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State of the Art Review of Atmospheric Icing Sensors

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Abstract: A state of the art review of atmospheric icing sensors is presented in this article, in order to understand their design and working principle for future developments. It is found that most atmospheric icing sensors which are capable of delivering maximum information are based upon direct measurement of the physical properties (electrical or mechanical) of atmospheric ice. Some field measurements and cold climate design constraints are also discussed. This discussion leads to either improve the performance of existing sensors and to develop a hybrid sensory unit for improved performance and detailed information delivery. *Copyright © 2016 IFSA Publishing, S. L.*

Keywords: Atmospheric ice, Capacitive, Dielectric, Direct measurement, Microwave, Resonance, Ultrasonic.

1. Introduction

Ice accretion can be defined as, *any process of ice build up and snow accretion on the surface of objects exposed to the atmosphere* [1, 2]. This accretion can take place either due to freezing precipitation or freezing fog. It depends mainly on the shape of the object, wind speed, temperature, liquid water content (amount of liquid water in a given volume of air) and droplet size distribution (conventionally known as the median volume diameter). The major *effects of atmospheric ice accretion* on structure are the static ice loads, wind action on iced structure and dynamic effects.

Generally, an icing event is defined as the period of time when temperature is below 0 °C and relative humidity is above 95 %. Atmospheric icing is traditionally classified according to two different processes (see Fig. 1), which are [1, 2],

i. Precipitation icing;
ii. In-cloud icing.

Fig. 2 shows the type of accreted ice as a function of wind speed and temperature. It can be observed in this figure that the curve shifts to the left with increasing wind speed and decreasing air temperature. A classification of atmospheric ice is also shown in Table 1.

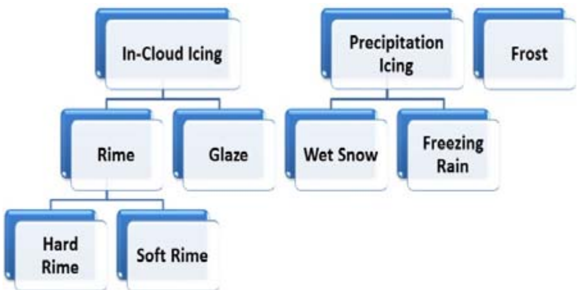

Fig. 1. Ice Types [1].

This article is an extension version of Mughal and Virk [3]. The first section of this article is a brief introduction of atmospheric icing sensors. The second section is the review of available direct measurement patents, techniques and commercially available sensors. The third section is related with the problems and issues associated with presently available sensors. The fourth section is linked with the general sensor design and sensory system

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constrains due to cold region. The last section is the discussion and future recommendations for next generation of atmospheric icing sensors.

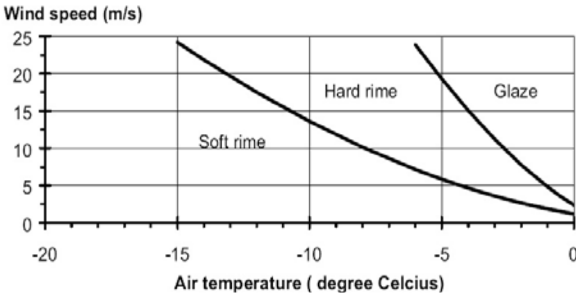


Fig. 2. Atmospheric ice type changing with wind speed [1].

Table 1. Properties of Accreted Atmospheric Ice [1].

Type of ice	Density (kg/m^3)	General Appearance	
		Color	Shape
Glaze	900	Transparent	Evenly distributed/icicles
Wet Snow	300-600	White	Evenly distributed/eccentric
Hard Rime	600-900	Opaque	Eccentric, pointing windward
Soft Rime	200-600	White	Eccentric, pointing windward

2. Atmospheric Icing Sensors

Due to the increasing trend of activities in polar regions, human and inventory hazards is increasing. At present, commercially available atmospheric icing sensors can detect either one or two of the icing parameters such as detection of an icing event, determination of icing type, measurement of icing load and icing rate; under any icing conditions simultaneously. Ice sensors can be integrated with anti/deicing systems; therefore it is important for these sensors to deliver sufficient information to be able to operate ice mitigation devices effectively. Power requirements for the removal of snow and ice is different, hence, to distinguish between snow and ice can be considered a limiting factor for de-icing systems. Most devices for the removal of snow are normally ineffective for the efficient removal of ice or hard packed snow [4]. Also, measurement of an icing event bounds a set of requirements, which include the ability of a sensor to detect icing with high sensitivity without influencing the measured quantity due to the ambient conditions, this is defined as the loading error. These atmospheric ice measurement techniques are categorized into indirect and direct methods (Homola, et. a. [5]):

Indirect Methods

The indirect methods of ice detection involve measuring weather conditions, such as humidity and temperature, that lead to icing, or detecting the effects of icing. for example, reduction in the power generated by the wind turbine, reduction in the speed of anemometers or measuring the variables that cause icing or variables that correlate with the occurrence of icing, such as cloud height and visibility [1]. Empirical or deterministic models are then used to determine when icing is occurring. Homola, *et al.* [5] outlined five indirect measurement methods. The reduction in the speeds of anemometers method of Craig and Craig [6] and the noise generation frequency method of [7] are typical examples of indirect methods.

Direct Methods

Direct methods of ice and snow detection are based on the principle of detecting property changes caused by accretion such as mass, dielectric constants, conductivities, or inductance. Homola, *et al.* [5] outlined twenty four direct measurement methods, which can be categorized as follows:

a. Capacitance Measurement Techniques;
b. Ultrasonic Energy Measurement Techniques;
c. Resonance Measurement Techniques;
d. Microwave Energy Measurement Techniques;
e. Impedance Measurement Techniques;
f. Infrared Energy Measurement Techniques;
g. Axial Load Measurement Technique;
h. Hybrid Measurement Technique.

The above direct measurement techniques would be discussed in the following sections.

2.1. Capacitance Measurement Techniques

Capacitive ice sensors generate an electric field to detect the presence of dielectric materials. An electric field radiates outward around the probe and a dielectric material in close proximity of the field affects the measured capacitance. This attribute enables non-invasive measurements. The application of the electrical properties to the measurement of ice thickness, temperature, crystal orientations are presented in Evans [8]. It is mentioned in Sihvola, et. al. [9] that for dry snow, the dielectric constant is determined by the density and for wet snow, the imaginary part and the increase of the real part due to liquid water have the same volumetric wetness dependence. In Sihvola, et. al. [9], the results indicate that the complex dielectric constant is practically independent of the structure of snow. The static dielectric constants ε_{rs} of both polycrystalline and single crystals of ice have been carefully determined, Auty and Cole [10]. Weinstein [11] and Jarvinen [12] proposed two different capacitive based ice detection methods, which would be discussed here. In general, sensing method proposed by Gerardi [13, 14] also use the same principle as proposed by Weinstein [11].

2.1.1. Capacitive Ice Sensor by Weinstein

This ice sensor / sensing technique was proposed by Weinstein [11] and can be utilized for the determination of the thickness of ice (22) (see Fig. 3) on the outer surface (12) of an object independent of temperature and the composition of the ice (22). First capacitive gauge (16), second capacitive gauge (18), and the temperature gauge (20) are embedded in embedding material (14) which is located within a hollow portion of outer surface (12). First capacitive gauge (16), second capacitive gauge (18), and temperature gauge (20) are respectively connected to first capacitance measurement circuit (24), second capacitance measurement circuit (26), and temperature measuring circuit (28). The geometry of first and second capacitive gauges (16) and (18) is such that the ratio of voltage outputs of first and second capacitive gauge (24) and (26) is proportional to the thickness of ice (22), regardless of ice temperature or composition. This ratio is determined by offset and dividing circuit (29).

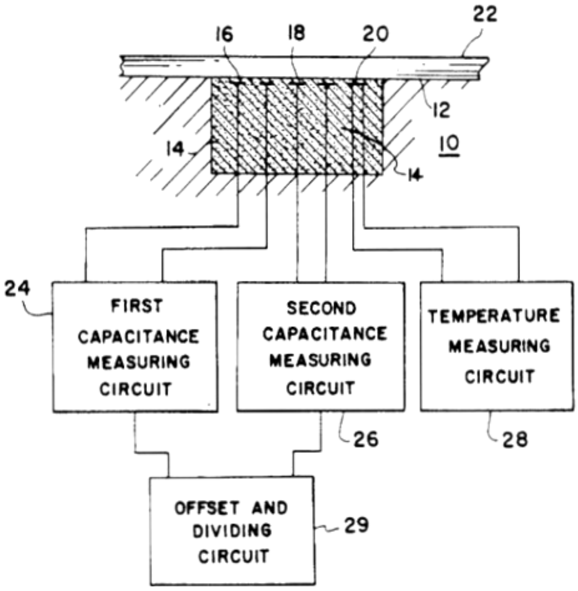


Fig. 3. Construction of Weinstein Ice Sensor [11].

In this sensor both first (16) and second capacitive gauges (18) are made from thin conductors with a thickness of approximately 0.001 of an inch. The first capacitance gauge (16) is connected to first capacitance measuring circuit (24) and second capacitance gauge (18) is connected to second capacitance measuring circuit (26) shown in Fig. 4. A dual timer LM556 (42), is used in a stable mode to generate 7 μs pulses at 1.5 kHz, for example, or pulses at any other similar frequencies, which are used to trigger a monostable timer (44). The timing capacitor of monostable timer (44) is gauge 16. The output from the monostable timer is converted by the low pass filter (46) to produce an output DC signal, which is directly proportional to the capacitance of first capacitance gauge (16). First capacitance measuring circuit (24) and second capacitance measuring circuit (26) are connected to offset the dividing circuit (29). The output voltage V_{out} of this offset and dividing circuit (29) for ice conditions is determined by the relation:

$$V_{out} = \frac{(V - V_o)_2}{(V - V_o)_1}, \quad (1)$$

where V is the voltage output for the ice conditions and V_o is the initial voltage for no ice conditions. Subscripts (1) and (2) refer respectively to capacitive measurements from first capacitance measuring circuit (24) and second capacitance measurement circuit (26). V_{out} is independent of both temperature and ice decomposition since both effects results in identical scaling factors resulting in no changes in Equation 1. The variation of capacitance as a function of thickness is shown in Fig. 5.

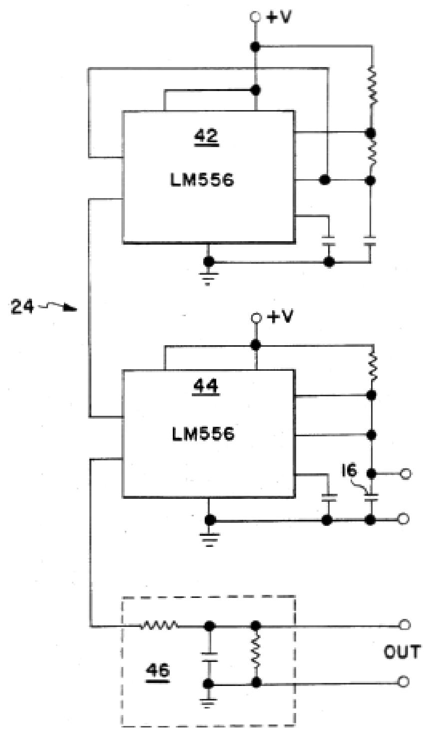


Fig. 4. Electrical schematic of capacitance measuring circuit [11].

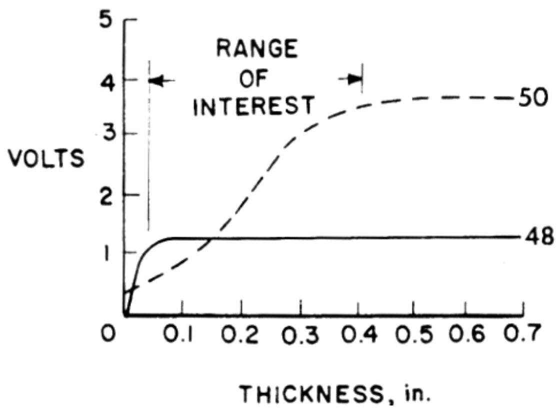


Fig. 5. Ratio of capacitance gauge as a function of thickness [11].

In Fig. 5, output voltages from first and second capacitive measuring circuits (24) and (26) for various thickness of ice (22) formed on the outer surface (12) is shown. Curve (48) represents the output voltage V_1 from the first capacitance measuring circuit (24) at a fixed temperature and ice impurity level. Also, the curve denoted (50) represents the voltage output V_2 from the second capacitance measuring circuit (26). At a fixed configuration, both curves will vary with temperature change or ice impurity change. It can also be seen that both curves do not go to zero output voltage even when the ice thickness is zero.

2.1.2. Capacitive Ice Sensor by Jarvinen

This ice sensor / sensing technique was designed by Jarvinen [12] and is capable of detecting ice, its thickness and type. The dielectric properties of ice and snow show variation when an alternating current is supplied through it as mentioned by a review of Evans [10] and Stiles [16]. A lot of the dielectric measurements based upon Cole – Cole plot[1] [17] on wet snow, pure snow, granular snow and compact snow were conducted by Kuroiwa [18] and many others. In this sensor, Jarvinen [12] used the method for detecting the presence and the accretion of ice by first measuring the properties of the contaminant layer overlying the ice sensor using variation in Cole Cole Plot and comparing the measured results for magnitude and shape with laboratory property data taken at the same temperature and stored in the processor. Using this it is possible to distinguish between ice or rain water or deicing fluid or snow. These differences, if found to exist, are used to correct the initially chosen ice thickness value based on the assumption of normal ice: ice with no flaws, cracks or voids or higher electrical conductivity, see Fig. 6. Furthermore, this sensor uses *AD5933*. The response signal from the impedance is sampled by the on board Analog to Digital Converter ADC and a discrete Fourier transform is processed by an on board Digital Signal Processing DSP engine. The Discrete Fourier Transform DFT algorithm returns a real and imaginary data word at each output frequency.

[1] Cole and Cole have proposed that an Argand diagram for complex dielectric constant for multiple relaxation times can be constructed using the equation

$$\varepsilon_r^* - \varepsilon_{r\infty}^* = \frac{\varepsilon_{rs}^* - \varepsilon_{r\infty}^*}{1 + \left(j\omega\tau_0 \right)^{1-\alpha}},$$

where ε_r^* is the complex relative permittivity, $\varepsilon_{r\infty}^*$ is the relative permittivity at very high frequency of excitation, 'ε_{rs}^*' is the relative permittivity at dc excitation, 'ω' is the excitation frequency, τ_0 is the relaxation time for ideal case and 'α' lies in the interval [0,1] which is 0 for materials having single relaxation time (such as ice) but makes flatter the Debye semi-circle as the mixture varies.

Furthermore it is explained by Hobbs [15] that ice can be replaced by an equivalent circuit as shown in Fig. 7.

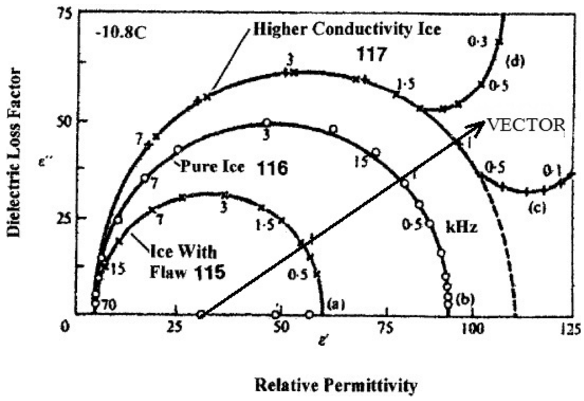


Fig. 6. Cole Cole plot for pure ice, ice with flaw and ice with higher conductivity value [12].

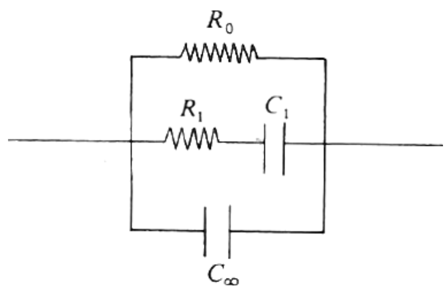


Fig. 7. Equivalent circuit for dielectric material [20].

The total complex impedance Z of the circuit Fig. 7, is given as

$$\frac{1}{Z} = \frac{1}{R_\circ} + \frac{1}{R_1 + \frac{1}{j\omega C_1}} + j\omega C_\infty \tag{2}$$

Now if the ice is characterized by a capacitance *C*, then

$$\frac{1}{Z_c} = j\omega C = \frac{j\omega A\varepsilon_\circ\varepsilon_r}{L}, \tag{3}$$

where *L* is the thickness of ice, *A* is the surface area of a block of ice and ε_o is the permittivity of free space. Also, we can write

$$\varepsilon_{rs} = \frac{L}{\varepsilon_\circ A}\left(C_1 + C_\infty\right), \quad \varepsilon_{r\infty} = \frac{LC_\infty}{\varepsilon_\circ A} \tag{4}$$

which is, when substituted in Cole-Cole equation, then we have,

$$\varepsilon_r = \frac{LC_1}{\varepsilon_\circ A(1+j\omega\tau)} + \frac{LC_\infty}{\varepsilon_\circ A}, \quad (5)$$

where $\tau = R_1C_1$ is the dielectric relaxation time of the circuit, that is the time taken for the voltage across the ice block to reach $1\text{-}e^{-1} = 0.63$ of its final value when a step voltage is applied. Similarly we can also write the complex permittivity as,

$$\varepsilon' = \frac{L}{\varepsilon_\circ A}\left(\frac{C_1}{1+\omega^2\tau^2} + C_\infty\right)$$
$$\varepsilon'' = \frac{L}{\varepsilon_\circ A}\left(\frac{\omega\tau C_1}{1+\omega^2\tau^2}\right) \quad (6)$$

A second possible simplified means for confirming the presence of ice is also provided based on demonstrating that the magnitude and angular inclination of a vector from a point on the ordinary relative permittivity axis near the high frequency end of the complex dielectric locus, the vector starting near the locus.

2.2. Ultrasonic Energy Measurement Techniques

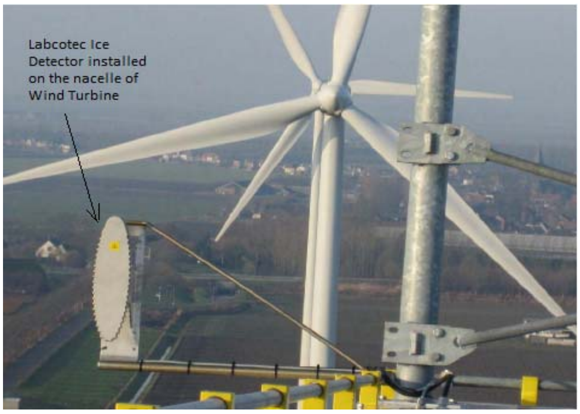
Ultrasonic ice sensors typically consists of two transducer elements, where one element generates ultrasonic vectors, which are detected by the second element. By measuring the attenuation levels, icing between the two elements can be detected. Like capacitive sensors, ultrasonic sensors need low power, low cost and are directionally sensitive. Luukkala [16] and Watkins [17] proposed two different ultrasonic based ice sensing techniques, which are discussed in the following sections.

2.2.1. Ultrasonic Ice Sensor by Luukkala

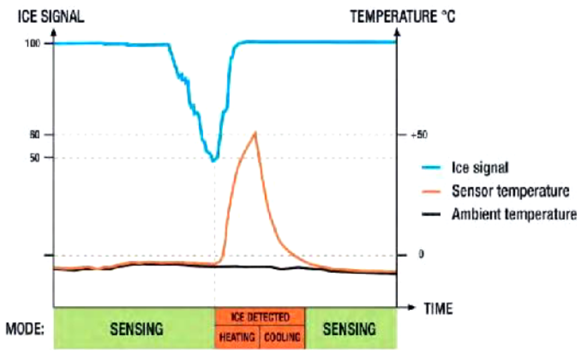
In this ice-sensor/sensing-technique designed by Luukkala [16], a mechanical ultrasonic signal is transmitted along a thin thread or strip at one end and the intensity of the ultrasonic signal having passed through the thread is measured at the other end. If the thread is covered with a water layer, the ultrasound will not be attenuated, however if the water freezes, the ultrasound cannot propagate in the thread, but will be abruptly attenuated. If the thread is covered with a sludge, the ultrasound will be somewhat attenuated to a kind of intermediate level, at which detection of sludge is also possible. A viscosity difference exists between ice and water, and thus the intensity of the ultrasound having passed through the thread will also be different.

These ultrasonic sensors are comprised of a measuring transducer, a thread-like or tape-like acoustic waveguide having an ultrasonic transmitter at one end, an ultrasonic receiver at other end, and a device which comprises electronic components for measuring the intensity and the attenuation of an ultrasonic pulse having passed through the transducer thread in the case of ice formation. Electric resistance of the thread is measured simultaneously with the measurement of the attenuation of the ultrasound. With the help of measured resistance, the amount of required heating for the thread can be provided optionally to melt the surrounding ice, whereby the ultrasound intensity resumes its initial level.

This technique has been practically utilized in Labkotec 3300IP [18] and is primarily aimed to detect ice on wind turbines, see Fig. 8a. During icing conditions the ultrasonic signal amplitude will start to decrease and the ice alarm will make the turbine stop to start the blade heating. Also just at the right time when the ice is detected, the sensor starts heating itself to melt the detected ice. After a set delay, the alarm will go off and turbine will start functioning again, see Fig. 8b [19].



(a) Labcotec Ice Detector installed on the nacelle of wind turbine.



(b) Working cycle of detector

Fig. 8. Labcotec Ice Detector.

This sensor has been approved by the Technical Research Centre of Finland (VTT), and more than 2,000 units have already been supplied to the largest wind turbine manufacturers. LID ice detectors are in use at airports and weather stations also. This ice detector is based on longitudinal wire waves. It is reasonably easy to adjust the parameters of the device to correspond with different icing climates. However, Labko's different versions have suffered from snow induced icing conditions and the inability to melt all the ice.

2.2.2. Ultrasonic Ice Sensor by Watkins

This ultrasonic sensor is designed by Watkins [17] consists of two ultrasonic transducers. The first transducer is energized to cause propagation of ultrasonic waves through a portion of a solid metal sheet along its predominant component parallel to the surface of the sheet and detecting the waves by means of the first ultrasonic transducer, while measuring the amplitude of the waves received by the second transducer, on the surface. If a layer of ice forms on the surface, the amplitude and intensity of the waves detected by the second transducer will decrease, as waves having their predominant component parallel to the surface will dissipate energy into the ice layer, but it is assumed that they will not dissipate energy into air or liquid [20]. The waves may be horizontally polarized, guided shear waves, or the waves may be a mode of lamb wave[2] [21] whose predominant component is horizontal. The transducers may be attached to the opposite surface of the portion of the sheet to which an ice layer may develop, and may be generated and received by piezoelectric or electromagnetic means.

Fig. 9a shows the design of Watkins's sensor to detect a layer of ice on a thin solid sheet. Two ultrasonic transducers are attached to the sheet; the first transducer is adapted to cause propagation of ultrasonic waves through the thin solid sheet having their predominant component parallel to the surface of the sheet. Such waves will dissipate energy into an icing layer adhering to the surface, but not into air or liquid water, in the case where liquid water is present. The second ultrasonic transducer is adapted to detect the waves propagating in the sheet and to give a signal representative of their amplitude. A discriminator responsive to the signal detects the presence of an ice layer on the surface. Fig. 9b shows that the transducer comprises six transducer strips parallel to each other extending perpendicular to the plane of the figure and spaced apart at a distance equal to the wavelength of ultrasonic shear waves in the sheet, held in a solid matrix. Each strip is of length 30 mm and is bonded to the surface by an electrically conducting layer and is made of piezo electric material and has contacts on opposing top and bottom surfaces by means of which it can be excited into vibrations parallel to its length. These vibrations are in phase with the other strips, and cause horizontally polarized shear waves to propagate in the sheet.

[2] Acoustic waves whose particle motion lies in the plane that contains the direction of wave propagation which is perpendicular to the solid plate in which the wave propagates, named after the English mathematician Horace Lamb

2.3. Resonance Measurement Techniques

In this ice sensing technique an element is allowed to vibrate at its resonance frequency. Due to the deposition of ice or any other mass on the vibrating element, its frequency spectrum varies. The variation in primarily fundamental / resonance frequency will then deliver information about the icing event. This type of ice sensor is a single point ice detection device, which delivers information about the presence of ice and cannot distinguish between the types of icing. Cronin [22] and Koosmann [23] proposed two different resonance based ice sensor designs, which are discussed in the following sections.

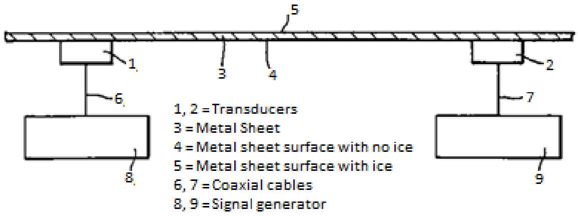
2.3.1. Resonance Ice Sensor by Cronin

This ice sensor / sensing technique [22] uses the principle of magnetostriction, which is defined as the ability of ferromagnetic materials to change dimensions under the influence of a fluctuating magnetic field (see Fig. 10).

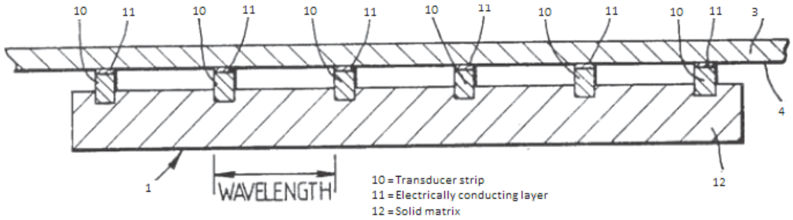
This sensing technique have been practically utilized in Goodrich 0871LH1 ice sensor. It has a 1in long cylindrical probe with a diameter of 0.25 in, which constantly vibrates at 40 kHz. When ice accretes on the probe, the vibration frequencies change due to the increase in mass. This sensor delivers a binary signal.

2.3.2 Resonance Ice Sensor by Koosmann

The ice sensing-technique/sensor proposed by Koosmann [23] was not completely novel but presented a further improvement on the method proposed by Werner, *et al.* [26]. This technique is different from the sensing technique proposed by May [27] and Roth [28] who used a diaphragm as a vibrating element. In the technique proposed by Koosmann [23] a vibrating element in a tube vibrates along the longitudinal axis of the tube. This tube is driven by an excitation coil at its natural frequency and is sealed by a diaphragm, which has a surface exposed to an air stream in which icing is to be sensed. The exposed diaphragm surface is deflectable during vibration of the tube at a flexible support portion of the diaphragm. As ice accumulates on the exposed surface the natural frequency of the cylindrical section changes and is sensed to determine that ice is accumulating. The diaphragm is of low mass and small size so that the stiffness of small amounts of ice can significantly change the spring constant of the flexible support. The diaphragm is also shaped to conform to adjacent aerodynamic surfaces.



(a) Design of Watkins sensor.



(b) Watkin's transducer with six transducer strips.

Fig. 9. Watkinss Icing Sensor [17].

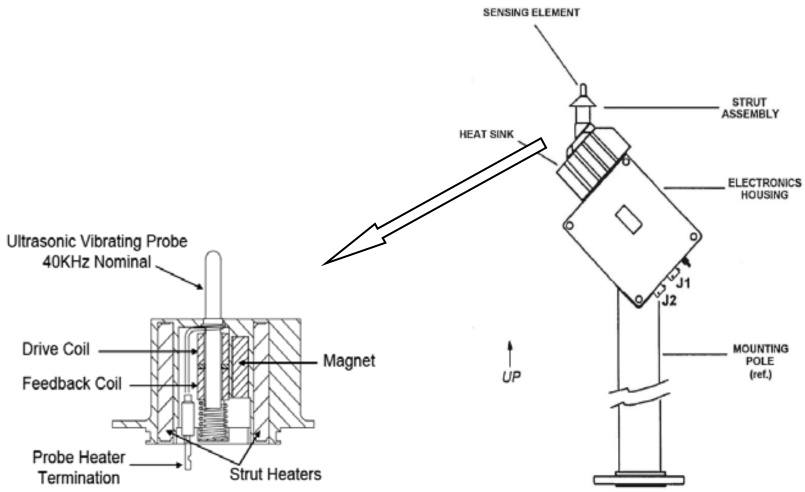


Fig. 10. Goodrich Ice Detector [24, 25].

2.4. Microwave Energy Measurement Techniques

In this technique microwave energy is allowed to pass through a substance using a waveguide. The amount of reflected energy can then be used to deliver information about the icing event and the amount of ice. Overall [29] and Magenheim [30] proposed two different microwave based ice sensors, which are discussed in the following sections.

2.4.1. Microwave Ice Sensor by Overall

The icing-sensor/sensing-technique designed by Overall [29] can detect the presence of ice or water on a road or other surfaces. In this detector, microwaves are directed via a waveguide to the underside of a window substantially transparent to the microwaves and installed substantially flush with the surface to be monitored. The presence and thickness, within reasonable limits, of any coating of ice or water present on the surface of the window is determined by measuring the amount of microwave energy reflected by the window. The reflected energy can be used to trigger a signal device such as a warning sign or to activate ice melting means.

Fig. 11 shows the block diagram of the basic elements of this sensor design, which serves to define the principle of operation. The microwave generator is coupled with the ferrite isolator, which functions to protect the generator from the reflected waves and to keep the power level and frequency of the generated signal constant in spite of variations in the reflected signal and drastic load changes. The waveguide couples the ferrite isolator to the window, which can be constructed of any dielectric element that is substantially transparent to microwave energy, as for example polymers of tetrafloroethylene, copolymers of hexafloropropylene and tetrafloroethylene, polyethylene. The microwave energy reflected at the window travels back along the hollow waveguide and meets a directional coupler, which bleeds from the main guide a small proportion of the reflected energy. A crystal rectifier positioned in the directional coupler is actuated by the reflected energy and the output from the crystal is amplified and displayed on an amplifier to quantitatively show the level of the reflected energy.

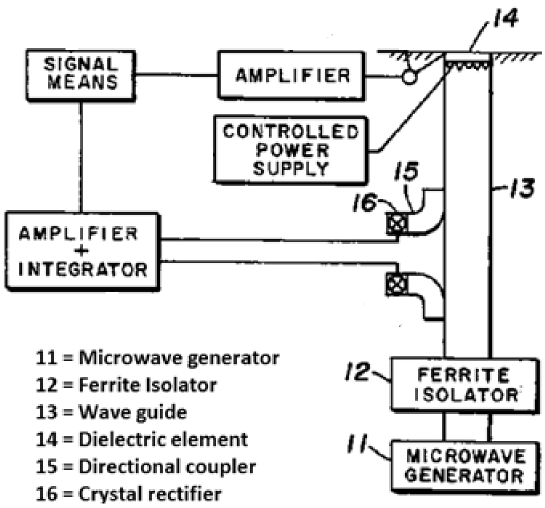
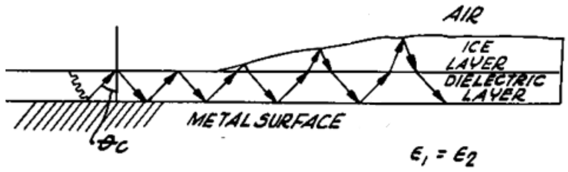


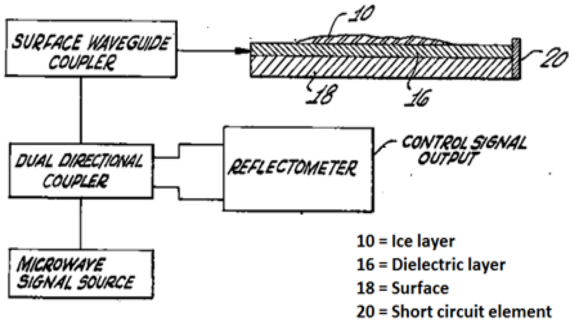
Fig. 11. Microwave ice detector by Overall [29].

2.4.2. Microwave Ice Sensor by Magenheim

In this design/technique [30], microwave electromagnetic energy (typical frequency falls 2 k – 20 k MHz) is transmitted into a surface of ice, and the reflection or impedance characteristic of the ice layer is monitored to determine the presence and amount of ice. This ice sensor includes a device to generate microwave electromagnetic energy, transmitting the microwave energy in to a surface layer of ice. The microwave energy reflected from the ice layer is used to determine the presence and relative amount of ice in the layer Fig. 12a. It also includes a permanent surface waveguide of such a thickness as to allow the propagation of microwave energy even when the ice layer is extremely thin. The design of this ice detector includes a short circuit element at the end of the surface waveguide remote from the end into which the microwave energy is transmitted. The short circuit element results in a partial or total reflection of the energy back along the surface waveguide and reflected energy being detected by the reflecto-meter means, see Fig. 12b. Since ice typically contains many impurities including a significant amount of unfrozen water, it will present a dielectric medium for the transmission of the microwave energy, and much less energy is reflected out of the waveguide when a layer of ice is present.



(a) Transmittance of microwave energy in iced surface



(b) Working Principle

Fig. 12. Microwave ice detector by Magenheim [30].

2.5. Impedance Measurement Techniques

The impedance based ice sensing technique is very similar to the capacitive measurement technique. The only difference between the two is the source of information delivered, which is current in the former and voltage in the later. The importance of the impedance measurement system is that saturation of the electrodes can be avoided and data points can be increase in this technique.

2.5.1. Impedance Ice Sensor by Seegmiller

The design of Seegmiller [31] is capable of delivering parameters such as the thickness of ice and the ice load for a relatively wide surface. This ice sensor is comprised of inductive ice sensing electrodes, temperatures sensors, a frequency generator, a voltage detector, resistance bridge and a processing unit. The inductive ice sensing electrodes are flush mounted on the surface of interest and comprise a transmitting electrode (at least one receiving electrode). These electrodes are insulated to avoid a spurious reading caused by conductive substance or electrolytes. The coefficient of coupling between the transmitting and receiving electrodes is determined by at least two factors, the first being the predetermined geometry and spacing between the electrodes and the second being the inductive coupling susceptibility of the ice in the general region of the spaced apart electrodes. This susceptibility is indicative of the presence and thickness of ice. The device for measuring temperatures is flush mounted onto the surface of interest. The frequency generator supplies an excitation signal and has means for being connected to the transmitting electrode of the inductive ice sensing array. The voltage detector has means for being connected to the receiving electrode of the inductive ice sensing array and detects a proportion of the supplied excitation signal to the transmitting electrode as a function of the coefficient of coupling between the transmitting and the receiving electrode. The voltage detector device generates an output signal representative of the thickness of adhering ice, frost or water substance in the general region between the spaced apart electrodes.

2.6. Infrared Energy Measurement Techniques

This technique is based on the absorption and reflection of active infrared light by the ice. By measuring the amount of reflected light, one can determine if ice is present at the surface.

2.6.1. HoloOptic Ice Sensors

HoloOptics sensor has the potential to detect the presence of any type of ice or snow. The working element comprises an infrared emitter together with a single head, two head or four head receivers, a photo detector and a probe, see Fig. 13.

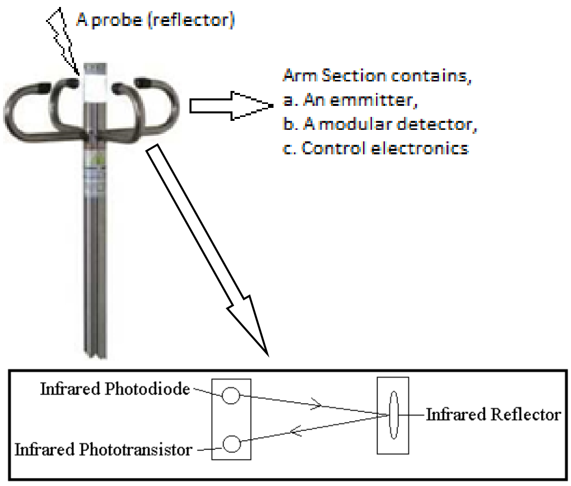


Fig. 13. T44 HoloOptic ice sensor [32].

The operating range of this sensor lies in the Near Infrared Radiation NIR range (0.88 µm to 0.92 µm). An icing event is recorded if more than 95 % of the probe is covered with a 50×10^{-10} m thick layer of glaze ice or a 90×10^{-10} m thick layer of other types of ice. Once icing is detected, the probe internal heating system is activated to melt the accreted ice. The time it takes to deice is dependent solely on the icing rate if sufficient amount of heating power is provided. The time lapse between icing events is used to determine the icing rate [32].

2.7. Axial Load Measurement Techniques

In this technique, an axial load is measured using strain gauges. It is important to highlight here that ISO 12494 [2], recommends an apparatus to measure icing load. The apparatus suggested is a slowly rotating steel rod that is at least *0.5 meter* long (1 meter if heavy icing is expected) and has the diameter of *30 mm*. This doubling of length of the steel rod due to heavy icing is probably aimed to uniform the drag distribution along its profile.

Two ice sensors (ice monitor & ice meter) have been developed to meet the ISO recommendations of a standard instrument. They are however freely rotation works on the basis of axial load measurement technique.

2.7.1. IceMonitor by Combitech

The IceMonitor® [33] is designed and manufactured in a reasonably close accordance with ISO 12494 standard [2]. It measures the mass of accumulated ice gravimetrically. The working element is a freely rotating steel pipe of *50 cm* in length resting on a rod of *3 cm* diameter, placed on a load cell Fig. 14. The other parts include a casing which contains the circuitry to measure the weight of collected ice and a heating system. As ice accretes on the freely rotating steel pipe, the ice load is weighed by the load cell. When ice accretes on the steel rod, aerodynamic drag will cause it to rotate in the case of free rotating icing technique, always facing the least amount of the iced part towards the wind.

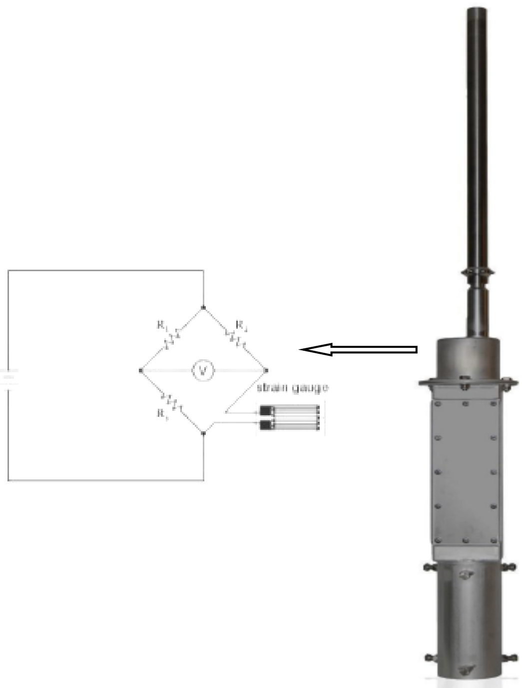


Fig. 14. IceMonitor by Combitech [33].

The Ice Monitor is manufactured by SAAB Technologies and was initially developed for power line surveillance systems. It can measure the rate because the readings from the load cell are recorded with time. The Ice-Monitor® is not able to detect ice over a wide area and cannot distinguish between the two types of in-cloud icing.

2.7.2. Ice Meter®

The ice meter was developed by the Institute of Atmospheric Physics, Prague, Czech Republic [34]. It measures the mass of icing accumulated on the surface of the collector. It has a horizontal rod, which is coupled with a cylindrical collector to the tensometric. The cylinder is orientated vertically in order to eliminate the detection of wet snow as much as possible but the orientation of this cylinder can be changed to horizontal, if required. Just like IceMonitor, in this sensor, the mass of accumulated ice is measured by means of a tensometric bridge (strain gage load sensor) the output of which is tied to the precise A/D converter. The digital signal is preprocessed by a micro-controller, which assigns the time and stores the data into the device memory. In order to prevent the freezing of the horizontal rod, which couples the cylindrical collector to the tensometer, which is located together with the electronics in the housing, the passage through the housing may be heated depending on the passage temperature. A test electromechanical impulse is applied each hour to verify the free force transition to the tensometric, and thus to check whether the acquired data are reliable or not.

2.8. Hybrid Measurement Technique

In this technique, two or more ice detection techniques can be combined to get a useful output. Jarvinen [12] and RIDE by Canadian Researchers [35] have used this technique.

2.8.1. Hybrid Ice Sensor by Jarvinen

As mentioned in Section 2.1.2 that this ice sensor/ sensing technique was designed by Jarvinen [12] and is capable of detecting ice, its thickness and type. In this technique the contaminants layer temperature, thermal conductivity and variation of total impedance versus ice sensor electrical excitation frequency are measured and the total impedance data is also converted to show the complex dielectric properties of the overlying layer. The measured properties and the complex dielectric properties are first used to differentiate between ice, rain water, deicer fluid or snow overlying the ice sensor and then used to differentiate between glaze and rime ice by comparing the results with laboratory measured ice data stored in computer memory collocated with the ice sensor. The presence of ice is confirmed by a measured thermal conductivity [3] [36] value in agreement with that of ice and its complex dielectric locus in near agreement with similar results calculated form the stored laboratory data.

2.8.2. A Remote Ice Detection RIDE System

This technique was proposed by Gagnon, Groves and Pearson in IWAIS 2013 [35]. This technique is useful to measure thickness of foggy or clear layers of ice or liquid on surfaces at distance in the range *6.5 to 30 m*. The main components of this technique are a low power laser with a long distance focusing optic, a compact telescope and a digital camera. Fig. 15 shows the telescope and camera used in this system. The telescope’s knob is controlled by a first servomotor. Also a filter is used in bright sunlight conditions which is controlled by second servomotor. Fig. 16 shows Helium Neon HeNe laser and optic for beam expansion and focusing. This optic is also controlled by servomotor. The complete configuration of this RICE device can be seen in Fig. 17.

3. Issues of Presently Available Sensors

In order to check the performance of icing sensors, some measurements were taken in the Winter 2001/02 at Luosta test station on the top of Luosta fell (500 m above sea level). It is a site class in Finland, which is elevated site with harsh and frequent icing. The Labko LID-3503 (work upon ultrasonic energy measurement technique) and the Rosemount 0872J (work upon resonance measurement technique) were installed. Both ice detectors indicate the presence of icing conditions. According to the performance of the instrument used for ice detections were not entirely reliable and difference were found between the performances of ice detectors. The ice detectors are to some extent insensitive to icing under heavy icing conditions. It was possible to record more or less accurately the start and ending of icing periods but not the accretions rate or type of the icing. The Rosemount sensor yielded fairly good measurements in comparison with Labko. It detected the presence of icing conditions. In soft icing conditions ice accretion may exist on the sensor probe during short periods of time especially in the beginning of the icing event but

[3] Pure glaze ice in the temperature range from 0 to -40ºC has a thermal conductivity value in the range 2.4 to 2.6 W/mK, rain water slightly above 0ºC has a value of 0.6 W/mK in the same units, air 0.023 W/mK and a 50/50 mixture of deicing fluid is 0.41 W/mK. The thermal conductivity of rime ice (density 0.38 gm/cm^3) have a thermal conductivity of 0.4 W/mK. Thus the presence of glaze ice is easily determined by the substantial difference in thermal conductivity between it and all other possible contaminants.

the sensor does not detect ice. This sensor is fairly adequate for icing measurements and it operated better than the other used instruments. Nevertheless, it cannot guarantee accurate measurements in all icing conditions [1].

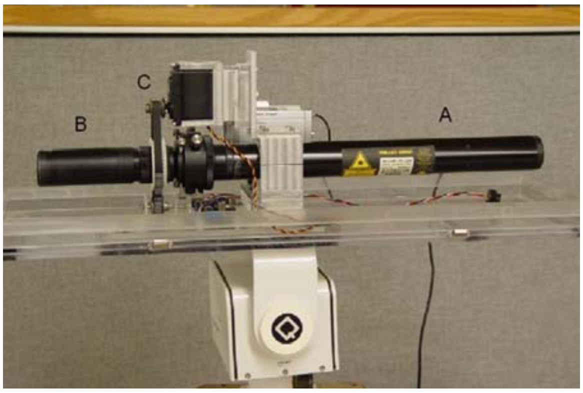


Fig. 15. Digital Camera (A), Telescope (B), First Servomotor (C), Second Servomotor [35].

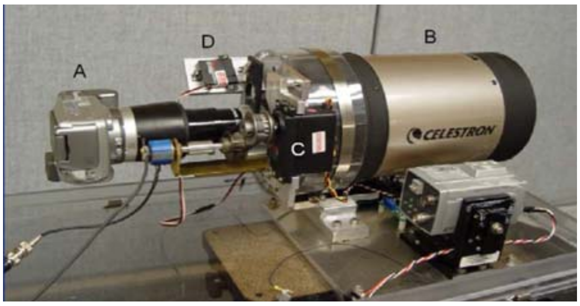


Fig. 16. HeNe Laser (A), Optic (B), Servomotor (C) [35].

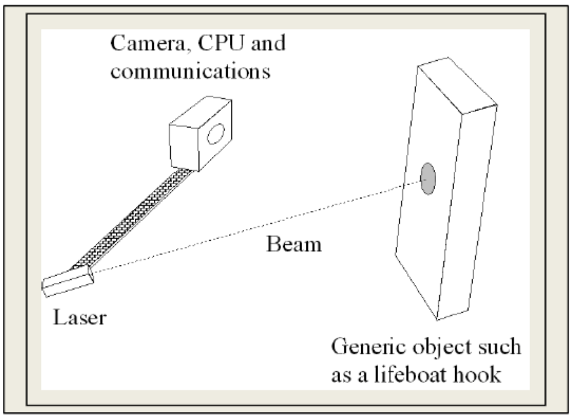


Fig. 17. A configuration of miniaturized RICE device [35].

The icemeter has been operated on the Milesovka peak, Czech Republic from 2000. Although icemeter installed in the site measured correctly most of the time, but there were also some time periods, when the instruments gave obviously wrong negative values. These times can usually be associated with the periods when the horizontal rod coupling the tensometric with the vertical collector became icebound to the instrument housing. Thus there was no free force transition which, can be identified by not observing a proper electromechanical pulse in the data. The following changes are expected to be made in icemeter for its better performance [1]:

a. Possibility to build an instrument with a rotating collector;

b. More focus on the sensors that measure accumulated icing.

Some measurement were taken in Narvik 2012/2013 [37]. An icing monitoring station under ColdTech RT3 was prepared to study the usefulness of the available icing sensors. The station was installed at Fagerness Mountain. The icing sensors used in this station were IceMoniter and HoloOptics T44. It was observed that HoloOptics sensor malfunctioned after a week and started to provide erroneous icing rates. Analysis of the error confirmed the combination of extreme weather conditions such as heavy ice loads which lead to the malfunctioning of the instrument.

A comparison of different icing sensors (such as IceMoniter by Combitech, Goodrich Ice Detector by Rosemount, LID Ice Detector by Labkotec, T44 by HoloOptics and 3 relatively strong heating commercial cup anemometers) was performed in order to develop a new ice measurement system to optimize performance of Wind Turbine. The overall outcome of this study was that the performance of all sensors was strongly dependent upon the circumstances and all have problems under certain conditions [38]. This study further proposes to combine sensors of different types to get a complete picture.

4. General Sensor Design and Sensory System Constrains Due to Cold Regions

The dimensions of design and operation problems which are faced during a useful operation during atmospheric icing conditions are crucial than normal. Out of many, some of the important sensor system design parameters are outlined here.

4.1. Temperature

Materials contract at low temperatures therefore electrical and mechanical properties changes therefore selection of sensor system material must be handled carefully.

4.2. Electrostatic Discharge

The electrostatic discharge phenomena could not be fully neglected in weather station breakdown. Temperature gradients in the ice particles produce charge separation because the concentration of H+ and OH- ions in ice increases rapidly with increasing temperature. H+ ions are much more mobile within the ice crystal than OH- ions. As a result, the colder part of an ice particle becomes positively charged, leaving the warmer part charged negatively [39]. The resulting electrostatic phenomena due to blizzard can be hazardous for the control circuitry inside the sensor module, provided the said consideration is not catered for in the design. Over and above this fact, the proper maintenance of earthing at the site becomes all the more critical in this perspective.

4.3. Adhesion

Water has high adhesion properties because of its polar nature. Mounting the sensor at an inclined angle in the final product is highly beneficial since it allows the water to flow down and thereby prevents the formation of water puddles. A slight inclination of at least 10^o from the horizontal can reduce the probability of water accumulation.

4.4. Intermittent Power Source

The sensor system installed at the location takes power from the available installed facility. Due to demographic location of the site in terms accessibility and complicated power infrastructure available in terms of maintenance, power breakdown may occur. Also the instantaneous power surge could also be one reason which may effect useful sensor operation [37].

4.5. Data Links / Interface Winterization

Interface links between the components are data and power based. Data links might include the Ethernet/Serial Links with supporting routing cables or interface panels, whereas power links have distribution panels, supplying power requirements to the computing and sensing equipment. Interface links with power support system are generally in direct exposure to cold climate conditions and sometimes they are under transitional states, hence are most vulnerable to degradation and failures [37].

4.6. Power Cable Insulation

Electrical insulation of external power cables is another big issue which need to be handled carefully. During a cold region operation the material properties changes and insulations may crack. Several commonly used PVC insulations cannot withstand low temperatures at least in the range -30ºC or below. They crack and peel off leaving exposed conductors, which may cause short circuiting or develop other problems such as grounding leading to make data unreliable [37].

5. Discussion and Future Work

5.1. Discussion

Table 2 is the summary of the available direct measurement atmospheric icing techniques and their present/potential outputs. Based upon this review study of design and working principle of various ice measurement sensors/techniques, it is found/observed that sensors based upon capacitive and infra-red techniques offer reasonable potential to detect some important parameters pertaining to ice accretion such as detection of an icing event, determining ice type, and icing rate. Also for icing load measurement only axial load measurement technique is commercialized. The geometric dimension of the instruments (IceMoniter by Combitech and IceMeter by Czech Republic) used for measuring icing load meet ISO 12494:2001 [2] but they do have some flaws such as no free force transition and non-uniform ice accretion around its surface due to freely rotation. It is important to highlight here that ISO 12494:2001 [2] mentions a slowly rotating ice collector and the measurement technique to measure icing load is not strictly specified in ISO 12494:2001 [2]. Makkonen and Stallabrass [40] have demonstrated the usage of constant slowly forced rotational principle in the icing tunnel in the Low Temperature Laboratory in Canada to measure the experimental collision efficiencies. They compared their results with the theoretical collision efficiency correlations of Langmuir and Blodgett [41] and found the results in close agreement.

Based upon this study it is found that if we utilize slowly forced rotating technique then it may be useful. The minimal advantages of this technique over freely rotating technique are:

a. Reasonably uniform ice accretion characteristics than freely rotating geometry;
b. Reasonably low icebound characteristics to the instrument housing than freely rotating geometry.

During this study it is observed that the sensor utilizing the natural properties of atmospheric ice working on an efficient algorithm would be expectedly an adequate sensor. This study further proposes to combine different techniques for measuring atmospheric icing parameters.

5.2. Future Recommendations

It is recommended to include a design based extensive experimental or laboratory study on the performance evaluation of all these sensing techniques in the new version of Cost 727. Also, it is recommended to design a hybrid icing sensor by combining two or different techniques together. If the new sensor is slowly forced rotational together with any other technique as e.g. capacitance or infra-red then it is possible to measure most of the required parameters such as detecting icing event, determine icing type, measure melting rate, measure icing load and measure icing rate/intensity. It will be more commercially suitable if the new sensor is modular, so that it can be integrated with a Cold Climate Weather Station for both Onshore and Offshore applications. The hybrid and modular characteristics of this new generation of icing sensor could also suit to integrate this sensor with Intelligent Ice Protection System for Onshore and Offshore applications.

Table 2. Available Direct Measurement Atmospheric Icing Sensor Techniques and Patents.

Patents and Sensors	**Potential Capability**					
	Detection	Type	Thickness	Load	Icing Rate	Melting Rate
	Capacitance Based Measurement Technique					
Weinstein [11]	☑		☑			
Jarvinen [12]	☑	☑	☑		☑	
	Impedance Based Measurement Technique					
Seegmiller [31]	☑					
Wallace	☑					
	Ultrasonic Energy Measurement Technique					
Luukkala [16] (LID 3300IP is commercial sensor)	☑ *(false indication due to heavy rain)*				☑	
Watkins [17]	☑					
	Resonance Measurement Technique					
Cronin [22] (Goodrich 0872F1 is commercial sensor)	☑ *(false indication due to heavy rain)*				☑	
Kooseman [23]	☑					
	Microwave Energy Measurement Technique					
Overall [29, 30]	☑					
Magenheim	☑					
	Infra Red Energy Measurement Technique					
HoloOptic Sensor [32] *(Commercial Sensor)*	☑	☑			☑	
	Axial Load Measurement Technique					
IceMoniter & Icemeter [33, 34] *(Commercial Sensors)*	☑			☑	☑	
	Hybrid Measurement Technique					
Jarvinen [12]	☑	☑	☑		☑	
RIDE [35]	☑	☑	☑			

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