A Capacitive Sensing System for Non-Contact Detection of Ice

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**Abstract**—This paper presents a capacitive sensing system for non-contact detection of ice from a distance of 8 to 10 cm and distinguishes it from water. It is well known that the Relative Permittivity (RP) of ice and water are almost equal at low frequencies, in the range of a few kHz. At a high frequency of excitation, i.e., about 100 kHz and above, the RP of water remains same, but that of ice substantially reduces. A capacitive sensor, wherein, the ice or water layer forms part of the sensing volume can be used to detect presence of ice. It can be distinguished from water by measuring and then comparing the capacitance values at low as well as high frequencies. Such a sensor for road ice detection has been reported, but it requires the sensing electrodes to be in close contact with the ice layer. Recently, a capacitive non-contact ice detector has been reported. The sensing range of this system was limited to 3 cm, even after employing active shielding to reduce the effect of offset capacitance. As the distance between ice layer and sensor increases, the ratio of change in sensor capacitance to offset capacitance becomes very small. This paper reports application of a capacitance measurement circuit that can provide an output as a function of presence of ice. The proposed scheme does not require active shield even when the sensor has large offset capacitance. A prototype of the new scheme has been developed and tested in the laboratory. It detected presence of ice layer of thickness 2 mm from a distance of 10 cm and distinguished it from water.

**Index Terms**—ice detector; grounded capacitive sensor; capacitance-to-voltage converter; offset capacitance.

I. INTRODUCTION

Ice detectors are used to detect formation of ice on aircraft surface, its engines and air induction systems [1], [2], and in the winter season it is used to monitor deposits of ice layers in the runways [3], road surface [4] and wind turbine blades [5]. Slippery road surface due to black ice [6] is a major cause of accidents during winter. Statistics show that 458 deaths were reported in USA due to ice on roads [7] during 2009-2010 winter seasons. Slippery walkways are dangerous for pedestrians. Airline accidents were also reported due to the formation of ice on runways [8]. Number of such accidents can be significantly reduced, by employing appropriate ice detectors to monitor formation/deposit of ice which enables timely precautionary actions to be taken. Ice detectors based on infrared thermometer [9], optical [4], ultrasonic [2], [10] and capacitive [3], [11] are available. Among these, the ultrasonic and capacitive work well, when the ice and sensor are in physical contact. Even though capacitive sensors provide good sensitivity and a less expensive solution, its usability is limited without having a non-contact detection feature. In an earlier work [11], the authors presented a non-contact capacitive ice detector but its sensing range was limited to 3 cm. In some of the practical applications, which requires non-contact measurement, a larger non-contact sensing range is preferred. Also, [11] uses complex active which shielding may cause stability problems [12]. Thus, it will be better if a larger range than reported in [11] can be achieved without the use of active shielding schemes.

This paper presents a new capacitive ice detector system that has a detection range of about 8 to 10 cm. It uses a high sensitive Capacitance-to-Voltage Converter (CVC) suitable for grounded capacitive sensor [13]. This circuit is capable of nullifying the effect of offset capacitance and provide an output proportional to the change in sensor capacitance alone. The paper is organized as follows. Block diagram and theory of operation of capacitive ice detector are explained in Section II. Details about the high frequency limitations of CVC reported in [13], design of the CVC for high frequency excitation and complete schematic of the interface circuit are also given in Section II. In Section III, results of the Finite Element Analysis (FEA) are presented. Experimental set-up and results are discussed in Section IV.

II. CAPACITIVE NON-CONTACT ICE LAYER DETECTOR

An overall block diagram of the capacitance based non-contact ice layer detection system is shown in Fig. 1. C_x represents a single electrode capacitive sensor. This can also be called as a grounded capacitive sensor as it has just one
electrode and the other electrode is at ground surface. A pictorial view of the single electrode capacitive sensor is given in Fig. 2. It has a sensor electrode (indicated as first electrode) and a ground plane acting as second electrode. The sensor electrode and ground plane are separated by a thin insulating layer. When the sensor electrode is excited with a voltage signal $V_S (f_L)$, there will be fringing electric field lines from the sensor electrode to ground which pass through the surface under test/observation as shown in Fig. 2. Now, if a layer of ice is present as shown, it will modify the electric field. This will introduce a change in capacitance. Similar changes in capacitance will be observed in the presence of a water layer. It has been reported that ice and water have high Relative Permittivity (RP), of about 80, at low frequency of excitation (a few kHz). The RP of ice decreases (to about 3.1) at higher frequencies (above 100 kHz) while that of water remains unaltered in this frequency range [3]. This frequency dependent RP characteristic of ice is utilized to differentiate it from water.

In the proposed scheme, the sensor electrode is connected to a Capacitance-to-Voltage Converter (CVC) which converts the sensor capacitance to voltage signal. Two separate CVCs are used to measure capacitance at low and high frequencies. As in Fig. 1, the switch $S_1$ switches the sensor capacitance $C_a$ between the CVC’s. The CVC_H measures the capacitance at high frequency $f_H$, and CVC_L measures at low frequency $f_L$. The block CVC_L is implemented with a high sensitive grounded capacitance-to-voltage converter discussed in [13]. When excited with voltage signal $V_S (f_L)$, the CVC_L provides a voltage $V_o (f_L)$ as a function of capacitance $C_a$. The CVC_H also employs the same measurement circuit, discussed in the [13], but modified to operate at a high frequency $f_H$. The output voltage $V_o (f_H)$ of CVC_H corresponds to capacitance $C_a$ at frequency $f_H$. The details of the circuit is explained in Section II-A.

The CVC outputs, $V_o (f_L)$ and $V_o (f_H)$ are connected to two separate Synchronous Demodulators (SD), SDLF (SD-Low Frequency) and SDHF (SD-High Frequency) as shown in in Fig. 1. Switched gain amplifier (SGA) and Low Pass Filter (LPF) are part of SD [14]. SGA separates the in-phase (I) and quadrature-phase (Q) components by multiplying CVC output with excitation signal and quadrature shifted excitation signal as shown in the Fig. 1. These signals are passed through separate low-pass filters, which reduce the high frequency excitation and noise signals, and only pass the low frequency capacitance voltage output. The I and Q components of two frequencies ($V_{L1}$,$V_{LQ}$ and $V_{H1}$,$V_{HQ}$) are given to a Data Acquisition System (DAS). DAS converts the analog information into digital data. DPC processes this information and extract the capacitance change. DPC also generates a control signal $V_{S1}$ that regulates switch $S_1$.

A. Capacitance-to-Voltage Converter with High Frequency Excitation

As discussed earlier, for non-contact ice detection and to differentiate an ice layer from a water layer, a multi-frequency capacitance measurement is required. Fig. 3 shows a modified schematic of interface circuit presented in [13]. Compared to the circuit in [13] a few capacitors, $C_2$, are included. Here $C_{OS}+C_x$ is the sensor capacitance, where $C_{OS}$ represents the large offset capacitance and $C_x$ is the small variable capacitance, that changes with measurand. By setting the value of reference capacitance $C_R$ equals to $C_{OS}$, the effect of $C_{OS}$ on the output voltage can be removed [13]. Then the voltage $V_{O1}$ (without the capacitor $C_2$ in Fig. 3) can be expressed as

$$V_{O1} = \frac{V_S}{R} \left[ R_1 + R_2 + j \omega R_1 R_2 (C_{OS} + C_x) \right].$$  (1)

From (1), it can be noticed that the voltage $V_{O1}$ starts increasing with frequency, after the cut-off frequency. This leads to the saturation of opamp $OA$ at high frequency, limiting the frequency of excitation signal $V_S$. This saturation of the opamp $OA$ can be avoided at high frequency by introducing capacitors $C_2$ across resistors $R_2$ as shown in
the Fig. 3. The expression for output of opamp OA, in this condition can be written as in (2).

\[
\vec{V}_{o1} = -\frac{\vec{V}_S}{R} \left( R_1 + R_2 + j\omega R_1 R_2(C_{OS} + C_x + C_2) \right) \frac{1}{1 + j\omega R_2 C_2}
\]  

As in (2), \(C_2\) introduces an additional pole which stops \(\vec{V}_{o1}\) increasing with frequency. And now, the circuit can measure capacitance at high frequency. The output voltage for the modified circuit (for \(C_R = C_{OS}\)) can be obtained as in (3). In (3), \(R_P = \frac{R_1 R_2}{R_3 + R_2}\).

\[
\vec{V}_o = -A \vec{V}_s \frac{R_1}{R} \frac{j\omega R_P C_x}{1 + j\omega R_P (C_{OS} + C_2)}
\]

As can be seen from (3), with the increase in \(C_2\), pole in the equation will move towards left (cut-off frequency decreases) and this modifies the bandwidth (B.W) of the circuit. Value of \(C_2\) can be suitably selected to achieve the condition \(1 << j\omega R_P (C_{OS} + C_2)\).

**B. De-modulator**

The output \(\vec{V}_o\) is modulated with change in capacitance \(C_x\). In [13], a Synchronous Demodulation (SD) technique [14] was used to extract \(C_x\). The SD can be implemented using a computer. For this, a Data Acquisition System (DAS) will be required for acquiring data. Sampling rate of DAS must be much better than the high frequency \(f_H\) employed. This will increase the overall cost of the system. On the other hand, the synchronous demodulator can be implemented using a circuit as shown in Fig. 4.

The complete schematic of the CVC with synchronous demodulator is shown in Fig. 4. From (3), it can be noticed that the output signal \(\vec{V}_o\) and excitation signal are not in phase. Or \(\vec{V}_o\) contains both in-phase and quadrature components. These components are handled separately (in-phase and quadrature demodulators) as shown in the Fig. 4. The output of the CVC is connected to two Switched-Gain Amplifier (SGA) [14] circuits.

The excitation signal \(\vec{V}_S\) controls the switches of in-phase SGA. The excitation signal is also passed through a phase shifter circuit. This 90° shifted signal controls the switches in SGA for quadrature phase component. Outputs from the SGAs are connected to Low-Pass Filters (LPF). The cut-off of the LPF is higher than maximum expected frequency of variation of the measurement capacitance. And, it blocks the inter-modulation components present above \(2f\). Output from the two filters are connected to separate channels of Data Acquisition System, DAS. As this signal is a demodulated output, the highest frequency it has is limited to the highest frequency at which the \(C_x\) changes, which will be much less than \(f_H\). Thus a DAS with a low speed ADC will be sufficient for this purpose. The digital data is acquired to a virtual instrument (developed in LabVIEW). As indicated in Fig. 4, the data corresponding to separate channels are squared and added. Square root of this, \(\sqrt{V_{out}}\) gives the voltage corresponding to the value of capacitor \(C_x\).

**C. Switching scheme and cross-coupling**

The sensor capacitor is switched between the low and high frequency measurement circuits as in Fig. 1. Since both the circuits are in operation all the time, there is a possibility of cross coupling through the switch \(S_1\). In order to minimize this cross sensitivity at both the frequencies, the two separate capacitance measurement circuits were connected to the sensor as shown in Fig. 5. The block CVC is implemented with the CVC explained (in Fig. 3). The same circuit without capacitor \(C_2\) is used to realize CVC. The blocks SDLF and SDHF
Fig. 6. Results from FEA studies. (a) Shows the streamline plot of relevant electric field lines with ice layer of Relative Permittivity \(\varepsilon_r = 80\) and (b) with ice layer of \(\varepsilon_r = 3.1\). The electrode structure shows an offset capacitance of 663.586 pF and change in capacitance of 33 fF.

represents, signal extraction circuit discussed in Section II-B. The sensor electrode is shared between two circuits with the help of SPDT switches \(S_1\) and \(S_6\). When the sensor electrode is connected to one of the circuits (High frequency/Low frequency) the other circuit (Low frequency/High frequency) is connected to the reference capacitance \(C_{RS}\). By connecting a reference capacitor \(C_{RS}\) the drift related errors of idle circuit can be tracked and corrected [13]. This further improves the performance of the measurement.

In Fig. 5, when the switches are at position 1 (as in Fig. 5), the sensor is connected to the \(CVC_H\) circuit and \(C_{RS}\) to the \(CVCL\). When the switches change to position 2, \(CVCL\) measures the sensor capacitance and \(CVC_H\) gets connected to \(C_{RS}\). Thus the measurement and tracking can be alternatively done using this arrangement. Instead of using a normal dual switching arrangement, a special arrangement using 6 switches is implemented. As described in the beginning of this section, in a dual switching arrangement, the floating terminal of the switch is connected to the other circuit. Due to the stray capacitance between terminals of the switch, there will be some cross talk. This effect will be noticeable, when signal frequencies are higher. This interference is eliminated by using \(S_1\) and \(S_6\). The switches are arranged in such a way that, the second terminal of the switch, which is not connected to the sensor or reference capacitor is grounded. This significantly reduces the cross-coupling between the low and high frequency circuits through the switching arrangement.

Fig. 7. Photographs of the test setup inside a climatic chamber. (a) Shows the full view of the experimental setup. (b) A close-up view of the electrodes.

III. SIMULATION STUDIES

A Finite Element Analysis (FEA) has been performed on the sensor structure using COMSOL Multiphysics. A 2D structure of the second electrode maintained at ground potential and first (sensing) electrode were developed in COMSOL multiphysics. The sub-domains of the sensor and ground plane were selected as copper. The boundary of sensor electrode was set as 1V, while boundary of the ground plane was set to ground. The distance between electrode and test surface was 10 cm. Initially, the Relative Permittivity (\(\varepsilon_r\)) of the ice layer was set to 80 (\(\varepsilon_r\) of ice at low frequency). The (relevant) stream line plots obtained are given in Fig. 6(a). The boundary integration of the sensor electrode gave a capacitance of 663.619 pF. Then, the \(\varepsilon_r\) of the ice layer was set to 3.1 (\(\varepsilon_r\) at high frequency) and solved. The resulting change is shown in Fig. 6(b). The calculated capacitance was 663.586 pF. The results show that the electrode structure has a an offset (fixed) capacitance of 663.586 pF and the change in capacitance (between high and low frequencies) is 33 fF. The proposed interface circuit can measure such small value capacitance and and offset correction is possible up to 1000 pF [13].

IV. EXPERIMENTAL SETUP AND RESULTS

A prototype of the proposed capacitive sensor and the measurement circuit for non-contact ice layer detection were developed and tested. A single sided PCB of dimensions 10 cm \(\times\) 15 cm was used as the sensing electrode. Another single sided PCB with dimensions 30.5 cm \(\times\) 30.5 cm was used as ground electrode. The sensor electrode was separated from ground electrode with a 0.2 cm thick plexiglas (insulating layer). The same dimensions were used for FEA. The prototype of the CVC's for the measurement of sensor capacitance were built using commercially available IC's. All opamps in the circuit in Fig. 4, were realized using opamp IC TL084. IC INA129 was used for Instrumentation amplifier INA. Switched gain detectors were realized using IC AD630. The resistors and the capacitors of the low-pass filter were selected in such a way that it gives a bandwidth of 200 Hz. The phase shifter circuit was tuned to give a shift of 90°. A 16 bit, 1.25 MSa/s Data Acquisition System (DAS) from National Instruments (USB-6259) was used to acquire the output signal from the filter circuit. A total of 4 channels of the DAS were used, 2 channels for high frequency (in-phase and quadrature phase) output signals and 2 for low frequency signal outputs. The
squearing, adding and square root operation, shown in Fig. 4, were performed in a virtual instrument developed in LabVIEW environment. The SPDT switches S1 to S5 in the Fig. 5, were implemented using IC MAX4053. The high frequency \( V_h(f_H) \) and the low frequency \( V_L(f_L) \) excitations were generated using an arbitrary function generator AFG3022B from Tektronix. One channel of the function generator generated \( V_h(f_H) \) at 1 kHz while the second channel generated \( V_L(f_L) \) at 200 kHz. The resistor values of the low frequency AFC were selected as \( R_{H1} = 40 \, k\Omega, R_{H2} = 220 \, k\Omega, R_{H3} = 180 \, \Omega \). And for the high frequency AFC, \( R_{H1} = 100 \, k\Omega, R_{H2} = 220 \, k\Omega \) and \( C_{H1} = 1 \, nF \) were used. The gain of the instrumentation amplifier was adjusted, so that overall gains of both the AFC’s were same. Proper ground plane and shielding were provided to keep the external and inter-circuit interferences low.

The sensor structure developed was placed inside a climatic chamber WK111 from WIESS, as shown in the photograph in Fig. 7. The experimental set-up inside the climatic chamber was always monitored, during the test, using a video camera installed in it. The sensor was connected to the CVC’s using a 2 m long shielded cables. The offset capacitance of the sensor structure with cable capacitance was measured as 812 pF. This offset capacitance was corrected by adjusting \( C_R \) to the same value. Different tests were performed by keeping the sensor inside the climatic chamber.

Initially, the effectiveness of the error tracking mechanism was tested. For this test the sensor was kept at a height of 10 cm from the surface (ice or water layer). The circuit was excited and the temperature of the climatic chamber was set to 10°C. The offset capacitance correction was performed before measurement. A 0.1 cm thick water layer was introduced for a short period and then removed. The output \( V_h(C_X) \) of the AFC when the switch was connected to sensor \( C_X = C_{OS} + C_r \), and, the output \( V_h(C_{RS}) \) when switches are connected to \( C_{RS} \) were recorded, plotted and given in Fig. 8. The variation in output due to change in circuit parameters was corrected by taking \( V_h(C_X) - V_h(C_{RS}) \). This is also shown in the Fig. 8.

In another test, the sensor electrode was set at a height of 3 cm from the surface. The temperature of the climatic chamber was adjusted to 2°C. Both \( C_{RS} \) were adjusted to correct the offset capacitance. Then a thin layer of water with 0.1 cm thickness was introduced. Output corresponding to both high and low frequencies, \( V_h(f_H) \) and \( V_L(f_L) \) were recorded. The output is shown in Fig. 9(a). As expected, the change in output when a layer of water was introduced was equal at both the frequencies. Then the temperature of the climatic chamber was adjusted to -5°C and a 0.1 cm thick ice layer was introduced. The output recorded is shown in Fig. 9(b). The results show that the change in capacitance when an ice layer comes under the proximity of sensor was different at both frequencies. From the difference between \( V_h(f_H) \) and \( V_L(f_L) \), the layer of ice can be differentiated from water. A relative percentage change \( \left( \frac{V_h(f_L) - V_h(f_H)}{V_h(f_H)} \times 100 \right) \) of 102 % was observed when the ice was introduced. Then the height of the sensor electrode was increased to 5 cm from the surface and a layer of ice was introduced. The output recorded is shown in Fig. 9(c). The relative percentage change observed was 63 %. The same experiments were done for an electrode at a height of 10 cm from the surface. In this case, a relative change of 18 % was observed. Recorded output is shown in Fig.9(d). The above results show that the relative change in capacitance at two frequencies decreased drastically as the distance of the electrode from the surface increased. Increasing the height of electrode increases the air gap, which reduces the effect of thin ice layer on the total sensor capacitance.

RP of ice layer slightly varies with the temperature [15]. The effect of change in temperature of ice layer on the sensor is studied by introducing ice layers at different temperatures. During this test, the electrode was kept at a height of 8 cm from the surface. A layer of ice of thickness 0.1 cm was introduced by setting the temperature of the climatic chamber to -9°C. The temperature of the ice layer was monitored using LM35 temperature sensor. Fig. 10(a) shows the output recorded when the temperature of the ice was -9°C. Then temperature of the climatic chamber was increased to -2°C and then to 0°C. The measured reading at both the temperatures are shown in Fig. 10(b) and Fig. 10(c), respectively. The results show a clear difference in output in both the frequencies. Reading at -9°C shows a relative change of 40 %. The chamber
temperature was then changed to -2°C. The relative change decreased to 27%. With further increase in temperature, close to 0°C, relative change was 24%. These results indicate that the temperature of the ice has some effect on the relative permittivity of the ice, as expected.

To verify the effect of change in ambient temperature on the sensor, temperature of the climatic chamber was varied between 0°C and -5°C. The distance between sensor and ice layer surface was 8 cm. A layer of ice was introduced, during the test. The output observed was recorded and plotted in Fig. 11. The result shows that the ambient temperature variation will affect both high frequency and low frequency outputs ($V_{ol}(f_H)$ and $V_{ol}(f_L)$), almost equally. As we are measuring the relative change between the outputs at two frequencies, for the detection of ice, the variation in temperature will have much effect.

V. CONCLUSION

An improved non-contact ice layer detector is presented in this paper. It uses a modified, high-sensitive Capacitance to Voltage Converter (CVC) to measure change in capacitance at two different frequencies. A prototype of the grounded electrode type capacitive sensor has been developed and interfaced with the prototype circuit. Test results show that the sensor system can detect ice layer from a height of 10 cm, compared to 3 cm detection range of the previous work [11]. The new interface removes the guard electrode and active shielding which improves the stability of the system. Various effects such as effect of electrode height on sensor output, effect of temperature of the ice layer, etc. were experimentally analyzed.

Test results show that the circuit can significantly reduce the effect of ambient temperature in the output, with multi-frequency measurement. Based on the experimental studies, it can be concluded that the developed non-contact ice detection system provides reliable output for a large range of about 8-10 cm, even for a thin (0.1 cm thickness) layer of ice. The developed scheme can be attached to an inspection vehicle to detect presence of black ice on runways and roads.

REFERENCES