Distributed Interdigital Capacitor (IDC) Sensing for Cable Insulation Aging and Degradation Detection

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DISTRIBUTED INTERDIGITAL CAPACITOR (IDC) SENSING FOR CABLE INSULATION AGING AND DEGRADATION DETECTION

by

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DEDICATION

To my family
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First and foremost, I would like to express my sincere and profound gratitude to my advisor, supervisor, and mentor Dr. Mohammod Ali for helping me to learn the fundamentals of research and grow as a researcher. Without his outstanding leadership, constant support, guidance, encouragement, valuable suggestions throughout the course of guidance, I would have never finished this journey. Dr. Mohammod Ali is not only a great mind in his research fields but also a wonderful human being. His thorough attention and guidance to my academic and personal quarries has helped me to navigate those circumstances. It has been a great opportunity and honor for me to work with him and be his PhD student.

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ABSTRACT

Nuclear power plants (NPPs) contain myriad power, control, instrumentation, and other types of cables. The polymer insulation and jacket materials of such cables degrade over time due to operation and environmental conditions e.g., heat, humidity, and radiation. Since the life span of NPPs may extend beyond 40-50 years regular monitoring of cable insulation and jacket polymers is critical to ensure safe and reliable operation. The aging-related degradation of cables causes changes in the relative permittivity or dielectric constant of the insulation and jacket materials. Capacitor sensors, if properly designed and developed can measure this change and thus can provide an estimate of cable insulation health. Such low-cost sensors can be attractive for cable insulation aging detection because they can be deployed in large numbers and could potentially be wireless enabled for ease of data telemetry. Since real-life aged cable specimens are normally not available for testing cable specimens are aged under an accelerated aging environment in an oven the condition of which is governed by the modified Arrhenius equation to simulate real-life aging condition.

This dissertation focuses on the study, design, and application of capacitor sensors like the interdigital capacitor (IDC) sensor and the serpentine (SRC) capacitor sensor. Typically, such a sensor applies a low frequency (kHz) AC signal on a set of driving electrodes which create localized electric fields within a material under test (MUT) e.g., cable jacket or insulation. A set of sensing electrodes that are connected to a circuit or chip measures the permittivity change in the MUT in the form of an appropriate interelectrode
capacitance. The challenges with capacitor sensor design and development include achieving high sensitivity, electric field penetration depth, effects of air-gap mitigation, conformability on cylindrical surface, and conductor integrity. Furthermore, for cables containing both the jacket and the insulation it is currently not possible to measure the aging related permittivity variation of both the jacket and insulation with a single sensor because of electric field penetration depth being dependent on sensor geometry and material characteristics.

This dissertation is motivated to address the above challenges. First, insights are gained from analytical model review and studies of sensors using analytical methods to understand the influence of sensor design parameters on sensitivity and electric field penetration depth. Unit-cell IDC sensors are analyzed using full-wave finite element electromagnetic (EM) simulations using Ansys Maxwell that reveal that the presence of a conducting backplane is highly beneficial in achieving both high sensitivity and electric field penetration depth. Analyses also demonstrate that extremely thin substrates are conducive from both performance and installation point of views.

Experimental sensor design, fabrication, and testing are conducted considering a variety of sensor substrate materials and cables. Cable specimens with and without jackets that had undergone accelerated aging testing are measured using IDC sensors demonstrating their feasibility and applicability. To allow sensor electrode conformability, electrode integrity, and effects of airgap reduction a flexible fabric-based IDC sensor is built and tested on Okoguard Okolon and Okoguard aerial jumper cables. Okoguard Okolon cable specimens aged at 140°C show capacitance more than doubling when a sensor is placed on the CPE jacket of a cable specimen that had undergone accelerated
aging from zero to 840 hours. This aging amounts to about 52.5 years of real-life field aging considering 70°C operating temperature. Tests conducted on the EPR insulation of this cable show a capacitance increase by 33% from its original state. The effects of airgap on the measured capacitance due to aging related material surface degradation is also studied that reveal the need for airgap reduction when sensors are installed on curved surfaces.

Finally, the challenges of measuring thru-the-jacket insulation only permittivity variation of a cable a novel reconfigurable capacitor sensor is designed, developed, and tested. The electric field penetration depth for this sensor was changed by activating and deactivating PIN diode switches. In one instance, the sensor measures the permittivity variation of the jacket while in the next, it measures the permittivity variation of both the jacket and the insulation. By leveraging previously developed permittivity estimation models from large scale finite element simulations these two sets of measurement data are then used to evaluate the aging related permittivity variation of the insulation.
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CHAPTER 1: INTRODUCTION

1.1 Motivation and Objective

Nuclear power plants (NPPs) have myriad varieties of power, control, instrumentation, and other types of cables [1]. Polymeric materials (e.g., insulation and jacket) in cables are used to provide high insulation resistance against current leakage and electrical breakdown and to protect the conductor from harsh environmental conditions. Dielectric constant reveals polymers’ relative charge storage capacity in an electric field [2]. Exposure to heat, moisture, radiation, and other environmental factors can contribute to the change in the chemical structure of the jacket/insulation polymers [3], with chain scission being reported as one of the most common material alterations caused, in which one polymer molecule breaks into two halves [4]. In [5], Tobolsky reported that nearly all initial active chains were broken due to heating over extended periods. Such polymeric structural modifications in turn change the material’s electrical (dielectric constant, insulation resistance) and mechanical properties (tensile strength, compressive modulus). As reported in [4], the polymer properties degrade further as a result of free radicals, which create new bonds by cross-linking them with the existing bonds.

Cables in nuclear power plants are typically designed and permitted to run for up to 40 years, and there have been few age-related cable failures over that time [5,6]. Replacing all of the cables in an NPP, which generally has more than 1000 kilometers of cable, would be a significant financial burden. License renewal up to 60 or possibly even
80 years has been considered, raising questions as to whether or not cables can be left in operation for longer than initially intended. However, to justify life extensions to 60 and 80 years, real-time condition monitoring programs for cable aging is required to monitor cable performance under normal operation as well as overload conditions. Condition monitoring methods can be divided into Destructive evaluation (DE) methods and Non-Destructive evaluation (NDE) methods. Currently, Elongation at break (EAB) test is the most used method for condition monitoring. For EAB test, a polymeric sample needs to be extracted from an in-use cable and tested in the laboratory. Thus, EAB test is a destructive evaluation (DE), intrusive and ex-situ method which prevents it from being used as condition monitoring technique of an established system. For continuous monitoring of an established infrastructure, cable aging status evaluation technique needs to be of the NDE type, in-situ, and non-intrusive, should demonstrate a trend with degradation level and can be correlated with the remaining useful life of the material.

NDE methods can be classified as Bulk electrical tests (like time domain reflectometry (TDR), frequency domain reflectometry (FDR), Tan δ, partial discharge,) and local tests (like indenter modulus test, interdigital capacitance, infrared spectral measurement, ultrasound velocity measurement). Bulk measurements are intrusive whereas local measurements are non-intrusive. TDR and FDR require disconnecting at least one end of the cable from the system to perform the test and they can only detect if a part of the insulation is absent. Tan δ requires disconnecting both ends of a cable, and it does not locate the damaged location. Partial discharge can cause noise and damage to the nearby systems and does not provide any information of the damaged location. Thus, Bulk measurements test the entire cable assembly for insulation missing and, in some cases,
provide information about the weakest section of the assembly, but to detect degradation of electrical and mechanical properties or indication of cable replacement requires local assessment of the damaged area.

Figure 1.1 (a) Electrode layout of one type of capacitor (IDC) sensor, (b) IDC sensor on top of a cable surface.

Among the local test methods, Intender modulus is broadly accepted but does not work well for harder insulation material like XLPE. Infrared spectroscopy works well for some materials-particularly jacket materials. Ultrasound velocity test is difficult to adapt to in-situ field measurement and its application field is material selective. Capacitive type sensing has been found to be promising due to their low cost, high sensitivity, controllable electric field penetration depth, ease of installation and potential for making them wireless enabled [7]. The most common types of capacitor sensor are parallel plate capacitor and Interdigital Capacitor (IDC) sensors. A Parallel plate capacitor sensor is not applicable for all shape and type of test materials because the material must reside in between the electrodes whereas an IDC being on the same plane as the MUT allows measurement on most shapes of dielectric material. Figure 1.1 shows the electrode layout of an IDC sensor and its placement on top of a cable. When an IDC sensor is placed on a polymeric material
under test, its fringing electric fields penetrate the material. As aging-related degradation of cables causes changes in the dielectric constant of the polymeric material, any change in the dielectric constant of the material is reflected as a change in the sensor capacitance. Thus, IDC sensors can be effective tools to characterize aging-related degradation of cable polymers. Such sensors can be used for manual in-service periodic tests or placed as permanent monitoring sensors throughout the NPP, especially where cables are more prone to degradation. In a field scenario one can envision numerous such sensors being deployed throughout an NPP as shown in Figure 1.2. As seen from the figure, capacitor sensor and its measurement circuitry can be assembled easily and can also be wirelessly enabled for data telemetry.

IDC sensors have been researched and investigated before in the context of a variety of applications. They have been proposed for application in humidity sensing [8-10], water level detection [11-16], gas detection [17,18], moisture in concrete [19], wood [20] detection, resin curing [21], and strain measurements [22-25], etc. In [9], a fully packaged CMOS IDC humidity sensor was presented with polysilicon heaters which showed good linearity and repeatability during the whole testing range of 35% to 90% relative humidity. In [11], a water level detection set up using IDC sensor was presented where the sensor was submerged into a bucket water. They compared the measured water level using IDC with the actual water level and found the maximum errors when the bucket was nearly empty and when it was nearly full. In [19], Alam et al. investigated the prospect of measuring moisture in concrete using an IDC sensor and found a distinctly linear relationship between the moisture content in the concrete and the measured capacitance. A novel IDC strain sensor on flexible polyimide substrate for strain measurement of
automobile tires was proposed in [25]. In [26], Bhuiyan et al. introduced a meander and a quarter circular IDC sensor for water tree detection in polyvinyl chloride (PVC) and polyurethane (PUR) insulated power line cables. In [27], Liu et al. showed the effects of electrode width and interelectrode gap on sensor performance. They also fabricated IDC sensors on FR4 substrate to detect artificially created water trees in XLPE cables. Sheldon et al. [28] tested IDC sensors fabricated on a Kapton® film to evaluate insulation damage of chemically aged aircraft wires. The aircraft wire segments were submerged in different fluids for 10 days. They found the lowest capacitance for the pristine condition and capacitance increased differently for different chemicals from its pristine state. Glass et al. [29] have performed accelerated aging on EPR flat specimens and Okoguard®-Okolon® TS-CPE Type MV-90 2.4kV unshielded power cable samples in the lab at 140ºC. They developed an IDC sensor and a new clamping arrangement to place it on cable and tested those specimens using LCR meter. Measured data showed 4% increase in capacitance for the EPR flat specimens from the unaged to the 35 days aged specimen. Measured capacitance on the fully jacketed and part jacketed Okoguard cable samples showed 2% and 6% increase in capacitance, respectively due to 35 days of aging.

As stated above, IDC sensors have been proposed as a device to measure the change in the dielectric constant of materials. Therefore, this also applies to cables that are used in NPPs as long as such cables do not contain a metallic shield on the outside. Since real field-aged cable specimens are normally not available for testing cable specimens are aged under an accelerated aging environment in an oven that is governed by the modified Arrhenius equation to simulate real-life aging condition. In general, a low frequency (kHz) AC signal is applied on a set of driving electrodes (Figure 1.1) which create localized electric fields
within a material under test (MUT) e.g., cable jacket or insulation. The sensor also contains a set of sensing electrodes that are connected to a sensing circuit or chip. When the sensor is placed on a material under test e.g., a cable specimen that has undergone accelerated aging it measures a new capacitance which is different from the capacitance on an unaged cable specimen. From this comparison, one arrives at an estimate of the degree of cable degradation. The challenges with IDC sensor design and development include achieving high sensitivity, electric field penetration depth, effects of airgap mitigation, conformability on cylindrical surface, and conductor integrity. These performance metrics heavily rely on sensor geometrical properties like electrode width, interelectrode gap, presence of a conductive backplane, substrate thickness, and substrate dielectric constant. Furthermore, for cables containing both the jacket and the insulation it is not possible to measure the aging related permittivity variation of both the jacket and insulation with a single sensor because of electric field penetration being dependent on sensor geometry e.g., electrode width and interelectrode gap. The focus of this dissertation is to study the underlying governing parameters of IDC sensors to address the above challenges in the context of NPP cables. Nevertheless, many of the design approaches, techniques and findings may also be adapted to other cable or wiring diagnostics e.g., those in electric utility systems, vehicles, trains, aircrafts etc.
Figure 1.2 An illustration of future possibility where numerous surface mount patch-like capacitor sensors can be deployed throughout an NPP for continuous monitoring (CM) of cable health.

1.2 Contributions

In this dissertation, first, insights are gained from analytical model review and studies of IDC sensors using analytical methods to understand the influence of sensor design parameters on sensor performance. In order to design and develop IDC sensors to detect changes in the dielectric constant of flat specimens, full-wave finite element electromagnetic (EM) simulations are conducted on various types of sensors using Ansys Maxwell solver. Unit-cell IDC sensors are analyzed using full-wave finite element electromagnetic simulations using Ansys Maxwell that reveal that the presence of a
conducting backplane is highly beneficial in achieving both high sensitivity and electric field penetration depth. Analyses also demonstrate that extremely thin substrates are conducive from both performance and installation point of views. Analyses of multi-electrode IDC sensors with and without conductive backplane and with or without guard electrodes are also studied to understand surface charge characteristics, electric field penetration depth, capacitance, and above all sensitivity.

Second, Experimental sensor design, fabrication, and testing are conducted considering a variety of sensor substrate materials and cables. Cable specimens with and without jackets that had undergone accelerated aging testing are measured using IDC sensors. To allow sensor electrode conformability, electrode integrity, and airgap reduction a flexible fabric-based IDC sensor is built and tested on Okoguard Okolon and Okoguard aerial jumper cables. The sensor because of its soft flexible structure eliminates the problem of sensor conductor damage and is easily mountable using a hook-and-loop mechanism. Simulation and experimental results demonstrate that fabric-based sensors create significantly smaller airgaps compared to PCB-based sensors (even those on very thin flexible film material, such as liquid crystal polymer (LCP)). With this sensor Okoguard Okolon cable specimens aged at 140°C show capacitance more than double when a sensor is placed on the CPE jacket of a cable specimen that undergoes aging from zero to 840 hours of aging. This aging amounts to about 52.5 years of real-life field aging considering 70°C operating temperature. Tests conducted on the EPR insulation show a capacitance increase by 33% for the same duration. IDC sensors applied on the EPR insulation of Okoguard aerial jumper cables show capacitance increase by about 19% from zero to 225 hours of accelerated aging at 160°C. This aging amounts to about 58 years of real-life field
aging considering 70°C operating temperature. The effects of airgap on the measured capacitance due to aging related material degradation is also studied that reveal the need for airgap reduction when sensors are installed on curved surfaces.

Third, the feasibility of designing and using IDC sensors for application on thinner cables that have smaller circumferences hence less surface area for multi-finger IDCs is demonstrated by developing IDC sensors with high length to width aspect ratios. To evaluate the effectiveness of IDC on harder insulation material, IDC sensors are developed to test XLPE insulated and HFI jacketed cable that have undergone accelerated aging at 160°C for 1400 hours. This aging emulates about 118 years of real-life field aging considering 80°C operating temperature. Test results of XLPE show a 25% increase in capacitance from unaged to 1400 hours of aging.

Finally, we have proposed a reconfigurable sensor which can estimate jacket and insulation permittivity separately in a nondestructive evaluation (NDE) approach which currently cannot be done. When an IDC sensor is placed on top of the jacket of an unshielded cable, electric fields can penetrate either only the jacket or both the jacket and the insulation depending on how it is designed and what its electric field penetration depth is. For the latter case, the measured sensor capacitance is the sum of the capacitance due to both the jacket and the insulation. Disaggregation is necessary to determine the insulation only aging characteristics. Also, insulation, being the material that surrounds and protects the conductor and resists electrical leakage is probably very important to monitor. In the event that the jacket material is degraded with relatively undamaged insulation, the cable may still function safely. Thus, if a sensor can be developed that can measure the aging status of both the jacket and insulation that would be a tremendous breakthrough. We have
explored that possibility and developed the design, fabrication and testing of a reconfigurable capacitor sensor using which through the jacket insulation permittivity can be measured and hence insulation aging can be detected. The electric field penetration depth for this IDC sensor is changed by activating and deactivating PIN diode switches. In one instance, the sensor measures the permittivity variation of the jacket while in the next, it measures the permittivity variation of both the jacket and the insulation. By leveraging previously developed permittivity estimation models from large scale finite element simulations for a specific cable these two sets of measurement data are then used to evaluate the aging related permittivity variation of the insulation.

1.3 Outline

This dissertation is organized as follows. Chapter 2 presents a literature review of analytical and empirical models of capacitive sensors. A comparative analysis is also presented between computed capacitances from those models, simulated capacitance from ANSYS Maxwell and measured capacitance from experimentally fabricated IDCs. The analyses are divided into two parts: i) sensor without backplane and ii) sensor with conducting backplane underneath the substrate. Chapter 3 focuses on the optimization of sensor geometry to maximize its performances within the measurement constraints using simulation models of unit cell IDC as well as multi-electrode IDC. These simulations focus on investigating and understanding the dependency of sensor performance e.g., change in capacitance with aging, electric field penetration depth on electrode width, interelectrode gap, substrate dielectric constant and thickness, the presence of a backplane and guard electrodes, electrode thickness and length, and number of electrodes. Surface charges and electric fields emanating from the electrodes are also presented. Chapter 4 describes the
rationale of accelerated aging and the cable specimens that have undergone accelerated aging in our laboratory. It presents the experimental setup, measurement circuitry for testing the cable specimens using fabricated IDC sensors and result analysis, followed by the challenges and uncertainty of the measurement procedure using conventional PCB based IDC sensors. It also proposes a solution to mitigate the challenges of PCB based IDC sensors where electrodes are fabricated using conductive fabric on nonconductive fabric substrate. Chapter 4 presents a new high length to width aspect ratio IDC sensor design for thin coaxial cables where the electrode length is increased to compensate for low sensor sensitivity due to fewer number of electrodes. It also demonstrates the inclusivity of IDC sensors in detecting aging related degradation of soft EPR and hard XLPE insulation materials. Chapter 5 presents the concepts, design, and operation of a reconfigurable IDC sensor that can be used to perform through the jacket insulation permittivity measurement and hence cable insulation aging status determination. Chapter 6 concludes this dissertation with some suggestions of possible future works.
CHAPTER 2: INTERDIGITAL CAPACITOR FUNDAMENTALS

Interdigital capacitors (IDC) have been studied by many researchers since the early 1970s. In the early stages of development, the applications of IDCs included those in microwave integrated circuits [30,31], optical and surface acoustic wave devices [32], thin-film acoustic–electronic transducers and tunable devices [33] and dielectrics on thin films [34]. More recently, IDCs have been researched and investigated for their sensing ability.

An IDC consists of a finger or comb like periodic pattern of conducting electrodes printed on a dielectric substrate (Figure 2.1). There are normally two types of electrodes, the driving, and the sensing electrodes. Another type of electrodes called the guard electrodes are sometimes also used to shield the sensor from external electric fields. Each electrode has a width, $W$ and inter-electrode gap, $a$. The spatial distance is defined as the distance between the centerlines of two fingers belonging to the same type of electrode. By applying two different potentials, $V_D$ and $V_S$, on the driving and sensing electrodes, electric fields are created within the material under test (MUT) and the substrate. The capacitance measured between the electrodes depends on the dielectric constants of the substrate and the MUT which is placed on top of the electrodes. In some designs, a conducting backplane may be placed underneath the substrate which can work as a shield. The backplane typically confines more of the generated electric fields in the material under test. The measured capacitance between the interdigitated electrodes depends on $W$, $a$, the electrode length ($L_e$) and the electrode thickness ($t_e$) and the number of electrodes ($N$).
The total capacitance of an IDC depends on the dielectric constant of the materials ($\varepsilon_r$), thickness of the material under test ($h$) and the ratio ($r=h/\lambda$) where $\lambda$ is the spatial wavelength. Spatial wavelength ($\lambda = 2(W + a)$) is twice the sum of electrode width and interelectrode gap which is fixed for a particular IDC [26]. The spatial wavelength determines the reach of the fringing electric fields in the depth direction of material under test. The widespread use of IDCs has led to the development of many analytical and/or empirical models. Some of the reported models in the literature are discussed below.

Figure 2.1 Interdigital capacitor (IDC) design.

2.1 Analytical models

One of the early models for IDCs was introduced by Alley [30] in 1970, based on lossless coupled microstrip line theory. This model is an approximation, which can estimate the capacitance of an IDC consisting of equal electrode width and interelectrode gap. An infinitely thick top air layer was considered. Since experimentally measured capacitances were in good agreement with the computed capacitances using this method,
it was used as a first step to design an IDC [35]. Alley’s model was later modified by Hobdell [36] in 1979 where a loss component was included. This was further improved by Esfandiari et al. [37] in 1983 who introduced the effect of finite conductor thickness, loss terms for an array of microstrip lines and unequal electrode width and inter-electrode gap in the analysis.

2.1.1 Wei model

In 1977, Wei [32] proposed a model based on conformal mapping (CM) technique to compute the capacitance of an IDC with an infinite top air layer. CM techniques were used to three most prominent modulator (e.g., LiNbO₃ waveguides) structures: periodic grating, 2-electrode stripline, and 3-electrode stripline. The capacitance formulas were shown to exhibit a common form other than a single parameter which is simply related to the electrode width and spacing. The CM concept is illustrated in Figure 2.2 which considers a region, bounded by equipotential and continuous flux lines then transforms into a parallel plate capacitor in a new coordinate system. The flux lines and equipotentials remain orthogonal but lie along rectangular coordinates. The net distributed capacitance per unit electrode length is given as,

\[ C = \varepsilon_{eff} \cdot \left( \sum \frac{\Delta U}{\Delta V} \right)_{y>0} \]

\[ \varepsilon_{eff} = \left[ \varepsilon_{air} + (\varepsilon_x \varepsilon_y)^{1/2} \right] \]

where \( \varepsilon_{eff} \) is the effective dielectric constant of the modulator, \( \varepsilon_{air} \) is the dielectric constant of air and \( \varepsilon_x, \varepsilon_y \) are the dielectric constants of LiNbO₃. The summation sign is a reminder that more than one mapping might be necessary.
Figure 2.2 (a) Periodic grating modulator, (b) An intermediate mapping of the hatched region in (a), (c) The final mapped configuration for all three modulator geometries [32].
The electrooptic axis of LiNbO$_3$ is assumed to lie along either the x or y axis. The
general per unit capacitance for the three modulators is given as,

$$
C = \varepsilon_{eff} \left[ A \frac{K'(k)}{K(k)} B \frac{K'(k_1)}{K(k_1)} \right] \quad (2.1)
$$

where $K(k), K'(k)$ and $K(k_1)$ and $K'(k_1)$ are complete elliptic integrals of the first
kind of modulus $k$ and $k_1$. The parameters $A, B, k$, and $k_1$ for the three modulators are listed
in Table 2.1.

These findings are applicable to isotropic media and any material that has
orthogonal principal dielectric axes, for example cubic semiconductors. The capacitance
formulas given in [32] remain valid if a single medium surrounds the electrodes. The
conditions imposed in these models are often not realistic, since they estimate the
capacitance considering an infinite top air layer which is not the case for most sensing
applications.

Table 2.1 $A, B, k$ and $k_1$ parameters for different modulators

<table>
<thead>
<tr>
<th>Modulator</th>
<th>Parameter</th>
</tr>
</thead>
<tbody>
<tr>
<td>Periodic grating</td>
<td>$A = 1/2, B = 0. \quad k = \cos [\pi W/(2a + W)]$</td>
</tr>
<tr>
<td>Two-electrode modulator</td>
<td>$A = \frac{1}{2}, B = 0. \quad k = a/(a + 2W)$</td>
</tr>
</tbody>
</table>
| Three-electrode modulator  | $k = 1 - \{-(W/W + 2a)^2\} [1 - (W + 2a/3W + 2a)^2]/[1 - (W/3W + 2a)^2]]$  
|                            | $k_1 = [1 - (1 - (W + 2a/3W + 2a)^2)/[1 - (W/3W + 2a)^2]]$  
|                            | $A = 1/2, B = 1/2$ for self-capacitance ($C_{11}$)  
|                            | $A = \frac{1}{2}, B = -1/2$ for mutual capacitance ($C_{21}$) |


2.1.2 Wu Model

The Wei model discussed before was extended and improved by Veyres and Hanna [38] by considering a finite layer test material on top of an IDC. Based on the Veyres and Hanna model, Wu et al. [33] introduced an improved model by considering a multi-layer structure consisting of a test material and an infinite air layer on top of that. They fabricated a thin film IDC by depositing a 300-nm film of \( Ba_x Sr_{1-x} TiO_3 \) using metal organic deposition (MOD) technique on a patterned film of YBaCuO. The 300-nm YBaCuO epitaxial thin film was deposited by laser ablation on a LaAlO\(_3\), single crystal substrate (Figure 2.3). This film was then patterned using standard photolithographic techniques and etched by saturated Ethylene diamine tetra acetic (EDTA) acid solution in an ultrasonic bath. The electrode width \( W \) and inter-electrode gap \( a \) were the same.

![Integrated superconducting tunable interdigital capacitor](image)

Figure 2.3 Integrated superconducting tunable interdigital capacitor [33].

First, the IDC was analyzed as a periodic structure with a unit cell consisting of three interdigital lines. Each unit cell was modeled as a coplanar waveguide on a finite ground plane. The conformal mapping approach was then used to evaluate the capacitance per unit length \( C_{p\mu} \), of each unit cell. The total capacitance \( C_t \) is expressed as,
\[ C_t = \frac{N-1}{2} \cdot C_{pu} \cdot l \quad (2.2) \]

where \( N \) is the number of electrodes, and \( l \) is the electrode length. Per unit capacitance, \( C_{pu} \) is given as follows,

\[ C_{pu} = 4\varepsilon_0 \left[ \frac{k(k) + \frac{(\varepsilon_t-1) k'(k_1)}{2}}{k'(k_1)} + \frac{(\varepsilon_{t2}-1) k(k_2)}{2} \right] \quad (2.3) \]

where the first term within the square bracket is contributed by the air layer, the second term by the test material, the BST thin film, and the third term by the substrate. In the above,

\[ k = \frac{W}{W + 2a} \sqrt{\frac{2W}{2W + a}} \]

\[ k_1 = \frac{\sinh \left( \frac{\pi W}{4h} \right)}{\sinh \left( \frac{\pi}{2h} \left( \frac{W}{2} + a \right) \right)} \cdot \sqrt{\frac{\sinh^2 \left[ \frac{\pi}{2h} \left( \frac{W}{2} + a + W \right) \right] - \sinh^2 \left[ \frac{\pi}{2h} \left( \frac{W}{2} + a \right) \right]}{\sinh^2 \left[ \frac{\pi}{2h} \left( \frac{W}{2} + a + W \right) \right] - \sinh^2 \left[ \frac{\pi W}{4h} \right]}} \]

\[ k_2 = \frac{\sinh \left( \frac{\pi W}{4h_s} \right)}{\sinh \left( \frac{\pi}{2h_s} \left( \frac{W}{2} + a \right) \right)} \cdot \sqrt{\frac{\sinh^2 \left[ \frac{\pi}{2h_s} \left( \frac{W}{2} + a + W \right) \right] - \sinh^2 \left[ \frac{\pi}{2h_s} \left( \frac{W}{2} + a \right) \right]}{\sinh^2 \left[ \frac{\pi}{2h_s} \left( \frac{W}{2} + a + W \right) \right] - \sinh^2 \left[ \frac{\pi W}{4h_s} \right]}} \]

where \( W \) is the electrode width and \( a \) is the separation, \( h \) is the thickness of the 1st layer test material, \( \text{Ba}_x\text{Sr}_{1-x}\text{TiO}_3 \), thin film, and \( h_s \) is the thickness of the substrate.

Although the Wu model [33] is the first one that deals with a multi-layered structure, it does not differentiate between the exterior and interior electrodes and also does not consider the capacitance introduced by the electrode endings. The electric field distributions due to the exterior and interior electrodes are generally different. Figure 2.4 shows the electric field distributions of the inner and outer electrodes for a three electrode IDC. As seen, there are additional fringing fields at the external edges of the electrodes.
which for narrow electrodes will contribute into the capacitance substantially. There are no such fringing fields for the internal electrodes of an IDC. The Wu model assumes that the capacitance of the IDC is a sum of the capacitances of unit cells composed of the three electrodes, which in fact is not the real case and therefore the values computed by the Wu model are therefore higher than the real capacitance. In fact, a three-electrode configuration gives rise to extended electric field lines below and above the electrode plane [39, 40].

![Electric field distribution of a three electrode IDC](image)

**Figure 2.4** Electric field distribution of a three electrode IDC [41].

### 2.1.3 Gevorgian Model

In 1996 Gevorgian et al. [41] proposed a more improved model for IDCs considering the Wu model. The model proposed in [41] considers the electric field distributions of the interior and exterior electrodes. The model also considered effective finger width modification albeit for only in one case where the substrate was much thicker than the electrode width. The model proposed in [41] does not require the electrode widths and spacing between them to be the same. For IDCs with electrodes much longer than the width, the “end” capacitance is a small fraction of the total capacitance. Wheeler’s first order approximation [31] was applied to account for the thickness, $t_e$, of the electrodes. The effective width of the electrodes is presented as follows,
\[ W = W_g + \left( \frac{t_e}{\pi} \right) [1 + \ln \left( \frac{4\pi W_g}{t_e} \right)] \]

where \( W_g \) is the physical (geometric) width of the strip. The layout and cross-section of an IDC are shown in Figure 2.5. The dielectric constants of the substrate, \( \varepsilon_1 \), superstrate, \( \varepsilon_2 \), and cover layer, \( \varepsilon_3 \), may have arbitrary values including \( \varepsilon_1 > \varepsilon_2 \). The thickness of the substrate is larger than the thickness of the superstrate, \( h_1 > h_2 \).

![Figure 2.5 IDC sensor (a) layout (b) cross-section][32].

The Capacitance of an IDC with \( n > 3 \) was presented as the sum of the capacitance of three external electrodes capacitor, \( C_3 \) and the capacitances of a periodical \((n - 3)\) structures, \( C_n \) and a correction term for the fringing fields due to the ends of the electrodes, \( C_{end} \). As this model divides the total capacitance into outer and inner electrode capacitances, the deviation of the computed capacitance from the experimental value is considered to be smaller than what is obtained using the Wu model. The total capacitance, \( C \) is given as,

\[ C = C_3 + C_n + C_{end} \quad (2.4) \]
In this model, the width of the external strips, \( W_1 \), is considered different than the width of central strips, \( W \). The capacitance of the three external electrodes section, \( C_3 \)

\[
C_3 = 4 \varepsilon_0 \varepsilon_3 \frac{K(k_{o3})}{K(k_{o3})} t
\]  

\[
\varepsilon_{e3} = 1 + q_{13} \frac{\varepsilon_1 - 1}{2} + q_{23} \frac{\varepsilon_2 - \varepsilon_1}{2} + q_{33} \frac{\varepsilon_3 - 1}{2}
\]

\[
q_{i3} = \frac{K(k_{i3}) K(k'_{o3})}{K(k'_{i3}) K(k_{o3})}, i = 1, 2
\]

\[
k_{o3} = \frac{W}{W + 2a} \sqrt{\frac{1 - \left(\frac{W + 2a}{W + 2W_1 + 2a}\right)^2}{1 - \left(\frac{W}{W + 2W_1 + 2a}\right)^2}}; k'_i = \sqrt{1 - k_i^2}
\]

\[
k_{i3} = \frac{\sinh \left(\frac{\pi W}{4h_i}\right)}{\sinh \left(\frac{\pi (W + 2a)}{4h_i}\right)} \sqrt{\frac{(1 - \sinh^2[\frac{\pi W}{4h_i}])/\sinh^2[\frac{\pi (W + 2W_1 + 2a)}{4h_i}]}{(1 - \sinh^2[\frac{\pi W}{4h_i}])/\sinh^2[\frac{\pi (W + 2W_1 + 2a)}{4h_i}]}}
\]

\[
= 1, 2, 3
\]

The capacitance of the periodic section, \( C_n \) is represented as a sum of partial capacitances due to the i) air filling, \( C_{n0} \), ii) substrate, \( C_{n1} \), iii) superstrate, \( C_{n2} \), and iv) cover layer, \( C_{n3} \),

\[
C_n = (n - 3)(C_{n0} + C_{n1} + C_{n2} + C_{n3})l
\]  

\[
C_n = (n - 3) \varepsilon_3 \varepsilon_{en} \frac{K(k_o)}{K(k'_o)} t
\]

\[
\varepsilon_{en} = 1 + q_{1n} \frac{\varepsilon_1 - 1}{2} + q_{2n} \frac{\varepsilon_2 - \varepsilon_1}{2} + q_{3n} \frac{\varepsilon_3 - 1}{2}
\]

\[
q_{in} = \frac{K(k_{in}) K(k'_{on})}{K(k'_{in}) K(k_{on})}
\]

\[
k_{0n} = \frac{W}{W + a}
\]
\[ k_{in} = \frac{\sinh \left( \frac{\pi W}{2h_i} \right)}{\sinh \left( \frac{\pi (W + a)}{2h_i} \right)} \sqrt{\left( \cosh^2 \left[ \frac{\pi (W + a)}{4h_i} \right] + \sinh^2 \left[ \frac{\pi (W + a)}{4h_i} \right] \right) \left( \cosh^2 \left[ \frac{\pi W}{4h_i} \right] + \sinh^2 \left[ \frac{\pi W}{4h_i} \right] \right)}; \quad i = 1, 2, 3 \]

\[ k'_1 = \sqrt{1 - k_1} \]

For long electrodes, \( l/w >> 1 \), computed IDC capacitance without taking into account the correction for the fringing fields at the ends of the electrodes has in general good accuracy. Nevertheless, some simple formulas are given in this model for the “end” capacitances associated with the fringing fields between the ends of the fingers and the leads (see Figure 2.6).

![Figure 2.6 Field distribution at the end of an electrode [41].](image)

As a first approximation, it was assumed a region with a regular field distribution neighboring the end of the electrode strip and two nonregular regions (dashed in Figure 2.6) near the corners. Thus, a virtual magnetic wall at distance \( x \) from the end of the electrode was considered. The width of external or connecting electrode was considered to be finite (\( W_2 \)) and separated from the internal electrode by a gap \( a_{end} \). The “regular end” capacitance was considered to be half of the three external electrodes capacitor, \( C_3 \) of equation 2.5. The two nonregular regions near the end of each finger are approximated as
a $\frac{\pi W}{2}$ extension to the finite width. Hence, the total electrode end capacitance of n, number of electrodes is expressed as,

$$C_{\text{end}} = 2nW(2 + \pi)\varepsilon_{0}\varepsilon_{\text{en}d} \frac{K(k_{\text{en}d})}{K(k'_{\text{en}d})}$$ \hspace{1cm} (2.8)

$$\varepsilon_{\text{en}} = 1 + q_{1\text{en}d} \frac{\varepsilon_{1} - 1}{2} + q_{2\text{en}d} \frac{\varepsilon_{2} - \varepsilon_{1}}{2} + q_{3\text{en}d} \frac{\varepsilon_{3} - 1}{2}$$

$$q_{i\text{en}d} = \frac{K(k_{i\text{en}d})}{K(k'_{i\text{en}d})} \frac{K(k'_{\text{en}d})}{K(k_{\text{en}d})}, \quad i = 1,2,3$$

$$k_{0\text{en}d} = \frac{x}{x + a_{\text{en}d}} \frac{1 - \left(\frac{x + a_{\text{en}d}}{x + W_{2} + a_{\text{en}d}}\right)^{2}}{\sqrt{1 - \left(\frac{x}{x + W_{2} + a_{\text{en}d}}\right)^{2}}}$$

From the field distribution at the end of the fingers, the authors expected that $x \leq \frac{W}{2}$ when $W \approx a$, though they suggested to use full wave analysis or experiment to determine more accurate value of $x$. For longer electrode length compared to its width, the contribution of end capacitance to the total capacitance is smaller, whereas for shorter length of electrode the contribution is found to be larger [41]. Accuracy of total computed capacitance using this model is expected to be poor for $W/h < 1$ limit, where field lines become dominantly normal to the film/substrate interface and the magnetic wall approximation fails to work. Though the Gevorgian model differs from the Wu model on the choice of the unit cell, as well as it accounts for the error introduced by the electrode endings and sensor boundaries, the computed capacitance using this model still does not agree very well with experimental and finite element analysis results.
2.1.4 Rui Igreja Model

In [39], Igreja and Dias presented a new analytical expression for the capacitance of a periodic IDC sensor, based on conformal mapping technique. This proposed model can be applied for any space and electrode width as well as for any number of layers with different thickness and dielectric constant of MUT. They discussed the effects of monotonically decreasing and increasing permittivity profiles of the dielectric layers above the interdigitated electrodes. They found that their results correlated considerably better with numerical finite-element simulations than models previously reported by Wu and Gevorgian. Figure 2.7. (a) shows a layout of the electrode plane and a schematic diagram of the cross-section of an IDC with two interpenetrating comb electrodes (driving and sensing). Each comb electrode is connected to a fixed potential (either $+V$ or $-V$) and the electrode length is $L$. The spatial wavelength is ($\lambda = 2(W + a)$) and the metallization ratio is $\eta = \frac{2w}{\lambda}$.

By symmetry, the perpendicular planes halfway between the electrodes are equipotential planes with $V = 0$ (ground electric walls), with electric field lines crossing normal to these equipotential planes (see Figure 2.7(b)). For symmetry reasons, the capacitance of one single semi-infinite layer can be evaluated as a function of two types of capacitances (see Figure 2.7(c)): (1) $C_I$—being half the capacitance of one interior electrode relative to the ground potential and (2) $C_E$—the capacitance of one outer electrode relative to the ground plane next to it. Using network analysis to evaluate the equivalent circuit of Figure 2.7(c), the total capacitance between the negative and positive electrodes of a semi-infinite layer IDC-S to be equal to

$$C = (N - 3) \frac{C_I}{2} + 2 \frac{C_I C_E}{C_I + C_E}; N > 3 \quad (2.9)$$
Structures with number of electrodes, \( N = 2 \) and 3 cannot be considered in the scope of this model, although these structures can be easily studied with small modifications of the present model. A simple representation of the splitting of a two-layered IDC (in the upper half plane) is shown in Figure 2.8, where \( \varepsilon_1 \) and \( \varepsilon_2 \) are the dielectric constants of layers 1 and 2, respectively.

Figure 2.7 (a) Layout of electrode plane; (b) cross-section of a periodic IDC sensor showing the electric potential boundary planes distribution; (c) example of the equivalent circuit [39].
The capacitance of a sensor taking into account for the different layers is expressed as the sum of the partial capacitances,

\[
C_u = C_{h=\infty} + (\varepsilon_1 - 1)C_{h=h_1} + (\varepsilon_2 - \varepsilon_1)C_{h=h_2} \tag{2.10}
\]

where \(C_u\) is the total capacitance of the upper half plane (test materials) and \(C_h\) is the geometric capacitance of one layer, which depends on its height \(h\) and on the particular electrode geometry. Both interior \((C_{I,u})\) and exterior \((C_{E,u})\) capacitances need to be calculated to find the total capacitance using Eq. (2.9). The capacitance for the lower half plane (substrate) is calculated in the same way and adds to the capacitance calculated for the upper half plane to obtain the total capacitance of the sensor.
Figure 2.9 Conformal transformations for the calculation of $C_I$ [39].

Figure 2.10 Conformal transformations for the calculation of $C_E$ [39].
The model proposed in [39] used conformal mapping techniques to map an appropriate region of the IDC onto a parallel plate capacitor geometry for which the capacitance value is known. The conformal mapping techniques for $C_I$ and $C_E$ are illustrated in Figures. 2.9 and 2.10, respectively. The parameters, $r = \frac{h}{\lambda}$, together with $\eta = \frac{2w}{\lambda}$ are considered to be the two key geometrical parameters in this model to determine the capacitance with a specific thickness of the MUT. The corresponding equations of this model for calculating $C_I$ and $C_E$ for finite thickness (substrate, test material) and infinite thickness (air) are listed in Table 2.2.

Using the equations of Table 2.2 and the partial capacitance technique, a typical IDC-S with a thick substrate with relative permittivity $\varepsilon_S$ and one sensitive layer of relative permittivity $\varepsilon_1$, will have their total capacitances $C_{I,IDC}$ and $C_{E,IDC}$ as,

$$C_{I,IDC} = C_{I,air} + C_{I,1} + C_{I,S\infty}$$

$$C_{I,IDC} = \varepsilon_0 L \left( \frac{K(k_{I1\infty})}{K(k_{I1\infty})} + (\varepsilon_1 - 1) \frac{K(k_{I1,1})}{K(k_{I1,1})} \right) + \varepsilon_S \frac{K(k_{I1\infty})}{K(k_{I1\infty})}$$

And

$$C_{E,IDC} = C_{E,air} + C_{E,1} + C_{E,S\infty}$$

$$C_{E,IDC} = \varepsilon_0 L \left( \frac{K(k_{E\infty})}{K(k_{E\infty})} + (\varepsilon_1 - 1) \frac{K(k_{E,1})}{K(k_{E,1})} \right) + \varepsilon_S \frac{K(k_{E\infty})}{K(k_{E\infty})}$$

Total capacitance from Eqn. 2.9,

$$C_{IDC} = (N - 3) \frac{C_{I,IDC}}{2} + 2 \frac{C_{I,IDC} C_{E,IDC}}{C_{I,IDC} + C_{E,IDC}}$$

$\text{Sn}(z, k)$ of Table 2.2 is the Jacobi elliptic function of modulus k and $\nu_2, \nu_3$ are the Jacobi theta functions. Though the Igreja model provides capacitance values that are the closest to experimentally measured capacitance and capacitance obtained from finite element analysis (FEM), it still has a few shortcomings. This model does not consider the
electrode ending capacitance. Moreover, the infinite substrate thickness assumption used in this model is not the case when an IDC is fabricated on a practical substrate.

Table 2.2 Detailed equations needed for the calculation of $C_I$ and $C_E$ for a finite layer as well as for an infinite layer [39].

<table>
<thead>
<tr>
<th></th>
<th>Interior electrodes</th>
<th>External electrodes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Finite layer</td>
<td>$C_I = \varepsilon_0\varepsilon_r \frac{K(k_I)}{K(k'_I)}$</td>
<td>$C_E = \varepsilon_0\varepsilon_r \frac{K(k_E)}{K(k'_E)}$</td>
</tr>
<tr>
<td></td>
<td>$k_I' = \sqrt{1 - k_I^2}$</td>
<td>$k_E' = \sqrt{1 - k_E^2}$</td>
</tr>
<tr>
<td></td>
<td>$k_I = t_2 \frac{t_4^2 - 1}{\sqrt{t_4^2 - t_2^2}}$</td>
<td>$k_E = \frac{1}{t_3} \frac{t_4^2 - t_3^2}{\sqrt{t_4^2 - 1}}$</td>
</tr>
<tr>
<td></td>
<td>$t_2 = \text{sn}(K(k)\eta, k)$</td>
<td>$t_3 = \cosh\left(\frac{\pi(1 - \eta)}{8r}\right)$</td>
</tr>
<tr>
<td></td>
<td>$t_4 = \frac{1}{k}$</td>
<td>$t_3 = \cosh\left(\frac{\pi(1 + \eta)}{8r}\right)$</td>
</tr>
<tr>
<td></td>
<td>$k = \left(\frac{\nu_2(0,q)}{\nu_3(0,q)}\right)^2$</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$q = \exp\left(-4\pi r\right)$</td>
<td></td>
</tr>
<tr>
<td>Infinite layer</td>
<td>$C_I = \varepsilon_0\varepsilon_r \frac{K(k_{I\infty})}{K(k'_{I\infty})}$</td>
<td>$C_E = \varepsilon_0\varepsilon_r \frac{K(k_{E\infty})}{K(k'_{E\infty})}$</td>
</tr>
<tr>
<td></td>
<td>$k_{I\infty} = \sin\left(\frac{\pi}{2} \eta\right)$</td>
<td>$k_{E\infty} = \frac{2\sqrt{\eta}}{1 + \eta}$</td>
</tr>
</tbody>
</table>
The equations for $C_{I,IDC}$ and $C_{E,IDC}$ can be modified by considering the substrate thickness ($h_s$) non-infinite and introducing an infinite air layer below the substrate. According to Feng et al. [40] Eq. 2.11 and 2.12 can be modified as,

$$C_{I,IDC} = 2C_{I,\text{air}\infty} + C_{I,1} + C_{I,S}$$

$$C_{E,IDC} = 2C_{E,\text{air}\infty} + C_{E,1} + C_{E,S}$$

2.2 Empirical Model

For insulation degradation detection, e.g., cable aging, the output of an IDC should solely reflect the change in the dielectric property of the material under test (MUT) and not the IDC substrate. Introducing a conducting backplane underneath the substrate generally ensures that most of the electric fields are confined within the MUT instead of leaking through the substrate [26]. Figure 2.11 shows that the presence of a backplane redistributes the fringing electric fields of an IDC sensor and draws electric fields towards itself. As seen, most of the substrate penetrating electric fields end at the backplane instead of the sensing electrode, hence, measured capacitance between the driving and the sensing electrodes of an IDC with backplane mostly immune from the effect of the substrate permittivity and its thickness. Thus, the substrate capacitance of an IDC sensor with backplane has very negligible contribution to the interelectrode capacitance.

Figure 2.11 Electric field distribution of IDC sensor (a) without and (b) with the presence of backplane.
Bhuiyan et al. [26] developed a new empirical model for IDCs with conducting backplane and verified the obtained capacitance with simulation and experimental results. The new model can fairly approximate the effect of the backplane on the IDC performance. The authors used the short-circuit current method to calculate the capacitance of the IDC [18,21], as shown in Figure 2.12(a). In this method, the driving electrode is excited by a low-frequency sinusoidal voltage ($V_D$), the sensing electrode is virtually grounded by an op-amp, and the op-amp output voltage ($V_F$) is measured across a known feedback capacitor ($C_F$). A simplified equivalent circuit shown in Figure 2.12(b) can be used for the calculation of the capacitance between the driving and the sensing electrodes. Here, $C_{DG}$ represents the capacitance between the driving electrode and the grounded backplane and $C_{DS}$ is the capacitance between the driving and the sensing electrodes, which depends on the dielectric constant of the test material. As most insulating materials have nearly infinite resistance, the current is solely due to the capacitive reactance. Taking the summation of the currents at the virtually grounded node, the interelectrode capacitance is expressed as,

$$C_{DS} = \frac{V_F}{V_D} C_F$$  \hspace{1cm} (2.13)
If $C_m$ and $C_s$ is the per unit capacitance of the material under test and the substrate, respectively for an IDC without backplane, then the per unit capacitance is expressed as,

$$C_{ms} = \varepsilon_0 \frac{(\varepsilon_m + \varepsilon_s) K[\sqrt{1-(a/(W+a))^2}] K(a/(W+a))}{2}$$

(2.14)

where $C_{ms}$ is the sum of $C_m$ and $C_s$ and $K[\sqrt{1-(a/(W+a))^2}]$ and $K(a/(W+a))$ are the complete elliptic integrals. If the trapped air within the interelectrode gap has a thickness of $t_e$ which is equal to the thickness of electrode and capacitance of $C_a$, then

$$C_a = \varepsilon_0 \varepsilon_a \frac{t_e}{a}$$

The total per unit capacitance ($C_{pu}$) of the sensor without the backplane is the sum of $C_{ms}$ and $C_a$. If the electrode length is $L_e$ and the total sensor width is $W_s$, then the total capacitance is given by,

$$C_{DS} = \left(\frac{W_s-(W+a)}{2(W+a)}\right) L_e C_{pu}$$

(2.15)

The above equations do not include the effect of a conducting backplane and assumes that the field penetration depth is equal to the substrate thickness. Due to the inherent difficulty in developing exact analytical formulas for such a complicated geometry, the authors proposed an empirical equation based on simulation and measurement results on several materials. Therefore, neglecting the contribution from the substrate capacitance and modifying the per unit capacitance of Eqn. 2.14,

$$C_{pu,c} = A\varepsilon_0 \left[\frac{\varepsilon_m K[\sqrt{1-(a/(W+a))^2}]}{2 K(a/(W+a))} + \varepsilon_a \frac{t_e}{a}\right]$$

(2.16)

where $C_{pu,c}$ is the corrected per unit capacitance and $A$ is a correction factor which corresponds to the redistribution of the field lines of $C_m$ and $C_a$. $A$ can be calculated as
\[ A = p \varepsilon_m + 0.4 \]  \hspace{1cm} (2.17)

where \( p \) is a constant, whose value is estimated based on ANSYS Maxwell simulations. The total interelectrode capacitance can be found by replacing \( C_{pu} \) by \( C_{pu,c} \) in Eqn. 2.15. The authors observed that the correction factor \( A \) increases linearly with the dielectric constant of the material under test (\( \varepsilon_m \)). For dielectric constant values between 1 and 3, they found the correction factor to be, \( A = 0.4 \) and \( A = 0.45 \). For dielectric constants ranging from 3 to 5, the correction factor is considered to be, \( A = 0.45 \) to \( A = 0.5 \). Most cables used in power plant have insulation materials whose dielectric constants are within the range of 2 to 10. Thus, for dielectric constant ranging from 2 to 10, an approximate value of \( p \) can be chosen as 0.02 to obtain the correct correction factor, \( A \).

### 2.3 Comparison between Different models

For IDCs both with backplane and without backplane, a comparative analysis was performed to compare the computed capacitance data from the analytical and empirical models with the simulated and experimentally measured capacitance data. To evaluate the computed capacitance with simulated and measured capacitance, IDC electrodes were designed on RT/Duroid 5880 substrate (\( \varepsilon_{rs} = 2.2 \)) and a flat Rogers TMM3 specimen (\( \varepsilon_{rm} = 3.27 \)) was used as MUT in the ANSYS Maxwell simulations and experimental design. Other parameters were: \( L_e = 30mm \), \( t_e = 17.5\mu m \), \( t_s = 0.51mm \), \( h = 3.15mm \), \( N = 16 \). As the electrode width (\( W \)) and inter-electrode gap (\( a \)) are the two most important design parameters for IDC, \( W \) and \( a \) were varied in the analysis, thus the \( W/a \) ratio of the IDC was varied (Table 2.3). For the different \( W/a \) ratio of IDCs without backplane, the computed capacitance from Igreja, Wu, Gevorgian models and the simulated capacitance data are plotted in Figure 2.13.
Table 2.3: Different electrode width (W), inter-electrode gap (a) and the W/a ratio of the IDCs.

<table>
<thead>
<tr>
<th>W (mm)</th>
<th>0.5</th>
<th>1</th>
<th>1.5</th>
<th>1</th>
<th>1.5</th>
<th>1</th>
<th>1.25</th>
<th>1.5</th>
<th>1.75</th>
<th>2</th>
</tr>
</thead>
<tbody>
<tr>
<td>a (mm)</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>1</td>
<td>1</td>
<td>0.5</td>
<td>0.5</td>
<td>0.5</td>
<td>0.5</td>
<td>0.5</td>
</tr>
<tr>
<td>W/a</td>
<td>0.25</td>
<td>0.5</td>
<td>0.75</td>
<td>1</td>
<td>1.5</td>
<td>2</td>
<td>2.5</td>
<td>3</td>
<td>3.5</td>
<td>4</td>
</tr>
</tbody>
</table>

Figure 2.13 A comparison of the analytical models and simulated capacitance data for IDCs with different W/a ratios. Simulated capacitance data of IDCs with backplane and without backplane are considered.

As seen from Figure 2.13, the computed capacitances from the Wu model are higher than the simulated capacitances whereas the capacitances from the Igreja model are lower than the simulation capacitances. A comparison between the Wu model and the Igreja model reveals that the Wu model capacitance is closer to the simulated capacitance than Igreja model capacitance until the W/a ratio reaches 1.5, after which the Igreja model...
capacitance closely approaches the simulated capacitance. The Gevorgian model gives the lowest capacitance data compared to the other two analytical models and the simulated capacitance data for IDCs without backplane. The three analytical models did not include backplane in the design though the design of IDC in this work considers backplane as a shield from the influence of external fields. The simulated capacitance data for IDCs with backplane are also shown the Figure 2.13 for comparison purpose. It is clear from Figure 2.13 that the computed capacitance data from the three analytical models do not match the simulated capacitance data of IDCs with backplane. The analytical model while providing valuable insight may not be directly useful in this research work.

![Graph](image)

Figure 2.14 A comparison of empirical model (Bhuiyan model), measured and simulated capacitance data for IDCs with backplane and different $W/a$ ratios.
IDCs with the same \( W/a \) ratios and other design parameters as the simulation model of IDC with backplane were fabricated and capacitance of each IDC was measured using Rogers TMM3 as test material. The computed capacitance data from the Bhuiyan model, and the measured and simulated capacitance data of the IDCs with backplane are plotted in Figure 2.14. As seen from the Figure 2.14, there are differences between the simulated and the measured capacitance data due to airgap between IDC electrodes and test material surface. The measured capacitance data are 5-9% lower than the simulated capacitance data. The Bhuiyan model has considered a backplane underneath the substrate, thus the results from the model follow the simulated capacitance data for a sensor with backplane. Though the capacitance increase pattern of the Bhuiyan model agrees with that for the simulated capacitance, the computed capacitance from the Bhuiyan model is found to be 12-16% higher than the simulated capacitance for each \( W/a \) ratio. The capacitance data obtained from the Bhuiyan model is even higher compared to the measured capacitance data.
CHAPTER 3: UNIT CELL AND MULTI-ELECTRODE IDC
SENSORS-PARAMETERS AND PERFORMANCE

Capacitor sensors are used in dielectrometry to measure material dielectric properties [42]. Planar parallel plate capacitor and Interdigital Capacitor (IDC) sensors are the most common capacitive sensors, with the former being best suited for applications where the material under test (MUT) can be placed between the two capacitor plates and form a sandwich arrangement [43]. IDC sensors, on the other hand, have the capacitor electrodes arranged on the same vertical plane next to each other. Because of its planar structure, it is suitable for mounting on most structures which makes them attractive for applications on cylindrical surfaces like cables or wires for their insulation aging/degradation detection. An IDC sensor can have more than two electrodes and may contain a backplane and several guard electrodes. For a simple case, when it contains only two electrodes, it is referred to as a unit cell. The ‘interdigital’ term refers to a finger-like periodically patterned capacitor consisting of multiple driving and sensing electrodes. The total capacitance is the combination of the distributed capacitances. A low frequency time varying voltage signal is applied to the driving electrodes of an IDC. For the case of a cable, the fringing electric fields emanating from the driving electrodes penetrate the cable insulation and terminate at the sensing electrodes. The capacitance of the IDC sensor placed on an MUT is proportional to the dielectric constant of that material. A sensory circuit attached in between the two types of electrodes can measure this capacitance thereby
inferring the change in the relative permittivity of the material. Thus, the degradation of the cable insulation can be detected by monitoring the change in the sensor capacitance. Since IDC sensors do not inject a traveling waveform, such as with reflectometry, their domain of influence is local. Thus, they can be deployed on cable locations that are particularly prone to insulation and/or jacket material aging. One of the advantages of IDC sensors is that they can be used on one side of a material, leaving the other side independent from the electric or magnetic fields of the sensor [21,44].

For optimum IDC sensor design, it is important to study sensor fundamental properties as function of the geometrical parameters and material characteristics employed. The objective here is to study IDC sensors with the objectives of maximizing the electric field penetration depth and enhance sensor sensitivity (change in capacitance as function of the change in the relative permittivity of the material under test). In order to design, develop and test IDC sensors, full-wave electromagnetic (EM) simulations were conducted on various types of sensors using Ansys Maxwell solver. Starting from a simple two-electrode unit cell IDC more sophisticated multi-electrode IDC sensor models were developed and studied. These simulations focused on investigating and understanding the dependency of sensor performance e.g., capacitance, electric field penetration depth, sensor sensitivity, surface charge distribution etc. on electrode width, interelectrode gap, the presence of a backplane, substrate dielectric constant and thickness, and material dielectric constant and thickness.

3.1 Unit Cell IDC Sensor

A unit cell IDC sensor’s function is fundamentally similar to conventional parallel plate capacitor, but the electrodes are coplanar for the former [44]. Figure 3.1 shows the
gradual transition of the fringing field capacitor sensor from its parallel plate counterpart. As shown in Figure 3.1(a), the electric field lines are straight, thus their length is equal to the linear distance between the electrodes of the parallel plate capacitor. However, for a unit cell fringing field capacitor sensor the electric field length is not equal to the geometric distance of the electrodes, the field lines are bent thus enabling one sided access to the material under test (MUT) [26]. In both cases, the electric fields penetrate the MUT, therefore the capacitance between the electrodes reflects the changes in the dielectric property of the MUT.

![Diagram](image)

(a) Parallel plate capacitor  
(b) Tilted plate  
(c) Unit cell IDC sensor

Figure 3.1 Transition from conventional parallel plate capacitor to unit cell IDC sensor.

A sensory circuit attached in between the two electrodes can measure this capacitance thereby inferring the change in the relative permittivity of the material. Figure 3.2 describes an IDC sensor unit cell consisting of a driving and a sensing electrode on top of sensor substrate. A copper backplane can be present underneath the substrate to shield the sensor from the influence of Electromagnetic Interference (EMI). In some IDC sensor designs, guard electrodes are also used to provide immunity from undesired EMI. Guard electrodes do not contribute to any advantage in sensing. For simplicity of analysis and full utilization of limited surface area of the MUT in sensing, we did not include guard
electrodes in our IDC design. However, a guard electrode can be added and would be at ground potential like backplane. To calculate and plot the electric field magnitudes, a MUT of 10 mm thickness was considered in the simulation model. A polyline was created at the center of the sensor (Figure 3.2) along which to calculate and plot the electric fields. A 10V DC field was applied to the driving electrode relative to the sensing electrode. The geometrical parameters of the sensor are defined in Table 3.1. The role of these geometrical parameters on sensor performance are evaluated using FEM simulation in ANSYS Maxwell.

![Figure 3.2 A unit cell of an IDC sensor with material under test (MUT).](image)

Table 3.1 Sensor parameter definitions.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electrode width</td>
<td>$W$</td>
</tr>
<tr>
<td>Electrode length</td>
<td>$L_e$</td>
</tr>
<tr>
<td>Interelectrode gap</td>
<td>$a$</td>
</tr>
<tr>
<td>Substrate thickness</td>
<td>$t_s$</td>
</tr>
<tr>
<td>Backplane conductor thickness</td>
<td>$t_b$</td>
</tr>
<tr>
<td>Electrode conductor thickness</td>
<td>$t_e$</td>
</tr>
<tr>
<td>Sensor substrate relative permittivity</td>
<td>$\epsilon_{rs}$</td>
</tr>
<tr>
<td>MUT relative permittivity</td>
<td>$\epsilon_r$</td>
</tr>
<tr>
<td>Sensor spatial wavelength</td>
<td>$\lambda = 2(W + a)$</td>
</tr>
</tbody>
</table>
3.2 IDC Sensor Performance Parameters

(C-V) measurements were Sensor sensitivity and electric field penetration depth are the two most important performance parameters of an IDC sensor. They are important to measure the degree of degradation of insulation/jacket materials of cables. An IDC sensor must be sensitive enough to measure the small changes in the relative permittivity of the insulation/jacket materials. Also, it must also allow the electric fields to penetrate up to the required level in the depth direction of the MUT. Sensitivity (S) is defined as the gradient of the change in the capacitance as a function of the relative permittivity of the material under test [27].

\[
S = \frac{C_n - C_0}{\varepsilon_n - \varepsilon_0}
\]  

(3.1)

where \(\varepsilon_0\) is the relative permittivity of the cable’s insulation before any aging, \(C_0\) is the corresponding measured or simulated capacitance, \(\varepsilon_n\) is the relative permittivity of the insulation after aging, and \(C_n\) is the corresponding measured or simulated capacitance.

Electric field penetration depth is a performance parameter that measures the intensity of the electric field in the depth direction of the MUT. In [21], Mamishev et al. and in [26], Bhuiyan et al. considered the Electric field penetration depth, or simply penetration depth as approximately one-third of the spatial wavelength (\(\lambda/3\)). Spatial wavelength (\(\lambda = 2(W + a)\)) is twice the sum of the electrode width and interelectrode gap. For an initial design, this definition of E-field penetration depth is an acceptable approximation. However, other sensor parameters besides \(W\) and \(a\) may have effects on the field penetration depth, hence it may not be suited for all types of IDC designs. The E-field Penetration depth can also be defined based on the change in capacitance as a function
of MUT thickness ($h$). Thus, field penetration depth can be calculated using the relative capacitance ($\delta C$) [45]

$$\delta C = \frac{C_h - C_{h\rightarrow\infty}}{C_{h\rightarrow\infty}} \times 100\% \quad (3.2)$$

where $C_h$ is the sensor capacitance for an MUT with thickness $h$ mm and $C_{h\rightarrow\infty}$ is the stable capacitance for a large thickness of the MUT. The field penetration depth can be defined to be the distance from the surface of the MUT to an internal location within the MUT where the relative capacitance is 10% [46] or 3% [47] for an IDC sensor. To calculate the E-field penetration depth using the 3% relative capacitance guideline, a unit cell IDC sensor with conducting backplane was modeled and simulated using Ansys Maxwell. The unit cell parameters were: $W = 1.5 \text{mm}$, $a = 1.5 \text{mm}$, $t_e = 0.05 \text{mm}$, $t_s = 0.2 \text{mm}$. The substrate considered was Duroid 5880 ($\varepsilon_{rs} = 2.2$) while the MUT considered was Rogers RO3003 ($\varepsilon_{rs} = 3$). To resemble a cable like MUT, a 0.05mm thick conductor was placed on top of the MUT (opposite side of the sensor). The thickness of the MUT ($h$) was varied from 0.1 mm to 8 mm in 0.1 mm increment. Simulated capacitances are plotted in Figure 3.3.

As seen from Figure 3.3, capacitance decreases with increasing thickness ($h$); it becomes stable after a certain MUT thickness which can be defined as $C_{h\rightarrow\infty}$. Using equation (3.2), the relative capacitance can be calculated, and 10% or 3% relative capacitance can be defined as the effective E-field penetration depth (Figure 3.4). One-third of the spatial wavelength ($\frac{\lambda}{3}$) can be a good approximation for one layer material under test where it is not obligatory to restrict the electric fields within the layer. But 3%
relative capacitance ($\delta C$) as penetration depth should be used for multi layered material under test where it is required to confine the electric fields up to a certain layer.

Figure 3.3 Unit cell IDC sensor capacitance as a function of MUT thickness. The unit cell parameters were: $W = 1.5 \text{ mm}$, $a = 1.5 \text{ mm}$, $t_e = 0.05 \text{ mm}$, $t_s = 0.2 \text{ mm}$. Substrate was Duroid 5880 ($\varepsilon_{rs} = 2.2$) and Rogers RO3003 ($\varepsilon_{rs} = 3$) was the material under test.

Figure 3.4 Relative capacitance as a function of MUT thickness.
3.3 Effects of Sensor Parameters on Performance

3.3.1 Electrode Width and Inter-Electrode Gap

Electrode width ($W$) and inter-electrode gap ($a$) are the two key geometrical parameters that can be used to optimize an IDC sensor performance e.g., E-field penetration depth and sensitivity. For a sensor with a fixed number of electrodes, electrode width and inter-electrode gap are optimized to achieve maximum sensitivity and the required E-field penetration depth. To build a relationship between the sensitivity and sensor geometrical parameters ($W, a$), a unit cell IDC sensor was modeled, and parametric analysis was adopted. Other sensor parameters were kept fixed at $t_s = 0.2 \, mm$, and $t_e = 0.1 \, mm$. Duroid 5880 ($\varepsilon_{rs} = 2.2$) was assigned as substrate material and relative permittivity of the MUT was varied from 3.5 to 4.5. Simulated capacitances when the permittivity of the MUT is 3.5 for different electrode widths and inter-electrode gaps is shown in Figure 3.5. Simulated capacitances for both relative permittivities of MUT were subjected to multivariate regression analysis and the capacitance data showed a linear relationship with electrode width ($W$) and inter-electrode gap ($a$).

\[
\text{Case I. For } \varepsilon_r = 3.5 \rightarrow C = 27.84 + 50.23 \times W - 1.01 \times a
\]

\[
\text{Case II. For } \varepsilon_r = 4.5 \rightarrow C = 33.75 + 50.65 \times W - 1.36 \times a
\]

These two linear relationships show that sensor capacitance increases with the increase in electrode width and decreases with the increase in inter-electrode gap. Using the definition of sensor sensitivity of equation (3.1), sensitivity was calculated from the two sets of capacitance data where relative permittivity of MUT was 3.5 and 4.5. Figure 3.6 shows the surface plot of the sensor’s sensitivity Vs. electrode width ($W$) and inter-electrode gap ($a$). From Figure 3.6, it is evident that larger electrode size and small inter-
electrode gap will be needed to achieve high sensitivity. To develop a relationship between sensitivity and the sensor geometrical parameters, sensitivity is plotted as function of electrode width and inter-electrode gap ratio \((W/a)\) in Figure 3.7. The \(RMSE\) and \(R^2\) coefficient indicate that the polynomial model provides a good fit between the sensitivity and \(W/a\). As seen from Figure 3.7, sensor sensitivity increases with increasing in \(W/a\). Increase in sensitivity is higher (almost doubled) when the ratio increases from 0.1 to 1. Thus, the ratio of electrode width and inter-electrode gap needs to be as high as possible to maximize sensitivity provided that fabrication limitations do not present that to be unfeasible to realize.

![Figure 3.5 Simulated capacitance data of unit cell IDC sensor vs. electrode width \((W)\) and inter-electrode gap \((a)\). MUT thickness = 2mm and \(\varepsilon_r = 3.5\). Other sensors parameters: \(\varepsilon_{rs} = 2.2, t_s = 0.2\, mm, and\, t_e = 0.1\, mm.\)](image)

45
Figure 3.6 Sensitivity unit cell IDC sensor vs electrode width ($W$) and inter-electrode gap ($a$). MUT thickness = 2mm and $\varepsilon_{r1} = 3.5, \varepsilon_{r2} = 4.5$. Other sensors parameters: $\varepsilon_{rs} = 2.2$, $t_s = 0.2$ mm, and $t_e = 0.1$ mm.

Figure 3.7 Sensitivity unit cell IDC sensor vs. ratio of electrode width and inter-electrode gap ($W/a$). MUT thickness=2mm and $\varepsilon_{r1} = 3.5, \varepsilon_{r2} = 4.5$. 

Sensitivity

<table>
<thead>
<tr>
<th>W &lt; a</th>
<th>a &lt; W</th>
</tr>
</thead>
</table>

$W/a$

Sensitivity

3  4  5  6  7  8  9  10  11

$W/a$

3  4  5  6  7  8  9  10  11
To evaluate the role of electrode width \((W)\) and interelectrode gap \((a)\) on E-field penetration depth, unit cell IDC sensors with different \(W\) and \(a\) were modeled and simulated. Other parameters were kept fixed at \(t_s = 0.2\ mm,\ and\ t_e = 0.05\ mm\). Duroid 5880 \((\epsilon_{rs} = 2.2)\) was used as the substrate material for the sensor while Rogers RO3003 \((\epsilon_r = 3)\) was used as the MUT. A 0.05 mm thick conducting backplane was present underneath the substrate. A parametric analysis was adopted where the thickness of the MUT was varied from 0.1 mm to 10 mm with 0.1 mm increment for each \(W\) and \(a\) pair and 3% relative capacitance \((\partial C)\) was considered as the guideline to estimate the E-field penetration depth. Field Penetration depth for each \(W\) and \(a\) pair is shown in Figure 3.8. As seen, the penetration depth is directly proportional to the electrode width for the same interelectrode gap. Also, the field penetration depth increases with the increase in the interelectrode gap for the same electrode width. Comparing Figures 3.6 and 3.8 it is clear that with the increase in the interelectrode gap for the same electrode width the field penetration depth increases while the sensitivity and capacitance decrease.

It is clear from figures (Figure 3.5 through Figure 3.8) that for a fixed electrode width, a small interelectrode gap is the key to achieve high capacitance and sensitivity which will likely ensure improved sensor measurement quality. On the other hand, smaller interelectrode gaps are inherently limiting in terms of electric field penetration depth. Thus, a compromise must be reached to design an IDC and would likely depend on the application scenario. Again, for the same gap, larger electrode width is key to achieve higher capacitance and sensitivity, hence better measurement quality. Similarly, larger electrode size will allow strong field penetration depth. However, from a practical
fabrication and implementation point of view this may not be achievable in practice necessitating design optimization.

![Figure 3.8 Electric field Penetration depth of unit cell IDC sensor as a function of electrode width and interelectrode gap. Duroid 5880 ($\varepsilon_{rs} = 2.2$) as substrate and Rogers RO3003 ($\varepsilon_r = 3$) as MUT. Other sensor parameter: $t_s = 0.2 \text{ mm, and } t_e = 0.05 \text{ mm}$.

3.3.2 The Role of Substrate Thickness

The thickness of the IDC sensor substrate material, $t_s$ was varied to study its effect on the magnitude of the electric field and the capacitance. In the simulation model, the width of the electrode ($W$) was 5 mm while the interelectrode gap ($a$) was 2 mm. The substrate material had a relative permittivity, $\varepsilon_{rs} = 4.3$ and the MUT was Rogers RO4003 ($\varepsilon_r = 3.55$). The thickness of electrodes and backplane was, $t_e = 0.1 \text{ mm}$ and the thickness of MUT was $h = 10 \text{ mm}$. Substrate thickness ($t_s$) was varied from 0.1 mm to 3 mm to represent thinner and thicker substrate. The resulting changes in the decay of the normalized electric field magnitude in the depth direction of the MUT for different $t_s$ are
shown in Figure 3.9. As seen, the field decay rate with reference to its peak at 0 dB is lower for the thinner substrate compared to the thicker substrate. For example, for \( t_s = 0.1 \) mm, the normalized electric field magnitude is only -12 dB at the penetration depth of the unit cell (\( \lambda/3 = 4.6 \) mm). Whereas the magnitude of the normalized electric field is -15.5 dB for \( t_s = 3 \) mm. Therefore, for larger field penetration depths, thinner substrates should be used.

![Electric field decay graph](image)

Figure 3.9 Decay in normalized electric field magnitude in MUT with sensor substrate thickness, \( t_s \) as the parameter. MUT is RO4003 with \( \varepsilon_r = 3.55 \), MUT thickness=10mm. Other sensor parameters: \( W=5 \) mm, \( a=2 \) mm, \( t_e = 0.1 \) mm.

To determine the effect of substrate thickness on sensor sensitivity, the relative permittivity of the MUT was varied from 3 to 4 for different substrate thickness and the corresponding sensor capacitance and sensitivity are listed in Table 3.2. It is evident from Table 3.2 that sensor sensitivity decreases with the increase in substrate thickness.
Sensitivity decreases by 7% when substrate thickness increases to 0.5 mm from 0.1 mm. As the field penetration depth is higher with thinner substrate, the electric fields will penetrate the MUT more which will result in higher sensitivity than thicker substrate. Thus, to achieve larger sensitivity and higher field penetration depth, thinner substrates should be used. Also, thinner substrate sensor creates less airgap between sensor and cable surface during sensor conformation on cable surface (discussed in Chapter 4).

Table 3.2 Effects of substrate thickness on sensor sensitivity

<table>
<thead>
<tr>
<th>Substrate thickness, $t_s$ (mm)</th>
<th>Capacitance, pF</th>
<th>Sensitivity</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$\varepsilon_r = 3$</td>
<td>$\varepsilon_r = 4$</td>
</tr>
<tr>
<td>0.1 mm</td>
<td>981.22</td>
<td>986.25</td>
</tr>
<tr>
<td>0.15 mm</td>
<td>662.93</td>
<td>667.9</td>
</tr>
<tr>
<td>0.2 mm</td>
<td>502.69</td>
<td>507.59</td>
</tr>
<tr>
<td>0.3 mm</td>
<td>342.76</td>
<td>347.48</td>
</tr>
<tr>
<td>0.4 mm</td>
<td>262.75</td>
<td>267.44</td>
</tr>
<tr>
<td>0.5 mm</td>
<td>214.82</td>
<td>219.5</td>
</tr>
</tbody>
</table>

3.3.3. Effects of Sensor Substrate Material

The effect of the relative permittivity of the substrate on the decay rate of the normalized electric field magnitude and sensor sensitivity was studied. As substrate material, Duroid 5880 ($\varepsilon_{rs} = 2.2$) and Duroid 6010 ($\varepsilon_{rs} = 10.2$) were selected. Sensor parameters used were $W = 5$ mm, $a = 2$ mm, $t_s = 0.2$ mm, and $t_e = 0.1$ mm. Rogers RO4003 ($\varepsilon_r = 3.55$) was used as the MUT. Figure 3.10 compares the decay of the normalized electric field magnitude for these two substrate materials. As seen in Figure 3.10, decay of the normalized electric field magnitude at 4.6 mm penetration depth for the two materials are
respectively \(-16.3\ \text{dB}\) and \(-17\ \text{dB}\). Thus, the substrate material has a minor role on the normalized electric field magnitude decay.

Simulations were performed to compare the sensitivity when the IDC substrates are Duroid 5880 and Duroid 6010, respectively. Considering Duroid 5880 and Duroid 6010 as substrate materials capacitances were computed for 11 different MUTs representing varying permittivity from Air \((\varepsilon_r = 1)\) to Duroid 6010 \((\varepsilon_r = 10.2)\). Using linear regression, capacitance vs. the relative permittivity of the MUTs is plotted in Figure 3.11. Capacitance is larger for the sensor on Duroid 6010 than the one on Duroid 5880 for all MUTs. To be noted that the ability to sense rather small changes in the relative permittivity of the MUT is important. The slopes of the two lines (sensitivity) representing Duroid 5880 and Duroid 6010 are 4.8 and 4.9, respectively. Thus, the relative permittivity of sensor substrate is seen to have negligible effect on sensor sensitivity.
Figure 3.11 Change in capacitance vs. relative permittivity of MUT with Duroid 5880 and Duroid 6010 as the substrate. Sensor parameters: $W = 5 \text{ mm}$, $a = 2 \text{ mm}$, $t_s = 0.2 \text{ mm}$, and $t_e = 0.1 \text{ mm}$.

3.3.4 Role of Electrode Thickness

The thickness on standard ½ oz and 1 oz copper PCB is 0.0175 mm and 0.035 mm, respectively and the choice of thickness depends on the application and availability. To evaluate the effect of conductor or electrode thickness on sensor performance, a unit cell IDC sensor with different electrode thickness was simulated. The substrate considered was Duroid 5880 ($\varepsilon_{rs} = 2.2$) while the MUT considered was RO3003 ($\varepsilon_r = 3$). The thickness of the MUT was 10 mm. Other sensor parameters were: $W = 2 \text{ mm}$, $a = 2 \text{ mm}$, $t_s = 0.2 \text{ mm}$. Electrode and backplane thickness were varied from 0.01 mm to 0.3 mm. Electric field decay rates of the unit cell for different electrode thicknesses are shown in Figure 3.12.
Figure 3.12 Decay in normalized electric field magnitude in MUT for different electrode thickness. Sensor substrate Duroid 5880 ($\varepsilon_r = 2.2$) and RO3003 ($\varepsilon_r = 3$) as MUT. MUT thickness was 10mm. Other parameters were: $W = 2\, mm$, $a = 2\, mm$, $t_s = 0.2\, mm$.

Table 3.3 Effects of electrode thickness on sensor sensitivity

<table>
<thead>
<tr>
<th>Electrode thickness, $t_e$ (mm)</th>
<th>Capacitance, pF</th>
<th>Sensitivity</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$\varepsilon_r = 3$</td>
<td>$\varepsilon_r = 4$</td>
</tr>
<tr>
<td>0.01 mm</td>
<td>121.34</td>
<td>127.4</td>
</tr>
<tr>
<td>0.05 mm</td>
<td>121.83</td>
<td>127.77</td>
</tr>
<tr>
<td>0.1 mm</td>
<td>122.33</td>
<td>128.21</td>
</tr>
<tr>
<td>0.3 mm</td>
<td>123.94</td>
<td>129.83</td>
</tr>
<tr>
<td>0.5 mm</td>
<td>124.77</td>
<td>130.59</td>
</tr>
</tbody>
</table>

As seen, the E-field decay rate is slower for the thinner electrode compared to the thicker one. For example, field decay at the penetration depth point is -8 dB for the sensor with 0.01mm thick electrode whereas field decay is -10.2 dB for sensor with 0.3mm thick electrode. To calculate the effect of electrode thickness on sensitivity, the relative
permittivity of the MUT was changed from 3 to 4 for different electrode thicknesses. The simulated capacitance and corresponding sensitivity are listed in Table 3.3. Although the capacitance increases as the electrode thickness increases, the sensor sensitivity decreases. Sensor sensitivity drops about 4% when electrode thickness is increased from 0.01mm to 0.3mm. The thicker the electrode is, the higher the thickness of inter-electrode gap becomes which decreases sensor sensitivity.

3.3.5 Role of Conductive Backplane

Conductive backplanes have been suggested by researchers as a means to shield an IDC sensor from the interfering influence of external electric fields. Apart from shielding, conducting backplane may have further effects on the performance of an IDC sensor. To evaluate the effect of the presence of a conductive backplane, unit cell IDC sensors with and without backplane were simulated. The decay of the normalized electric field magnitude was investigated using $\varepsilon_{rs} = 4.3$ as sensor substrate and an RO4003 ($\varepsilon_r = 3.55$) as MUT. Other parameters were: $W = 5 \text{ mm}, a = 2 \text{ mm}, t_s = 0.2 \text{ mm}, and t_e = 0.2 \text{ mm}$. The backplane conductor thickness was, $t_b = 0.1 \text{ mm}$. The decay results of the normalized electric field magnitude are plotted in Figure 3.13.
Figure 3.13 Decay in normalized electric field magnitude in MUT with and without backplane. Sensor substrate $\varepsilon_{rs}=4.3$ and RO4003 ($\varepsilon_r=3.55$) as MUT. Other parameters were: $W = 5 \text{ mm}$, $a = 2 \text{ mm}$, $t_s = 0.2 \text{ mm}$, and $t_e = 0.1 \text{ mm}$.

Table 3.4 Capacitance of the sensor with and without backplane for different MUTs.

<table>
<thead>
<tr>
<th>$\varepsilon_r$ of MUT</th>
<th>Capacitance (pF)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>With backplane</td>
</tr>
<tr>
<td>3</td>
<td>506.20</td>
</tr>
<tr>
<td>3.55</td>
<td>509.44</td>
</tr>
<tr>
<td>4</td>
<td>511.35</td>
</tr>
<tr>
<td><strong>Sensitivity</strong></td>
<td><strong>5.15</strong></td>
</tr>
</tbody>
</table>

The drop in E-field magnitude for the sensor with and without a backplane at the field penetration depth ($\lambda/3 = 4.6 \text{ mm}$) distance in the MUT’s depth direction is seen to be -12.5 dB and -16.5 dB, respectively. This is a significant outcome change for the sensor with the backplane which allows far slower field decay than the standard sensor without a backplane. Therefore, use of a conductive backplane underneath the substrate decreases the E-field magnitude decay and increases the penetration depth. Computed capacitance values and sensitivity with and without a backplane for different MUTs are listed in Table
3.4. Capacitance is observed to be much larger with a backplane resulting in enhancement of the measurement capability of the sensor. The backplane also increases sensor sensitivity (5.15 Vs. 4.87).

![Diagram of Multi-electrode IDC Sensor](image)

Figure 3.14 Geometry of IDC sensor with 7 driving and 6 sensing electrodes.

### 3.4 Multi-electrode IDC Sensor

To enhance the sensing ability of the unit cell fringing field capacitor, the unit cell structure discussed so far can be repeated many times as needed as available space and installation scenario warrant. Figure 3.14 illustrates the geometry of a multi-electrode IDC sensor. It consists of seven driving and six sensing electrodes on top of a substrate and a copper backplane underneath the substrate. All driving electrodes are connected to the driving electrode (DE) Common while all sensing electrodes are connected to sensing electrode (SE) Common. A 10 V excitation was applied to the driving electrodes while keeping the sensing electrodes at 0 V reference. To evaluate the effect of electrode length ($L_e$), number of electrodes ($N$), and presence of backplane and guard electrodes on sensor performance, full-wave electromagnetic (EM) simulations were conducted in ANSYS Maxwell.
3.4.1 Role of Electrode Length and Electrode Number

Multi-electrode IDC sensor’s electrode length ($L_e$), number of electrodes ($N$), electrode width ($W$) and interelectrode gap ($a$) depends on the area of the MUT. Although fabrication limitation can restrict the electrode width and gap, the electrode length and the number of electrodes can be optimized for a fixed electrode width ($W$) and gap ($a$) to achieve best sensor performance. To assess the role of electrode length and electrode number on sensor sensitivity, a set of multi-electrode IDC sensor was modeled and simulated. First, the number of electrodes ($N$) was varied from 2 to 20. Second, for a fixed electrode number, the electrodes length ($L_e$) was varied from 10 mm to 100 mm. Other sensor parameters were: $W = 1$ mm, $a = 1$ mm, $t_s = 0.1$ mm, $t_e = 17$ µm, $t_b = 17$ µm, and $\varepsilon_{rs} = 2.2$. The MUT thickness considered was 5 mm while its relative permittivity was varied from 3 to 4. Corresponding simulated sensitivities can be seen plotted in Figure 3.15 which show that sensitivity is linearly proportional to the electrode length for a fixed number of electrodes. Sensitivity increases with increasing number of electrodes when the electrode length is fixed. Thus, depending on the available MUT surface area the electrode length ($L_e$) and the number of electrodes ($N$) can be so chosen to achieve the desired sensor sensitivity.

To maximize sensor sensitivity, an IDC sensor can be designed with electrode length ($L_e$) being equal to the length of an MUT specimen if possible. In that case, the electrode width ($W$), the interelectrode gap ($a$), and the number of electrodes ($N$) need to be designed considering the width of the MUT. To understand the relationship between these three sensor parameters and sensor sensitivity, IDC sensors with different $W/a$ ratio and electrode number ($N$) were modeled and simulated. Other sensor parameters were:
$L_e = 30 \text{ mm}, t_s = 0.1 \text{ mm}, t_e = 17 \mu m, t_b = 17 \mu m, \varepsilon_{rs} = 2.2,$ and MUT thickness, $h = 8 \text{ mm}$. The relative permittivity of the MUT was varied from 3 to 4 and the corresponding capacitance data were used to determine sensitivity. Sensor sensitivity as a function of $W/a$ and the number of electrodes ($N$) is shown in Figure 3.16. As seen, sensitivity increases with increasing in $W/a$ for a fixed electrode number ($N$). Similarly, sensitivity increases with increasing in $N$ for a fixed ($W/a$). Also, the effect of $N$ on sensitivity is higher when is $W/a$ ratio is high. For example, when electrode number ($N$) increases from 16 to 20, change in sensitivity is 0.5 for $W/a = 0.75$ and change in sensitivity is 0.8 for $W/a = 3$. Thus, $W/a$ and the number of electrodes ($N$) need to be chosen to maximize sensor sensitivity based on the width of the MUT.

![Graph showing sensor sensitivity as a function of electrode length ($L_e$) and number of electrodes ($N$). Sensor parameters: $W = 1 \text{ mm}, a = 1 \text{ mm}, t_s = 0.1 \text{ mm}, t_e = 17 \mu m, t_b = 17 \mu m, \varepsilon_{rs} = 2.2,$ and MUT thickness, $h = 5 \text{ mm}$.](image)
Figure 3.16 Sensor sensitivity of IDC sensor as a function of $W/a$ ratio and number of electrodes ($N$). Sensor parameters: $L_e = 30 \text{ mm}$, $t_s = 0.1 \text{ mm}$, $t_e = 17 \mu\text{m}$, $t_b = 17 \mu\text{m}$, $\varepsilon_{rs} = 2.2$, and MUT thickness, $h = 8 \text{ mm}$.

3.4.2 Effect of Backplane on Multi-electrode IDC

The advantage of having a conductive backplane underneath an IDC sensor substrate was demonstrated earlier for a unit cell IDC. This was further investigated for a multi-electrode IDC sensor using ANSYS maxwell. The IDC sensor considered for this case contained seven driving and six sensing electrodes (D7S6) which were all printed on a Duroid 5880 ($\varepsilon_r = 2.2$) substrate. A planar dielectric material with variable relative permittivity and 4mm thickness was considered for the MUT. Cases with and without a conductive backplane were considered. Other sensor parameters included: $W = 1 \text{ mm}$; $L_e = 20 \text{ mm}$; $a = 2 \text{ mm}$; $t_s = 0.25 \text{ mm}$, $t_b = 35 \mu\text{m}$, $t_e = 17 \mu\text{m}$. Simulated capacitance data for this study are listed in Table 3.5 which show clearly that the capacitance obtained for the sensor with the conductive backplane is significantly higher than that obtained by the
sensor without it. The presence of the conductive backplane also results in a modest increase in the sensitivity compared to the one without the backplane.

Table 3.5 Simulated Capacitance with IDC sensor on planar dielectric materials

<table>
<thead>
<tr>
<th>$\varepsilon_r$ of MUT</th>
<th>Capacitance (pF)</th>
<th>With backplane</th>
<th>Without backplane</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>13.60</td>
<td>4.47</td>
<td></td>
</tr>
<tr>
<td>3.55</td>
<td>14.14</td>
<td>5.06</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>14.85</td>
<td>5.61</td>
<td></td>
</tr>
<tr>
<td>Sensitivity</td>
<td>1.25</td>
<td>1.14</td>
<td></td>
</tr>
</tbody>
</table>

3.4.3 Further Analysis of the Backplane and Material Thickness

Further simulation studies of the multi-electrode IDC were conducted considering the presence and absence of a conductive backplane, substrate dielectric material property, presence and absence of guard electrodes, and substrate thickness to determine meaningful design guidelines. An IDC with 5 driving, 2 sensing and 2 guard electrodes was considered. Other geometrical parameters were: $W=1.125\text{mm}$, $a=2.25\text{mm}$, $L_e=20\text{mm}$, $t_e=17\,\mu\text{m}$, and $t_b=35\,\mu\text{m}$. Substrate dielectric material and thickness were varied. To compute and plot the E-field magnitudes within the MUT, horizontal polylines were created in Maxwell (on the XY plane) for different values of Z (Figure 3.17). The closest polyline along the z-direction was at a height of 1µm above the electrodes.

The magnitude of the electric field was plotted on the polylines for the sensors with and without backplane. The E-field magnitudes on polyline1 for the sensor with and without backplane are shown in Figure 3.18. Although the E-field magnitude undulates throughout the polyline there is a location of the peak field in either geometry. The peak E-field magnitudes for the IDC with and without the backplane are 41897 V/m and 8923
V/m, respectively. The peak E-field magnitude with the backplane is nearly 4.5 times the peak E-field magnitude without the backplane.

Figure 3.17 An IDC sensor simulation model with polyline1. Sensor parameters were: $W=1.125\text{mm}$, $a=2.25\text{mm}$, $L_e=20\text{mm}$, $t_e=17\mu\text{m}$, and $t_b=35\mu\text{m}$.

It was understood that this phenomenon of high E-field for the IDC with the backplane may not hold for any substrate thickness as because with increasing substrate thickness there will be stronger field concentration between the electrodes and the backplane. This phenomenon can further be described from the electric field redistribution due to the presence of the backplane (see Figure 2.11 in chapter 2). The distance between the driving electrode and the backplane is the thickness of the substrate. The farther away the backplane (thicker substrate) is positioned from the driving electrode, the further down the electric field lines are drawn away from the electrode, resulting in a decreased electric field magnitude in the MUT direction [47].
Figure 3.18 Simulated E-field magnitude along Ployine1 (a) with backplane, (b) no backplane. Ployine1 is at x=18mm. Sensor parameters: $W=1.125\text{mm}$, $a=2.25\text{mm}$, $L_e=20\text{mm}$, $t_e=17\ \mu\text{m}$, and $t_b=35\ \mu\text{m}$, $t_s=0.1\text{mm}$, Duroid 5880 substrate ($\varepsilon_r=2.2$).

Therefore, numerous simulations were performed considering $t_s$ values of 0.1, 0.2, 0.4, 1.2, and 1.4mm for a variety of substrate materials to investigate and evaluate a
threshold thickness for each material type. The Maximum values of the electric field magnitude in $V/m$ for all these cases are listed in Table 3.6 through Table 3.10 for Duroid 5880, RO4003, FR4, TMM6, and Duroid 6010 substrates.

Table 3.6 Magnitude of peak electric field ($V/m$). There are 5 driving, 2 sensing and 2 guard electrodes on Duroid 5880 substrate ($\varepsilon_{rs}=2.2$). Other parameters: $W=1.125\text{mm}$, $a=2.25\text{mm}$, $L_e=20\text{mm}$, $t_e=17\ \mu\text{m}$, and $t_b=35\ \mu\text{m}$.

<table>
<thead>
<tr>
<th>Duroid 5880 substrate thickness, $t_s$ (mm)</th>
<th>E-field magnitude ($V/m$) with Backplane</th>
<th>E-field magnitude ($V/m$) No Backplane</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.1</td>
<td>46897</td>
<td>8923</td>
</tr>
<tr>
<td>0.2</td>
<td>37520</td>
<td>9552</td>
</tr>
<tr>
<td>0.4</td>
<td>18331</td>
<td>10198</td>
</tr>
<tr>
<td>1.2</td>
<td>12233</td>
<td>11726</td>
</tr>
<tr>
<td>1.4</td>
<td>11835</td>
<td>12817</td>
</tr>
</tbody>
</table>
Table 3.7 Magnitude of peak electric field (V/m). There are 5 driving, 2 sensing and 2 guard electrodes on RO4003 substrate ($\varepsilon_{rs}=3.55$). Other parameters: $W=1.125\text{mm}$, $a=2.25\text{mm}$, $L_e=20\text{mm}$, $t_e=17\ \mu\text{m}$, and $t_b=35\ \mu\text{m}$.

<table>
<thead>
<tr>
<th>RO4003 substrate thickness, $t_s$ (mm)</th>
<th>E-field magnitude (V/m) with Backplane</th>
<th>E-field magnitude (V/m) No Backplane</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.1</td>
<td>54522</td>
<td>9919</td>
</tr>
<tr>
<td>0.2</td>
<td>35381</td>
<td>9298</td>
</tr>
<tr>
<td>0.4</td>
<td>30613</td>
<td>11250</td>
</tr>
<tr>
<td>1.2</td>
<td>18462</td>
<td>12280</td>
</tr>
<tr>
<td>1.4</td>
<td>15014</td>
<td>14267</td>
</tr>
</tbody>
</table>

Table 3.8 Magnitude of peak electric field (V/m). There are 5 driving, 2 sensing and 2 guard electrodes on FR4 substrate ($\varepsilon_{rs}=4.4$). Other parameters: $W=1.125\text{mm}$, $a=2.25\text{mm}$, $L_e=20\text{mm}$, $t_e=17\ \mu\text{m}$, and $t_b=35\ \mu\text{m}$.

<table>
<thead>
<tr>
<th>FR4 substrate thickness, $t_s$ (mm)</th>
<th>E-field magnitude (V/m) with Backplane</th>
<th>E-field magnitude (V/m) No Backplane</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.1</td>
<td>55581</td>
<td>9212</td>
</tr>
<tr>
<td>0.2</td>
<td>40106</td>
<td>8701</td>
</tr>
<tr>
<td>0.4</td>
<td>30399</td>
<td>11825</td>
</tr>
<tr>
<td>1.2</td>
<td>16385</td>
<td>11276</td>
</tr>
<tr>
<td>1.4</td>
<td>12189</td>
<td>12938</td>
</tr>
</tbody>
</table>
Table 3.9 Magnitude of peak electric field (V/m). There are 5 driving, 2 sensing and 2 guard electrodes on TMM6 substrate ($\varepsilon_r=6$). Other parameters: $W=1.125\text{mm}$, $a=2.25\text{mm}$, $L_e=20\text{mm}$, $t_e=17\ \mu\text{m}$, and $t_b=35\ \mu\text{m}$.

<table>
<thead>
<tr>
<th>TMM6 substrate thickness, $t_s$ (mm)</th>
<th>E-field magnitude (V/m) with Backplane</th>
<th>E-field magnitude (V/m) No Backplane</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.1</td>
<td>62801</td>
<td>10599</td>
</tr>
<tr>
<td>0.2</td>
<td>33279</td>
<td>9769</td>
</tr>
<tr>
<td>0.4</td>
<td>30609</td>
<td>13174</td>
</tr>
<tr>
<td>1.2</td>
<td>18462</td>
<td>14098</td>
</tr>
<tr>
<td>1.4</td>
<td>14297</td>
<td>17160</td>
</tr>
</tbody>
</table>

Table 3.10 Magnitude of peak electric field (V/m). There are 5 driving, 2 sensing and 2 guard electrodes on Duroid 6010 substrate ($\varepsilon_r=10.2$). Other parameters: $W = 1.125\text{mm}$, $a = 2.25\text{mm}$, $L_e=20\text{mm}$, $t_e=17\ \mu\text{m}$, and $t_b=35\ \mu\text{m}$.

<table>
<thead>
<tr>
<th>Duroid 6010 substrate thickness, $t_s$ (mm)</th>
<th>E-field magnitude (V/m) with Backplane</th>
<th>E-field magnitude (V/m) No Backplane</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.1</td>
<td>58417</td>
<td>8358</td>
</tr>
<tr>
<td>0.2</td>
<td>34815</td>
<td>6952</td>
</tr>
<tr>
<td>0.4</td>
<td>22648</td>
<td>10675</td>
</tr>
<tr>
<td>1.2</td>
<td>16945</td>
<td>11045</td>
</tr>
<tr>
<td>1.4</td>
<td>15076</td>
<td>13421</td>
</tr>
</tbody>
</table>
Examining the results listed in Table 3.6 through Table 3.10, it is clear that with thinner substrates ($t_s \leq 0.2\text{mm}$), the peak E-field magnitude for the IDC with the backplane is almost 5 times that for the IDC without the backplane. This conclusion holds for any of the materials considered here thus spanning dielectric constants ranging from 2.2 to 10.2 for the substrate material which may include PTFE based substrates as well as substrates such as Si, GaAs, or sapphire etc. In addition, for high dielectric constant materials as the substrate, the Field Accentuation Factor (FAF) i.e., the ratio between the peak field with backplane and no backplane is higher. For example, for $t_s = 0.1\text{mm}$ this factor is 5.2 for Duroid 5880 while it is 6.9 for Duroid 6010.

Finally, with all the substrate materials studied here increasing $t_s$ results in the FAF to decrease and eventually it reaches a reversal point where the sensor without the backplane yields higher peak electric field than the sensor with the backplane. For the cases studied, this reversal occurred when $t_s$ exceeded 1.2 mm. To examine whether this was related to the electrode width ($W$) and the interelectrode gap ($a$) those parameters were varied, and the E-field behavior was studied. The observation that thinner substrates with backplane yielded higher fields in the MUT did still hold. Finally, the number of electrodes were increased, and their effects were also studied. For 6 driving and 3 sensing electrodes, the peak E-field magnitudes for the IDC are given in Table 3.11 which shows that increasing the number of electrodes does not change the effect that much. So, for getting higher magnitude of the electric field of the sensor with backplane, the substrate thickness should be thinner.
Table 3.11. Peak E-field magnitudes for Duroid 5880 substrate ($\varepsilon_{rs}=2.2$).
Number of driving Electrodes=6, sensing electrodes=3 and guard electrodes=2.
Other parameters: $W=0.5\text{mm}$, $a=2.25\text{mm}$, $L_e=20\text{mm}$, $t_e=17\ \mu\text{m}$, and $t_b=35\ \mu\text{m}$.

<table>
<thead>
<tr>
<th>Duroid 5880 substrate thickness, $t_s$ (mm)</th>
<th>E-field magnitude (V/m) With Backplane</th>
<th>E-field magnitude (V/m) No Backplane</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.1</td>
<td>62067</td>
<td>10579</td>
</tr>
<tr>
<td>0.2</td>
<td>36071</td>
<td>9552</td>
</tr>
<tr>
<td>1.2</td>
<td>15447</td>
<td>17410</td>
</tr>
<tr>
<td>1.4</td>
<td>16370</td>
<td>16642</td>
</tr>
</tbody>
</table>

3.4.4 Role of Guard Electrodes

The use of guard electrodes with an IDC has been suggested [26, 44] as a shield against the deleterious influence of external electric fields. However, the availability of high-quality sensing circuits/chips and the ability to use a conductive backplane warrants further evaluation of such suggestion. For example, if guard electrodes can be eliminated the sensor size can be reduced or if the size remains the same more sensing electrodes could be added to increase sensitivity. Two evaluate this first, an IDC with 7 driving, 4 sensing, and 2 guard electrodes, (labeled D7S4G2) was considered (Figure 3.19(a)). Next, the 2 guard electrodes were converted into sensing electrodes thus creating a sensor labeled D7S6G0 (Figure 3.19(b)). Each sensor contained a conducting backplane. Sensor parameters were: $W = 1\ \text{mm}$, $a = 1\ \text{mm}$, $t_s=0.2\ \text{mm}$, $t_b = 17\ \mu\text{m}$, $t_e = 17\ \mu\text{m}$, $L_e = 30\ \text{mm}$, $\varepsilon_{rs}=2.2$. Simulated capacitances and sensor sensitivity for these two cases are listed in Table 3.12.
Figure 3.19. IDC sensor (a) with and (b) without guard electrodes. Sensor parameters: \( W = 1 \) mm, \( a = 1 \) mm, \( t_s = 0.2 \) mm, \( t_b = 17 \) µm, \( t_e = 17 \) µm, \( L_e = 30 \) mm, \( \varepsilon_{rs} = 2.2 \).

Table 3.12. Capacitance data and sensor sensitivity of multi-electrode IDC sensor with guard and without guard electrodes. Sensor parameters: \( W = 1 \) mm; \( L_e = 30 \) mm; \( a = 1 \) mm; \( t_s = 0.2 \) mm, \( t_b = 17 \) µm, \( t_e = 17 \) µm, \( \varepsilon_{rs} = 2.2 \).

<table>
<thead>
<tr>
<th>Sensor type</th>
<th>Capacitance, pF</th>
<th>Sensitivity</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>( \varepsilon_r = 3 )</td>
<td>( \varepsilon_r = 4 )</td>
</tr>
<tr>
<td>D7S4G2</td>
<td>3.56</td>
<td>4.27</td>
</tr>
<tr>
<td>D7S6G0</td>
<td>5.46</td>
<td>7.24</td>
</tr>
</tbody>
</table>

As seen in Table 3.12, the sensor with no guard electrodes yields higher capacitance and higher sensitivity. Sensitivity of the sensor without the guard electrodes is 2.5 times the sensitivity with the guard electrodes. Assuming no external interference can cause deleterious effects to the measured capacitance because of the presence of the conductive backplane the guard electrodes can be converted into sensing electrodes to achieve high sensitivity. Therefore, the benefits of using a conductive backplane are twofold: backplane works as a shield against unwanted effect of EMI and, when combined with two additional sensing electrodes, it enhances sensor performance.
3.4.5 Surface Charge Distributions on Electrodes

Computing the surface charge distributions on the various electrodes of an IDC consisting of multiple driving and sensing electrodes may reveal some important information in terms of the actual electric field concentration on the electrodes since electric fields are caused by the surface charges. Ansys Maxwell simulated surface charge distributions on the driving and sensing electrodes of an IDC are shown in Figure 3.21. The sensor had 6 driving electrodes, 3 sensing electrodes and 2 guard electrodes. All six driving electrodes were at 10V potential while the three sensing and the two guard electrodes were at zero potential. Other sensor parameters were: $W=1 \text{mm}$, $a=1.5 \text{mm}$, $t_s=1.5 \text{mm}$, $L_e = 15 \text{mm}$, $t_b = 0.5 \text{mm}$, $t_e = 0.5 \text{mm}$, $\varepsilon_{rs}=2.2$.

Simulated surface charge distributions of Figure 3.20 clearly highlight the driving electrodes with high surface charge density concentrated at the edges of the electrodes. Intense surface charge concentration is also seen at the tip of the electrodes. Only small amounts of surface charges can be seen on the horizontal conductor that joins all six driving electrodes. It appears that the 2 guard electrodes will have very minor if any role in the sensor design. Thus, the sensor can be miniaturized by eliminating the guard electrodes.
Figure 3.20. Simulated surface charge distribution on an IDC. Other parameters: \(W=1\text{mm}, \ a=1.5\text{mm}, \ t_s=1.5\text{mm}, \ L_e=15\text{mm}, \ t_b=0.5\text{mm}, \ t_e=0.5\text{mm}, \ \varepsilon_{rs}=2.2.\)

3.4.6 Electric Field Plots for IDCs

To understand the nature of the E-fields along multiple vertical planes that are orthogonal to the sensor planes E-fields were computed along three separate vertical planes. In light of the non-uniform surface charge distribution observed in Figure 3.20 it was anticipated that the E-fields in certain planes will be more intense than the other vertical planes. The locations of the three vertical planes with respect to the sensor geometry can be seen in Figure 3.21. The specific sensor in question contains 5 driving, 3 sensing, and 2 guard electrodes. The sensor electrodes were designed on a 1.5 mm thick Duroid 5880 substrate which also contained a conducting backplane. The other sensor parameters were: \(W=1\text{mm}, \ a=2\text{mm}, \ L_e=20\text{mm}, \ t_b=0.5\text{mm}, \ t_e=0.5\text{mm}.\)
Figure 3.21 An IDC sensor simulation model in Ansys Maxwell and computed E-fields along a vertical plane.

The locations of Planes 1, 2, and 3 are at x=4mm, 10mm, and 18mm, respectively. The height of each vertical plane is 15mm. Note that the vertical planes are hypothetical non-model planes created to compute and illustrate the E-fields that would be available in the MUT as because the MUT will reside on the IDC sensor. Computed E-field magnitudes on Plane3 is plotted in Figure 3.21(b). Similar E-fields on Planes 1 and 2 are plotted in Fig
3.22. Comparing the fields in Figure 3.21(b) and Figure 3.22 it is apparent that the E-fields on Plane3 are more intense and deeply penetrating than those on Planes 1 and 2. This observation agrees well with the surface charge distribution plots shown in Figure 3.20 which indicated large charge concentration at the edges and at the tip of the driving electrodes. The location of Plane3 with respect to the IDC sensor geometry is indeed near the sensor tip.

Figure 3.22. Computed E-fields along two vertical planes.
CHAPTER 4: IDC SENSOR DESIGN AND APPLICATION IN
CABLE INSULATION AND JACKET AGING DETECTION

Based on our understanding of the unit cell IDC and multi-electrode IDC design (presented in Chapter 3) we have designed multi-electrode IDCs on different substrates for application in cable insulation and jacket aging detection. Since real-life aged cable specimens are difficult to obtain researchers often use a process called accelerated aging to artificially age cables inside an oven at high temperatures to simulate real-life aging conditions. We will also conduct our studies on cable specimens that have undergone accelerated aging. The objectives of this chapter are two-fold: (1) to design and develop multi-electrode IDC sensors and (2) to apply them on cable insulation and jacket to detect their aging. We will first define the accelerated aging process followed by the cable types that we aged using that process and then the design, fabricate, and test various IDCs on the aged cable specimens.

4.1 Accelerated Aging

The aging-related degradation of cables causes changes in the relative permittivity of cable insulation and jacket materials. Aging in insulation materials may create irreversible damage that may affect cable performance and shorten cable remaining useful life. It is impractical in the laboratory to evaluate cable aging under normal service operating conditions (live cable with current flowing in it) because the time required would be too long (50 to 60 years) to complete such evaluation. Accelerated aging is a well-
established technique that has been used by many researchers to artificially age cables in a laboratory by exposing them to a high temperature over a fixed period [48-50].

The rationale behind accelerated aging or testing of electric cables at a high temperature for a fixed duration is to simulate the real-life aging condition of a cable in a laboratory setting. For example, the operating temperature of Okoguard aerial jumper cables (EPR insulation) is 90ºC at 298 Amps per conductor. In [51], Beausoliel et al. showed experimentally that the difference in temperature between the cable conductors and insulation layer was typically only 1º or 2º C. So, the insulation temperature can be assumed to be equal to the conductor temperature. The cables in a power plant will not be operating at their maximum current carrying condition all the time. It is considered that a MV power plant cable operates at its rated temperature for 1/3rd of its life and the other 2/3rd of its life it is operated at lower temperature [52,53]. Thus, the operating temperature could be considered to be somewhat lower like 70ºC for a MV power plant cable of 90ºC rated temperature. To simulate the real-life aging of 50-60 years in laboratory through accelerated aging, researchers have used the modified Arrhenius equation [54].

In accelerated aging, cables are exposed to a higher temperature than normal operational temperature in an oven for a period of time which can be correlated with an equivalent operational service age using the modified Arrhenius equation [54],

\[
\ln\left(\frac{t_s}{t_a}\right) = \frac{E_a}{k} \left(\frac{1}{T_s} - \frac{1}{T_a}\right)
\]

Here, \(T_a\) (K) is the accelerated aging temperature inside the oven, \(t_a\) is the aging time in the oven, \(T_s\) (K) is the actual service temperature, \(t_s\) is the service age, \(E_a\) is the activation energy (eV) of the material whether insulation or jacket and \(k\) is Boltzmann’s constant (0.8617× 10-4 eV/K). For a MV power plant cable (EPR insulation), service
temperature was considered 70°C [53] and the activation energy was considered to be 1.1 eV [55], [56]. To deduce the necessary accelerated aging time (hours) in an oven at a prefixed temperature, equation (3.1) was plotted in Figure 4.1. It is evident from Figure 3.1 that to simulate 60 years real field aging, the duration of the accelerated aging test is 225 hours at 160°C and 950 hours at 140°C.

![Figure 4.1 Required time (hours) for accelerated aging of EPR insulation at different temperature. Activation energy ($E_a$) of EPR is considered to be 1.1 eV.](image)

### 4.2 Cable Specimens Considered

Nuclear power plants (NPPs) have myriad varieties of power, control, instrumentation, and other types of cables. Cables used in an NPP would normally be single or multi-conductor and would contain an insulation and a jacket. Some may contain a semiconductor screen, a metallic shield over the conductor, etc. Generally, power cables may have circular, compacted, and stranded conductors of copper or aluminum. The conductor shield, or strand screen is a semi-conductive material which is used to provide a smooth interface between the conductor and the insulation. The insulation provides high insulation resistance, which prevents current leakage and electrical breakdown. A layer or
extruded semiconductive insulation screen is used to create a smooth interface between the insulation and the shielding tape. A layer of shielding copper or aluminum tape is often helically wrapped around the insulation screen to drain away the circulating (capacitive and inductive) currents. The jacket serves as a protection against mechanical and chemical stresses and may provide flame resistance to the cable assembly. The choice of polymeric components of NPP cable is based on the application and severity of the surrounding environmental factors. Cross-linked polyethylene (XLPE) and ethylene propylene rubber (EPR) are the most commonly used insulation materials in NPP cables. Chlorosulfonated polyethylene (CSPE), chlorinated polyethylene (CPE), and polyvinyl chloride (PVC) materials are generally used in NPP cable jackets. The insulation and jacket material properties of different types of cables are listed in Table 4.1.

Table 4.1 Application and dimensions of different kind of NPP cables [58,59].

<table>
<thead>
<tr>
<th>Application</th>
<th>Temp. rating</th>
<th>Insulation &amp; thickness, mm</th>
<th>Jacket &amp; thickness, mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>LV power and control (600V -2kV)</td>
<td>90ºC</td>
<td>EPR, XLPE 1 – 4 mm</td>
<td>CPE, PVC 0.4 -3 mm</td>
</tr>
<tr>
<td>MV power (2.4kV, 5/8kV,15kV)</td>
<td>90ºC - 105ºC</td>
<td>EPR, XLPE 3 – 6 mm</td>
<td>CPE, PVC, CSPE 1.5 - 4.5 mm</td>
</tr>
<tr>
<td>Instrumentation multi-conductor cable (300V,600V)</td>
<td>90ºC - 105ºC</td>
<td>PVC, XLPE 0.3-0.8 mm each</td>
<td>PVC, CSPE 0.9-2 mm</td>
</tr>
</tbody>
</table>

A typical NPP cable schematic is shown in Figure 4.2. In an NPP cable selection, A and C are always present but the presence of B, D, F, and E vary depending on requirements [57]. However, IDC sensors are not suitable for NDE tests on insulation material of shielded cables because the electric field lines from the sensors will not be able
to penetrate the insulation layer since the sensor electrodes have to face a conducting or semiconducting shield when placed on the outermost jacket layer [34].

![Typical NPP cable schematic](image)

**Figure 4.2 Typical NPP cable schematic**

<table>
<thead>
<tr>
<th><strong>Conductor</strong></th>
<th>Extra-flexible rope tin-coated copper, flexible rope stranded, diameter = 11.43 mm</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Conductor Screen</strong></td>
<td>Taped conductive screen</td>
</tr>
<tr>
<td><strong>Insulation material</strong></td>
<td>EPR Thickness = 5.94 mm; Nominal relative permittivity = 3.1 [43]; Cable outer diameter = 23.3 mm</td>
</tr>
</tbody>
</table>

Table 4.2: Okoguard® Aerial Jumper Cable, 15 KV, 90°C rating [58].

In this chapter, two types of cables were subjected to accelerated aging: (i) Okoguard® Aerial Jumper Cable (see cable properties in Table 4.2) and (ii) Okoguard®-Okolon® TS-CPE/EPR Type non-shielded power cable (see cable properties in Table 4.3).

For the Okoguard® aerial jumper cables, a single cable was used to prepare 8 separate
specimens, each 18 cm in length. These specimens were aged at 160ºC for multiple durations. Photographs of these specimens can be seen in Figure 4.3(a). The accelerated aging or heating cycle was structured as daily 8 hours of heating, followed by 16 hours of no heating for seven days a week. The cable specimens were aged thermally for 4, 8, 12, 16, 20, 24, and 28 days to create age-related variation in relative permittivity of the EPR insulation. Thus, the last specimen was heated for 224 hours.

Figure 4.3 Photograph of (a) aerial jumper cable specimens, cable cross section and aging period (b) TS-CPE and EPR cable samples, cable cross section and aging period, (c) cable specimens inside an oven for accelerated aging test.
Table 4.3 Okoguard®-Okolon® TS-CPE/EPR Type MV-90 2.4 KV non-shielded power cable, 90°C rating [58].

<table>
<thead>
<tr>
<th>Conductor</th>
<th>Coated, stranded copper, diameter = 12 mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Conductor Screen</td>
<td>Extruded semiconducting EPR</td>
</tr>
<tr>
<td>Insulation material</td>
<td>Okoguard® (EPR-based), thickness = 3.2 mm; Nominal relative permittivity = 3.1 [43]</td>
</tr>
<tr>
<td>Jacket material</td>
<td>Okolon® TS-CPE, thickness = 2 mm, Nominal relative permittivity = 3.5 [43]; Cable outer diameter = 22.4 mm</td>
</tr>
</tbody>
</table>

The Okoguard®-Okolon® TS-CPE/EPR Type cable specimens underwent accelerated aging at 140°C. Photographs of these specimens are shown in Figure 4.3(b). The aging/heating cycle was 24 hours per day continuous. Five cable specimens were aged thermally for various numbers of days and hence the names: 7-day, 14-day, 21-day, 28-day, and 35-day. Once all accelerated aging experiments were completed, part of the jacket from each specimen was removed to expose the insulation for direct measurement.

4.3 Preliminary IDC Design and Experimentation

To monitor the changes in the relative permittivity of the insulation and the jacket of Okoguard®-Okolon® TS-CPE/EPR Type cable specimens, which is a function of insulation aging, several IDC sensors were fabricated on two different substrate materials, Rogers 5880LZ R4 ($\varepsilon_r = 2.00\pm0.04$) and liquid crystal polymer (LCP, $\varepsilon_r = 2.9$). Each sensor had seven driving electrodes, six sensing electrodes, and a conducting copper backplane. Other parameters were: $W = 1.125$ mm; $L_e = 20$ mm; $a = 2$ mm, $t_b = 17.5$ µm, $t_e = 17.5$
µm. For the sensor on the Rogers 5880LZ R4 substrate, $t_s = 0.25$ mm while that on the LCP substrate was $t_s = 0.1$ mm. The sensor on the Rogers 5880LZ R4 substrate was placed on the cable’s insulation and the sensor on the LCP substrate was placed on the cable’s jacket. To provide driving voltage to the DE Common, and to measure the output signal from the SE Common, wires were soldered to the extended parts of the respective commons and the backplane.

4.3.1 Test Mounting Structure, Chip, Compensation

Sensors were either wrapped around the cable’s insulation or the jacket where the electrodes came in intimate contact with those surfaces. As can be seen from Figure 4.3(b), the jacket (black color) has been removed from a section of each cable for direct measurement on cable insulation. To ensure intimate contact between each sensor and the respective surfaces, plastic clamps were used to wrap the sensor firmly. The diameter of each cable without the jacket was 18.4 mm and the diameter of each clamp was 19.1 mm. To fill the gap between the two, several sheets of paper were placed in between the clamp and the sensor. Because the circumference of the cable was 54.5 mm and the sensor was 47 mm long, it was possible for the sensor to cover nearly 86% of the cable’s circumference. Figure 4.4(a) illustrates sensor placement on the cable’s insulation. To measure capacitance using the IDCs, an FDC1004EVM 4-Channel Capacitive to Digital Converter Evaluation Module was used. The CINn, Ground and SHLDx channels of the FDC1004EVM were used to perform the test. Capacitance was measured between the CINn port and the Ground. The SHLDx port was connected to the backplane. A residual capacitance was present in the output because of the soldered connecting wires. This residual capacitance was fixed for a stable connection and fixed length of connecting wires.
Furthermore, to de-embed the effects of the wires, the residual capacitance resulting only from the wires when connected to the TI circuit board (FDC1004) was measured. This residual capacitance was subtracted from all measured capacitance data presented in the work. In practical application, wires will likely be placed inside a plastic flexible conduit or wire harness, so the uncertainty with the wires moving and hence fluctuations in the measured capacitance will be eliminated. A fixture was constructed by machining a cylindrical hole within two acrylic blocks to hold the cable which allowed deterministic measurement. A photograph of the experimental setup is shown in Figure 4.4(b).

![Figure 4.4 Sensor wrapped around insulation surface using clamps.](image-url)

![Figure 4.5 Box and whisker plot of measured capacitance on (a) cable’s insulation, (b) cable’s jacket.](image-url)
4.3.2 Results

For each measurement case (i.e., one insulation and one jacket measurement), several measurements were taken. Measured capacitance data are plotted in Figure 4.5. It is evident from Figure 4.5 (a) that capacitance increases by 12.5% from unaged to 35-day aged cable for the sensor placed on the insulation. On the other hand, capacitance increases by 91.3% from unaged to 35-day aged cable for the sensor placed on the jacket (Figure 4.5 (b)). The rates of change for both cases demonstrate that the degradation of the jacket material is faster than the degradation of the insulation material due to the differences in their chemical composition and perhaps due to their proximity to the external environment during exposure.

4.3.3 Challenges with Airgap and Conductor Damage

Quality of sensor conformation on cable surface is a major source of measurement uncertainty. Airgap between sensor electrodes and cable surface leads to air capacitance which varies in every measurement depending on the quality of contact. Accurate capacitance measurement using IDC sensors requires the elimination of airgaps between the sensor and the cable’s insulation surface. This was difficult for two reasons: (1) the relatively thick sensor substrate created airgap when conformed to take the shape of the cable’s curvature and (2) the cable specimen insulation having a non-uniform surface in many places due to the manual jacket removal process (Figure 4.6). The extent to which airgaps can change capacitance was evaluated by constructing simulation models in ANSYS Maxwell (Figure 4.7 (a)). In experimental measurement, airgap between sensor electrodes and cable surface is not uniform but it is inconsistent. As it is not possible to determine the exact dimensions of airgap from the experiment, airgap is assumed to be
uniform. In the simulation models, the sensor was created on a curved substrate, a uniform airgap was created between the sensor electrodes and the cable’s insulation and the thickness of the uniform airgap was kept as variable (Figure 4.7 (b)). Simulated capacitance data as a function of airgaps are listed in Table 4.4. As seen, capacitance decreases by as much as 7.5% for as small as a 0.05 mm uniform airgap. If one assumes a uniform airgap between 0.1 to 0.3 mm, capacitance could be reduced by 10 to 16%.

Figure 4.6 Pictures of (a) a uniform surface on an unaged cable, (b) defects in a 14-day aged cable surface, and (c) a knife cut-induced channel on a 35-day aged cable.

Figure 4.7 ANSYS Maxwell simulation model of (a) IDC sensor’s electrodes on cable surface, (b) cross section of sensor and cable assembly with uniform airgap.
Table 4.4 Simulated capacitance with conformal IDC sensors on cable insulation in the presence of airgap.

<table>
<thead>
<tr>
<th>Uniform airgap thickness</th>
<th>Capacitance (pF)</th>
<th>Percentage of decrease from zero airgap</th>
</tr>
</thead>
<tbody>
<tr>
<td>Zero airgap</td>
<td>12.98</td>
<td>0</td>
</tr>
<tr>
<td>0.05 mm</td>
<td>12.01</td>
<td>7.5%</td>
</tr>
<tr>
<td>0.1 mm</td>
<td>11.68</td>
<td>10.07%</td>
</tr>
<tr>
<td>0.3 mm</td>
<td>10.87</td>
<td>16.27%</td>
</tr>
</tbody>
</table>

We found out during measurement that as sensor needed to be conformed to the cylindrical cable surface there was an issue of conductor trace damage, especially for a sensor on thick substrate (Fig. 4.8). This also occurred because during multiple measurements on separate locations on a cable specimen (to get an average value) the sensor needed to be taken off and placed back multiple times. We also observed that it was not possible to predict when a particular electrode or trace will get damaged.

Figure 4.8 Conventional PCB based IDC sensor conductor trace fragility.
To evaluate conductor damage problem, a deterministic approach was undertaken. First, aerial jumper cable specimens (Figure 4.3(a)) were tested using the sensor on thicker Duroid substrate and then on thinner LCP substrate. Several IDC sensors were fabricated on Rogers Duroid 5880LZ R4 ($\varepsilon_r = 2.00 \pm 0.04$) and liquid crystal polymer, LCP ($\varepsilon_r = 2.9$) substrate materials. Each IDC sensor was made of eight driving electrodes, seven sensing electrodes (D8S7), and a conducting copper backplane. All driving electrodes were connected to the DE Common while all sensing electrodes were connected to the SE Common. Other sensor parameters were: $W = 1.5$ mm, $L_e = 25$ mm, $a = 2$ mm, $t_b = 17.5$ µm, $t_e = 17.5$ µm. The total length and width of the sensor were 60 mm and 45 mm, respectively. For the sensor on the Duroid 5880 substrate thickness, $t_s$ was 0.25 mm while that on the LCP substrate, $t_s$ was 0.1 mm.

For each specimen, two measurements on two separate locations on a Okoguard aerial jumper cable specimen were recorded. Once measurement at the first location was completed, the sensor was taken out and placed on the second location for measurement. This process was repeated for subsequent specimens. Measured average capacitance data from the two locations for each specimen labeled “Sequence 1” are shown in Figure 4.9. Figure 4.9 shows that for the first 3 specimens capacitance increases with increased accelerated aging. Capacitance increases by 1.4% and 2.2% for specimens 2 and 3 compared to the unaged specimen (specimen 1). While measuring the capacitance on specimen 4, a sharp decrease in the measured capacitance was observed. This was the 7th sensor installation on a cable specimen given that there are 2 for each specimen. We suspected that the sensor electrode(s) or common(s) might have been damaged. To allow for inspection, the sensor was removed from the specimen and examined under a
A crack on one of the electrodes (driving electrode 4) was found at 5 mm from the DE Common. The location of this crack, labeled as crack 1, can be seen in Figure 4.10. The presence of this crack resulted in precipitous decrease (21.5%) of the measured capacitance for specimen 4.

In order to study possible further damage to the sensor more measurements were taken. The previous sequence of measurements was repeated. Results from these measurements are also shown in Figure 4.9 labeled as “Sequence 2.” Observing the measurement data for Sequence 2, it can be seen that capacitance again dropped precipitously when placed on specimen 4. When the sensor was inspected under the microscope another crack was discovered on SE Common (see Figure 4.10). Due to the new crack, the sensor effectively became a D8S3 (eight driving electrodes and three sensing electrodes) sensor as opposed to a D8S7 sensor which resulted in a 52.6% decrease in the capacitance.

![Figure 4.9 Measured capacitance for IDC sensor on Duroid 5880 substrate when placed on the Okoguard aerial jumper cable specimens. Specimens have undergone accelerated aging at 160ºC.](image-url)
Similar measurements were repeated using an IDC sensor fabricated on LCP film substrate assuming that a sensor fabricated on a flexible thin film substrate will likely cause less of a challenge in terms of sensor damage. Results from these measurements are shown in Figure 4.11. With this sensor a monotonic capacitance increase with accelerated aging was observed till the 6th specimen. For example, capacitance increases by 12.7% between specimen 1 and specimen 5. Measurements on the 6th specimen again showed a sharp decrease (40.4% compared to its neighbor) in capacitance. Inspection of this sensor under the microscope revealed a crack on the DE Common. The location of this crack is illustrated in Figure 4.12 which shows that due to this crack the D8S7 sensor effectively became a D3S7 sensor (consisting of only three driving electrodes and seven sensing electrodes). Further measurements were taken on specimen 1 using the sensor with the crack, which showed capacitance decreased by 37.5% compared to the initial results for specimen 1. To understand the effect of this crack, an LCP IDC sensor with a crack at the exact location was modeled and simulated on unaged specimen (EPR, $\varepsilon_r = 3.1$) using ANSYS Maxwell. The sensor showed a decrease in capacitance of 36.8% compared to the LCP IDC sensor without any crack. This result is in direct agreement with the measured result.
4.4 Flexible Fabric Based IDC Sensor and Application

As discussed in the previous section, the sensor electrodes and/or Common electrodes (DE Common and SE Common) of PCB based sensors can easily get damaged while bending and conforming to a curved surface like a cable. To overcome this challenge, a new fabric-based IDC sensor system is proposed which utilizes conductive fabrics to construct the sensor electrodes and the backplane and secures them on a nonconductive thin fabric.
e.g., polyester. The complete embodiment is then installed on the cable surface using a hook-and-loop mechanism (Figure 4.13).

Fabric-based sensors, proposed by other researchers [60-62] for wearable applications, are planar in nature and are of the parallel plate type. The capacitance for these sensors is primarily a function of the applied pressure to the material in between the plates. While these sensors are suitable for biomedical application like respiration monitoring, they are not suitable to monitor the permittivity variation of a cable insulation or jacket due to aging. For our application, a fabric-based IDC is an ideal choice, the electrodes of which can make contact with the test material directly and the test material e.g., cable insulation does not need to be sandwiched in between the plates of the sensor (e.g., parallel plate capacitor sensor).

![Figure 4.13 Illustrating an IDC sensor and its associated additional components.](image)

### 4.4.1 Proposed Flexible Fabric IDC Sensors

Our experiments conducted using sensors fabricated using PCB techniques on two separate substrates indicated the fragile nature of the sensor electrodes and/or commons, especially when the conformal sensor is placed on a cylindrical surface. Although initial measurements were successful, sensor damage occurred when measurements were repeated and there is a high probability that the sensor electrode(s) and/or common(s) could be damaged during installation or as a function of time after being installed. The issue with
sensor damage can be solved using an innovative method of IDC sensor fabrication and installation which considers the sensor electrodes and the commons (DE Common and SE Common) to be fabricated using conductive fabric materials on non-conductive fabric substrates. Under this approach the sensor electrodes, the commons and the backplane all are fabricated using conductive fabric material (copper polyester taffeta). These are then attached to a non-conductive fabric (Polyester [63]) substrate using adhesives. To mount the sensor on a cable specimen a hook and loop mechanism (e.g., Velcro) is used. This sensor installation system instead of rigid shape like clamps makes repetition of measurement easier and puts uniform pressure on the sensor to conform on the cable surface. The scenario is illustrated in Figure 4.14.

The specifications for the conductive fabric are: thickness \( t_e \) and \( t_b = 0.08 \) mm, weight 80 g/m\(^2\) (~35%Cu), surface resistivity = 0.05 \( \Omega \)/sq and operating temperature range -40\(^\circ\) C to 150\(^\circ\) C, up to 200\(^\circ\) C for short term. The connecting wires to and from the extended parts of the DE Common, SE Common and the backplane were electrically connected using conductive epoxy which was cured in an oven at 120\(^\circ\) C for 15 minutes. Parameters of the fabric sensor were: \( W = 1.5 \) mm, \( L_e = 22 \) mm, \( a = 2 \) mm. A photograph is shown in Figure 4.15.
Figure 4.14 Fabric sensor installation and usage on cable specimens.

Figure 4.15 Photograph of the fabricated fabric sensor.
This sensor was tested on all the Okoguard® Aerial Jumper cable specimens. Measured capacitance data and the percentage change in capacitance with reference to specimen 1 are shown in Figure 4.16. As seen, capacitance increases with increased accelerated aging. Percent change in capacitance for specimen 2 is 1.8%, which increases to up to 19.3% for specimen 8. The monotonic increase in measured capacitance data with cable accelerated aging demonstrates the durability of the fabric sensor. No crack or damage occurred after repeated placement, measurement, removal cycles.

Figure 4.16 Measured capacitance and change in capacitance using the fabric sensor on Okoguard® Aerial Jumper Cable.
Figure 4.17 Measured capacitance and change in capacitance using the fabric sensor on the Okoguard®-Okolon® Cable specimens (on insulation).

Figure 4.18 Measured capacitance and change in capacitance using the fabric sensor on the Okoguard®-Okolon® Cable specimens (on jacket).

A second fabric sensor with the same parameters as the previous one was fabricated and tested on the EPR insulation and CPE jacket of the Okoguard®-Okolon® TS-CPE/EPR type cable specimens. These specimens underwent accelerated aging tests as described in
Figure 4.3(b). Measured capacitance results and the percentage change in capacitance with respect to specimen 1 when placed on the cable insulation and on the jacket are shown in Figs. 4.17 and 4.18, respectively. When tested on the insulation, capacitance increased by 2% for specimen 2 and 33.3% for specimen 6. When tested on the jacket, capacitance increased by 13.4% for specimen 2 and 123.5% for specimen 6. The jacket material ages much faster than the insulation, likely because it is on the exterior plus it is well known that CPE jacket material ages faster than EPR. There were no sensor cracks developed during the course of these measurements.

4.4.2 Analysis of Airgap Between Sensor and Specimen

Since the IDC sensor to be used must conform to a cable surface there is a high likelihood that while shaping and bending the sensor unintentional airgaps between the sensor electrodes and the surface of the test specimen could be created. This would lead to reduced measured capacitance. If the airgap is consistent and well defined from specimen to specimen it may not be a problem. However, if the airgap varies from specimen to specimen or if airgap changes as function of time since the sensor was installed there could be additional measurement uncertainty created. Thus, airgap reduction and airgap consistency are important to accurately estimate the permittivity variation in cable insulation material due to aging. To understand and analyze the effect of the airgap various experiments and simulations were performed. The objective was to compare the effect of airgap among the sensors that were considered: Sensors on Duroid 5880, on LCP, and on fabric. Along with tests on the unaged cable specimen these sensors were also placed on a machined cylindrical foam (Rohacell with $\varepsilon_r = 1.05$). Simulations for each case were also performed. Since simulation models did not contain any airgap, a percentage difference
between simulated and measured capacitance for each case considering simulated value as the reference can be represented as the effect of airgap. These results are listed in Table 4.5. As seen, the largest percentage difference in capacitance between simulation and measurement is observed for the sensor on Duroid 5880 (for both on foam and on unaged cable). Although this percentage difference decreases significantly for the sensor on LCP, the smallest percentage difference is observed for the fabric sensor. This is expected because the fabric sensor allows increased conformability and more intimate contact with the cylindrical surface of the host.

| Sensor substrate material | Sensor placed on cylindrical shaped Foam | | | |
|---|---|---|---|
| | Measured | Simulated | Percentage Diff. |
| Duroid 5880 | 1.251 pF | 1.7859 pF | 30% |
| LCP | 1.511 pF | 1.779 pF | 15% |
| Fabric | 1.3343 pF | 1.5206 pF | 12.3% |

<table>
<thead>
<tr>
<th>Sensor placed on unaged cable specimen</th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Measured</td>
<td>Simulated</td>
<td>Percentage Diff.</td>
<td></td>
</tr>
<tr>
<td>Duroid 5880</td>
<td>4.276 pF</td>
<td>5.6416 pF</td>
<td>24.2%</td>
</tr>
<tr>
<td>LCP</td>
<td>4.518 pF</td>
<td>5.6716 pF</td>
<td>20.3%</td>
</tr>
<tr>
<td>Fabric</td>
<td>4.304 pF</td>
<td>4.8526 pF</td>
<td>11.3%</td>
</tr>
</tbody>
</table>

Two types of cables that underwent accelerated aging were tested using a new fabric IDC sensor. The proposed fabric IDC sensor is thin and flexible and is thus easy to conform to the surface of a cable. Such sensors can also be used on other cylindrical or
curved surfaces with ease. Given the sensor electrodes are made of conductive fabric pieces that are securely attached and bonded to a host nonconductive fabric using adhesive, electrode or conductor damage encountered with PCB based IDC sensors is avoided. Secondly, the new fabric IDC sensor reduces the airgap that exists between sensor electrodes and the test material enabling consistent measurement. Measurement results on the insulation of Aerial Jumper Cables show capacitance increasing by 19.3% from unaged to 224 hours aged cable at 160°C accelerated aging temperature. Results on the insulation material of the Okoguard®-Okolon® TS-CPE/EPR type cable specimens show capacitance increasing by 33.3% from unaged to 35-day aged cable at 140°C accelerated aging temperature. Finally, measurement results on the CPE jacket of the Okoguard®-Okolon® TS-CPE/EPR type cable specimens show capacitance increasing by 123.5% from unaged to 35-day aged cable at 140°C accelerated aging temperature. These results clearly indicate that fabric-based IDC sensors are advantageous to conventional substrate (e.g., PCB) based sensors for use on curved surfaces. Furthermore, the results suggest that fabric-based IDC sensors may be installed and used reliably for in-situ permittivity change measurement of insulation and/or jacket material as such materials age due to operating and environmental conditions.

4.5 IDC Sensor on Thin Coaxial Cable

A coaxial cable consists of an inner conductor surrounded by a concentric conducting shield where the two conductors are separated by a layer of insulating material and one or two jacket layers as protective outer sheath. IDC sensors are not suitable to monitor the degradation of the insulation of shielded coaxial cables since the electric fields generated from the sensor cannot reach the insulating layer through a conducting shielding
Thus, aging related degradation detection of a shielded cable using an IDC sensor is possible only for the outer jacket layer. In jacketed cables, jackets provide the first line of defense against external vulnerabilities like moisture, flame, mechanical, and chemical damages, etc. Generally speaking, the jacket layer of a cable degrades faster than the insulation layer [65]. Therefore, the jacket layer is the first and the leading indicator of local stresses and damages prior to severe insulation damages. For this reason, the analysis of aging related dielectric property degradation in this study focuses on the jacket layer degradation of shielded cables.

The cables tested so far were large diameter power cables having 60 -70 mm circumference. In many applications insulation and/or jacket material aging for thinner cables (20-25 mm circumference) such as instrumentation cables are desired. This would necessitate fewer electrodes for the IDC for it to be accommodated on the cable’s surface. This constraint is present because of the need for a specific separation distance between the driving and sensing electrodes dictated by the need for a minimum electric field penetration depth required to test the material. Thus, sensor width needs to be re-designed and adjusted depending on the cable’s circumference and, consequently, the number of electrodes needs to be adjusted based on the sensor width. However, since IDC sensor sensitivity is linearly related to the number of electrodes sensitivity decreases with number of electrodes hence sensor width reduction. To compensate for the sensitivity reduction, we propose to increase the electrode lengths. This approach will allow new slender IDC design consisting of fewer electrodes with longer lengths that will have the required sensitivity and electric field penetration depth.
4.5.1 Accelerated Aging of Thin Coaxial Cable

Habia RG58 coaxial cable was used as test specimen. Figure 4.19 shows the cable structure and parameters. The cable had inner conductor and conducting shield, between them is the dielectric material of XLPE and copper foil. There are two layers of HFI 90L (\(\varepsilon_r = 2.29\)) jackets. Its service life can be up to 40 years at a rated temperature of 90ºC. The dimension of the cable components is listed in Table 4.6.

84 cable specimens were collected from Xuan Wang and Dr. Bin Zhang of Department of Electrical Engineering at the University of South Carolina. These specimens were prepared from Habia RG58 coaxial cable of which the 1st one was unaged and other 83 specimens underwent accelerated aging at 120ºC in the oven for 83 days. The aging or heating cycle was structured as daily 8 hours of heating, followed by 16 hours of no heating. After a heating cycle of 24 hours, a specimen was taken out from the oven and labelled appropriately. Thus, specimen 1 was the unaged sample and specimen 84 was aged for 664 hours (83 days \(\times\) 8 hours).

![Sectional view of Habia RG58 coaxial cable.](image-url)
Table 4.6 Outer diameter of the Habia RG58 coaxial cable after every component.

<table>
<thead>
<tr>
<th>Components</th>
<th>Outer diameter, mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inner conductor</td>
<td>0.90</td>
</tr>
<tr>
<td>Insulation</td>
<td>2.95</td>
</tr>
<tr>
<td>Conducting shield</td>
<td>3.6</td>
</tr>
<tr>
<td>Jacket layer I</td>
<td>4.95</td>
</tr>
<tr>
<td>Jacket layer II</td>
<td>8.20</td>
</tr>
</tbody>
</table>

4.5.2 Sensor Design and Experimental Setup

To design an IDC sensor for thin cable, two sensor performance criteria (e.g., sensitivity and penetration depth) need to be optimized. IDC sensor sensitivity depends on the ratio between electrode width and interelectrode gap ($W/a$), the number of electrode ($N$) and electrode length ($L_e$). As seen from Figure 3.16 in chapter 3, sensitivity increases with the increase in number of electrodes and for a fixed number of electrodes, sensitivity increases as the ratio ($W/a$) increases. For an IDC sensor with $W/a$ ratio of 1, the effects of the number of electrodes ($N$) and the electrode length ($L_e$) on sensor sensitivity are shown in Figure 4.20. As seen, both $N$ and $L_e$ have linear relationship with sensor sensitivity. Thus, to design an IDC sensor with greater sensitivity, the geometrical parameters like $W/a$, $N$ and $L_e$ need to be optimized depending on the available space on the cable surface. Another parameter of interest is the electric field penetration depth into the MUT. Also, for a layered MUT, e.g., cable with jacket and insulation layer, it is required to design the spatial wavelength to concentrate the fringing electric fields up to a certain layer.
As the circumference of the cable specimen is approximately 25 mm, the sensors need to be designed within a width of 14-15 mm in such a way that there is enough space for the hook and loop mechanism. It is evident from Figure 4.20 that the sensitivity of IDC sensor with fewer electrodes can be compensated by increasing electrode length, for a fixed \((W/a)\) ratio. For example, when the \((W/a)\) ratio is 1, an IDC sensor with 20 electrodes and 20 mm electrode length will have a sensitivity of 1.9. Similarly, a sensor having 12 electrodes and 40 mm electrode length can provide a sensitivity of 2.1 when the \((W/a)\) ratio is 1. Thus, the sensor is designed with six driving and six sensing electrodes and electrode length \((L_e)\) of 40 mm. The parameters \(N\) and \(W/a\) within the fixed sensor width were optimized in terms of sensor sensitivity and penetration depth. Thus, to achieve high sensitivity, the \((W/a)\) ratio was selected to be 1 and to obtain a penetration depth of 0.8 mm, sensor was designed with: \(W = 0.6 \text{ mm}, a = 0.6 \text{ mm}\). Hence, the change in sensor capacitance is solely due to the degradation in the outer jacket layer.

Figure 4.20 IDC sensor sensitivity as a function of number of electrode \((N)\) and electrode length \((L_e)\). Sensor parameters: \(W = 1 \text{ mm}, a = 1 \text{ mm}, t_s = 0.1 \text{ mm}, t_e = 17 \mu\text{m}, t_b = 17 \mu\text{m}, \varepsilon_{rs} = 2.2,\) and MUT thickness, \(h=5 \text{ mm}\).
Several IDC sensors were fabricated on 0.05 mm thick Rogers XT/Duroid 8000 ($\varepsilon_r = 3.23 \pm 0.05$) substrate with 17.5 µm thick copper cladding on top and bottom sides. All the driving and sensing electrodes were connected to their respective common terminals (DE Common and SE Common). The sensor parameters were: $W_S = 13.8$ mm, $L_S = 55$ mm. Wires were soldered to the extended parts of one driving electrode, SE common, and backplane to provide driving voltage and to measure sensor capacitance.

Each sensor was wrapped around the surface of a cable specimen using a hook and loop mechanism (Velcro) where the electrodes were oriented in the longitudinal direction with respect to the cable specimen. Thus, only the SE and DE Commons were in the transverse direction with respect to the cable specimen. A FDC1004EVM 4-Channel circuit board module from Texas Instruments (TI) was used to measure the sensor capacitance. The experimental setup is illustrated in Figure 4.21.

![Illustration of experimental setup.](image)

**Figure 4.21 Illustration of experimental setup.**

### 4.5.3 Result Analysis

Fabricated IDC sensors were placed on various aged cable specimens and capacitance data were measured. Five different sensor placement zones each measuring 40 mm in length were marked on each specimen surface (see Figure 4.22). An IDC sensor was
placed one sensor per zone at a time and the capacitance was measured. Since the sensor length is longer (55 mm) than the zone length there exists a 15 mm long overlapping surface area between two successive zones during sensor placements. Within each zone three separate measurements were taken and thus for a single specimen 15 measurements were taken and recorded. For each measurement, a sensor was mounted on the specimen using Velcro and then taken out after recording the capacitance. This process was repeated for every measurement.

![Figure 4.22 A cable specimen with markings on five different zones.](image)

Capacitance measurements were started by mounting the first sensor on specimen number 1 and then the next specimen. As expected, measured sensor capacitance data exhibited a gradual increase with the increase in the accelerated aging time. However, after the measurements were completed on specimen number 19 a precipitous decline in capacitance was observed. A crack was discovered on the SE common of the sensor when inspected under a microscope. This crack on the SE common essentially reduced the number of electrodes. Therefore, the first sensor was not used in any further measurements. An identical second sensor with the same dimensions as the first sensor was used to take measurements, starting from specimen number 19. To complete the measurements on all specimens a total of four identical sensors were used. The cracks on the first three sensors appeared on either the SE common or the DE common, as they resided in the transverse direction with respect to the cable’s axis.
Boxplots of measured capacitance data on specimens 1 thru 84 are shown in four subplots of Figure 4.23 which clearly show the capacitance increasing as function of cable specimen aging. Capacitance increases slowly for specimens 1 thru 21, then it rapidly increases for the remaining specimens. For specimens 22-42, 43-63, and 64-84 capacitance increases almost in a linear fashion. As seen from the subplots, mean capacitance increases monotonically with increased accelerated aging. The mean of measured capacitance increases by 86% for specimen 84 compared to specimen 1.

![Figure 4.23 Boxplots of measured capacitance for specimens 1 thru 84. Each boxplot contains 15 measured capacitance data. Total 84 boxplots were divided into 4 subplots, each having boxplots of 21 specimens.](image)

An observation can be made from Figure 4.23 about the presence of outlier data points per specimen. The number of outlier data points for the first 1-21 specimens are very few (only 7 out of 300). But for specimens 22-42, 43-63, and 64-84 the number of outlier data points are higher and is in the vicinity of 25-35 out of 300. As the specimens went through more and more accelerated aging in an oven the outside surface of each specimen...
suffered some physical degradation or unevenness. This unevenness occurred in various places on the specimens as can be seen from Figure 4.24. The uneven surfaces on specimens resulted from the experimental placement of the specimens in the oven. The contact area between a specimen’s surface and the metal rod shelf of the oven caused indentation of the material in such locations. An example uneven surface area on Specimen 70 in Figure 4.24 shows zones IV and V having large portions of uneven areas, hence the two outliers of Specimen 70 are in zones IV and V.

This caused an airgap challenge for the sensor. This surface degradation is the reason for the presence of more outlier data points in the later part of the aging process. As apparent from Figure 4.23 the outlier capacitance data are mostly lower than the mean capacitance indicating airgap related measured capacitance reduction.

Figure 4.24 Photograph of specimen number 70 showing uneven surface.

4.6 IDC Application on XLPE Cables

As discussed in Chapter 1, the majority of local NDE test methods are material selective. For example, intender modulus does not work well on harder XLPE insulation material, infrared spectroscopy is effective on particular jacket materials but not on insulation materials, and ultrasound velocity is also material selective. However, a reliable NDE local test method should be suitable to all types of jacket and insulation materials, or at the very least to the most frequently used materials. To evaluate the efficacy of an IDC
sensor on different jacket and insulation materials, accelerated aging was performed on most commonly used jacket (e.g., CPE) and insulation materials (e.g., EPR, XLPE), and then IDC sensors were tested on them. Section 4.4.1 of Chapter 4 proves the effectiveness of IDC sensor on CPE jacket and EPR insulation materials, and section 4.5.1 demonstrates the effectiveness on HFI 90L jacket material. For the test on XLPE insulation, 15 specimens of RSCC Firewall® III-J XLPE insulated Power Cable had undergone accelerated aging at 160ºC in our laboratory. Table 4.7 describes the dimensions of the cable and Photographs of these specimens are shown in Figure 4.25. Jacket material (CSPE) was removed from all the specimens before accelerated aging to expose the XLPE insulation material. The heating cycle was structured as daily 10 hours of heating, followed by 14 hours of rest for seven days a week. Every specimen was heated 100 hours more than its previous one and labelled accordingly. The number 1 specimen was kept unaged and thus the aging hours of the number 15 specimen was 1400 hours. The activation energy \( E_a \) of XLPE is 1.088eV [66] and the service temperature \( T_s \) is considered to be 80°C [59]. Using the modified Arrhenius equation (3.1), 1400 hours of accelerated aging at 160ºC can be considered equivalent to 118 years of real-life aging.

To assess the degradation of XLPE insulation over accelerated aging period, two IDC sensors were fabricated with different \( W/a \) ratio: one with \( W = 1 \)mm, \( a = 1 \)mm and other one with \( W = 1.5 \)mm, \( a = 0.8 \)mm. The IDC sensors were designed with 8 driving and 8 sensing electrodes on top of Rogers R04835T substrate (\( \varepsilon_{rs} = 3.3 \)). Other parameters were: \( L_e = 40 \)mm, \( N = 16 \), \( t_s = 0.06 \)mm, \( t_e = 17 \)um, and \( t_b = 17 \)um. These sensors were tested on the 15 XLPE insulated specimens and the measured capacitance data of sensors with \( W = 1 \)mm, \( a = 1 \)mm and \( W = 1.5 \)mm, \( a = 0.8 \)mm are shown in Figs. 4.26 and 4.27, respectively. As seen
from the figures, capacitance increases with increased accelerated aging. Capacitance increases by 1.3pF and 1.7pF from unaged specimen 1 to specimen 15 when tested using sensors with $W=1\text{mm}$, $a=1\text{mm}$ and $W=1.5\text{mm}$, $a=0.8\text{mm}$, respectively. This increase in measured capacitance data with cable accelerated aging period demonstrates the effectiveness of the IDC sensor on hard insulation material like XLPE. Thus, regardless of the jacket and insulation materials, the IDC sensor is effective in evaluating aging-related degradation.

Table 4.7 RSCC Firewall® III-J Power Cable, 600 V, Class 1E Nuclear, 90ºC rating [59].

<table>
<thead>
<tr>
<th>Conductor</th>
<th>Annealed, tin-coated copper, Class “B” strand, diameter = 17.3 mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Insulation material</td>
<td>XLPE Thickness = 1.65 mm;</td>
</tr>
<tr>
<td>Jacket material</td>
<td>CSPE Thickness = 1.65 mm; Cable outer diameter = 23.9 mm</td>
</tr>
</tbody>
</table>
Figure 4.25: CSPE jacket material was removed from all the specimens before accelerated aging.

Figure 4.26 Measured capacitance data using the sensor with $W = 1\text{mm}$, $a=1\text{mm}$ on RSCC Firewall® III-J XLPE insulated Power Cable.
Figure 4.27 Measured capacitance data using the sensor with $W = 1.5$ mm, $a = 0.8$ mm on Firewall® III-J XLPE insulated Power Cable.
CHAPTER 5: RECONFIGURABLE PLANAR CAPACITOR SENSOR
FOR THRU THE JACKET INSULATION DIELECTRIC
CONSTANT MEASUREMENT

Conductors hidden within the insulation and jacket while not necessarily being affected by cable aging, the jacket will usually exhibit the first signs of aging. However, since the insulation material resides in the immediate vicinity of the conductor, protects the conductor, and prevents electrical leakage it is crucial to ensure its integrity. Considered unlikely, but even if the jacket material is degraded but the insulation remains relatively intact, the cable may still function safely [43]. As discussed in chapter 4, IDC sensors were fabricated on different substrates to evaluate the aging status of cable specimens containing CPE jackets and EPR insulation that had undergone accelerated aging at 140º C temperature for 35 days in an oven. Since the EPR insulation material is underneath the CPE jacket from over half of the length of each specimen the jacket was physically removed to measure the aging of the insulation aging.

However, it is impractical to remove the jacket from a cable and measure its insulation’s aging status especially if one considers real-time cable jacket/insulation aging monitoring using numerous distributed wireless-enabled capacitor sensors. If a sensor can be developed that can measure the aging status of both the jacket and the insulation that would be a tremendous breakthrough. This chapter explores that possibility and develops
the design, fabrication and testing of a reconfigurable capacitor sensor using which through
the jacket insulation dielectric constant can be measured and hence insulation aging can be
detected.

Measuring only the aging related change in the jacket’s dielectric constant is
straightforward because it resides on the outside surface of the cable. To measure the
change in the dielectric constant of the insulation the E-field penetration depth must
increase which requires larger interelectrode spacing for the sensor. That is the underlying
innovation of this chapter. We propose to activate and deactivate some of the sensor
electrodes with the help of electronic switches (PIN diodes) to control the E-field
penetration depth. It should be noted that even with increased E-field penetration depth the
sensor will measure a capacitance that reflects the aging status of both the jacket and the
insulation. We must disaggregate the insulation aging alone using some innovative scheme.
That is also another innovative aspect of this chapter.

5.1 Working Principle of Reconfigurable Capacitor Sensor

The key concept of the proposed reconfigurable capacitor sensor is illustrated in
Figure 5.1. A conformal capacitor sensor consisting of say 10 electrodes is depicted on a
cable specimen in both Figs. 5.1(a) and 5.1 (b). The driving and sensing electrodes are as
marked. All electrodes for the case in Fig 5.1 (a) are activated while only electrodes 1, 4,
7, and 10 are activated for the case in Figure 5.1 (b). For the case in Figure 5.1 (a) the
spatial wavelength, $\lambda_a$ is small because of the smaller interelectrode gap allowing the E-
fields to only penetrate the jacket while for the case in Figure 5.1 (b), the spatial
wavelength, $\lambda_b$ is large allowing the E-fields to penetrate both the jacket and the insulation.
Since the measurement for the second case would reflect the aging of both the jacket and
the insulation, we need a method to extract the insulation only aging. Straightforward subtraction would not apply here because the sensing in the two cases have different E-field penetration depths.

Therefore, along with a new reconfigurable sensor concept we also introduce a method that can be used to extract the insulation only aging behavior. This can be achieved by developing and applying two separate models developed using full-wave electromagnetic (EM) simulations in conjunction with the measurement data using the reconfigurable sensor. For any specific cable type, one will first develop dielectric constant estimation models for the jacket and the insulation material aging from a large number of electromagnetic (EM) simulations using regression analyses (e.g., linear, multivariate, and polynomial). Such models will depend on the cable’s geometrical and material properties. For example, two separate dielectric constant estimation models can be developed (as will be shown) for say for the Okoguard®-Okolon® TS-CPE/EPR type MV-90 2.4kV unshielded 2/0 AWG power cable with 22.4 mm outer diameter, 3.2 mm insulation and 2 mm jacket thickness using large scale ANSYS Maxwell simulations. We envision that in a real-world application scenario, a user will have access to the two separate dielectric constant estimation models for the type of cable they are concerned.
Figure 5.1 Change in E-field penetration depth by activating and deactivating electrodes. (a) All the electrodes are active, (b) electrode number 1, 4, 7 and 10 are active. Thickness of the electrode and interelectrode gap are very small (17 - 35 µm) but they are drawn thicker for illustration purpose.
Figure 5.2 The process flow of reconfigurable SRC sensor for estimating insulation permittivity in NDE and in-situ approach. Output of step 1 is used as input of step 2. The output of step 2 is the insulation permittivity through cable jacket.

The complete process can be understood from Figure 5.2. As shown, there are two separate pre-existing dielectric constant estimation models (one on the left and one on the right outside of the dashed-line box) developed from full-wave EM simulations. In Step 1, an operator uses the reconfigurable sensor in its switch ON mode, takes a measurement and then applies model 1 to obtain the dielectric constant of the jacket. In Step 2, the operator uses the same sensor in its switch OFF mode, takes a measurement, and then
applies model 2 which utilizes the dielectric constant derived from model 1 before. The output from Step 2 is the dielectric constant of the insulation material.

According to [67, 68] estimation models utilize known data then develop linear or nonlinear models consisting of two or more variables that can provide estimates for new data. To develop such models, in this work, simulated data from both modes of sensor operation considering ideal switches (copper strip) were used. Subsequently, measured capacitance data obtained from the fabricated reconfigurable sensor when tested on aged cable specimens were applied on the models to find the estimated the dielectric constants of the jacket and insulation materials. The challenges in making realistic measurements due to air-gap related uncertainty were added in the simulation model as uncertainty. To verify the estimated dielectric constant of the insulation using this NDE approach, further measurement and simulation were performed by placing the sensor in its non-reconfigured state (switch OFF mode) directly on the insulation where the jacket was manually removed.

Developing and applying a reconfigurable IDC sensor on a cable may be challenging because of the number of switches that may be involved (see Figure 5.3). Increasing the number of electrodes (commonly required to achieve higher sensitivity) would require even more switches. Large number of surface mount switches would pose two problems: (1) airgap between sensor electrodes and cable jacket surface and (2) switch connection fragility. It would be highly desirable to be able to reduce the number of switches to be used if the same sensitivity can be achieved within about the same sensor size.
An SRC sensor’s electrode layout (Figure 5.4) can be a good solution which will only require just two switches. An SRC sensor’s electrode layout embodies two sets of meandered electrodes (Figure 5.5 (a)) and interdigitated electrodes (Figure 5.5(b)) in a single structure. Figure 5.5 (c) illustrates the electrode layout of an SRC sensor consisting of 3 driving, 3 sensing interdigital electrodes and two sets of meandered driving and
sensing electrodes. The design constraints of a reconfigurable capacitor sensor depend on the jacket \( t_j \) and insulation thicknesses \( t_i \).

\[
\frac{\lambda_a}{3} < t_j < \frac{\lambda_b}{3} \quad \text{(5.1)}
\]

\[
\text{and,} \quad \frac{\lambda_b}{3} \leq (t_j + t_i) \quad \text{(5.2)}
\]

Figure 5.5 Electrode layouts of (a) meandered, (b) interdigital, and (c) serpentine (SRC) capacitive sensors.

Considering an Okoguard®-Okolon® TS-CPE/EPR Type unshielded power cable with outer diameter = 22.4 mm, jacket thickness = 2 mm, and insulation thickness = 3.2
mm as a practical case a sensor can be designed with the following parameters (Figure 5.5(c)): electrode width, $W = 1 \text{ mm}$, interelectrode gap, $a = 1 \text{ mm}$, electrode length, $L_i = 23 \text{ mm}$, $L_o = 26 \text{ mm}$, substrate thickness, $t_s = 0.1 \text{ mm}$, electrode thickness, $t_e = 17 \mu\text{m}$, and backplane thickness, $t_b = 17 \mu\text{m}$. The length ($L_S$) and width ($W_S$) of the sensor were 28 mm and 31 mm, respectively. A conducting backplane is present underneath the substrate to shield the sensor from unwanted external fields.

![Diagram](image)

(a) Switch On mode  
(b) Switch Off mode

Figure 5.6 SRC sensor is operating in (a) switch ON mode (b) switch OFF mode.

A reconfigurable SRC sensor of alternating electric field penetration depth can be designed by connecting and disconnecting the meandered driving and sensing electrode sets from the DE and SE Commons using only two switches. This resulted in the geometry shown in Figure 5.4. When the meandered electrode sets are connected to the Commons (switch ON mode), the spatial wavelength ($\lambda_a = 2(W + a)$) of the sensor is 4 mm and the E-penetration depth ($\lambda_a/3$) is approximately 1.3 mm (Figure 5.6(a)). In the switch OFF mode, the meandered electrode sets remain deactivated and thus only 3 driving and 3
sensing electrodes function as active electrodes (Figure 5.6(b)). The spatial wavelength ($\lambda_b$) for this case is 12 mm allowing the E-field penetration depth to be approximately 4 mm.

5.2 A Comparative Analysis Between IDC and SRC Sensor

As SRC sensor will be used as reconfigurable capacitor sensor instead of IDC sensor, a comparative analysis is done between these electrode layouts of capacitor sensors. The effects of electrode layouts on sensor performance are studied by means of finite element simulation where the geometrical dimensions (except electrode length) and material characteristics of both sensors are identical. IDC and SRC sensors with equal sensor area are modeled and simulated on a cable’s insulation surface using ANSYS Maxwell electromagnetic field simulation software. A comparative analysis of IDC and SRC sensors conformed on the cable insulation is demonstrated in terms of sensor sensitivity and electric field penetration depth. In addition, the effects of change in electrode width, inter-electrode gap, and number of electrodes on SRC and IDC sensor’s comparative performance are evaluated.

For the comparative analysis an IDC sensor was designed with 7 driving, 7 sensing electrodes (D7S7 as shown in Figure 5.7(a)) and a conducting copper backplane underneath a polyester substrate ($\epsilon_{rs} = 1.4$). Sensor parameters were as follows: $W = 1.5$ mm, $a = 2$ mm, $a_{end} = 0.75$ mm, $L_e = 19.25$ mm, substrate thickness, $t_s = 0.1$ mm, electrode thickness, $t_e = 17$ $\mu$m, and backplane thickness, $t_b = 17$ $\mu$m. Sensor length ($L_s$) and width ($W_s$) were 23 mm and 47 mm, respectively. Figure 5.7(c) illustrates the electrode layout of an SRC sensor which consists of 2 driving, 2 sensing interdigitated electrodes and a set of meandered driving and sensing electrodes. Other than electrode length ($L$), the parameter
dimensions were the same for the SRC sensor as for the IDC sensor. The electrode lengths of SRC sensor were: \( L_m = 13.25 \text{ mm}, \ L_4 = 14.75 \text{ mm}, \ L'_m = 17.75 \text{ mm} \). Figs. 5.7(b) and (d) illustrates the electrode layout of the conformal IDC and SRC sensor on a cable insulation.

Figure 5.7 (a) IDC sensor electrode layout, (b) IDC sensor on a cable insulation, (c) SRC sensor electrode layout, and (d) SRC sensor on a cable insulation.

### 5.2.1 Sensor Sensitivity

First, conformal IDC (D7S7) and SRC sensors were modeled on a hypothetical cable. The conductor diameter and insulation thickness of the cable were 11.4 mm 5.7 mm, respectively. Unaged dielectric constant of 3.1 was considered which is the same permittivity of the ethylene-propylene rubber (EPR) insulation of an unaged Okoguard® Aerial Jumper Cable. It was shown in [65] that the relative permittivity of the EPR insulation increased as a function of accelerated aging of the cable. Although accelerated aging of EPR insulation nominally may increase the sensor (D7S6, 0.25mm thick Rogers 5880LZ R4 substrate) capacitance by about 12.5%, we extended the permittivity change
beyond that in this simulation study. Thus, the permittivity of the MUT was varied from 3.1 to 7.

Simulated capacitance data and sensitivity of the IDC and SRC sensors are shown in Figure 5.8(a) as a function of the relative permittivity of the MUT, i.e., cable insulation. As seen, the SRC produced higher capacitance for a given relative permittivity. The difference in capacitance between SRC and IDC sensors is 0.7 pF when the relative permittivity of the insulation is 3.1. The sensitivity of the SRC sensor is also 13.3% higher than the IDC sensor. These results could be explained from the surface area utilization by the electrodes of the SRC sensor as opposed to the IDC sensor. The former occupies 8% more surface area than the latter. To evaluate the effect of number of electrodes on comparative sensitivity of IDC and SRC sensor, a new IDC with 9 driving and 9 sensing electrodes and it’s equivalent SRC sensor were modeled on the cable. Figure 5.8(b) shows the simulated capacitance data for sensors with an increased number of electrodes. It is observed from Figure 5.8(b) that the difference in capacitance between SRC and IDC sensors is 0.86 pF when the relative permittivity of EPR is 3.1. Again, the sensitivity of SRC sensor is 15% higher than the IDC sensor. Comparing with Figure 5.8(a), the difference in capacitance between SRC and IDC sensors increases by 22.8% with the increase in the number of electrodes. Also, the difference in sensitivity between SRC and IDC sensors increases with the 4 added electrodes.
Figure 5.8 Simulated capacitance of IDC and SRC sensors as a function of insulation relative permittivity. (a) D7S7; IDC sensor had 7 driving and 7 sensing electrodes (b) D9S9; IDC sensor had 9 driving and 9 sensing electrodes. SRC sensors were derived from their respective IDC sensors.

As shown in Chapter 2, electrode width \(W\) and inter-electrode gap \(a\) are two key parameters among the geometrical parameters that govern the sensitivity of the sensors. To analyze their influence, \(W/a\) is varied from 0.5 to 1.5 with 0.25 increments. Other parameters were kept constant. IDC and SRC sensors were modeled on the hypothetical cable where insulation thickness was changed from 5.7 mm to 2 mm. To maintain the same outer diameter of the cable, the conductor diameter was increased from 11.4 mm to 18.8 mm. Insulation thickness was reduced to maintain a good level of field penetration depth. Figure 5.9 shows simulated results of sensitivity for these sensors.

For each sensor, sensitivity increases as \(W/a\) increases from a small value to 1. For example, for the IDC sensor sensitivity increases by 23\% from \(W/a = 0.5\) to \(W/a = 1\). For the SRC sensor, sensitivity increases by 31\% for the same parameter. For either sensor, sensitivity nearly saturates as \(W/a\) is 1.25 or higher. There can be various arrangements while designing these sensors. For example, very narrow electrodes accompanied by relatively wider gaps will ensure \(W/a\) less than 1. For the same \(W/a\) value, the SRC
sensor provides higher sensitivity than the IDC sensor due to the fact that its electrodes utilize the surface area more effectively as stated before. The sensitivities of both sensors increase gradually with increasing $W/a$. With the increase in $W/a$ from 0.5 to 1, the difference in sensitivity ($\Delta S$) increases from 0.07 to 0.2. After that, $\Delta S$ decreases from 0.2 to 0.12 when $W/a$ increases from 1 to 1.5.

![Figure 5.9 Simulated sensor sensitivity as a function of electrode width and inter-electrode gap.](image)

5.2.2 Electric Field Penetration Depth

Spatial wavelength ($\lambda = 2(W + a)$) is the key parameter that regulates the penetration depths for these types of sensors. IDC (D7S7) and SRC sensors with different spatial wavelengths were modeled and simulated to compare their penetration depths within the cable. Insulation thickness was varied from 1 mm to 8 mm. Figure 5.10(a) shows the simulated capacitance of the IDC and SRC sensors as a function of the spatial
wavelength and insulation thickness. As demonstrated, the capacitance of both IDC and SRC sensors decreases with the increase in insulation thickness. Sensor capacitance in the presence of a cable conductor is the summation of the capacitance between the driving and sensing electrodes and the capacitance between the driving electrodes and the conductor [33]. Because of the increase in insulation thickness, the relative distance between driving electrodes and conductor increases, which results in a decrease in electric fields. Thus, with the increase in insulation thickness, the capacitance of the sensors conformed on the cable surface decreases.

Figure 5.10(b) shows the relative capacitance (%) of the sensors deduced from Figure 5.10(a) using equation 2. The corresponding penetration depths (10% relative capacitance) of the sensors from Figure 5.10(b) are summarized in Table 5.1. As seen, penetration depth decreases for both IDC and SRC sensors with the decrease in spatial wavelength. Also, both IDC and SRC sensors show a decrease in penetration depth with the increase in $W/a$. For the same spatial wavelength and $W/a$, the IDC sensor has a deeper penetration level compared to the SRC sensor. When the spatial wavelength is 7 mm, the penetration depth of the SRC sensor is 18.8% lower than that of the IDC sensor. Again, the E-field penetration depth of the SRC sensor is almost 17% lower than the IDC sensor when the spatial wavelength is 5 mm. The above results demonstrate that there is a tradeoff between sensitivity and penetration depth when designing a capacitive sensor considering the layout of electrodes.
Figure 5.10 (a) Simulated capacitance and (b) corresponding relative capacitance of IDC and SRC sensors as a function of electrode width, inter-electrode gap, and insulation thickness.

Table 5.1 Simulated penetration depth of IDC and SRC sensors.

<table>
<thead>
<tr>
<th>Electrode Width, $W$</th>
<th>Inter-electrode gap, $a$</th>
<th>Spatial Wavelength, $\lambda$</th>
<th>$W/a$</th>
<th>Penetration depth</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>IDC sensor</td>
</tr>
<tr>
<td>1.5 mm</td>
<td>2 mm</td>
<td>7 mm</td>
<td>0.75</td>
<td>2.65 mm</td>
</tr>
<tr>
<td>1.5 mm</td>
<td>1 mm</td>
<td>5 mm</td>
<td>1.5</td>
<td>1.9 mm</td>
</tr>
</tbody>
</table>

Further, simulations of IDC and SRC sensors were accomplished to evaluate the effect of the number of electrodes on E-field penetration depth. D7S7 and D9S9 IDC sensors and their equivalent SRC sensors with the spatial wavelength of 7 mm were modeled on the cable. Figure 5.11 shows the relative capacitance of these sensors with the variation of insulation thickness. As seen, penetration depth of both IDC and SRC sensors decreases slightly with increased electrodes. For the 4 additional electrodes, penetration depth of the IDC and SRC sensors decreases by 6.4% and 6%, respectively. The difference
in penetration depth between D9S9 IDC and SRC sensor is 18.5% when the spatial wavelength is 7 mm. Comparing with Figure 5.10(b), the effect of the additional electrodes on the difference of penetration depth is very small.

Figure 5.11 Relative capacitance of IDC and SRC sensors as a function of number of electrodes and insulation thickness. \( W = 1.5 \text{ mm}, a = 2 \text{ mm} \).

Therefore, this comparative analysis shows a tradeoff between IDC and SRC sensors in terms of sensitivity and penetration depth. The SRC sensor yielded higher capacitance and sensitivity than the IDC sensor because of its more effective utilization of the available surface area. By contrast, the electric field penetration depth was higher for the IDC sensor than for the SRC sensor. The difference in sensitivity between the SRC and the IDC sensor was the highest at unity electrode width and inter-electrode gap ratio. With the increase in electrodes number, the difference in sensitivity between SRC and IDC sensor further increases. Field penetration depth decreased for both sensors with increased electrode width and inter-electrode gap ratio.
5.3 Reconfigurable SRC Sensor Fabrication and DC Biasing

A reconfigurable SRC sensor was photo-etched on one side of a double-sided copper cladded insulating substrate (Rogers R04835T, $\varepsilon_r=3.32$) with 0.1 mm thickness (Figure 5.12(a)). BAR 64-03W PIN diodes from Infineon Technologies were used as electronic switch. To reduce airgaps during sensor conformation on the cable surface, the switches and their biasing circuits were designed and soldered on the backplane side of the sensor. Thru-hole vias were created on the DE Common, SE Common, driving and sensing meandered electrodes to provide ac conducting paths (Figure 5.12(b)). The bias circuit (Figure 5.12(c)) consists of a current limiting resistor, $R = 220 \, \Omega$, RF choke inductors,
$L = 100 \, \mu H$, and DC block capacitors, $C = 100 \, nF$. A 5 V DC supply was used to turn ON the PIN diode switches. Switch insertion loss was 0.18 dB for 20 mA of forward current while isolation was 35 dB at 0 bias. A photograph of the fabricated reconfigurable SRC sensor is shown in Figure 5.13. A hook and loop mechanism using Velcro was used to mount the sensor on the cable and wires were soldered to the extended part of the DE, SE Commons, backplane, and bias circuit to apply the DC bias voltage. Okoguard®-Okolon® TS-CPE/EPR Type unshielded 2/0 AWG power cables reported in Figure 4.3(b) were used as the test specimens to test the reconfigurable SRC sensor.

Figure 5.13 Photograph of a fabricated reconfigurable SRC sensor and its biasing circuit.
The sensor was wrapped on the cable jacket and subsequently on the exposed cable insulation to measure capacitance for each specimen. As reported in [21, 69], sensor capacitance can be measured using the short circuit current method. In this method, sensor is excited by a low frequency time varying driving voltage ($V_D$), the SE Common is virtually grounded by an op-amp. The op-amp output voltage is measured ($V_F$) across a known feedback capacitor ($C_F$) and the sensor capacitance ($C_{DS}$) can be calculated from the following equation,

$$C_{DS} = \frac{V_F}{V_D} C_F$$  \hspace{1cm} (5.3)

A 1 MHz, 10 $V_{p-p}$ sinusoidal voltage ($V_D$) was applied to the DE Common from a waveform generator and the backplane was kept at ground potential. A voltage ($V_S$) was measured at the SE Common using an op-amp circuit. A 100pF capacitor was used as the
reference capacitor ($C_F$) which further prevented the op-amp from saturating [26]. Schematic diagram of the experimental setup is shown in Figure 5.14.

5.4 Results

5.4.1 Reconfigurable Sensor Simulation Results

As a preliminary step towards developing Model 1 illustrated in Figure 5.2 we performed EM simulations of the reconfigurable sensor by placing it on top of the jacket of a Okoguard®-Okolon® TS-CPE/EPR Type cable in ANSYS Maxwell. To simulate the ON state of the switches we placed copper strips in the switch locations. To simulate the OFF state, we kept those locations empty. The sensor was conformed on the cable surface such that the electrodes would be in the longitudinal direction with respect to the cable axis. Thus, the sensor width covered almost 45% of the cable circumference when placed on cable jacket.

In the simulation models for both the switch ON and OFF conditions, the jacket dielectric constant was varied from 3 to 7 and for every jacket dielectric constant value the insulation dielectric constant was varied from 3 to 4 with 0.1 increment. Simulated capacitance data as a function of the jacket and insulation dielectric constant variations for both switch ON and OFF cases are plotted in Figs. 5.15 and Figure 5.16, respectively. It is observed from Figs. 5.15 and 5.16 that the capacitance of the reconfigurable SRC sensor increases with the increase in the relative dielectric constant of the jacket material in both cases. It is apparent that in the switch ON case (Figure 5.15) the capacitance data do not show any significant vertical spread which will represent the change in the insulation dielectric constant. This is expected because in this case, because of low E-field penetration depth the sensor fails to probe the insulation dielectric constant variation. By contrast, in
the switch OFF case (Figure 5.16) there is quite a significant vertical spread in the capacitance reflecting the insulation dielectric constant variation. The latter results explain that the switch OFF mode capacitance represents the dielectric constant variation due to both the jacket and the insulation.

![Graph showing change in capacitance of SRC sensor in switch ON mode.](image)

Figure 5.15 Change in capacitance of SRC sensor operating in switch ON mode.
5.4.2 Model Development and Air-Gap Uncertainty

It is obvious to the reader that it makes little difference if whether the dielectric constant of the jacket material is measured using a conventional or a reconfigurable sensor. To determine the aging related dielectric constant of a cable’s insulation from measured capacitance results using the reconfigurable sensor we used Maxwell EM simulation data and then applied regression analysis to develop dielectric constant estimation models. Such models when used in conjunction with the measured data obtained from the reconfigurable sensor can be used to extract the insulation dielectric constant. Meaningful conclusions on the aging status can be drawn by comparing the dielectric constant of an aged cable specimen with that of an unaged specimen.

There are some inherent challenges in using simulation data to develop models and then applying measured data on the developed models: simulation environments are in general foreseeable, whereas measurements often contain uncertainty e.g., data...
fluctuations and external noise [70]. Therefore, models that are developed considering simulation data may present some error or an over-fit [71], e.g., error in the value of the estimated dielectric constant. To alleviate this situation, we introduced defects into the simulation models to mimic close to real-world situations. In chapter 4, we demonstrated that when shaping and bending, a capacitor sensor on a cable surface, unintentional and inconsistent airgaps between the sensor electrodes and the surface of the cable specimen is generated. This then inevitably leads to reduced measured capacitance. Because simulation models do not normally include any airgap, the airgap can be responsible for the difference between the simulated and measured capacitance. We found 8-20% difference between simulated and measured capacitance for unaged specimens depending on the thickness and flexibility of the sensor’s substrate material.

Figure 5.17. depicts a box-whisker plot (31 separate measurements) as a visual summary of the variations in measured capacitance data recorded with a switch ON mode reconfigurable sensor on an unaged Okoguard®-Okolon® TS-CPE/EPR type cable specimen. From the box-whisker plot, the measured capacitance data spread from 6.2 pF to 7.4 pF, with two outliers. The simulated capacitance with no airgap is a fixed capacitance of 7.73 pF.
Figure 5.17 Fluctuations in measured capacitance data using switch on mode reconfigurable sensor on unaged Okoguard®-Okolon® TS-CPE/EPR type cable specimen. The simulated capacitance (no airgap) of the same situation is given for comparison purpose.

To investigate this further we performed simulations of the switch ON state sensor when placed on the cable jacket by including variable airgap in the model. The differences between the simulated capacitance (7.73 pF) without airgap and the measured capacitance data in Figure 5.17 can be represented using uniform airgap thickness (Fig 5.18(a)) in the simulation model. Every measured capacitance can be represented by a uniform airgap thickness. The distribution of the uniform airgap thickness which reflects the differences between the measured data and the simulated fixed capacitance is shown in Figure 5.18(b). It is clear that these data are not normally distributed; they are right skewed. The airgap thickness ranged from 0.0039 mm to 0.048 mm.
Figure 5.18 (a) Variations in measured capacitance data of switch on mode reconfigurable sensor on unaged specimen, (b) corresponding equivalent uniform airgap thickness distribution.

To identify the probability distribution of the airgap thickness data, distribution tests were performed. Distribution tests consider a null hypothesis and an alternative hypothesis.

\[ H_0: \text{The data follow the hypothesized distribution.} \]

\[ H_1: \text{The data do not follow the hypothesized distribution.} \]

In general, if the p-value for a certain distribution test is low (e.g., \( \leq 0.05 \)), it can be understood that the null hypothesis is then not supported by the data and that the data do not follow the given distribution. Anderson-Darling statistic that compares various distributions to determine the distribution that best fits the data must be much lower than those of the other distributions. [72-74]. In terms of probability plot, the data reside along the center line for the best fitted distribution. The results of goodness of fit test for four different distributions (i.e., Normal, Lognormal, Weibull, Gamma) are listed in Figure 5.19 (using Minitab® software). As seen, the p-value is less than 0.05, indicating that the data
do not follow normal distribution. In comparison to other distributions, the lognormal distribution has the highest p-value of 0.239 (>0.05) and lowest Anderson-Darling statistic, hence, the airgap thickness data follow the lognormal distribution. Probability plots for the four distributions are also shown in Figure 5.19. As seen, the data points for the normal, weibull, and gamma distribution don’t fall along the center line, whereas the data points fall along the center line for the lognormal distribution which further proves the lognormal case.

Figure 5.19 Distribution identification for airgap thickness and results of goodness of fit test for four different distributions (Minitab® software).

A set of random numbers was generated from the lognormal distribution with the distribution parameters: location (-4.51509) and scale (0.72133). To incorporate uncertainty to the simulated capacitance data, these random numbers were used as the
uniform airgap thickness in both switch ON and OFF mode simulation models of unaged and aged specimens. There was no significant change in the outer diameter due to aging, and the same sensor was used throughout the measurement, which validated the use of random numbers generated from the unaged specimen's airgap distribution as the aged specimen's airgap thickness.

Earlier we observed (Figure 5.15) that when the sensor resides on the cable jacket and the switches are in the ON state, with the insulation permittivity varying the change in the sensor capacitance is negligible. Therefore, to develop Model 1 with an extended dataset, we varied the dielectric constant of the cable jacket from 2 to 15 while keeping the insulation dielectric constant fixed at 3. We also introduced uncertainty in the model by incorporating the above-described random numbers that generated uniform airgaps in the model. The simulated capacitance data resulting from these considerations were then used to develop Model 1.

Also, recalling the results shown in Figure 5.16, when the sensor resides on the cable jacket and the switches are in the OFF state, capacitance changes significantly with the change in the insulation dielectric constant. An expanded data set was used to develop Model 2 under this scenario where the jacket dielectric constant was varied from 2 to 15 with 0.5 increment. For a specific jacket dielectric constant, the insulation relative permittivity was varied from 2 to 7 with 0.2 increment. Uncertainty was introduced using uniform airgaps from the previously described set of random numbers. The corresponding simulated capacitance data were implemented to create Model 2.
5.4.3 Jacket and Insulation Dielectric Constant Models

To develop Model 1 capacitance ($C_1$) from simulations was considered as the independent variable and the jacket dielectric constant ($\varepsilon_{r,j}$) was considered as the dependent variable. These were then subjected to regression analysis (Figure 5.20). The relationship illustrated in Figure 5.20 is linear with the coefficient of determination ($R^2$) being 97%, which indicates a good fit for the data. Model 1 is given by

$$\varepsilon_{r,j} = 0.7007C_1 - 1.56$$  \hspace{1cm} (5.4)

where $C_1$ is the measured capacitance by the reconfigurable SRC sensor in its switch ON state. All models developed in this work are specific to the TS/CPE Okoguard Okolon cable. For other cables new models must be developed based on their geometrical and materials characteristics.

Second, Model 2 was developed that utilizes the relationship between the insulation dielectric constant, the jacket dielectric constant, and the switch OFF mode capacitance. Since the insulation dielectric constant ($\varepsilon_{r,i}$) as dependent variable ($y$) depends upon multiple independent variables like the jacket dielectric constant ($\varepsilon_{r,j}$ as $x_1$) and simulated switch OFF mode capacitance data ($C_2$ as $x_2$), multivariate regression analysis was performed to find the best fit. Multivariate polynomial regressions (MPR) including interaction terms could provide a better fit for our case compared to multivariate linear regression (MLR). The root mean square error ($RMSE$) and the coefficient of determination ($R^2$) will be used to assess the goodness of fit. MPR technique considers the development of a polynomial-based relationship between the dependent variable and the multiple independent variables [75, 76]. The interaction terms between $\varepsilon_{r,j}$ and $C_2$ indicate that the relationship between $C_2$ and $\varepsilon_{r,i}$ differs depending on the value of $\varepsilon_{r,j}$ (and vice
versa). From the preliminary analysis, it is observed that the jacket dielectric constant has a polynomial relationship with insulation dielectric constant whereas switch OFF state capacitance has a linear relationship with insulation dielectric constant. Hence, only the order of the jacket’s dielectric constant was changed from 1 to 5 and the order of the switch OFF state capacitance was kept at 1 in the higher order multivariate polynomial regressions with interaction terms for estimation model 2.

![Graph](image)

**Figure 5.20 Model 1 to determine the jacket dielectric constant.**

The simulation data set of Model 2 was split into 80% training and 20% test data sets. Five-fold cross validation was performed in the training process to prevent the estimation model from being overfit [76]. Goodness of fit ($R^2$ and $RMSE$) of the higher order MPR for train and test data is shown in Figure 5.21. The $RMSE$ error and $R^2$ coefficient of train data from Figure 5.21 show that the linear model is not complex enough to fit the data. From linear to 3rd order polynomial, the $RMSE$ errors and
$R^2$ coefficients provide a sharp decrease and increase, respectively. RMSE error and $R^2$ keep decreasing and increasing till 5th order polynomial though the change is not significant for the higher orders. The goodness of fit data for train and test data set is also similar starting from polynomial 13. Thus, considering the complexity in the higher (4th and 5th) order polynomial models, RMSE, and $R^2$ coefficients, 3rd order polynomial is selected as model 2. The 84%, $R^2$ value of the 3rd order polynomial infers that the variation in insulation dielectric constant is strongly correlated to the independent variables considered in this MPR. The complete equation of the 3rd order multivariate regression models is as follows:

$$
\varepsilon_{r,i} = 52.7C_2 - 6.982C_2\varepsilon_{r,j} - 0.2821C_2\varepsilon_{r,j}^2 - 7.488\varepsilon_{r,j} + 1.063\varepsilon_{r,j}^2 - 0.04362\varepsilon_{r,j}^3 + 0.5964 \\
(5.5)
$$

where $C_2$ is the measured capacitance by the reconfigurable SRC sensor in its switch OFF state and $\varepsilon_{r,j}$ is the dielectric constant of the jacket obtained from (5.4).

Figure 5.21 $R^2$ and RMSE of the higher order MPR for Model 2.
5.4.4 Measured Results and Comparison

Measured capacitance data from step 1 (switch ON mode) and step 2 (switch OFF mode) were applied on the models to determine the jacket and insulation dielectric constants. Switch ON mode capacitance data of the specimens were applied on Model 1 to determine the jacket dielectric constant. The jacket dielectric constants of the specimens were then used as input variable along with the switch OFF mode capacitance data in Model 2 to determine the insulation dielectric constant. Measured capacitance data of the specimens and their estimated dielectric constants are listed in Table 5.2.

Table 5.2 Measured capacitance and estimated dielectric constants of jacket and insulation.

<table>
<thead>
<tr>
<th>Aging period in days at 140°C</th>
<th>Switch ON mode</th>
<th>Switch OFF mode</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Measured capacitance (pF)</td>
<td>Estimated $\varepsilon_r$ of jacket (CPE)</td>
</tr>
<tr>
<td>unaged</td>
<td>7.03</td>
<td>$\varepsilon_r = 3.36$</td>
</tr>
<tr>
<td>7 days</td>
<td>7.61</td>
<td>$\varepsilon_r = 3.75$</td>
</tr>
<tr>
<td>14 days</td>
<td>8.38</td>
<td>$\varepsilon_r = 4.31$</td>
</tr>
<tr>
<td>21 days</td>
<td>9.7</td>
<td>$\varepsilon_r = 5.22$</td>
</tr>
<tr>
<td>28 days</td>
<td>11.49</td>
<td>$\varepsilon_r = 6.48$</td>
</tr>
<tr>
<td>35 days</td>
<td>13.65</td>
<td>$\varepsilon_r = 8.0$</td>
</tr>
</tbody>
</table>
It is evident from Table 5.2 that the dielectric constant of cable jacket and insulation increase with the aging period. The dielectric constant of jacket increases by 138% from its unaged condition due to the accelerated aging period of 35 days at 140ºC whereas insulation dielectric constant increases by 29% during the same period.

To verify the efficacy of our proposed through the jacket insulation permittivity measurement method a final case of directly measuring the insulation permittivity was considered. The reconfigurable SRC sensor in the switch OFF mode was placed directly on the exposed insulation surface of the test specimens (see Figure 4.3(b)) and capacitance was measured. We will refer to it as the DE approach from now on because it requires the sensor to reside directly on the insulation. In order to determine the dielectric constant of the insulation from measured capacitance data a third model was developed using simulations. Maxwell simulations of the sensor in its non-reconfigurable state (switch OFF mode) were performed with the sensor residing directly on the insulation. The dielectric constant of the insulation was varied from 2 to 7 with 0.2 increment and uniform airgap related uncertainty was introduced. For this third model, simulated capacitance ($C_3$) was considered to be the independent variable (x) while the insulation dielectric constant ($\varepsilon_{r,i}$) was considered to be the dependent variable (y). Regression analysis showed that the insulation dielectric constant maintained a linear relationship as shown in Figure 5.22. Model 3 is expressed as follows

$$\varepsilon_{r,i} = 5.125C_3 - 0.3624$$

where $C_3$ is the measured capacitance by the reconfigurable SRC sensor in its switch OFF state with the sensor residing directly on the cable insulation.
Measured capacitance data (0.52pF, 0.548pF, 0.58pF, 0.617pF, 0.662pF, 0.71pF) obtained from switch OFF mode were applied in Model 3 to estimate the insulation dielectric constant. These results are compared with the results obtained using the thru-the-jacket measurements in Table 5.3. From Table 5.3, the estimated insulation dielectric constant data measured using the thru-the-jacket reconfigurable sensor are in good agreement with the dielectric constant obtained from direct measurement using the DE approach. The percentage difference between the two data sets is less than 5%.

Figure 5.22 Model 3 to estimate the insulation dielectric constant from destructive evaluation (DE) method.
Table 5.3 Estimated dielectric constant of insulation and percentage error between DE and NDE approaches.

<table>
<thead>
<tr>
<th>Aging period in days at 140°C</th>
<th>Estimated $\varepsilon_r$ of insulation (EPR)</th>
<th>Percentage difference</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Thru-the-jacket (NDE)</td>
<td>Sensor directly on insulation (DE)</td>
</tr>
<tr>
<td>unaged</td>
<td>$\varepsilon_r = 2.95$</td>
<td>$\varepsilon_r = 3.03$</td>
</tr>
<tr>
<td>7 days</td>
<td>$\varepsilon_r = 3.07$</td>
<td>$\varepsilon_r = 3.17$</td>
</tr>
<tr>
<td>14 days</td>
<td>$\varepsilon_r = 3.21$</td>
<td>$\varepsilon_r = 3.33$</td>
</tr>
<tr>
<td>21 days</td>
<td>$\varepsilon_r = 3.37$</td>
<td>$\varepsilon_r = 3.52$</td>
</tr>
<tr>
<td>28 days</td>
<td>$\varepsilon_r = 3.58$</td>
<td>$\varepsilon_r = 3.75$</td>
</tr>
<tr>
<td>35 days</td>
<td>$\varepsilon_r = 3.80$</td>
<td>$\varepsilon_r = 4$</td>
</tr>
</tbody>
</table>
CHAPTER 6: CONCLUSION AND FUTURE WORK

6.1 Conclusion

Interdigital capacitor (IDC) sensing is an NDE, in-situ, and non-invasive method that can be used to measure changes in dielectric constant of insulation materials. Since insulation aging is correlated with a change in its dielectric constant, an IDC sensor can measure that change via its measured capacitance. The specific focus of this dissertation is to investigate, design and develop IDC sensors to effectively conduct aging related cable insulation degradation sensing. To test these sensors on aged cables which are not commonly available, accelerated aging is performed on several types of cables to simulate real-life field aging. The challenges in designing and developing IDC sensor for cable insulation degradation detection are achieving high sensitivity and the required penetration depth within available cable space, reducing airgap, and eliminating conductor fragility. Detection of insulation aging through the cable jacket is another major challenge in cable material aging detection via NDE, but it is also one of the most important ones in terms of monitoring cable health because of its close proximity to the conductor.

First, the effects of geometrical parameters and sensor materials on the ability of IDC sensors to measure capacitance values of polymer materials were studied toward optimizing electric field penetration levels and facilitating tracking of polymer insulation properties. Simulations were performed for both unit cell and multi-finger IDC sensors.
Sensor substrate thickness was found to have a vital role in electrical field penetration level and in capacitance measurement sensitivity for both unit cell and multi-finger IDC sensors. Use of higher dielectric constant materials as substrates was not found to benefit performance of the unit cell sensor. A conductive backplane was found to provide significant performance benefits in terms of Enhanced Field Accentuation Factor (FAF) and sensitivity. However, these benefits are primarily restricted to sensors on thin substrates, preferably less than 0.2 mm. The surface charges in an IDC sensor were found to predominantly concentrate at the edges and the tips of the electrodes. Not being found to provide any benefit regarding electric field penetration depth or capacitance measurement, guard electrodes may be eliminated to facilitate sensor miniaturization.

Using these guidelines, IDC sensors were fabricated on different substrate materials to test cables that had undergone accelerated aging. IDC sensors fabricated on PCB substrates exhibited some uncertainties in measured data, such as fluctuation in capacitance due to airgap and conductor damage. To solve these challenges with conventional PCB substrates, a new flexible fabric-based IDC sensor is introduced for application on conformal curved cable surface. The proposed fabric IDC sensor is thin and flexible and is thus easy to conform to the surface of a cable. Given the sensor electrodes are made of conductive fabric pieces that are securely attached and bonded to a host nonconductive fabric using adhesive, electrode or conductor damage encountered with PCB based IDC sensors is avoided. Secondly, the new fabric IDC sensor reduces the airgap that exists between sensor electrodes and the test material enabling consistent measurement. Measurement results on the insulation of Aerial Jumper Cables show capacitance increasing by 19% from unaged to 224 hours aged cable at 160ºC accelerated aging.
temperature. Results on the EPR insulation material of the Okoguard®-Okolon® TS-CPE/EPR type cable specimens show capacitance increasing by 33% from unaged to 35-day aged cable at 140°C accelerated aging temperature. Finally, measurement results on the CPE jacket of the Okoguard®-Okolon® TS-CPE/EPR type cable specimens show capacitance increasing by 124% from unaged to 35-day aged cable at 140°C accelerated aging temperature. A comparative analysis between IDC sensors fabricated on 0.25mm thick Duroid 5880, 0.1mm thick LCP and fabric substrate showed that the airgap between sensor electrodes and cable surface was lowest for the fabric sensor. These results clearly indicate that fabric-based IDC sensors are advantageous to conventional substrate (e.g., PCB) based sensors for use on curved surfaces.

A new design of IDC sensor was introduced for thinner cables that have small circumferences and thus less available space for multifinger IDC to achieve high sensitivity. To compensate for this reduction in sensitivity, the sensor was designed with very different aspect ratio, where fewer number of electrodes was utilized but the electrode length was longer. These sensors with new design were tested on HFI jacket material of coaxial cables that had undergone accelerated aging at 120°C for 664 hours. Experimental results showed 86% increase in measured capacitance from unaged to 664 hours of aging. IDC sensors were also tested on hard insulation material like XLPE that had also undergone accelerated aging at 160°C for 1400 hours. Measured capacitance data demonstrated a 25% increase in capacitance with 1400 hours aging period. Test results on EPR and XLPE verify the effectiveness of IDC sensor in detecting insulation aging on soft as well as hard insulation materials.
Finally, the reconfigurable capacitor sensor presented in this dissertation addresses the challenge of detecting insulation aging through the cable jacket by measuring the jacket aging as well as insulation aging. Using the simulation based estimative dielectric constant models for specific cables, and measured capacitances from the two reconfiguration states of the sensor the aging related dielectric constant change of cable insulation can be extracted. The inclusion of random airgap in the simulation models ensures uncertainty incorporation as that is likely to occur during actual field measurements. Dielectric constant. Measured capacitance data using fabricated reconfigurable sensor in the switch ON mode indicate a 138% increase in jacket dielectric constant from unaged to 35 days of aging at 140°C. The relative dielectric constant of the jacket in the unaged condition is determined to be 3.36 which increases to 8 at 35 days of aging. In the switch OFF mode measured capacitance data show a 29% increase from unaged to 35 days of aging. The estimated relative dielectric constant (obtained from measured capacitance in the switch OFF mode and model 2) show that to be 2.95 for an unaged specimen which rises to 3.80 for the 35 days aged specimen. Estimated relative dielectric constant of the insulation from direct measurement on the insulation shows dielectric constant an increase by 32% from unaged to 35 days of aging. This increase in insulation dielectric constant from destructive approach verifies the estimated increase rate from the NDE approach using a reconfigurable capacitor sensor.

6.2 Future Work

The IDC sensor design, analyses and test presented in this work considers cable specimens with a single conductor. However, there are numerous applications that use multiconductor unshielded cables (see Figure 6.1). Such cables may typically contain three
layers of polymers; jacket, fillers, and insulation (wrapped around each separate conductor). The proposed thru-the-jacket permittivity measurement concept developed using a reconfigurable capacitor sensor must consider new geometrical configuration as such and design sensors to enhance both E-field penetration depth and sensitivity. New permittivity estimation models also need to be developed with included uncertainty in the models.

The permittivity estimation models developed in this work using Maxwell are appropriate for a specific cable type, the Okoguard Okolon TS CPE/EPR type cable with 22.4 mm outer diameter, 2 mm thick jacket and 3.2 mm thick insulation. To allow wide adaptability of the proposed approach other types of commonly used cables can be considered and cable specific permittivity models for specific cable types can be developed. It is understood that the reconfigurable IDC design will also likely have to adapt with changing cable scenarios. The proposed reconfigurable SRC can be considered as a starting point and other types of reconfigurable SRC or other sensors can be developed and tested.

![Figure 6.1 Schematic of an unshielded multi-conductor cable.](image)

Figure 6.1 Schematic of an unshielded multi-conductor cable.
Advanced concepts of interdigital sensing can be studied for cables with shields e.g., coaxial cables where sensors will have to become integral parts of the cable when manufactured. Key questions that need to be studied would include sensor design (including geometry, material, miniaturization, e.g., perhaps micro or nanoscale) with the cable’s shield being considered as the backplane, innovative concepts on how to excite such sensor, perform measurements, and retrieve data without damaging cable integrity. Collaboration with mechanical engineering, materials researchers could shine new light on how to circumvent some of the issues with manufacturing and reliability. Innovative sensor design may also consider the strategic locations of the conductor or conductors, the semiconducting shield, critical locations such as bend and presence of humidity that are prone to more material degradation and develop new ideas for miniaturized low-cost sensors.

Enabling wireless functionality and self-sustainment could serve as a major strength for these types of sensors. The challenges with self-sustainment include how to energize such sensors perhaps through energy harvesting from the existing wireless systems within the NPP environment, obtaining power from the cable itself through electromagnetic coupling etc. can be approached in conjunction with new sensor design concepts. Wireless data communication to and from the sensor must consider the channel, interference from cables and other objects in the environment. Electromagnetic simulations considering the NPP environment can inform any future design.

Finally, accelerated aging can be correlated with field aged cables and available elongation at break (EAB) test data to arrive at important conclusions. Although not necessarily a subject of a dissertation research but the effects of radiation and other
environmental factors on the life and usage of these sensors should be considered given the long lifespans of nuclear power plants.
REFERENCES


