current of up to 7200 A, with the other two phases being operated in parallel in order to minimize the rectifier's power use. The other 735 kV lines will be de-iced two phases at a time so that the line will be de-iced in two steps. For the 315 kV double-circuit line that is 183 km long, the two circuits will be de-iced simultaneously in a single step, as illustrated in Figure 7.13b, since this line has only small twin bundled conductors. Each de-icing step takes about an hour to complete. The insulated optical ground wire (OPGW) can also be de-iced at a lower current intensity using the same system. As installing a DC rectifier is relatively expensive for de-icing duty only, the Hydro-Québec rectifier circuit was designed to be reconfigurable so that it operates as a Static Var Compensator under normal operating conditions [107] so that it can operate continuously.

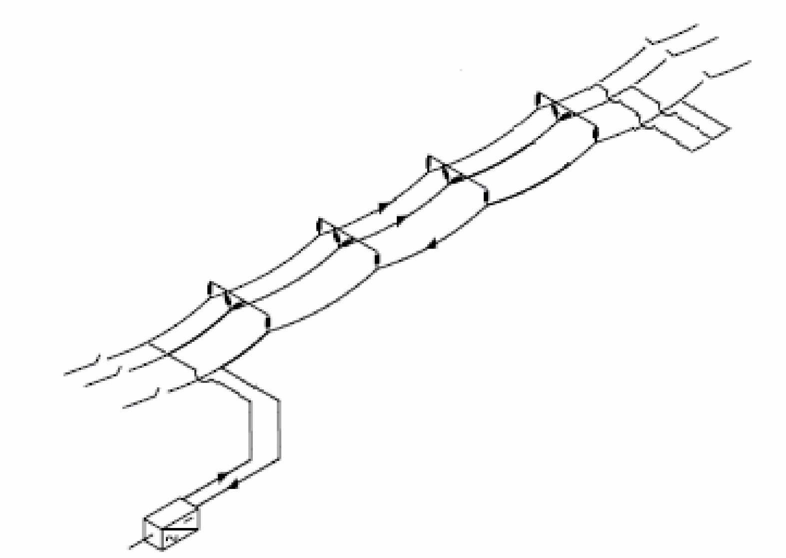


Figure 7.13a : One of the three-step sequences used to de-ice 735kV line phase conductors

The start-up of the de-icing process is based on the decision of a team of specialists who study weather conditions and forecasting. The analysis takes into account the weather conditions near the line, as well as the weight of the ice actually measured on the line to be de-iced. Based on the analysis, the de-icing parameters are quantified. For example the 7200 A current would be sufficient to melt 12 mm of ice in 30 minutes at -10°C and wind speed of 11 km/h. In the absence of any ice or wind, the conductor temperature should be about 95°C, which is the maximum allowable temperature. In other cases, however, different lower temperatures may be allowed.

Development and testing of an appropriate disconnect switch was also required to make sure it could operate safely considering the high current level with ice accumulation [106].

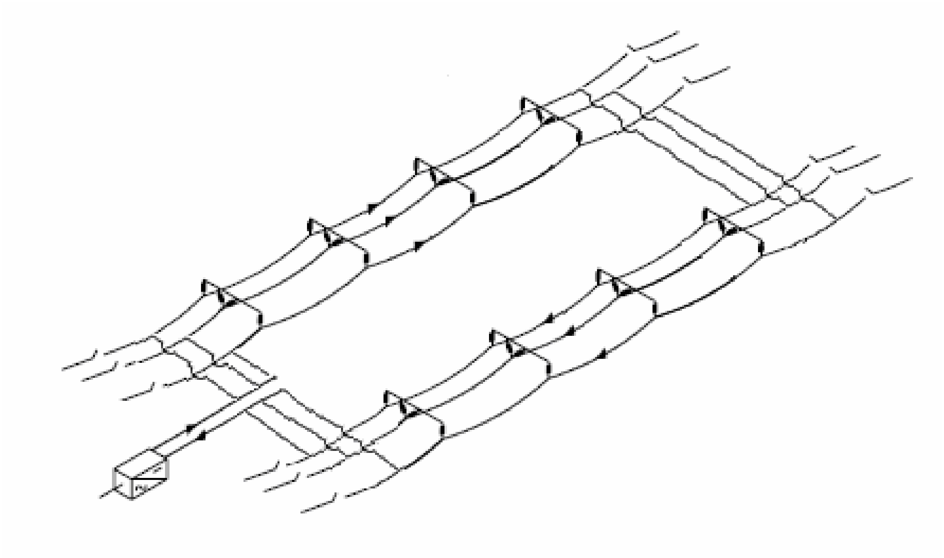


Figure 7.13b : Configuration used to de-ice double circuit 315kV line phase conductors

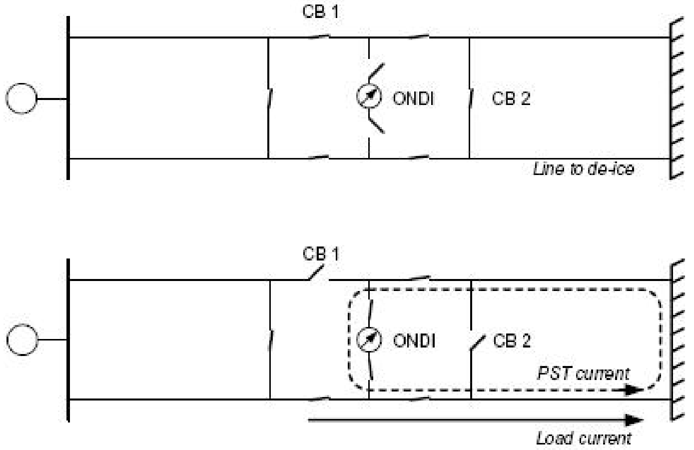


Figure 7.14 : ONDI energization and network configuration for de-icing [108]

d) Load network de-icer

Most of the Joule-effect de-icing methods mentioned require disconnecting the sections to be de-iced from the network. To overcome this problem, a new concept, the load network de-icer (ONDI) has recently been developed by CITEQ as a result of a project involving Hydro-Québec [108]. The ONDI concept is based entirely on the use of a phase-shifting transformer (PST) which is a special three-phase transformer employed for controlling power flows on transmission lines. During de-icing, the PST is connected in series with one of the two lines to create an AC current loop in the lines, as illustrated in Figure 7.14. By correctly adjusting the phase-shift of the PST, it is possible to increase the current flow by a factor of four in the line opposite to the PST line while maintaining the voltage in the network during the de-icing period. A similar method was used in the USA and presented by Ekstrom who suggested reconnecting transformer windings for a sixty-degree phase shift to deal with ice formation on 34.5 kV lines but limited to 40 to 46 km in length [109]. From the network simulations conducted by CITEQ, the ONDI system should be able to de-ice over 900 km of 230 kV or 315 kV lines and this by adequately switching existing circuit breakers to configure the network for de-icing. The simulations also demonstrated the possibility of line de-icing using the ONDI. This method can also be used to prevent icing of conductors. However, it is not suitable for de-icing lines made of bundles of three or four conductors which would require an excessive rating for the ONDI.

e) Contactor load transfer

This method was specially developed for bundled phases [110]. The originality of the proposed method is to replace actual bundle spacers by new spacers equipped with a contactor device in order to control the current flow in the bundle. During a de-icing sequence, the contactor forces the current, which normally flows in all the conductors, through one conductor only to melt the ice. The process is repeated for each conductor of the bundle until complete de-icing is obtained. The system can be automated and easily controlled remotely. However, this method is presently at a conceptual stage, and further studies are necessary to estimate the real need and the cost of its development and implementation.

f) Pulse electrothermal de-icer

In the same way as AC and DC Joule-effect methods, the pulse electro-thermal de-icer uses the current pulse to heat an external conductive coating surrounding the conductor [111]. This conductive coating can be made of a layer of conductor strands insulated from the main conductor body by a dielectric layer, as illustrated in the Figure 7.15. The main advantage of using current pulses is that the required average power can be reduced by a factor of 100 as compared to AC or DC current. Due to the very small duration of the current pulse, the thermal energy from the Joule heat of the external layer is entirely released at the ice/external layer interface, with a minimum diffusion into the dielectric layer. Also with this method, both anti-icing and de-icing can be obtained. However, it requires some significant modifications of the bare conductor by the addition of an insulated and a conductive layer sheath over the length of the conductor. This can cause problems during the installation, but also in the summertime when the thermal limitation of the conductor can be reached rapidly, leading to a reduction in service ampacity during warmer days. Finally, the efficiency of this method must be demonstrated as no laboratory or field tests on real stranded conductors have been done yet.

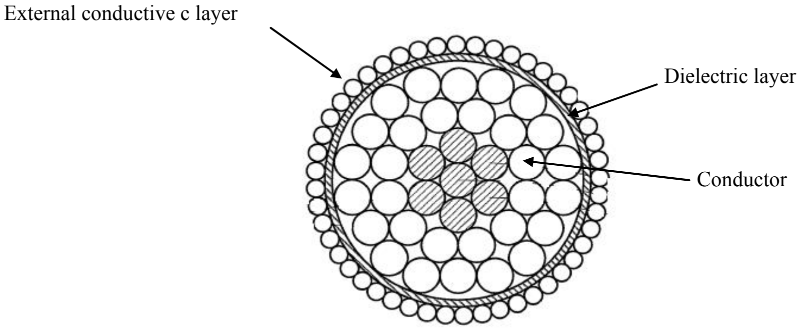


Figure 7.15 : Principle of pulse electrothermal de-icer applied to phase conductors [111]

7.5.1.3 Ground wire de-icing

Ground wire de-icing can be useful as part of a global approach to avoid major breakdown of transmission networks during severe ice storms. Ground wire de-icing by Joule effect requires a current source as well as an electrical insulation of the ground wires at towers, as shown in Figure 7.16 [112]. A medium voltage AC transformer (25 kV), to which current can be supplied by the main AC circuit, may be used as the current source. This method is very useful to de-ice several kilometres of ground wires. The range of de-icing is limited only by the withstand voltage of the insulators and arcing horns covered with ice. 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. However, opinions are still divided on the final approach to use. One philosophy recommends reinforcing the ground wires and the tower top members to withstand the amount of ice accumulation forecast associated with the geographical area. Another approach recommends changing the ground wires only once broken as the cost of this operation is little more than insulating the existing ground wire. Finally, the last solution recommends ground wire insulation for Joule-effect de-icing as the associated costs are partly compensated by the elimination of induction losses throughout the year (about 2 kW/km for a 735 kV line and 1 kA).

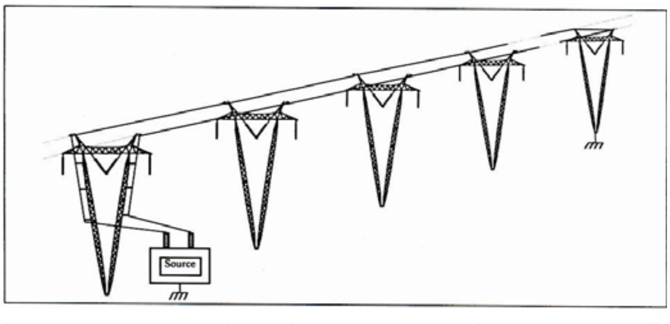


Figure 7.16 : Simultaneous de-icing of two ground wires (loop configuration) [112]

7.5.2 Other thermal methods

The methods described in this section use principles other than the basic Joule effect in order to melt the ice. The first method uses a superimposed high frequency electric field of around 100 kHz to induce dielectric losses in ice combined with the skin effect in the conductor to melt the ice sleeve [113]. Theoretically, this method can induce ice melting on line sections as long as 50 km. However, this solution, which was tested in a laboratory on 1-m sections of bare conductors, could generate electromagnetic perturbations likely to interfere with telecommunications. Also, in order to speed ice melting, an increase in high frequency voltage is required as well as the development of specific inductors to support this high voltage.

Other proposed methods use external heat sources in order to shed the ice sleeve. One such method consists in using radiation and specifically radio-waves to heat the conductor/ice interface [114]. Though efficient for de-icing railway lines, this method seems not so well adapted to power lines as it is limited to de-icing one span at a time and requires a mobile radio wave source.

Another method uses steam as a heat source. This method is actually used by Hydro-Québec to de-ice electrical equipment of substations like disconnect switches and post insulators [115]. For locally limited interventions, a vehicle has been adapted with an insulated telescopic arm for remote steam de-icing operation in high-voltage environment, as illustrated in Figure 7.17; it could easily be used to de-ice strategic or critical spans of power lines.

Figure 7.17 : Remote steam de-icing vehicle [115]

7.6 Concluding remarks

A summary of the main anti-icing (AI) and de-icing (DI) techniques described in this report is presented in Appendix II in the form of a table where each method is presented according to efficiency, operational status, disadvantages, country of use and cost level.

The literature review conducted for the preparation of this document shows clearly that the strategies adopted by the utilities converge towards the thermal methods based on the Joule effect for de-icing of overhead power lines on a large scale. Used for more than 80 years in several countries, the majority of these thermal methods are well known. However, to be effective, these methods must be selected and used adequately within the framework of a well established procedure which must take into account both the availability of the power on the network at the desired time and the weather data regularly updated on the icing sites. This suggests that the efficiency of a thermal de-icing strategy requires an adequate detection system of ice accretion on a line which could provide a real-time monitoring of the evolution of the ice build-up. Developing an efficient ice prevention strategy also requires synchronism between the various maintenance services in order to take full advantage of the time windows available to set up effective sequences of de-icing.

On the other hand, for specific localized interventions aimed at protecting short sections of strategic lines, the mechanical methods seem to be preferred. Indeed, shorter de-icing times can be achieved with mechanical methods compared to thermal methods, and they are well suited to extreme emergency situations, to avoid the collapse of overloaded towers, for example.

8 New materials and methods for ice prevention

8.1 Introduction

In the previous section, active methods for removing ice on overhead conductors were reviewed. It is obvious that a new coating or surface treatment exhibiting perfect icephobic properties would be far more attractive than any active method especially if the overall cost of such a coating procedure is less than the cost of fabrication, maintenance and energy needed to operate a mechanical or a thermal device. In reality, such perfect icephobic coatings do not exist yet and experience confirms that atmospheric ice eventually adheres to virtually all materials when icing conditions persist.

Mulherin and Haehnel [116] have summarized the main criteria to choose a suitable icephobic coating material. These are:

1. Efficiency: i.e. the coating must significantly reduce the adhesion strength of ice
2. Durability and longevity
3. Acceptable life-cycle cost
4. Ease of application.

While the first criterion will always be the most important one, the other three can be assigned different priorities depending on the specific application project. To illustrate the relative importance of criteria 2 to 4, a comparison is made in the two following examples. Among the different debris that are propelled upon NASA Space Shuttle launches, ice chunks coming off feedline brackets represent a considerable hazard [117]. In this particular situation, the longevity of a proper icephobic coating would not be an issue since the latter should keep its properties only during the pre-launching and launching stages (~ few days). On the other hand, icephobic materials used to coat high voltage power lines and/or the towers supporting them should remain active for about seventy years. This is a huge technical challenge considering that the coated material must withstand electrical, mechanical, and thermal constraints generated during the normal operating conditions or during specific events like short-circuits or lightning strikes [70].

In this section, different materials used to reduce ice adhesion are reviewed. Several publications can be found on the subject but they are either specific to one application [50,70,118], or too old to be considered [119]. In practically all the cited works, ice adhesion strength values were measured in direct shear mode. However, to avoid potentially misleading data comparison between different sources, no specific adhesion strength values will be given here; only qualitative information about the relative increase or decrease in adhesion strength. The rationale is that comparisons are impossible since the measurement methods were not always the same, the ice deposition process usually differed from one work to another, and coating roughness was not constant either.

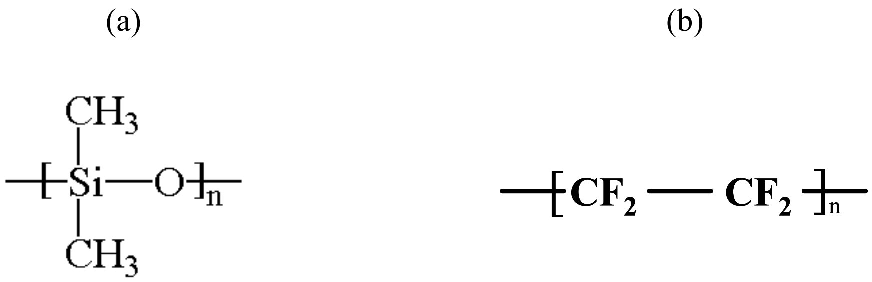
In view of the fact that a perfect icephobic coating does not exist, the emphasis will be put on more advanced and promising techniques developed recently by researchers to reduce ice adhesion on a given substrate. This information should help OHL engineers to explore various options and eventually adopt a technique that is optimal for the specific application of interest. Materials involving low surface energy polymers or molecules using techniques such as painting or spraying will be reviewed first, followed by a more in-depth study of recent advanced solutions to obtain highly hydrophobic or icephobic surfaces. These will include the production of heterogeneous surfaces, the use of hydrophobic self-assembled mono-layers, the production of diamond-like coatings (DLC) as well as the elaboration of superhydrophobic coatings. Other miscellaneous techniques or concepts will also be reviewed. Finally, possible options and critical views on icephobic materials as well as potential future developments in this area will be presented.

8.2 Deposition of hydrophobic or icephobic paints and polymers

Finding a material of surface energy as low as possible is the main design objective for icephobic coatings. Based on this statement, poly-dimethyl-siloxane (PDMS) or silicone, and Teflon® or poly-tetrafluoro-ethylene (PTFE), as displayed in Fig. 8.1, are the best candidates known to date as they possess very low surface energy (Table 8.1). Therefore, it is not surprising that most research efforts have dealt with these two families of polymers [47,48,65,116,120,121,122,123,124,125,126,127,128,129,130] In these studies, ice adhesion was usually assessed in direct shear mode, and coating deposition techniques were usually very simple, involving paints (alkyd or acrylic) with special solvents [48] or the use of polymer resins [125,127]. Overall, silicone-based polymers performed slightly better than the PTFE-based ones.

In 1978, Jellinek *et al.* reported that a PDMS film had a surface tension of 21 $\mathrm{mN.m^{-1}}$, which is characteristic of the methyl groups lying just at the surface of the polymer film, as displayed in Fig. 8.2, with the siloxane-carbonate block polymer [65]. Additionally, it was shown that the dimethylsiloxane content ($-O_2Si(CH_3)_2$ groups) must lie in a certain range of weight percent and chain length, and that the glass transition temperature T_g must remain low, T_g being a measure of segment mobility. When a polymer has a low T_g, the molecular segments can change place by actively sliding or jumping. The polymer is then said to be flexible or soft, and corresponds to an amorphous state. Ice adhesion can be lowered by the addition of silicone oil which enhances the softness of the PDMS surface by acting like a lubricant and a plasticizer. Also, it was shown that low T_g polymers exhibit a low interfacial shear strength which remains constant for $T_g < -50\ ^{o}\mathrm{C}$ [131]. In short, the dissimilar rheological-mechanical properties of ice- and polysiloxane-based polymers resulted in very low ice adhesion. That does not mean that this dissimilarity is necessary to achieve high hydrophobicity, polyfluorocarbon-based polymers being a good example of that.

For a polyfluorocarbon (PFC) based polymer, the $-CF_3$ group type exhibit exceptionally low critical surface tension (6 $\mathrm{mN.m^{-1}}$) [65] and can have high T_g values (> 150 ^{o}C). PFC-based materials exhibit better substrate adhesion and better mechanical properties (for wear, for instance) than their PDMS counterparts. Therefore, for temporary applications, PDMS-based coatings would be a preferable option. It is somewhat peculiar that PTFE, having strong hydrogen-type bonding with water molecules, as well as a high T_g value, is one of the most hydrophobic and icephobic substances known to date. This is explained by its very low permittivity ($\varepsilon = 2.04$) which drastically reduces the electrostatic force (see Section 6.2.1) that is the most important force involved in ice adhesion.



$-[Si(CH_3)_2-O]_n-$

$-[CF_2-CF_2]_n-$

Figure 8.1 (a) polysiloxane and (b) Polytetrafluoroethylene structures

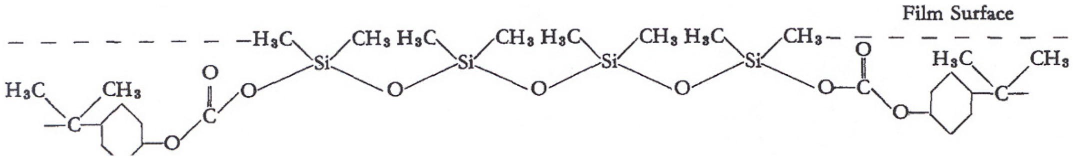


Figure 8.2 Siloxane-carbonate block polymer [65]

Mulherin and Haehnel [116] have tested 16 commercial materials labelled as “icephobic” and concluded that they indeed reduced the amount of energy needed to remove ice from the surface of these materials but did not prevent ice build-up. In fact, the tested materials offered little benefit over Teflon and polyethylene (UHMV) coatings and claddings. So in order to improve icephobicity, researchers have to formulate more advanced materials on the basis of the physics of ice–solid substrate interactions. The rest of this section will be dedicated to these more advanced and recent techniques as well as to some potential candidates to fight ice adhesion.

8.3 Heterogeneous and composite coatings

Several researchers [48,116,125] have found that better reduction in ice adhesion strength could be obtained by mixing polysiloxane and fluorocarbon materials than by using homogeneous coatings with either a PDMS or a PFC structure. However, this finding has not been explained yet.

In 1994, Murase *et al.* published a very important paper on heterogeneous polymer coatings aimed at decreasing ice adhesion [64]. Three different types of heterogeneous polymers were studied: one of them, the organopolysiloxane grafted fluoro polymer (FX), is displayed in Fig. 8.3. The other two are polyperfluoroalkyl(meth)acrylate combined with hydrophobic silicon dioxide (NX) and an organopolysiloxane modified with a lithium compound (SIII). Snow accretion did not occur on the NX coating while ice adhesion was reduced two times compared to PTFE. On the other hand, ice adhesion was 25 times lower for the SIII compound compared to PTFE while snow accretion was only divided by two.

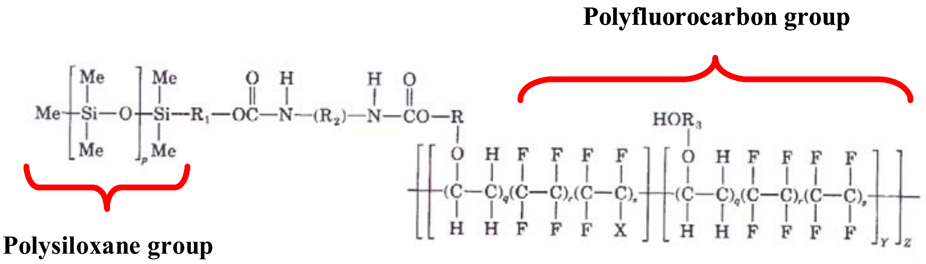
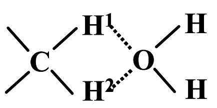
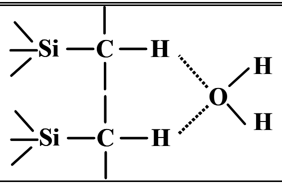
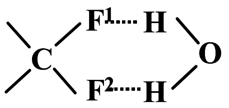


Figure 8.3 Organopolysiloxane grafted fluoro polymer (FX) [64].

To explain such a decrease in ice or snow adhesion in the presence of a heterogeneous polymer material, Murase et al. performed molecular orbital energy calculations using the SCF method with the MOPAC program. Three molecules were analyzed: ethane (LHC or C_2H_6), dimethylesiloxane (DMS) and hexafluoroethane (FHC or C_2F_6). The hydrogen bond lengths (O---H and F---H) as well as the different interaction energies are displayed in Table 8.1.

Table 8.1 – Interaction energies between hydrophobic polymer model molecules and water calculated by the SCF method [64].

Interactions Forms				
OH and FH bond length (nm)		0.252	**0.329**	**0.187**
Interaction Energies (kJ.mol^{-1})	E^1_1	-14.95	-15.64	**- 50.89**
	E^2_1	-5.70	-12.30	**- 48.51**
	E_2	-4.07	- 4.64	- 0.40
	E_3	-0.81	**+ 1.75**	**- 39.89**
	E_4	-1.40	**+ 1.79**	**- 35.81**

E_1: $O_{H2O} – H_{HC,DMS}\ F_{FHC} – H_{H2O}$
E_2: $O_{H2O} – mol_{HC, DMS}$
E_3, E_4: $H_{H2O} – mol_{HC, DMS, FHC}$

These values indicate that hydrogen bond energies and lengths vary considerably depending on the kind of molecular group involved. In reality, there is a slight repulsion between a water molecule and the siloxane group, while a strong attraction was calculated for the fluorocarbon group and a H_2O molecule. It is worth mentioning also that the water molecule orientations at the surface of the fluorocarbon group and at the polysiloxane one are completely different. Therefore, by creating various disparities at the molecular level in terms of energy bonding and water molecules orientation, the ice-material interface is weakened with the probable creation of a wide range of dislocations and slips in the structure of the liquid-like layer.

A US patent [132] from the Boeing company describes the elaboration of a Polysiloxane(amide-ureide) coating for icephobicity applications. The idea is the same as the one described by the Murase group: the heterogeneity of this polymer creates a synergistic effect which leads to low ice adhesion strength. Another US patent [133] describes an heterogenous coating using a tetrafluoroethylene and a silicone resin with an appropriate organic solvent.

8.4 Self-assembled monolayers (SAMs)

It was emphasized in [48] that -CH_3 and -CF_3 groups must be as close as possible to the coating surface in order to obtain maximum water repellence. An attractive technique to obtain such oriented layers is to employ self-assembled monolayers (SAMs). SAMs are molecular assemblies that are formed spontaneously by the immersion of an appropriate substrate into a solution of active surfactant in an organic solvent, as shown in Fig. 8.4. In this figure, an organosilicon type of anchoring group was chosen to illustrate this deposition technique since this group covalently binds to several important metal or non-metal oxides such as Al_2O_3, TiO_2, SnO_2, SiO_2, glass, etc. The spacer group consists of an alkyl chain while the surface group can be chosen following the desired surface property. In the case of icephobicity, CF_3 or CH_3 are the obvious choices for R.

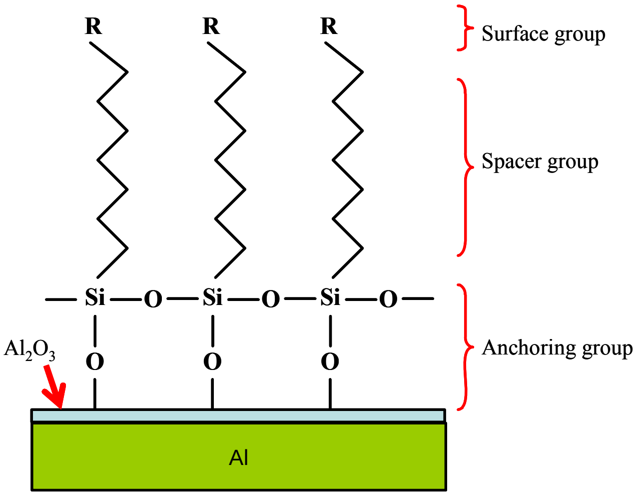


Figure 8.4 Schematic representation of SAMs grafted onto an aluminium substrate

The use of SAMs to obtain icephobic surfaces is very attractive; highly functionalized groups are in direct contact with water molecules of the ice surface and the anchoring of the alkyl chain is very strong (covalent bonds). The overall deposition technique is very easy to implement and inexpensive. However, very few studies have been reported in this particular area. Somlo and Gupta have shown that ice adhesion decreases when a SAM of dimethyl-n-octadecilchlorosilane is formed on an aluminium alloy surface [134]. More recently, Petrenko and Peng have applied mixtures of self-assembling 1-dodecanethiol and 11-hydroxylundecane-1-thiol with various degrees of hydrophobicity/hydrophilicity on Au surfaces, and have shown a good correlation between the contact angle of water and the ice adhesion strength [135]. Nanostructured superhydrophobic surfaces have also been prepared by self-assembly of hydrophobic n-octadecyltrimethoxysilane ($H_3C(CH_2)_{17}Si(OCH_3)_3$) and (3,3,3-trifluoropropyl)trimethoxysilane ($F_3C(CH_2)_2Si(OCH_3)_3$) monolayers from the gas phase on porous alumina, ZnO nanowire and GLAD (glancing angle deposition) surfaces [136].

Nevertheless, systematic knowledge is still lacking to explain how the microstructure and surface chemistry of SAMs influence their hydrophobic and icephobic properties [137]. In fact, the case depicted in Fig. 8.4 is an ideal one: the surface is perfectly plane and all the surface active groups are ideally positioned. In the presence of a porous or rough surface, chains of molecules become bent or collapse, resulting in a decrease in hydrophobicity due to surface exposition of alkyl groups such as $–CF_2$ or $-CH_2$ [137]. Another aspect that requires more study is the fact that the efficiency of a coating appears to be related only to one or two layers of molecular chains. In other words, if some patches of the substrate to be protected are damaged, the ice adhesion will likely increase. However, this technique is very promising to fight ice adhesion. The challenge is to develop robust SAMs that will remain active on complex surface topographies and will exhibit good ageing properties.

8.5 Diamond-like coatings (DLC)

Plasma Enhanced Chemical Vapour Deposition (PECVD) can produce diamond-like coatings (DLC) through the ionization and radicalization of a feeding gas like C_xF_y [138]. Highly reactive radical species such as $CF_2^\bullet$ or $CF_3^\bullet$ are produced during the PECVD process and are subsequently deposited on the desired surface forming a dense, hard and highly adhesive coating, with a long life expectancy.

Recent studies have demonstrated the potential of ultra thin films based on DLC associated with fluorocarbon gas [138,139,140,141,142]. Obtained by a common PECVD technology, these coatings exhibit high hydrophobicity with strong adhesion to aluminium and porcelain, as well as good mechanical properties. This technique may also be used to coat micro-textured surfaces to make them superhydrophobic. However, no ice adhesion tests have been done so far with these films.

Even though coatings with very good mechanical properties can be fabricated with the PECVD technique, several issues or limitations must be considered: high cost; the small thickness of the films (around 1 µm) as well as the difficulty to plate large and complex-shaped substrates.

8.6 Superhydrophobic coatings

Rugosity can have a spectacular influence on hydrophobic properties for a given surface. Numerous examples can be found in nature where the surface of some plants [143,144,145] or animals [146,147,148] exhibits the so-called superhydrophobic behaviour (Fig. 8.5). In that situation, water drops tend to behave like pearls and can roll down from the surface if it is slightly tilted or naturally curve-shaped. This phenomenon allows some plants or animals to remove dirt from their surface by collecting them through the water drop motion and fall. Some insects in hot desert regions use this superhydrophobic trick to gather life-saving water drops from the morning dew [146]. Some of the superhydrophobic coatings made by scientists in trying to mimic nature will be reviewed, but first of all a definition of what is meant by the superhydrophobicity is required

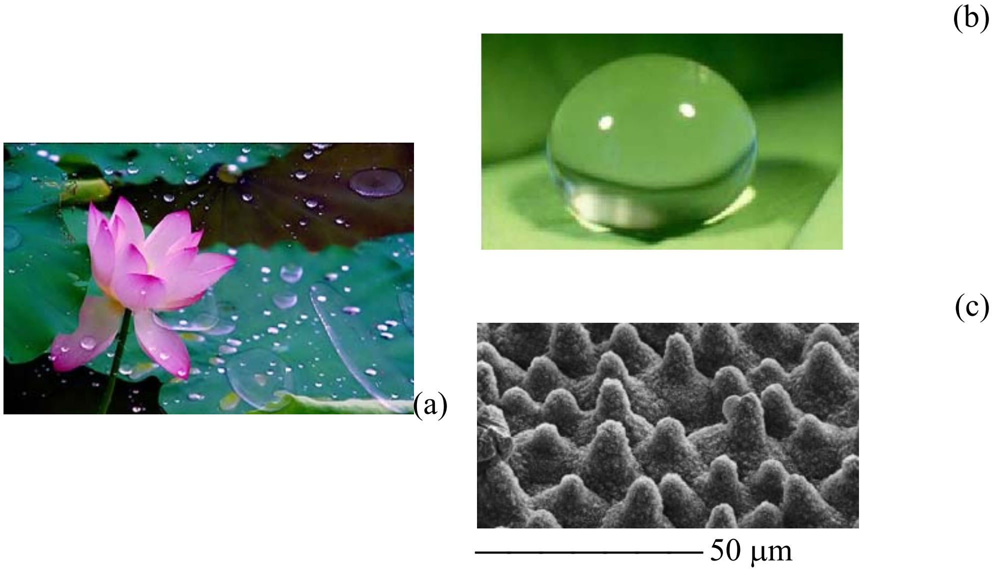


Figure 8.5 Water drops sitting on a Lotus plant leaf [145]:(a) overall picture, (b) high contact angle water drop and (c) microstructure of the leaf.

In order to evaluate the importance of the Wenzel and Cassie models described in Section 6.3, it is necessary to consider the work of He *et al.*[149]. Using photolithographic techniques, these authors have created micro-patterned surfaces to validate the models using a simple geometric layout, as shown in Fig. 8.6. From Equation 8.1,a geometrical parameter *A* is defined and new contact angles are proposed in Equations 8.2 and 8.3.

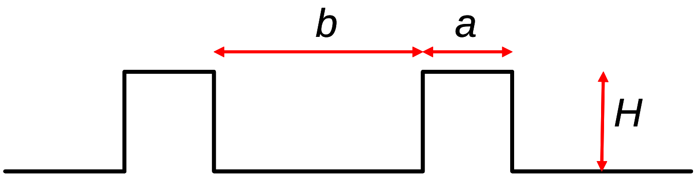


Figure 8.6 Two-dimensional geometrical representation of the patterned surface [149]

$$A = \frac{1}{\left((b/a)+1\right)^2} \tag{8.1}$$

$$\cos\theta_r^{cas} = A\left(1+\cos\theta_{flat}\right)-1 \tag{8.2}$$

$$\cos\theta_r^{wen} = \left[1+\frac{4A}{(a/H)}\right]\cos\theta_{flat} \tag{8.3}$$

Then, using different values of *b* and *a*, they plotted the theoretical contact angle obtained for the two models versus the *b*/*a* ratio (Fig. 8.7). It can be seen that the two models are completely different and the plots intersect at only one point, around *b*/*a* = 0.5

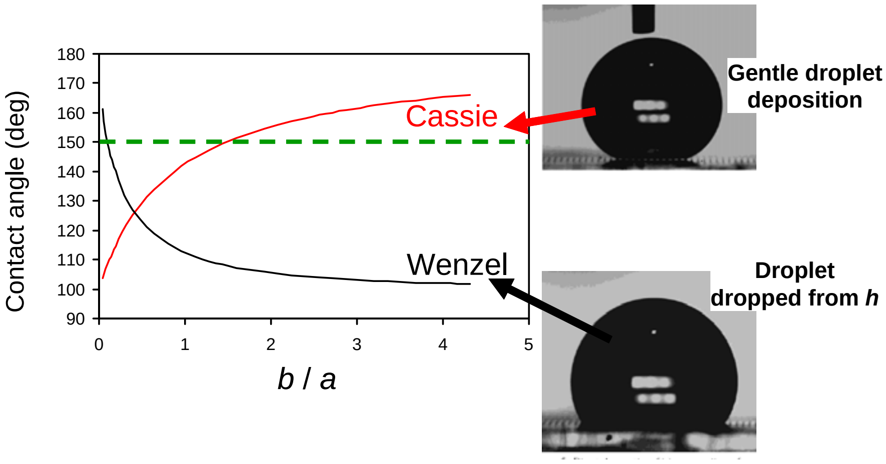


Figure 8.7 – Theoretical contact angles versus geometric factor *b*/*a* for the Wenzel and Cassie regimes [149]. *a* = 25 μm, Θ_{flat} = 100° and *a* / *H* = 0.83.

The most important result of this work is its experimental verification that the occurrence of the Wenzel or the Cassie model regimes depends on the water drop deposition process. As seen in Fig. 8.7, a gentle droplet deposition resulted in a Cassie type regime, while a droplet dropped from a certain height resulted in a Wenzel type regime. These results are crucial for the consideration of micro-textured materials for icephobic applications. In fact, during an ice storm, impinging supercooled water droplets on rough surface may result in liquid inclusion into surface asperities, and its subsequent and rapid freezing inside the three-dimensional structure. If ice growth occurs, this could be problematic since mechanical interlocking could take place.

Numerous studies can be found in the literature on the making of superhydrophobic micro- and nano-textured surfaces. However, virtually none of them were directly intended for icephobic applications. Researchers have created a primary porous structure either by etching a given substrate [150], depositing oxides nanoparticles [151], using nanolithography [152] or by electroplating polymers [153,154]. To enhance the hydrophobicity, subsequent coating with a low-surface energy compound is realized using various techniques such as PECVD, deposition of self assembled monolayers (SAMs) [136,156], passivation with stearic acid [157]. A review on the subject can be found in [158]. As far as nature mimicking micro- or nano-fibers are concerned, fewer works can be found. A PTFE superhydrophobic surface was made by extension of the fibers comprising the base material [155]. A superhydrophobic poly(vinyl alcohol) forest like nano-fiber structure was produced in the form a forest by extruding the polymer through holes with diameters comprised between 20 and 500 nm in an alumina template [159]. Lau *et al.* produced a carbon nanotube forest using the PECVD technique [160] which was subsequently coated with PTFE to obtain superhydrophobicity.

Production of nanofiber networks using the electrospinning process has recently drawn some attention. Block copolymer poly(styrene-b-dimethylsiloxane) fibers with submicrometer diameters in the range 150-400 nm were electrospun to produce superhydrophobic materials [161]. In another work, poly(caprolactone) was electrospun and then coated with a thin layer of hydrophobic polymerized perfluoroalkyl ethyl methacrylate (PPFEMA) by iCVD [162]. The electrospinning of poly(AN-co-TMI) with a perfluorinated linear diol (fluorolink-D) and tin(II) ethyl hexanoate in DMF [163] can also be cited. In each of these three cases, superhydrophobocity was reached when the microstructure of the materials was composed of both fibres and polymer beads.

Finally, the work of the Saito group in Japan was aimed at producing highly hydrophobic micro-textured coatings made of PTFE particles blended in a PVDF binder applied by a spray drying technique [164,165,166]. Snow accretion on antennae was dramatically reduced by such a coating. The work of Saito is the only one to date linking ice or snow adhesion to superhydrophobic coatings, which means that such coatings have to be studied in icing conditions. The fragility of their structure, their adhesion to a given substrate as well as their behaviour after several ice removals are major hurdles that scientists will have to face in future developments.

8.7 Other possible approaches

8.7.1 Joule-effect methods

Hydrophobic composites for coating Metal-PTFE can be produced by electrodeposition or electroless plating. PTFE micro or nanoparticles are dispersed in a given electrolyte and are entrapped during the reducing process of the metallic ions.

Using the electroless technique, Ni-P-PTFE coatings exhibiting a water contact angle of 110° were produced, as shown in Fig. 8.8 [167]. Similar results were also obtained by others with the same technique as reported in [168]. Ultra-dispersed nano-sized (300 nm) PTFE particles within a nickel matrix were produced using electrodeposition [169]. In this study, water contact angles ranging from 123° (28 % vol. inclusion of particles) to 155° (47 % of particles) were observed.

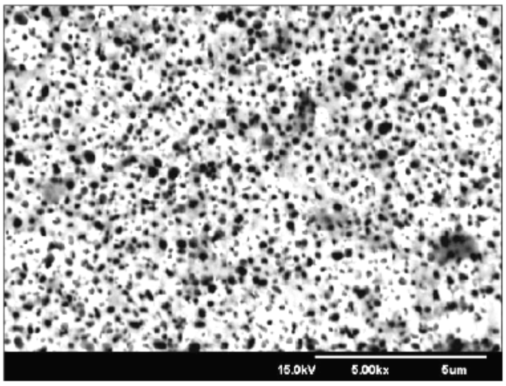


Figure 8.8: SEM photomicrograph of a composite Ni-P-PTFE coating [167]. The black spots correspond to the PTFE particles.

No studies on ice adhesion on electrocomposite coatings can be found in the literature. Even though the presence of high surface energy area (metal) may be problematic, the composite nature of such surfaces may lead to interesting new properties. Electrochemical deposition techniques are very cheap, and can produce thick adhesive films (between 1 and 100 μm). Additionally, large and complex parts can be plated with this technique.

8.7.2 Ice de-bonding induced by pressure build-up within rough surfaces

Various aspects of icing were studied on porous pavements [52]. One very interesting aspect of this study was the pressure increase during freezing inside an enclosed space. Because of the unique expansion of ice at freezing point, ice formed in blind pores would push tight against the walls, creating strong mechanical interlocking. However, if air is entrapped the pressure build-up can be significant, and lead to crack initiation and propagation as well as ice de-bonding. Pressure increase was also measured during freezing as a function of the initial volume of water trapped in the enclosed space. It was found that when 2 % of the water was frozen the pressure was 36 atm, and that it reached 420 atm with 20 % of the ice formed. The pressure generated within the specimen is manifested as internal or residual stress. To use the pressure, or residual stress, to their advantage (ice de-bonding), the researchers drilled holes into a pavement portion, which was then covered with ice. After top-down freezing, the ice caps popped up after a certain time depending of the size of the holes, as shown in Fig. 8.9.

In another work [47] at a different scale, replicas of ice sheared from four different PDMS coatings showed bubble-like features that strongly suggested that tiny air bubbles had been trapped between the ice and the coating, as seen in Fig. 8.10, resulting in lower ice adhesion properties.

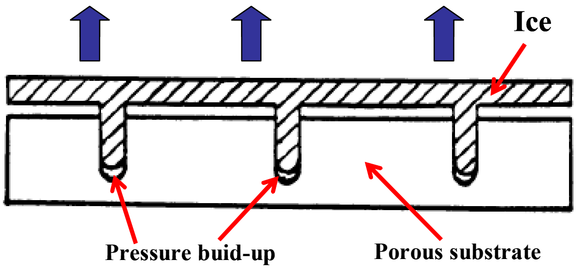


Figure 8.9: Ice de-bonding on a porous pavement section [52]

Although surface roughness can lead to potential strong mechanical interlocking and therefore to high adhesion strength, the two examples just described can be the basis of new coating materials having an optimum roughness in order to create enough internal stress to crack and possibly de-bond ice.

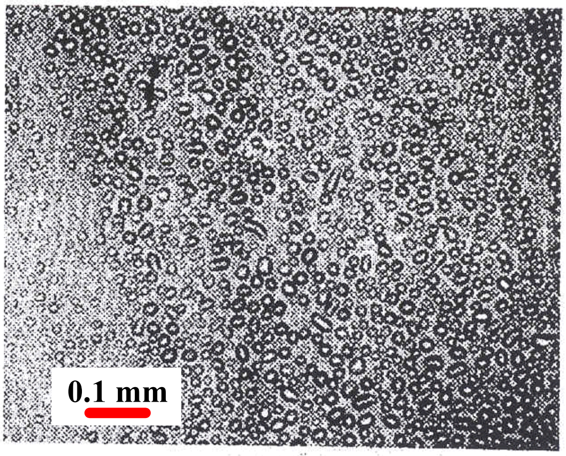


Figure 8.10: Replicas of ice sheared from polysiloxane polymer coatings [47]

8.8 Concluding remarks

Materials science studies aimed at developing icephobic coating are very scarce in the literature. On the other hand, considerable amount of scientific publications can be found on materials with high hydrophobic and superhydrophobic properties. The reasons for this are the lack of understanding of the physics behind ice-solid interactions, the availability of alternative methods such as active methods and hybrid methods (active and passive), or simply because such new materials are very difficult to fabricate. The time for merely testing commercial hydrophobic coatings to assess their icephobic properties has come to an end, and new pressures call for the development of innovative advanced coatings to drastically reduce ice adhesion. Environmental issues such as the hazard presented by de-icing fluids in the aeronautic sector, energy consuming mechanical and thermal methods in the case of wind turbines for example, potentially huge safety and economical costs generated by ice or snow storms as well as all the cost to operate active devices, are the main drivers to elaborate novel icephobic coatings.

Recent advances in ice adhesion physics, materials science (functionalized nano-materials, advanced deposition techniques, new polymers, etc.) and in analytical tools (STM/AFM) have spurred new interest in developing materials having enhanced specific properties. Icephobic materials are no strangers to such developments. It would be extremely difficult, if ever possible, to formulate a truly icephobic material (with zero ice adhesion strength). However, by drastically reducing its adhesion strength, ice may be removed using a minimum amount of work or heat or can even detach itself under its own weight.

To decrease ice adhesion on a given solid, its surface must be modified or coated with a material being able, at the molecular or crystal level, to disrupt the structure of the ice immediately adjacent to the solid. Several strategies may be exploited to reach such a goal:

1. Substrate coating with a low surface energy material.
2. Substrate coating with a low dielectric material.
3. Creation, at the molecular or nano-scale level, of a heterogonous surface promoting a non-uniform stress distribution in the ice adjacent to the solid.
4. Promoting the presence of tiny air pockets at the interface between the ice and the coating to disrupt bonding by creating stress concentrations.
5. Achieving an optimum degree of roughness to promote propagation of cracks in the ice.

It must be stressed that surface roughness may have a detrimental effect (mechanical inter-locking) on the decrease of ice adhesion. Therefore, it will be important for the engineer to test the new coatings in simulated or real weather conditions.

From a practical point of view, the durability or longevity of the coating, its cost and its ease of application are also major considerations. Adhesion of the coating itself, ageing due to corrosion (normal or accelerated by acid rain, airborne contaminants or the nearby presence of seawater), UV illumination, thermal exposure, wear (during installation for instance) as well as erosion/abrasion due to the combined effects of rain and wind are among the most important factors to be taken into account.

9 Modern meteorological model systems to monitor and predict the occurrence, extent and severity of icing events

Any operational de-icing system will always depend on a reliable system for monitoring and predicting icing events and their developments. Ice or snow build-up on overhead transmission lines is a problem which can occur over a wide geographical area in cold climates throughout a significant period of the year. Furthermore, it is often local in nature with some areas heavily affected while adjacent regions are virtually ice-free. This makes direct measurement of icing phenomena on transmission lines very difficult, e.g. for planning of de-icing or other operational measures, as a large number of sensors would be needed. Moreover, ice accretion often occurs in remote and mountainous areas where the supply of low voltage power and lack of telecommunications constitute obstacles to the installation of measuring systems.

Furthermore, using meteorological data from weather stations, radar and satellite observations has not proven to be reliable enough for predicting icing near the ground, especially for rime ice and wet snow [170]. The main reasons for this are that the existence and amount of liquid water in cloud air (rime ice), or the liquid water ratio in snowflakes (wet snow) cannot be estimated directly from such measurements.

In recent years the development of meteorological weather forecasting models of the atmosphere has reached a level of accuracy and details that makes it possible to estimate the amount of ice already accreted, or to forecast the expected ice build-up on standard objects. Such a method is described in [171]. The most important aspect with this technique is to insert local scale models into a global weather forecasting model by nesting. Since it is not possible to insert abrupt changes in model scale from several tens of kilometres (global models) to the order of hundreds of meters (local scale models) in one step because of stability in the models, such transitions are made by nesting of intermediate models, as shown in Fig 9.1. Here, the nested models have grid spacings of 12,8 km, 3,2 km and 0,8 km, respectively. For each nested model the ground surface characteristics are represented with corresponding resolution with the number of vertical layers adjusted accordingly.

Each model domain has its own set of equations for the dynamic and physical processes in the 3-D atmosphere. These processes are again forced by the corresponding processes in the outer model at the boundary between the two domains.

For the inner model any icing parameter can then be calculated for each grid point by applying any already established physical icing model, as for instance shown in [5] Hence a map of ice occurrence, or accumulated ice loads, may be produced for either a selection of points along one line, or in a 3-D (map or Google Earth). An example of such a regional icing map from Norway is shown in Fig. 9.2.

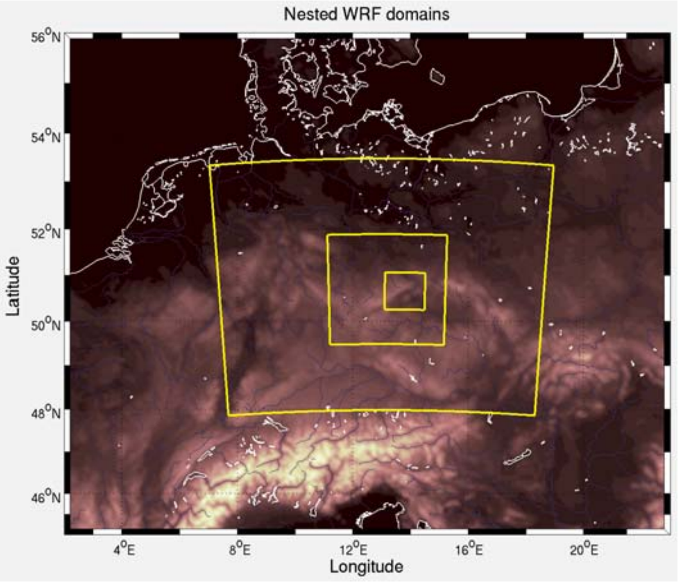


Figure 9.1 Nested Weather Research and Forecasting Model domains for the Zinnwald test station in Germany. The three domains are indicated by the yellow squares. The grid spacing from outer to inner domain is 12,8 km, 3,2 km and 0,8 km, respectively [171]).

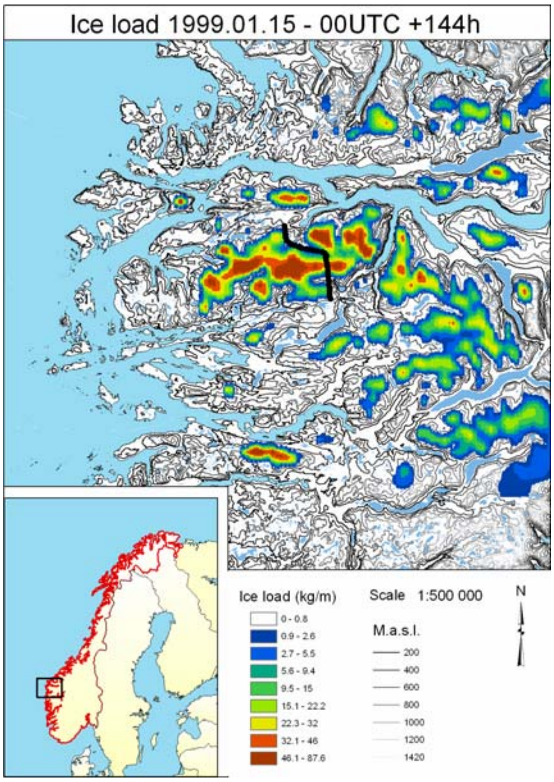


Figure 9.2 Accumulated ice (color shadings). The black line indicates a transmission line route. (adapted from [172])

Models of this type can be used for retrospective analyses of historical icing events or as operative forecasting of potential risks in an electrical network. Accordingly, it can be used to initiate any operational system for de-icing of overhead transmission lines.

Such models have already been successfully used for rime ice [171]. They have also shown promising results for wet snow during the COST Action 727 “Measurements and Forecasting of Atmospheric Icing” [173]. However, for freezing rain the prognoses of temperature inversions near ground are not yet accurate enough for this purpose.

It is important to recognize that local scale weather forecasting models cannot be as accurate as direct measurements. But it is also important to remember that reliable measurements are not always easy, or even possible to perform for the most important parts of a line route. Therefore the best way to get the needed information on icing events on a transmission line is to combine measurements and atmospheric models. A significant feature gained by combining measurements with atmospheric models is that the validity range of the measurements will be enhanced.

10 Conclusions

In this report, the most promising methods to combat ice accumulation on overhead line ground wires (GW) and phase conductors are discussed. However, in order to understand these methods, some fundamental aspects and processes of ice adhesion and accretion, as well as the mechanical and thermodynamic behaviour of ice and snow, including the shedding process, are covered.

A review of the existing de-icing (DI) and anti-icing (AI) technology showed interesting non-thermal methods, including passive methods, active coatings and devices and mechanical methods, but their scope is generally limited to local intervention. On the other hand, a survey of anti-and de-icing methods showed that the heating of ice-covered line conductors by electrical current has been accepted worldwide as the most efficient engineering approach to minimize the sometimes catastrophic consequences of severe ice events, thus increasing power system reliability. Either AC or DC has been used for ice melting. The technologies for both types of current are available, the methodology has been developed, and operational experience with ice melting systems has been acquired for several decades. For overhead lines up to 110-230 kV, AC is recommended, but for higher voltages (including UHV lines) DC should be used in order to provide the required large power to melt ice on long lines with large conductor bundles, which is typical for lines of 345 kV and higher voltages.

Furthermore, new technologies based on the use of icephobic materials are discussed. This approach is promising, and could present a good potential for future applications. Also, as any AI/DI techniques depend on reliable monitoring and predicting of icing events, the important role of modern meteorological forecasting systems is briefly discussed.

De-icing technologies and methods for the prevention of ice accretion should be a part of system planning specifications for new projects, standards and operational procedures in regions that are often affected by atmospheric icing events. This has already been done in some countries and can significantly reduce the risk of catastrophic damage. (or increase the reliability of the grid)

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APPENDIX I : Ice melting technologies

(*This Appendix is an adaptation of the draft document that was authored by the late Dr Yakov Motlis, a foremost expert in power line thermal de-icing, in view of the CIGRÉ WG B2.12 meeting in Paris, 2002. However, Dr Motlis passed away before he could finalize this document, which explains its sketchiness and occasional redundancies. Anyhow, because of its wide, deep and insightful coverage of the subject, and because it encompasses worldwide experience in this domain, it was essential to include it in this report. It will also be a tribute to his memory.)*

Both AC and DC can be used to heat line conductors as shown in the different configuration presented in Figures A.1 - A.5 of this Appendix. Using AC does not necessarily always 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. Melting of ice by DC is more advantageous for high power long lines with conductors of large cross-sections. For 220 kV lines, the capacity of DC power supply is about 20% of the required AC power supply.

A.1 North-American experience

The first experience involving ice melting occurred on the New England Company power network during a storm in 1920 [99]. The lines were cleared of ice in Western Massachusetts by using a group of 2300/220 –volt transformers connected in series and paralleled, to secure from 6000 to 8000 volts at 300 Amperes (line conductor size was 1/0 copper). This was only a temporary connection made up after six days of ineffective work trying to clear the lines, and much to the surprise of all it worked amazingly well. These were trained in the plant during remainder of the winter. The total apparatus tied up for sleet thawing consisted of one 60-cycle, 2300-volt generator, and two three-phase transformers. One of many conclusions of this paper is that “wherever possible it is advisable to install a thawing device if it can be done at a reasonable figure...It will pay for itself many times on transmission lines thus protected from the sleet storm.."

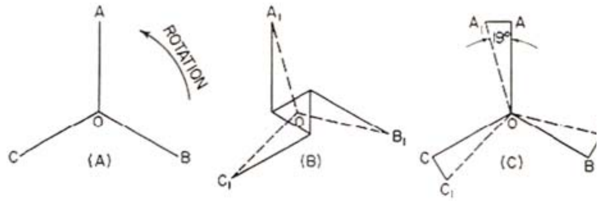
A paper [174] presents the particular problem of protection under conditions of sleet melting (forced loading, phase shifting or short-circuiting), and proposes a means of detecting faults on lines being ice-melted by the short-circuit method. The source of power for the short-circuiting method may be an isolated generator with a step-up transformer that may be adjusted to supply the proper current. Some lines because of their particular length may lend themselves to ice melting by direct connection to a station bus. Under these conditions, the normal relays cannot generally be set to give adequate fault protection. In the instance where several lines are connected in series for sleet melting, the relays at the sectionalizing points between extreme terminals must be removed from service.

Among a variety of methods evolved in USA over the years to combat ice formation on overhead lines, reconnecting transformer windings for a 60-degree phase shift was the most popular because it does not require interrupting service connected along the line affected [109].

Sixty-degree phase shifting is limited, however, in that it can be used on 34.5-kV lines of only 25 to 35 miles (40 to 56 km) in length, depending upon design impedance and conductor size. In general, the greater the length, the greater the impedance will be, eventually reducing the circulating current to a value too low to produce sufficient current to melt the ice at reasonable length of time. Adding enough of short lines in series like in the more densely populated areas to make up a total of 25 miles (40 km) involves a greater liability in the amount of load and number of customers affected; hence the need for lesser angles of phase shifts.

Figures A.1a-i show 19°,41°, 79° and 101° phase shifts achieved by reconnecting a 3-winding closed-tertiary transformer bank or polyphase transformer. Advantages of lesser phase-angle shifts include: being applicable to lines of shorter length or lower voltage; nearer normal voltage at mid-point of the line from which ice is being melted; ice prevention on longer lines; reduction of relaying problems due to fewer lines being connected in series and reduced hazard to customer service. Introducing the 120-degree roll has an added advantage in that the direction of a 60-degree phase shift can thereby be reversed, that is from lag to lead. This provides flexibility to meet specific conditions of in-service ice melting such as location in the line of the larger conductors, service to primary networks, and capacity of facilities serving the remote end of various lines. Greater phase-angle shifts provide another range of non-standard short-circuit voltages which make possible out-of-service ice melting on a still greater range of line lengths.

Icing precipitation has been of much concern to Pennsylvania Water and Power Company since 1910 [175]. The evolution in combating sleet on line conductors from simply heating a line is as follows: i) forecasting the appearance of ice formations; ii) detecting accumulations on conductors; and iii) applying heating current to the conductors to remove the ice.



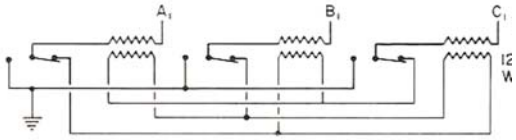
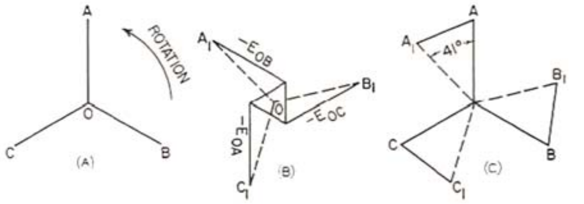


Figure A.1a Development of the 19-degree phase shift:
a) Voltage vector of normal 34.5-kV system;
b) Neutral ends of 34.5-kV windings reconnected to 12-kV tertiary;
c) Phase displacement between phase-shifted transformer and normal system

Figure A.1b Switching arrangement for the 19 degree phase shift



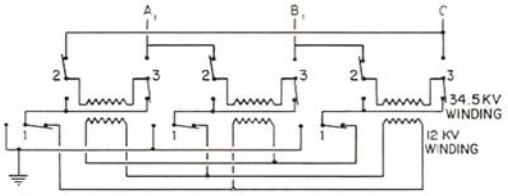
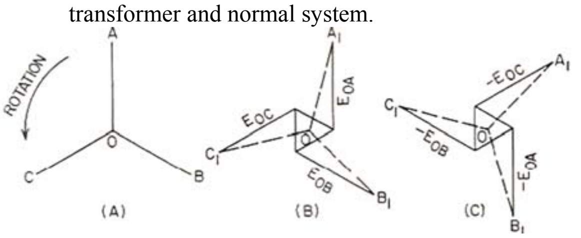


Figure A.1c Development of the 41 degree phase shift:
a) Voltage vector of normal 34.5-kV system;
b) 34.5-kV windings reconnected to 12-kV tertiary;
c) Phase displacement between phase-shifted transformer and normal system.

Figure A.1d Switching arrangement for the 41 degree phase shift



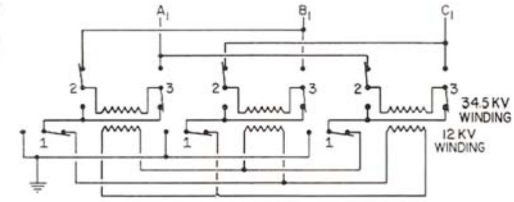
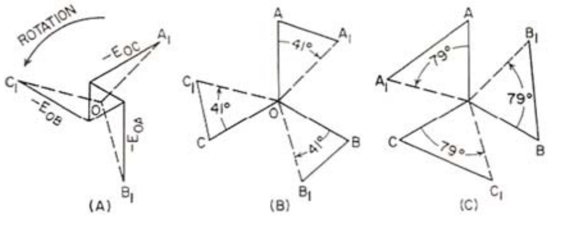


Figure A.1e Illustration of how reversing the delta tertiary reverses the direction of the phase shift
a) Voltage vector of normal 34.5-kV system;
b) Neutral ends of 34.5-kv windings reconnected to reversed 12-kV tertiary for 19 degree lag
c) Neutral ends of 34.5-kv windings reconnected to reversed 12-kV tertiary for 41 degree lag.

Figure A.1f Switching arrangement for the 41 degree lag phase shift



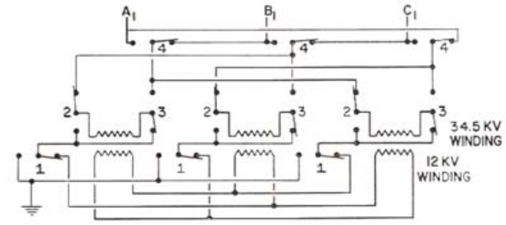
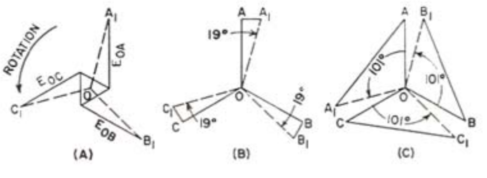


Figure A.1g Development of the 79 degree phase shift:
a) Development of 41 degree lag phase shift;
b) 41 degree lag phase displacement;
c) 79 degree lead phase displacement

Figure A.1h Switching arrangement for the 79 degree phase shift

Figure A.1i Development of the 101 degree phase shift:
a) Development of the 19 degree lag phase shift
b) 19 degree lag phase displacement;
c) 101 degree lead phase displacement



The American Gas and Electric Company adopted ice melting as a part of the project of designing a 330-kV system, in 1954. Using 132-kV power sources, necessarily of very substantial capacity, the ice-melting current was applied to short-circuited line sections within the range of 60 to 80 miles (96 to 128 km) in length as compared with 120- to 150-mile (192 to 240 km) sections for existing 132-kV lines [176].

Early developments in ice melting and ice detection methods on the American Gas and Electric System were described in 1939 papers [177]. These methods basically consisted in detecting ice formation by carrier-current means, and isolating and connecting in series of sufficient lengths of a 132-kV circuit to obtain the required ice melting current when the circuit is short-circuited at one end and connected directly to a 132 kV source at the other end. In planning ice melting procedures, some of the factors that must be considered are:

- The selection of a line combination and grounding and switching arrangement which will give as high a current as possible without endangering equipment and service to customers.
- The importance of melting as quickly as possible in order to keep the circuit outage time to a minimum. Early detection and the use of as high a current as possible will help to accomplish this.
- Any necessary adjustments in system load distribution and the need, if required, for help from interconnected companies.
- The short-time current-carrying capacity of busses, by-pass facilities, current transformers, and so forth. In some instances, it has been necessary to rebuild or replace equipment.
- The adequacy of conductor joints to withstand ice melting currents.
- The need for sending men to unattended stations and keeping them there throughout the switching period.

Ice melting becomes a factor in the 330 kV line design and in conductor selection.

A paper [178] presents the phase-shift method with particular emphasis on 60-degree shift. The system operator must have a clear picture of the problems involved in order to correctly apply the phase-shift method of ice melting. He must provide adequate active- and reactive-power capacity at the points where needed. He must know his line and the station equipment limitations. He must arrange his system for varying conditions due to storm location and line availability, being always mindful of his prime responsibility – that of keeping the power flowing.

Experience with accreted ice conditions on the Niagara Mohawk System has indicated that adequate planning is necessary if satisfactory results are to be secured from any ice melting program [179]. The planning extends from system design to operating procedures, to training. All must be coordinated to weather a severe storm successfully.

The Niagara Mohawk System recognized three principal methods of icing prevention or ice melting:

- **Load current method** The heating effect of load currents is used to prevent or remove ice on the conductor. Where necessary, normal operating conditions are modified in order to force more load current through a particular circuit. The use of this procedure is emphasized since switching is performed at manually operated stations, no markups are necessary, and a minimum of time is required to make the procedure operative.

- **Short-on-a-generator method** One or more generators are isolated from the rest of the system and connected to a circuit, which has also been isolated. The three phases of this isolated circuit are short-circuited at the far end. The generator field is gradually increased (from a subnormal value) to a value sufficient to produce the desired melting current.
- **Short-on-a-bus method** One or more transmission circuits are isolated from the rest of the system. The total length of these transmission circuits is predetermined so that, with normal operating voltage applied at one end and a 3-phase short-circuit established at the far end, the desired ice melting current will flow. Then, having established the 3-phase fault, the near end is connected to its regular bus (at normal voltage) through a circuit breaker.

The following procedures were applied by Niagara Mohawk:

- The system connections were changed as indicated by the AC network analyzer studies. In this instance, a complete auxiliary bus was added in a station to facilitate ice melting. The final decision as to design of two new 115 kV generating station busses was influenced by their adaptability for ice melting purposes.
- Step-by-step instructions and detailed drawings were developed for the various ice melting procedures.
- Ice melting tables were provided for the operating personnel. In those tables the following information is given for the system operators:
    - **For ice prevention** Conductors maintained at a temperature slightly above freezing would not accumulate ice. The current necessary to maintain this temperature depends on air temperature, wind velocity, conductor cross-section and conductivity.
    - **For ice melting** Once ice has formed on the conductors, it is necessary to go to sleet-melting currents, which, obviously, will be greater than sleet-preventing currents. The required current depends on thickness of ice formation, air temperature, wind velocity, amount of time available to remove the ice, conductor cross-sectional area and conductivity.

Manitoba Hydro, Canada, began using high currents to melt ice in the early 1970s as an experimental procedure [104]. To date, 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 (11mm to 18mm diameter) ACSR.

The following is the sequence of events adopted by this utility:

- Prior to the ice storm season, all required engineering calculations are made to determine the currents that can be obtained. Station equipment ratings are checked to see that all equipment is satisfactory for the expected current levels. Provisions are made to allow the connection of required lines and sources. This may require the upgrade of existing or installation of new equipment. Switching procedures are written up to accomplish these connections and emergency manuals produced, and kept up to date.
- Once icing is detected, the required melting current for the specific conductor size, weather, wind speed and ice thickness is determined. The location of jumpers for the desired length of line to be cleared is calculated.

- The line to be melted is isolated. The shorting jumpers are connected at the calculated distance down the line. Any required protection settings are applied to the equipment. Finally, the line is connected to a station transformer of appropriate voltage and size.
- The line to be melted is energized. Staff at the station monitors the current and staff at one or more points along the line watch the ice removal. When the ice has dropped, the melting process is terminated and the system is returned to normal.
- The details of ice accumulation, weather conditions, melting times and success rate are recorded for further analysis.
- If icing continues, a line may have to be melted more than once during a storm and the process may be repeated.

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.

(*For other and more recent ice melting methods, in the North-American context, the reader is referred to Section 7.5 of this Technical Brochure.*)

A.2 Russian experience

Power systems of the former USSR have developed and standardized on large-scale ice melting technologies [180] for their networks of all voltages up to and including 500 kV. The operational experience with ice melting systems has been described in many publications. The principles and philosophy adopted by Russia and other Republics of the former USSR are briefly given below.

- Analysis of design and operation experience has shown that there are a number of technical constraints, which determine the choice of parameters of ice melting devices (IMD). Among these are the following:
    - Load capacity of supply for ice melting
    - Maintaining an acceptable level of network voltage during ice melting procedure
    - Maintaining system frequency during IMD switching operation
    - Limitation of harmonic levels and voltage unbalance at consumers busbars, based on the existing standards
    - Possible conductor overheating by melting current at ice-free line sections
    - Ensuring the rate of ice melting on a group of lines, exceeding the rate of ice formation.
- When designing the IMD scheme one should keep in mind that it is determined mainly by the supply scheme, by the scheme of ice melting and by the type of melting current, AC or DC. The scheme of the IMD supply depends on the system configuration and on the types and parameters of equipment installed at the substation, supplying ice melting facilities. The type of melting current is chosen based on the length of the network lines.

- Selection of optimal IMD supply schemes is based on the features of the main substation scheme:
    - Substations with voltage control by tapped switches of transformers (autotransformers)
    - Substations with voltage control by line regulating transformers
    - Substations with voltage control by booster transformers.

- The ice melting project includes provisions for special observation posts and warning technologies. In some cases, preheating of conductors is done prior to the ice melting event.
- Development of an ice melting system requires the following technical parameters to be considered:
    - line voltage
    - type and size of conductors
    - scheme how the conductors will be connected
    - capability and other parameters of the feeding transformer(s)
    - special requirements for protection and control (P&C)
    - requirements to balance reactive power
    - requirements to the level of harmonics on the AC and DC side
    - requirements to combine the function of ice melting with the function of a static compensator
    - special requirements for the system specific for a project

- The organization of the IMD includes the following components:
    - Infrastructure to coordinate all activities and services in preparation to winter season and operational performance during the icing periods.
    - Ice melting devices/technologies
    - Data bank (look-up tables) “ice melting current – melting time” for each line considering weather conditions and terrain
    - Options of power utility’s power capacity balance during ice melting event
    - Sequence of lines to melt ice on.
    - Warning system(s) for the utility’s personnel about ice accretion and wind speeds
    - P&C systems to ensure safe operation during the ice melting event for IMD, substation equipment, and service personnel
    - Telecommunication systems e.g. warning about the dangerous ice accretion, communication during ice melting event, post-event system restoration.
- Ice melting devices/technologies are custom-made to meet the requirements for successful ice melting depending on the parameters of the particular line where IMD should be used.

- Capacities and voltages should be compared with the parameters required for ice melting on the lines, connected to the node. Melting of ice by AC is envisaged for the lines when the available parameters meet the requirements. If the capacity and voltage required for AC melting exceed the available parameters at substation, melting by DC should be considered.
- In case the required AC voltage for ice melting on certain lines is lower than the available voltage, the following measures should be considered:
    - Increasing the length of the heated loop
    - Regulation of melting current by means of substation transformers with tapped switches
    - Use of line regulating transformers
    - Use of booster transformers.

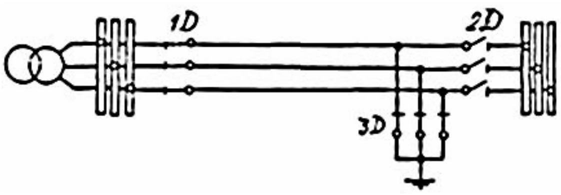


Figure A.2a Off-line AC ice melting with 3-phase short circuit

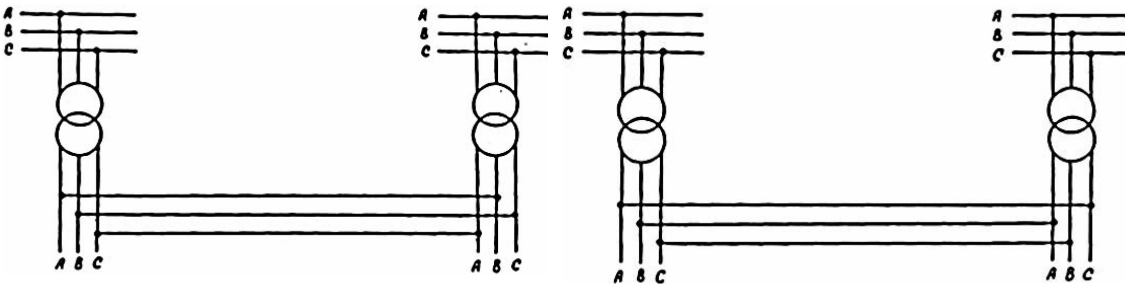


Figure A.2b Off-line AC ice melting by phase opposition connecting phases ABC to BCA

Figure A.2c Off-line AC ice melting by phase opposition connecting phases ABC to CAB

Figure A.2d Off-line AC ice melting with 2-phase short circuit

Figure A.2e Off-line AC ice melting with "Snake" scheme

Figure A.2: Schemes for off-line ice melting by AC

- Ice melting on all three phases is most expedient. The following schemes of melting (Figure A.2) can be used for this purpose:
    - Melting by method of short-circuit (Figure A.2a), The line is short-circuited at one end, the other end being connected to the voltage source, applying the required melting current. It may be working busbars, transformers, etc.
    - Melting by the method of phase opposition (Figures A.2b and A3.c). Conductors of the heated line are connected to different phases of supply sources at the line ends. Each phase of the line will be then at $U_L = \sqrt{3}U_{ph}$, i.e. phase voltage will be 73% higher, which results in

higher melting currents, and melting can be accomplished on longer lines.

- Melting by method of two- phase short-circuit (Figure A.2d).
- Melting by method of consecutive connection of line phases (one at a time) (Figure A.2e).

In Russia, typical ice melting applications are characterized as follows: conductor size up to 300 mm2, line length ranging from 10 to 15 km, 20 to 30 km, 50 to 70 km, and from 150 to 200 km, for supply voltages of 6,10, 35, and 110 kV respectively.

In large EHV systems, for example 500 kV networks, melting by AC at the rated voltage can be applied. The line being heated is short-circuited at the end and is connected directly to 500 kV bus; in this case, the line operates as a high power reactor. Shunt reactors are disconnected. The inductive melting current is compensated by the capacitive network current, and the resulting load of the supply source can be relatively small. In some cases, the existing sources can supply only high melting currents which can result in conductor overheating if applied for a long time. In such cases the method of heavy intermittent currents is used for melting. Heavy current is supplied to the line during a certain time (from 3 to 5 minutes), and then it is switched off, and in a certain time (from 4 to 5 minutes) switched on again. The heating and cooling cycles are repeated several times until the ice falls off.

For long lines with large conductors, ice melting with DC is more advantageous. In this case, at a constant voltage level, the current value can drop 30-40% due to the heating of conductor sections not covered by ice. To maintain the constant current level, special circuits of converter supply are used. These schemes enable to arrange ice melting both on very short 35-220 kV lines (less than 1 km) and on lines of medium length (100-150 km). The melting current is proportional to the load of autotransformer or shunt reactor, and is regulated by changing the transformation ratio of the booster transformer, with the voltage being self-regulated within certain limits.

In the majority of cases, the line to be heated must be taken out of service during melting. If this is not desirable, ice melting can be carried out using the phase-by-phase method where one phase is taken out of service while power is transmitted over the two other phases.

When the transformer neutrals are grounded, switching-off of one of the phases causes zero-sequence and negative-sequence currents. The latter condition, together with the melting current will influence line communication (if power-line carriers, PLC, are still used). Permissibility of such influence should be checked. Negative-sequence currents sometimes can exceed the admissible values for generators and motors. All this can limit application of the above schemes if special measures improving the quality of electric power at consumer buses are not taken.

The solution of the problem lies in the artificial balancing of unbalanced line conditions. The most simple and efficient method is compensating line inductive reactance of zero sequence by means of capacitor banks installed in the neutrals of the power transformers.

A.3 Ice melting power requirements

It should be noted that for an ice melting duration of 0.5 to 1 hour, a current density of about 2.5 to 3.0 A/mm2 is required, the lower value corresponding to low wind speeds and ambient temperature about 0°C, the higher value – to wind speeds of 0.5 to 10 m/sec and temperature of about –10°C. Typical heating currents required for single conductors are illustrated in Figures A.3a and A.3b.

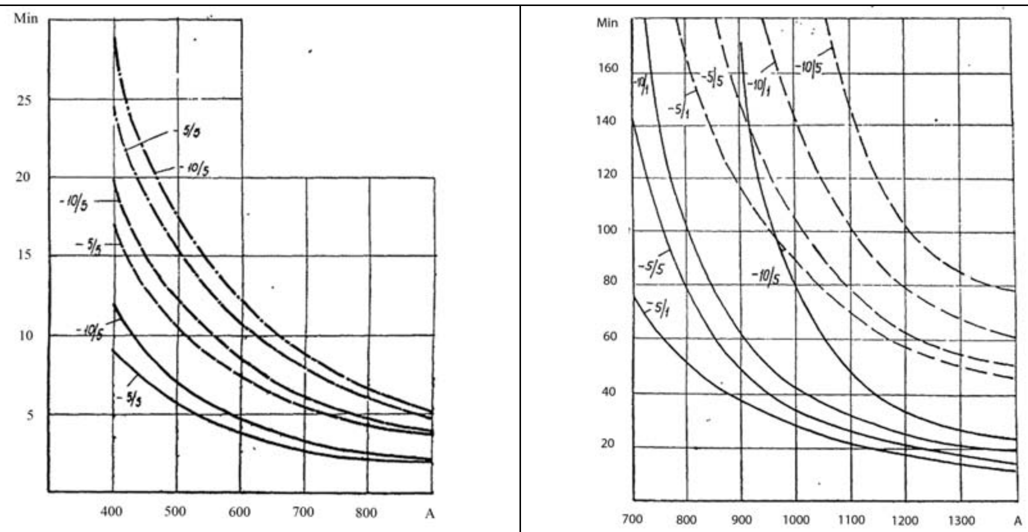


Figure A.3a Ice melting duration as a function of melting current (AC) for an ACSR 150/24 (d=17.1 mm) conductor and 0.2 g/cm^3 density hoar frost,
for ice sleeve diameters of 80 mm (— · — ·)
60 mm (– – –)
40 mm (solid lines)
where fraction numerators and denominators indicate air temperature and wind velocity, respectively.

Figure A.3b Ice melting duration as a function of melting current (AC) for an ACSR 400/51 (d=27.5 mm) conductor and 0.9 g/cm^3 density glaze ice,
for ice sleeve diameters of 90 mm (– – –),
50 mm (solid lines)
where fraction numerators and denominators indicate air temperature and wind velocity, respectively.

Figure A.3: Examples of Ice Melting Currents for Single Conductors

The efficiency of ice melting greatly depends on the procedure being carried out in due time. It is also very important that the lines to be heated are taken out of service for the shortest time possible, which requires the application of automatic switching operations on the lines before and after the ice melting procedure.

The active power needed for ice melting may vary from hundreds of kW for short lines with small conductors, up to tens and hundreds of MW for long lines with large conductors. It does not depend on the current type, AC or DC. The full power needed for ice melting is much larger than the active power due to the reactive power used during the ice melting process in conductors for AC, and in rectifiers for DC.

All ice melting schemes can be divided in two groups: ice melting without outage and ice melting with outage. Ice melting without outage is feasible for the following conditions:

- shifting or re-distributing the load between other lines of the same voltage or parallel lines of different voltages
- phase-by-phase melting using AC or DC.

Ice melting with outages applies to lines where short-circuit methods are used on radial lines. Thus, depending on the conditions, the three phases are connected in series or in parallel, sometimes using the earth as a return conductor.

After the severe January 1998 ice storm that hit Southern Québec and Eastern Ontario, a feasibility study on use of DC for ice melting [181] was carried out at University of Toronto, Canada, with the main findings displayed in Figures A.4 and A.5, providing a better insight on ice melting techniques using DC.

A.4 Off-line DC ice melting

Figure A.4a shows a schematic diagram of a three-phase AC line with a DC ice-melting system. During an ice-melting process involving a three-phase AC line with a DC ice-melting system, the line is disconnected from the network. The injected DC is supplied by an AC-DC converter. The converter is supplied from the network through a transformer, the return path for DC is through the ground. Depending on the rating of the converter 1, 2 or 3 phases can be injected at a time.

As Figure A.4b where there are parallel AC lines with grounded transformer neutrals a portion of the DC will return through the AC lines which may cause transformer saturation.

Figure A.4c illustrates a system configuration where the return path for the ice-melting DC is through the line itself and not through the ground. The return path can use 1 or 2 phases depending on the ice-melting cycle preferred by the user.

Where the AC-DC converter can supply the necessary power the configuration as Figure A.4d allows two parallel lines (in the same corridor) to be simultaneously de-iced.

If the AC transmission system has a radial structure, ice melting can be extended for a wider portion of the network as shown on Figure A.4e.

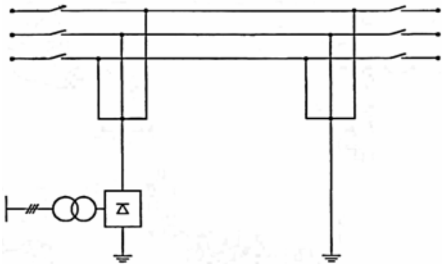


Figure A.4a Off-line DC ice melting with ground return

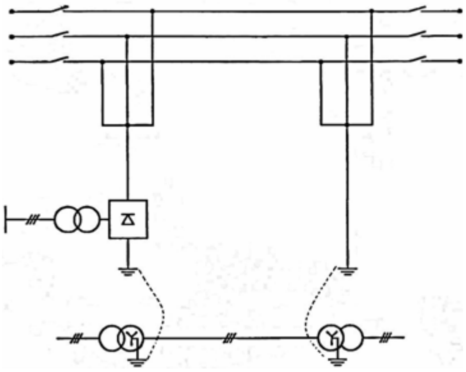


Figure A.4b Leaking of ice melting DC into a parallel AC line when ground return is used

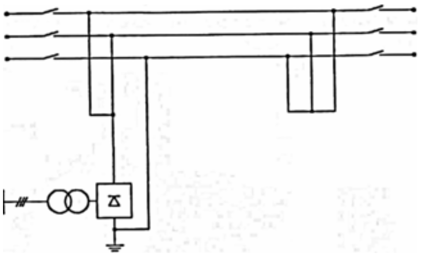


Figure A.4c Off-line DC ice melting with DC return through line conductor

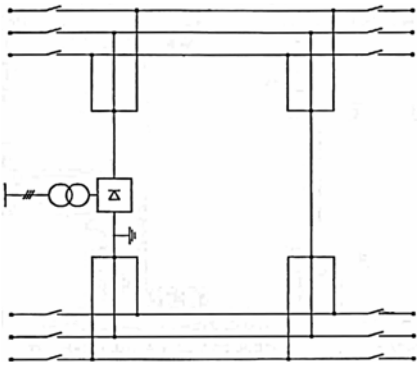


Figure A.4d Off-line DC ice melting of parallel AC lines (without using ground return)

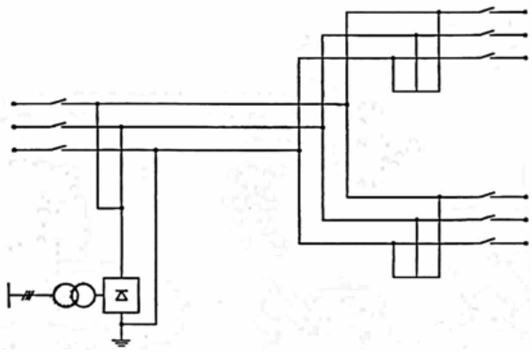


Figure A.4e Off-line DC ice melting of a radial AC system (without using ground return)

Figure A.4: Schemes for off-line ice melting by DC

A.5 On-line DC ice melting

On-line DC ice melting process consists in the injection of DC in an AC line without complete interruption of the AC power flow of the line. The main challenges of on-line DC ice melting process are:

- to contain the injected DC in the intended AC line and prevent it from being distributed in the remainder of the AC network,
- to prevent AC flow in the converter.
- to prevent magnetic saturation of power transformers due to DC.

There are two approaches to deal with the above challenges: The first is based on DC injection through the neutral of a Wye-connected power transformer, as Figure A.5a this transformer must be fitted with extra windings to prevent saturation of the core. The second circuit configuration for DC injection is one, as Figure A.5b where a combination of reactors provides a high impedance against the AC flow in the converter, DC is contained to the icy line by means of capacitor banks.

There are two options for on-line ice melting. Figure A.5c illustrates the first option where three-phases of the AC line remain connected to the AC network (through capacitors). Thus, with respect to AC operation, the three phases contribute to AC power flow. If two parallel lines are to be simultaneously de-iced, then the configuration of Figure A.5d can be adopted for on-line ice melting.

Figure A.5e provides an alternative circuit configuration to that of Figure A.5c. In the system on Figure A.5e, one phase of the AC line is used as the return path for DC and ground return is not utilised.

Figure A.5f shows schematic diagram of an AC line, which can be de-iced one phase at a time whilst two phases of the AC line remain connected to the network (without the need for series capacitors) and provide AC power flow. The third phase is disconnected from the network and subjected to DC injection. Ground is used as the DC return path.

Figure A.5g is an alternative configuration for on-line DC ice melting without using ground as the return path. DC is injected in two phases of the AC line through reactors. DC is confined to the line by means of series capacitor banks at both ends of the line. The third phase is disconnected from the AC network and used as the return path.

An AC-DC converter, Figures A.5a to A.5g, provides injected DC for ice melting. There are two types of converters which can be used for AC-DC conversion for ice-melting applications. The first type is a line-commutated converter which utilizes conventional thyristor valves, these typically have ratings up to 4000A DC, for the Hydro-Québec de-icer project near Québec, two thyristor valves were connected in parallel to provide up to 7960A DC. The second type is a forced-commutated converter which utilizes forced-commutated valves, e.g. GTOs, IGBTs or IGCTs, these typically have ratings up to 1000A DC.

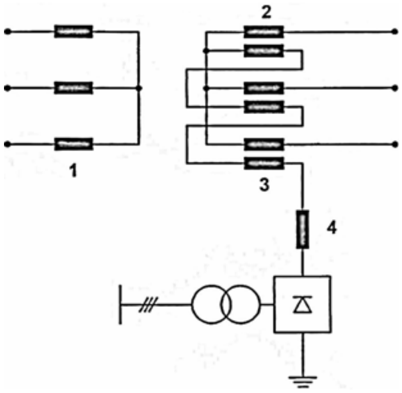


Figure A.5a DC injection through neutral of a Y-connected transformer winding

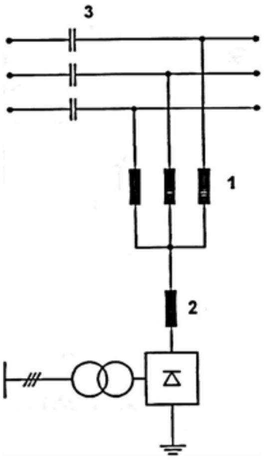


Figure A.5b DC injection in an AC line with DC blocking capacitors

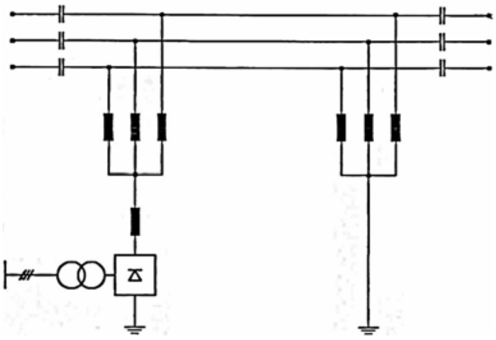


Figure A.5c On-line DC ice melting with ground return

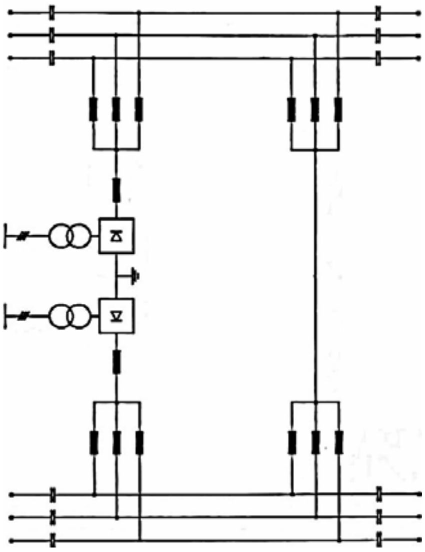


Figure A.5d On-line DC ice melting (without ground return)

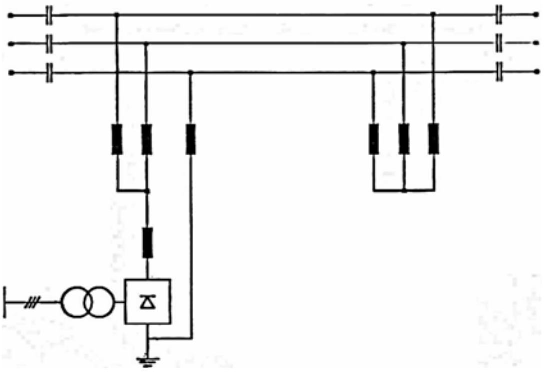


Figure A.5e On-line DC ice melting without ground return

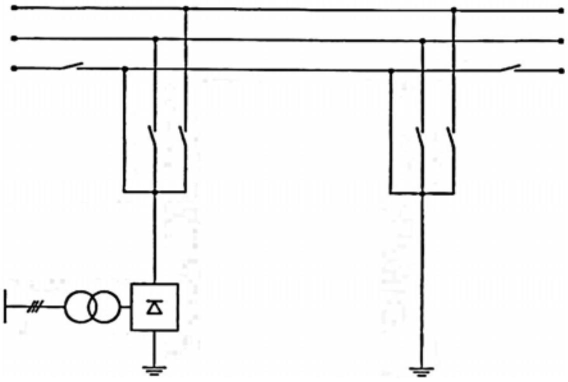


Figure A.5f On-line DC ice melting (one phase at a time) with ground return

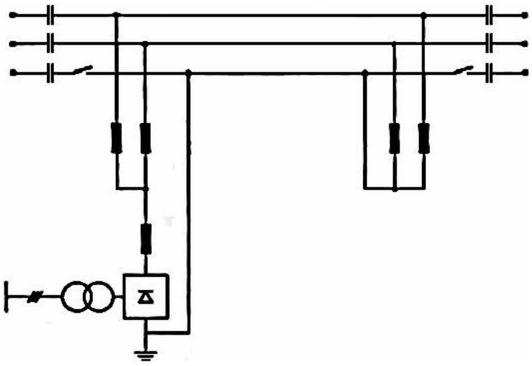


Figure A.5g On-line DC ice melting without ground return

Figure A.5: Schemes for on-line ice melting by DC

APPENDIX II: Summary of main AI/DI techniques and assessment

De-icing type	Technique	Description	Characteristics (status, disadvantages, line length, installation)	Country of Use	Cost level
Passive	Counterweights	Used for reducing ice or wet snow accretion	• Operational • Any line length • Permanent installation	Japan, Iceland France	Low
	Snow rings (SR), wires, combination of SR and counterweight	Used for reducing wet snow accretion	• Operational • Any line length • Permanent installation	Japan	Low*
	Modifying crossarms, using separate structures for each phase, rearranging phasing configuration	Used for minimizing the impact of icing on electrical clearances in double circuit lines	• Operational • Any line length • Permanent installation	New Zealand and others	Low-Moderate
	Installing inter-phase spacers (insulators)	Reduces probability of phase clashing	• Operational • Possible conductor fretting • Any line length • Permanent installation	New Zealand and others	Moderate
Active coatings and devices	LC spiral rods	Used for melting and shedding snow at milder temperatures	• Operational and promising short-term for anti-icing applications • Induces extra losses • Any line length • Permanent installation	Japan Scotland	Low*
	Heated tracers	Used for melting and shedding ice and snow at milder temperatures	• Operational but used only for water pipes • Needs external supply • Short line length due to need for supply • Permanent installation	Japan	Moderate-High
	Ice electrolysis	Applicable to wires equipped with electrodes energized with DC	• Not tested for real applications • Needs external supply. May degrade in UV light. • Short line length due to need for supply • Permanent installation	N/A	High
	De-icing using ropes or roller wheels	Used for manual de-icing of distribution lines up to 25 kV	• Operational • Labour intensive • Short line length • Temporary installation	Canada	Moderate

Mechanical	Remotely Operated Vehicle (ROV)	Used for de-icing of ground wires and line conductors up to 315 kV	• Promising in short-term • Installation onto line may be difficult • Up to 1km range • Temporary installation	Canada	Moderate
	Pneumatic hammer	Used for de-icing line conductors one span at a time	• Not tested for real applications • Labour intensive • Short line length • Temporary installation	Canada	N/A
	De-icer Actuated by Cartridges (DAC)	Used for de-icing conventional ground wires	• Promising in short-term • Labour intensive • Short line length • Temporary fitting	Canada	Low
	Electro-impulse methods	Used for de-icing of ground wires and line conductors	• Not tested for real applications • Risk of damage by lightning. May cause telephone interference. • Short line length due to need for supply • Permanent installation	N/A	High
	Ice-shedder devices	Used for de-icing of line conductors and ground wires by inducing certain vibration ranges	• Not tested for real applications • May damage line if used for long periods • Any line length • Permanent installation	Canada	N/A
	Twisting devices	Used for de-icing of single conductor lines one span at a time by mechanically twisting the cables	• Not tested for real applications • Any line length • Permanent installation	Canada	Low
	Weight attached to rope with large knots	Used for partial snow shedding in mountainous areas using helicopters	• Operational • Needs helicopter • Short line length • Temporary use	Canada	Moderate-High
	Dielectric coating	Application of dielectric coating onto the line and injection of high frequency supply	• Theoretical • May cause telephone interference • Short-medium line length • Permanent installation	N/A	High

Thermal	Load shifting method	Used for anti- and de-icing of line conductors by transferring or shifting loads from other circuits	• Operational • Only works on single conductor lines • Medium-long line length • Permanent installation	Many	Low
	Reduced voltage short-circuit method	Used for anti- and de-icing of line conductors by using 3-phase short-circuits	• Operational • Only practical on MV lines due to high power demand • Medium line length • Permanent installation	Many	Moderate
	DC current method	Used for de-icing of long sections of high current lines by running DC current at stages through the phase conductors. Can also be applied to ground wires.	• Operational • Large installation • Medium-long line length • Permanent installation	Former USSR / Canada	High
	On-load Network De-Icer method (ONDI)	Used for de-icing of lines by using a phase-shifting transformer to vary the current from one conductor to another, without requiring disconnecting the section to be de-iced from the network	• Promising • Only works on single conductor lines • Medium-long line length • Permanent installation	USA / Canada	High
	Contactor load transfer (bundle shifting) method	Used for de-icing of lines by allowing the current flowing in all conductors of a bundle into a single one	• Promising but not tested • May prove difficult to install into a real transmission line • Any line length • Permanent installation	N/A	N/A
	Pulse electrothermal de-icer method	Proposed for de-icing of line conductors by allowing the current pulse to heat an external conducting coating	• Not tested for real applications • Reduces line rating • Medium line length • Permanent installation	N/A	N/A

	Ground wire de-icing method	Used for de-icing many km of ground wires using a medium AC voltage transformer as current source. This requires the GW to be insulated from the towers.	• Operational • Short-medium line length • Permanent installation	N/A	High
	High frequency electric field method	Proposed for de-icing of line conductors by using a high frequency electric field to induce dielectric losses	• Not tested for real applications • May cause telephone interference • Medium line length • Permanent installation	N/A	N/A
	Steam generating device	Used for de-icing equipment like disconnect switches and post insulators	• Operational • Labour intensive • Short line length • Temporary use	Canada	Moderate
* : Cost is relatively low if installed at the time of line installation, otherwise conductors may need to be replaced					