Atmospheric Icing Sensors – An Insight

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Abstract **– To design a new atmospheric icing sensor, it is important to understand the existing atmospheric ice detection/measurement techniques. It is found that 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. Most of the ice detection methods are not able to deliver combined information about atmospheric ice type, its thickness and its rate simultaneously (very important factors for ice mitigation and design purposes). Based upon this study, it is found that sensors based upon the application of complex relative permittivity variations for different types of atmospheric ice at different ambient conditions offer good potential to detect atmospheric ice type, thickness and rate with minimum loading errors (effects of freezing ambient environment) due to their capacitive nature. This indicates that sensors based on capacitive and impedance measurement techniques are mostly suitable for the development of robust ice measurement sensors.**

Keywords **- Atmospheric Ice; Capacitive; Dielectric; Direct Measurement; Microwave; Resonance; Ultrasonic.**

I. INTRODUCTION

Due to increasing trend of activities in polar regions, human and inventory hazards are also increasing. Hence, development of robust techniques to detect and measure atmospheric ice accretion on structures is a very critical and challenging task. There is no ice sensor commercially available that can detect and measure all important icing parameters such as: icing rate, load and type under any icing conditions simultaneously [1]. Currently, most ice detectors available are capable of measuring either one or two phenomena such as detecting ice and indicating the rate of icing only. Ice sensors can be integrated with anti/deicing systems; therefore it is important for these 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 to be a limiting factor for de-icing system, because most devices for the removal of snow are normally ineffective for the efficient removal of ice or hard packed snow [2]. Also, measuring 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 ic measurement techniques are categorized into indirect and direct methods [3]:

Indirect methods of ice detection involve measuring weather conditions such as relative humidity, wind velocity, temperature etc. that lead to the prediction of an upcoming icing event [4]. Empirical or deterministic models are used in indirect methods to determine when icing will occur.

The direct methods of ice detection are based on the principle of detecting property changes caused by accretion such as mass, dielectric constants, conductivities, or inductance. This paper briefly describes the working principle of different available direct measurement techniques (categorized below) of atmospheric ice on structures.

i. Capacitive based techniques,
ii. Microwave based techniques,
iii. Impedance based techniques,
iv. Ultrasonic based techniques,
v. Load cell based techniques,
vi. Infrared based techniques,
vii. Resonance based techniques.

II. ATMOSPHERIC ICE PARAMETERS MEASUREMENTS USING DIRECT MEASUREMENT TECHNIQUES

A. *Capacitive based 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, Mughal et. al. [5]. This attribute enables non-invasive measurements. In Sihvola et. al. [6], the results indicate that the complex dielectric constant is practically independent of the structure of snow. It is also mentioned 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. The static dielectric constants ε_{rs} of both polycrystalline and single crystals of ice have been carefully determined by Auty and Cole [7]. Also, application electrical properties to the measurement of ice thickness, temperature, crystal orientations are presented in Evanes [8]. Weinstein [9] and Jarvinen [10] proposed two different capacitive based ice detection methods, which are discussed in the following sections. Sensing methods proposed by Gerardi [11, 12] also use the same principle as proposed by Weinstein [9].

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Capacitive ice sensor by Weinstein

The ice sensor proposed by Weinstein [9] as given in Fig. 1, can be used for the determination of the thickness of ice (22) 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) 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 gauge (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).

Both first (16) and second capacitive gauge (18) are made from thin conductors with a thickness of approximately 0.0254mm. A dual timer LM556 (42), used in an astable mode to generate 7μs pulses at any frequencies e.g 1.5kHz, to trigger a monostable timer (44). The timing capacitor of monostable timer (44) is (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 (16). Capacitance measuring circuits (24) and (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,

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

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 capactive 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 [13] resulting no changes in equation 14.

The variation of capacitance as a function of thickness is shown in Fig. 3. The 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 curve (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. Also it can be seen that both curves do not go to zero output voltage even when the ice thickness is zero.

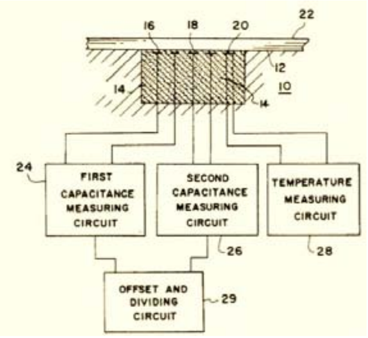


Figure 1. Construction of Weinstein Ice Sensor, Source[9]

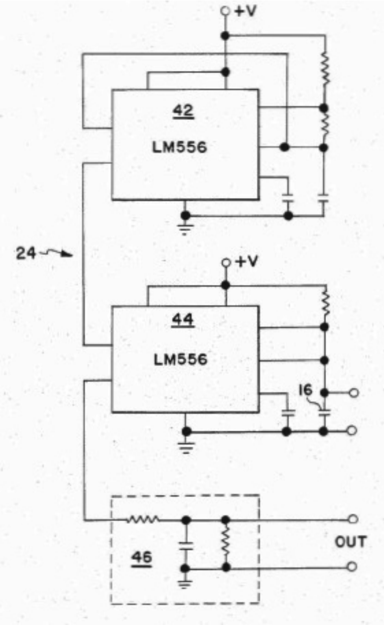


Figure 2. Electrical schematic of capacitance measuring circuit, Source[9]

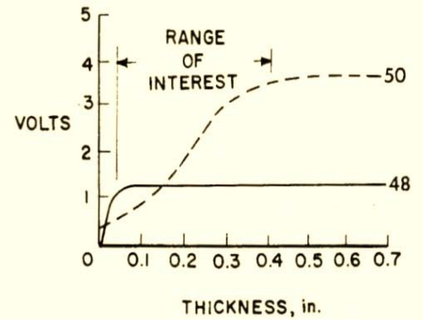


Figure 3. Ratio of capacitance gauge as a function of thickness, Source[9]

Capacitive ice sensor by Jarvinen

The ice sensor designed by Jarvinen [10] is capable of detecting the 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 [8] and Stiles [14]. A lot of the dielectric measurements based upon Cole – Cole plot [15, 16] on wet snow, pure snow, granular snow and compact snow were conducted by Kuroiwa [17] and many others. In this sensor, Jarvinen [10] 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. The contaminant layer's temperature, thermal conductivity and variation of total impedance versus ice sensor electrical excitation frequency are measured. The complex dielectric property subsystem monitors the dielectric property locus in dielectric space as the excitation frequency is varied from near dc to higher frequencies and compares the measured results for magnitude and shape with laboratory property data taken at the same temperature and stored in the processor. It double check using external ice (based upon the complex dielectric measurements) sensor whether it is ice or rain water or deicing fluid or snow. If the measured results form a semicircular shaped locus of dielectric properties in complex dielectric space during the frequency scan and those measurements are also determined to be in agreement with on board stored laboratory ice data, ice is confirmed to be present. The presence of ice is also confirmed if a particular vector can be constructed from the measured data taken at a single preselected excitation frequency and found to have a vector angle in agreement with the vector angle from stored laboratory results taken at the same measurement conditions. In addition, complex dielectric measurement algorithms identify whether cracks, flaws or voids or increased electrical conductivity exist in the ice covering and sensor from their effects on the shape and size of the measured complex dielectric locus or from the length of the vector at the pre selected frequency. The presence of flaws, cracks or voids or enhanced electrical conductivity are determined from the values for the low frequency and high frequency intercepts and the value for diameter of the complex dielectric locus if these values are found to differ from those calculated for ice based on stored ice data. 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. 5. For more details on the mathematical principle of this type of sensing technique see Mugal et. al. [16].

Pure glaze ice in the temperature range from *0* to *-40^{o}C* has a thermal conductivity value in the range *2.4* to *2.6 W/mK*, rain water slightly above *0^{o}C* 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. For more details follow [13]. Dielectric values are used in addition to discriminate between rain water, deicing fluid and low density rime ice.

Also, this sensor uses *AD5933* high precision impedance converter system that combines an on board frequency generator with a *12 bit, 1 MSPS, ADC*. The frequency generator allows an external complex impedance to be excited with a known frequency. The response signal from the impedance is sampled by the on board *ADC* and a DFT is processed by an on board DSP engine. The DFT algorithm returns a real and imaginary data word at each output frequency. *AD5933* chip measures total impedance magnitudes over the range from *100Ω* to *10MΩ* with a total system accuracy of *0.5%*. The sweep frequency range of the chip normally covers the range from *1kHz* to *100kHz*. By adding a clock dividing circuit we can lower the range to *10Hz* to *20KHz*. For this sensor this range is *40Hz* to *40KHz*.

From Impedance to Dielectric : It is explained in [18] that ice can may be replaced by an equivalent circuit as shown in Fig. 4. The total complex impedance Z of the circuit is given by,

$$\frac{1}{Z}=\frac{1}{R_{\circ}}+\frac{1}{R_1+\dfrac{1}{j\omega C_1}}+j\omega C_\infty \qquad (2).$$

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

$$\frac{1}{Z_c}=j\omega C=\frac{j\omega A\varepsilon_o\varepsilon_r}{L} \qquad (3)$$

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

$$\varepsilon_{rs}=\frac{L}{\varepsilon_o A}\left(C_1+C_\infty\right) \qquad \& \qquad \varepsilon_{r\infty}=\frac{LC_\infty}{\varepsilon_o A} \qquad (4)$$

Eq. (4) when substituted in Cole-Cole equation we get,

$$\varepsilon_r=\frac{\varepsilon_{rs}-\varepsilon_{r\infty}}{1+\left(j\omega\tau_0\right)^{1-\alpha}}+\varepsilon_{r\infty}=\frac{LC_1}{\varepsilon_o A\left(1+j\omega\tau\right)}+\frac{LC_\infty}{\varepsilon_o A} \qquad (5)$$

where τ = R_1C_1 is the dielectric relaxation time of the circuit that is time taken for the voltage across the ice block to reach *1-e^{-1} = 0.63* of its final value when a step voltage is applied.

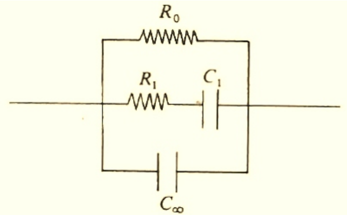


Figure 4. Equivalent circuit for ice [18]

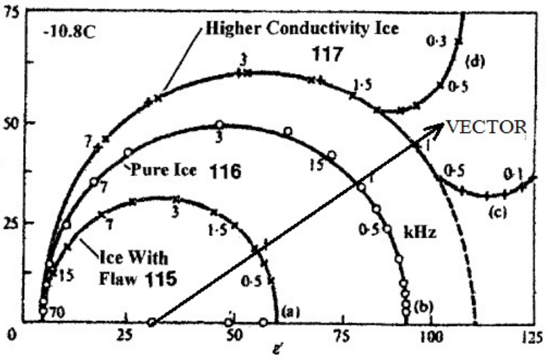


Figure 5. Cole Cole plot for pure ice, ice with flaw & ice with higher conductivity value, Source [10]

B. Ultrasonic based techniques

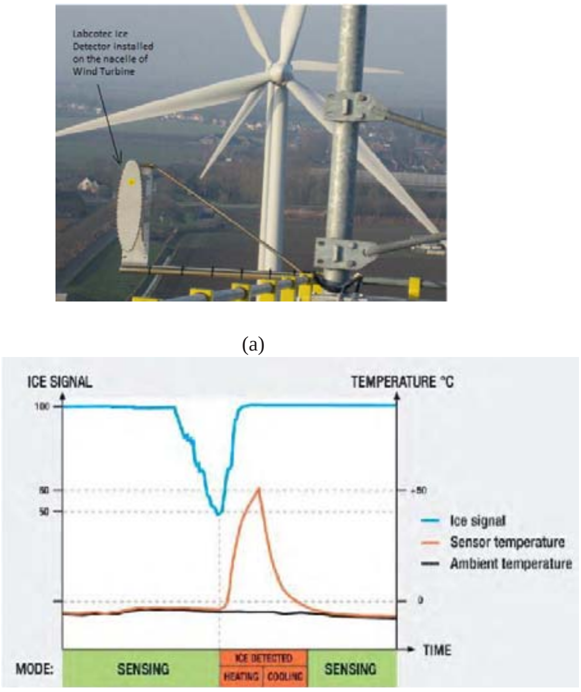
Ultrasonic ice sensors consist of two transducer elements, where one element generates ultrasonic vectors, which are detected by the second element. By measuring the attenuation levels, icing between the two elements can be detected. Like capacitive sensors, ultrasonic sensors need low power, low cost and are directionally sensitive. Luukkala [19] and Watkins [20] proposed two different ultrasonic based ice sensing techniques, which are discussed in the following sections.

Ultrasonic ice sensor by Luukkala

In the ice sensor designed by Luukkala [19] , 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 LID-3300IP [21] and are primarily aimed to detect ice on wind turbines, see Fig. 6a. 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 start heating itself to melt the detected ice. After a set delay, the alarm will go off and turbine will start functioning again, see Fig. 6b[22]. This sensor have 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 [4]. It is reasonably east 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 inability to melt all the ice.



(a)

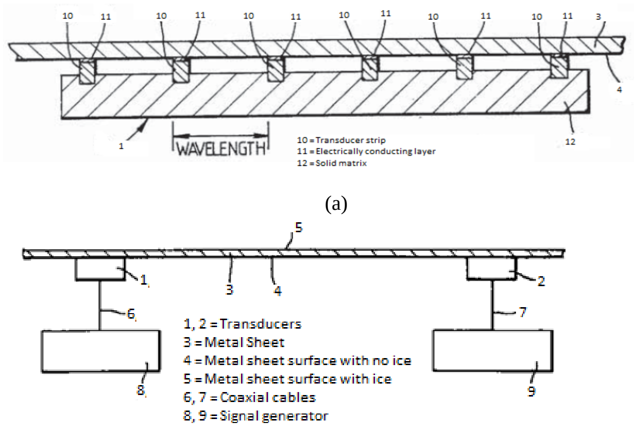
(b)

Figure 6. Labcotec Ice Detector, Source [22] (a) Labcotec Ice Detector installed on the nacelle of wind turbine, (b). Working cycle of detector

Ultrasonic ice sensor by Watkins

The ultrasonic sensor designed by Watkins [20] 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 [23]. The waves may be horizontally polarized guided shear waves, or the waves may be a mode of lamb wave [24] 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.

In Fig. 7a, the design of Watkins's sensor to detect a layer of ice on a thin solid sheet is shown. 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. In Fig. 7b it is shown 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.



(a)

(b)

Figure 7. Working Principle of Watkins's Icing Sensor ; Source [20]

B. Resonance based technique

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 [25], Kossmann [26] proposed two different resonance based ice sensor designs, which are discussed in the following sections.

Resonance ice sensor by Cronin

This ice sensor design [25] 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. 8). These magnetostrictive sensors vibrate ultrasonically at a set resonant frequencies. As ice accretes on the probe, the vibrational frequency decreases. At a specified frequency shift, usually a decreasing frequency, which is related to the ice mass on the probe, an output signal is generated and probe heaters are energized to remove the ice. The heater is then de-energized and when the probe cools down, begins to accrete ice again if the icing event was still persistent. This sensing method has been practically utilized in [27, 28]

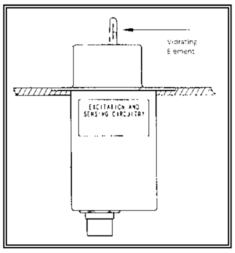


Figure 8. Cronin resonance based ice sensor; Source [25]

Resonance ice sensor by Koosmann

The ice sensing technique proposed by Koosmann [26] was not novel but presented a further improvement on the method proposed by Werner et. al. [29]. This technique is different from the sensing technique proposed by May [30] and Roth [31] who used a diaphragm as a vibrating element. In the technique proposed by Koosmann [26] 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.

C. Microwave based technique

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 [32] and Magenheim [33] proposed two different microwave based ice sensors, which are discussed in the following sections.

Microwave ice sensor by Overall

The icing sensor designed by Overall [32] 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.

In Fig. 9 it is shown 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.

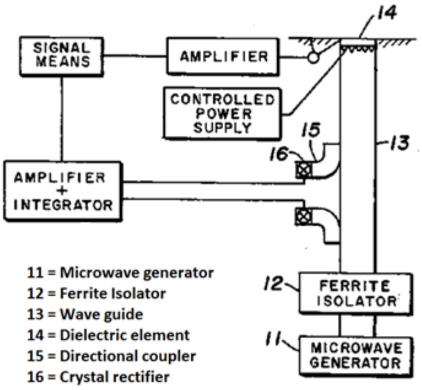
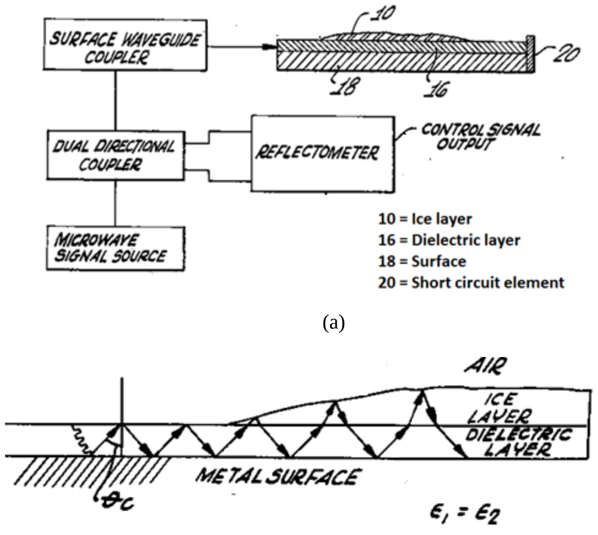


Figure 9. Microwave ice detector by Overal; Source [32]

Microwave ice sensor by Magenheim

In this design [33], microwave electromagnetic energy (typical frequency falls 2k – 20k 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. 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. 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)

(b)

Figure 10. Microwave ice detector by Magenheim; Source [33], (a) Transmittance of microwave energy in iced surface, (b) Working principle

D. Impedance based technique

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 we can avoid saturation of the electrodes in this technique and we can increase our data points.

Impedance ice sensor by Seegmiller

The design of Seegmiller [34] 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.

E. *Infrared based 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.

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. The operating range of this sensor lies in NIR range (0.88 μm to 0.92 μm), [35]. An icing event is recorded if more than 95% of the probe is covered with a 5nm thick layer of glaze ice or a 9nm 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 [36].

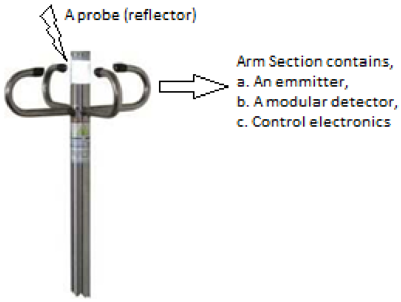


Figure 11. T44 Holoptic ice sensor; source [36]

F. *Load cell based techniques*

In the international standard ISO 12494 [37], a standard way of measuring ice accretion is suggested. In this method it is required to measure the load of atmospheric ice on a steel rod that is 0.5 meter high (1 meter if heavy icing is expected) and has the diameter of 30mm. The rod must be freely rotating or forced to rotate at a constant speed. When ice accretes on the steel rod, aerodynamic drag will cause it to rotate in the case of free rotating icing load monitor, always facing the least amount of the iced part towards the wind. This doubling of length of the steel rod due to heavy icing is primarily aimed to uniform the drag distribution along its profile. By measuring the weight of the iced steel rod with the help of load cells, the amount of ice that has accreted can be determined. Two ice sensors (ice monitor & ice meter) have been developed on the basis of this technique. The following sections describes these two sensors:

The IceMonitor

The IceMonitor® measures the mass of accumulated ice gravimetrically. The working element is a freely rotating steel pipe resting on a rod placed on a load cell. As ice accretes on the freely rotating steel pipe, the ice load is weighed by the load cell. 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 cannot distinguish between the two types of in-cloud icing.

Ice Meter®

The ice meter was developed by the Institute of Atmospheric Physics, Prague, Czech Republic. 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. 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 tensometric, 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 [38].

III. PROS/CONS OF AVAILABLE SENSORS

A. *Measurements in Finland*

The icing climate of the site has been characterized as site class A: an elevated site inland in northern Europe with harsh and frequent icing climate. The Labko LID-3503 and the Rosemount 0872J were installed at the site in the winter 2001/02. Both ice detectors indicate the presence of icing conditions. According to the measurements performed with the LID-3503 ice detector it was noted that the sensor is inadequate for icing measurements in extreme conditions. Also, the conventional humidity instruments measure incorrectly in icing conditions [4].

B. Measurements in Czech Republic

The icemeter has been operated on the Milesovka peak from 2000. Although icemeters 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 [4],

i. Possibility to build an instrument with a rotating collector.
ii. More focus on the sensors that measure accumulated icing.

C. Measurements in Finland

Rosemount 0872J (prototype) at the FMI’s test est. The test station is located in northern Finland on the top of Luosto fell (500m asl, N 67 08’, E 26 54’). The Luosto test sites represent an elevated site inland with harsh and frequent icing climate. According to the performance of the instrument used fo rice 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 has yielded fairly good measurements at Luosto and 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 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 especially in soft icing conditions [4].

IV. CONCLUSION AND SUGGESTIONS FOR FUTURE WORK

A. Conclusions/Findings

Based upon this review study of design and working principle of various ice measurement techniques, it is found/observed that sensors based upon capacitive and impedance techniques offer reasonable potential to detect important parameters pertaining to ice accretion such as ice type, ice thickness and icing rate. There is no extensive experimental and laboratory based study on the performance evaluation of all these sensing techniques because most of the literature found is based on theoretical performance evaluation hence it is a design conjecture. It is possible to combine two or three different techniques together particularly capacitance, impedance and resonance in order to measure these parameters and empirically develop an analytical relationship for the measurement of the icing parameters including ice load, it is anticipated to produce a more robust icing measurement device. In [3], Homola et. al. have described the unsuitable methods and suitable methods for detecting ice on wind turbines. He has also created a room for further investigations on the capacitive, inductance and impedance type of measurement techniques, which according to him appear the most promising sensing technique/method, which is also based upon conjecture without any detailed design study. During this study it is also observed that the sensor utilizing the natural electrical properties of atmospheric ice [14, 17] working on an efficient algorithm based upon the electromagnetism theory will be expectedly prove an efficient sensor and the practical example of this sensor is Jarvenin’s total impedance and complex dielectric property icing detection sensor. If we adopt the physics of this sensor along with a rotating part then we may get a robust sensor. As the capacitive sensing technique, provide less loading errors than other techniques therefore, it may essentially be a part of new robust atmospheric icing sensor.

B. Future Work

Detailed performance evaluation based upon the laboratory experiments and on situ experiments of the different sensing techniques/methods is being developed. A prototype sensor based upon the dielectric potential of atmospheric ice is designed and being developed in the cold room chamber of NUC, which can be then optimized according to the area of application. Although capacitive based sensing method seems reasonable for the measurement of atmospheric ice type, rate and thickness yet it has some coupling issues due to the fringing effects (electric field lines try to go through the air and into the sensor head on the sides), which may lead to inefficient calculations. Hence, to avoid this, the same sensor can be then further improved to develop a robust atmospheric icing detection and analyzing scheme by utilizing other sensing techniques such as resonance, impedance, inductance etc., which are ought to be reasonable. Also a big challenge to build a robust sensor which can work in freezing domains, material selection alongwith humidity protection is very critical.

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