Non-intrusive Microwave Surface Wave Technique For Cable Damage and Aging Detection

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NON-INTRUSIVE MICROWAVE SURFACE WAVE TECHNIQUE FOR CABLE DAMAGE AND AGING DETECTION

by

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DEDICATION

To my parents, wife, siblings, relatives, in-laws, and my amazing friends.
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ABSTRACT

Power plants, power distribution and transmission networks, automobiles, aircrafts, trains, industrial manufacturing plants etc. use a variety of cables and wires. The insulation and jacket polymer materials of cables can degrade over time due to operational stressors and environmental conditions. Materials may age, corrode, get chaffed and go missing which if remain undetected and unaddressed can result in major failures. Insulation degradation or damage detection from a distance normally involves the application of direct contact reflectometry techniques. This requires the cable to be disengaged and a diagnostic signal to be directly applied to a cable with a return path. While examples of non-conductor contact capacitive coupling associated with reflectometry and surface wave reflectometry have been proposed they are limited to detecting open or short circuit faults that result in reflected signals with large amplitudes and phase reversals. Such approaches are not suitable for insulation damage detection at various distances (and of various sizes and shapes) along the length of a cable.

This dissertation addresses that knowledge gap by focusing on studying, designing, and developing a non-conductor contact microwave surface wave reflectometry type cable diagnostic method to detect missing or damaged insulation and jacket materials on unshielded cables.

The key innovation proposed for insulation damage detection is to use a monopole type surface wave launcher (SWL) operating at high enough frequency (GHz range) that
has sufficient bandwidth and that can ensure high electromagnetic (EM) energy localization within the insulation material. A sinusoidal swept frequency broadband signal with appropriate frequency range is excited which causes the generation of surface waves that propagate along the length of the cable. The surface waves, upon reaching the location of the damaged insulation are reflected and then subsequently picked up by the SWL. The results are measured by a vector network analyzer (VNA) as one-port complex scattering (S) parameters as function of frequency. Further processing e.g., windowing and inverse-fast-Fourier transform is performed on the S parameters to determine the location and extent of the insulation damage. For example, the detection of a 4 cm-long insulation damage at 40m distance on a 50m long cable (2.44cm diameter) is demonstrated with the help of a 0.7-1.1 GHz surface wave launcher. Similarly, a 1-cm long quarter circumferential insulation damaged region is detected on a 0.3cm diameter and 61cm long wire with the help of a 5.5-8.5 GHz wave launcher. The proposed approach may be implemented on live cables as a nondestructive evaluation (NDE) method since it may be applied to the outer jacket/insulation and requires no contact to the conductor.

A second innovative aspect of this dissertation is the study, design, and development of a conformal SWL array that can be used on large diameter power cables to detect miniature insulation or jacket damage. The efficacy of the proposed approach is demonstrated by multiple simulations and experiments on a variety of cables (single conductor, multiconductor, with/without semiconducting screen etc.). Although utilization of microwave frequencies limits the distance over which the proposed method is effective, its ability to detect miniature cracks or damages without directly connecting to the
conductor makes it an excellent candidate for future cable NDE applications including on-line monitoring.

The proposed SWL being conformal easily lends to be mounted to the outer surface of the cable and can detect damages as small as the size of a slit (0.2 cm width, 1 cm length) on a 1.98 cm diameter cable with 0.58 cm thick insulation. Effects of damage detection feasibility in the presence of other cables in proximity and for cables containing semiconducting screen are also demonstrated.
TABLE OF CONTENTS

Dedication .................................................................................................................. ii

Acknowledgements .................................................................................................. iii

Abstract ..................................................................................................................... iv

Chapter 1: Introduction .............................................................................................. 1

1.1 Background ......................................................................................................... 1

1.2 Motivation and Objectives ............................................................................... 8

1.3 Organization ....................................................................................................... 12

Chapter 2: Direct-Contact Time-Frequency Reflectometry ..................................... 13

2.1 Introduction ....................................................................................................... 13

2.2 Materials and Methods ..................................................................................... 15

2.3 Simulation Results ............................................................................................. 19

2.4 Conclusion ......................................................................................................... 23

Chapter 3: Surface Wave Fundamentals and Analysis .......................................... 25

3.1 Introduction ....................................................................................................... 25

3.2 Surface Waves on a Single Conductor ............................................................. 26

3.3 Analysis of Surface Waves on an Insulated Conductor .................................... 29
3.4 Existing Surface Wave Launchers ................................................................. 44

3.5 Conclusion .................................................................................................. 47

Chapter 4: Proposed Surface Wave Reflectometry Technique ...................... 48

4.1 Introduction ............................................................................................... 48

4.2 Surface Wave Launcher and Frequency Choice ....................................... 50

4.3 Surface Wave and FDR Based Insulation Damage Detection ................ 55

4.4 Experimental Results ............................................................................... 66

4.5 Damage Detection in Multi-Conductor Cable or Conduit ....................... 70

4.6 Effect of Semiconducting Layer on Cable Insulation Damage Detection ... 74

4.7 Conclusion ................................................................................................ 78

Chapter 5: Conformal Surface Wave Launcher For Small
Insulation Damage/Aging Detection ............................................................... 81

5.1 Introduction ............................................................................................... 81

5.2 Proposed Conformal Surface Wave Launcher ......................................... 84

5.3 Simulation of Miniature Insulation Damage ............................................ 85

5.4 Experiments with Miniature Insulation Damage ..................................... 91

5.5 Aging Detection of Cable Insulation ....................................................... 94

5.6 Conclusion ............................................................................................... 99

Chapter 6: Conclusion and Future Works ..................................................... 101

6.1 Summary of Contributions ...................................................................... 101
6.2 Future Works ................................................................................................. 104

References ........................................................................................................ 106
# LIST OF FIGURES

<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.1</td>
<td>Example of cable insulation degradation: (a) water-tree formation [13], (b) cracks due to high mechanical stress [14], and (c) corrosion of cable insulation [15]</td>
<td>2</td>
</tr>
<tr>
<td>1.2</td>
<td>Cable condition monitoring techniques</td>
<td>3</td>
</tr>
<tr>
<td>1.3</td>
<td>(a) Reflectometry principle, and (b) conceptual illustration of TDR</td>
<td>5</td>
</tr>
<tr>
<td>1.4</td>
<td>Conceptual illustration of FDR</td>
<td>6</td>
</tr>
<tr>
<td>1.5</td>
<td>IDC sensors and measurement of insulation aging [55], [56]</td>
<td>6</td>
</tr>
<tr>
<td>1.6</td>
<td>Proposed non-intrusive technique for cable insulation damage and aging detection</td>
<td>11</td>
</tr>
<tr>
<td>2.1</td>
<td>Schematic comparison of TDR, FDR, and TFDR [63]</td>
<td>14</td>
</tr>
<tr>
<td>2.2</td>
<td>Construction of a 20.25 m long cable using multiple 25 cm long undamaged sections and one aged or physically damaged cable section</td>
<td>16</td>
</tr>
<tr>
<td>2.3</td>
<td>(a) Cross-section of coaxial cable, and (b) simulation model of cable end in Ansys HFSS. PVC = polyvinyl chloride</td>
<td>17</td>
</tr>
<tr>
<td>2.4</td>
<td>MATLAB-generated incident signal waveform in (a) time domain and (b) frequency domain</td>
<td>18</td>
</tr>
</tbody>
</table>
Figure 2.5. Circuit diagram representing the simulation in ADS. ..............................................18

Figure 2.6. Waveform containing incident and reflected signal for $\epsilon_r, aged = 2.60$. .................................................................20

Figure 2.7. CWT in time-frequency domain for (a) un-aged cable and (b) $\epsilon_r, aged = 2.60$ at aged section. ........................................21

Figure 2.8. Normalized CWT magnitude and (b) Relative CWT magnitude of reflected signal at dominant frequency, 102 MHz for $\epsilon_r, aged$ variation.................................................................21

Figure 2.9. Relative CWT magnitude of reflected signal at dominant frequency, 102 MHz for damage length variation.................................................22

Figure 2.10. Effect of cable attenuation on physical damage detection. .........................23

Figure 2.11. Detection two 10 cm long consecutive physical damages in a 50.250 m long cable at (a) 10 m, (b) 5 m, and (c) 2 m apart...........................................24

Figure 3.1. Typical surface waveguides. (a) Dielectric-coated plane, (b) Dielectric-coated wire, (c) Corrugated plane, (d) Corrugated Cylinder [67]..........................................................26

Figure 3.2. Surface wave propagation along the interface of two dissimilar media.................................................................27

Figure 3.3. Communication over Goubau line........................................................................28

Figure 3.4. Surface wave propagation along an insulated conductor (Goubau line). .................................................................29

Figure 3.5. (a) Confined power in dielectric and in air, and (b) surface wave velocity as a function of frequency.................................................................36

Figure 3.6. Fractional power density vs. radial distance from the cable.................................................................37
Figure 3.7. (a) Confined power in dielectric and in air, and
(b) surface wave velocity as a function of insulation thickness. ..........................38

Figure 3.8. (a) Confined power in dielectric and in air, and (b)
surface wave velocity as a function of insulation permittivity. ..........................38

Figure 3.9. (a) Confined power in dielectric and in air, and (b)
surface wave velocity as a function of conductor diameter.................................39

Figure 3.10. Exact and approximated eigenvalue equation
comparison: (a) Fractional power inside insulation and
the hypothetical cylinder and (b) surface wave velocity
when insulation thickness is varied. .................................................................40

Figure 3.11. Fractional power inside insulation and the hypothetical
cylinder for (a) $t = 0.1$ mm, and (b) $t = 3$ mm when $a = 5$ mm. ......................40

Figure 3.12. Surface wave velocity for (a) $t = 0.1$ mm, and
(b) $t = 3$ mm when $a = 5$ mm. .........................................................................41

Figure 3.13. (a) E field magnitude on a plane along a conductor,
(b) E field vector around the conductor, (c) H field vector
on a plane along the direction of propagation, (d) H field
vector around the conductor, and (e) Poynting vector
indicating the energy flow along the conductor. ..................................................42

Figure 3.14. E-field magnitude on a plane perpendicular to the
cable axis at 4 different frequencies simulated in HFSS. .................................43

Figure 3.15. (a) Goubau’s conical shape launcher, and (b) Elmore’s
slotted wave launcher [79]. ..................................................................................45

Figure 3.16. Vivaldi-style surface wave launcher proposed by
Sharma et al. [80].................................................................................................46

Figure 3.17. Conformal surface wave launcher for non-intrusive
surface wave excitation [81]. ................................................................................46
Figure 4.1. Proposed surface wave-based reflectometry method for insulation damage detection. IFFT shown in lower right. ........................................49

Figure 4.2. (a) Surface wave launcher and (b) HFSS simulation model (cable not shown)...........................................................................................................50

Figure 4.3. (a) Hypothetical cylinder surrounding the insulated conductor. (b) $R_p/a'$ vs $f_{sw}$ for $P = 50\%$. ..........................................................52

Figure 4.4. Simulated $|S_{21}|$ dB for two SWLs spaced at 61 cm on the thin wire. $w_{gnd} = 1.33\lambda$. Distance between the ground and the launcher was 0.08$\lambda$. Launchers 1 and 2 are identical. ..................54

Figure 4.5. E-field magnitude along the wire at (a) 5 GHz and (b) 8 GHz where $LSWL = 8.625 \text{ mm}$. ......................................................................54

Figure 4.6. (a) Illustration of surface wave reflection phenomenon. (b) Magnitude and phase of $S_{11}$ response, (c) Magnitude and phase of Kaiser Window (d) Transformation of the $S_{11}$ frequency response to the t-domain signal for a 3 m long thin wire with insulation missing at 2 m. ...........................................56

Figure 4.7. Performance comparison between different windowing techniques prior to IFFT. ............................................................57

Figure 4.8. Effect of $h$ on (a) reducing reflection coefficient ($S_{11}$) and (b) on insulation damage detection performance for insulation missing over 10 mm length at 2 m of a 3 m long thin wire. ..................................................................................59

Figure 4.9. Effect of the launcher length, $LSWL$ on insulation damage detection at 2 m in the same 3 m long thin wire. $w_{gnd} = 1.33\lambda$ and $h = 0.08\lambda$. ..........................................................60

Figure 4.10. Simulation results of damage detection at 1.7, 2.7, 4, and 6.5 m respectively in 3, 4.5, 6, and 8 m long thin wires. Detected damages are marked with black arrows..............................61
Figure 4.11. Simulation of insulation damage detection in 61 cm long thin wires. Tracking the growth of (a) a Type-I damage and (b) a Type-II damage at 30.5 cm. (c) Tracking the growth of a 10 mm long damage along the circumference. (d) Full circumferal damage with varying insulation depth over 10 mm section at 2 m on a 3 m long thin wire.

Figure 4.12. Effect of ground plane size and shape on damage detection performance.

Figure 4.13. Effect of an air-gap between the launcher and the cable on insulation damage detection.

Figure 4.14. Insulation damage detection for thin wire with different (a) insulation thicknesses and (b) insulation permittivity.

Figure 4.15. Simulation of insulation damage detection in a thick cable. (a) Detection of a 40 mm Type-I damage at 40 m distance in a 50 m long thick cable. Detection of (b) full-circumferential and (c) half-circumferential damage with varying width at 4 m on a 6 m cable. $f = 1 \text{ GHz}, \omega_{\text{gnd}} = 1.33\lambda$ and $h = 0.08\lambda$.

Figure 4.16. Experimental validation of the proposed method. (a) Fabricated launcher, and (b) frequency response measurement of the launcher along with a wire sample, and artificially created damage. Photographs of Type-I and Type-II damages are inset.

Figure 4.17. Experimental results demonstrating insulation damage detection on 61 cm long wire at 30.5 cm.

Figure 4.18. Experimental results demonstrating insulation damage detection on 61 cm long wire. (a) Tracking the growth of a Type-I damage, (b) Tracking the growth of a Type-II damage.

Figure 4.19. Experimental results demonstrating detection of two Type-I insulation damages at 1.425 m and 4.475 m in a 6 m long wire (marked with arrows).

Figure 4.20. Design and experimental results for a modified launcher and AW 541201 wire ($a = 1.05 \text{ mm and } t = 0.5 \text{ mm}$).
(a) Photograph of a fabricated slitted SW launcher, (b) Comparison between slitted and base SW launcher. .......................................................... 70

Figure 4.21. (a) Cross-section of a three-conductor cable and (b) Surface wave electric field magnitude along the cable axis at 4 GHz (Scale: 0-1000 V/m). ........................................................................... 71

Figure 4.22. (a) Insulation and jacket removed from top of two conductors, (b) Detecting insulation and jacket damage at 1 m distance on a 2 m long three-conductor cable. .............................................. 72

Figure 4.23. Detection of water-leak through the jacket at 1 m distance on a 2 m long cable. ................................................................................................. 73

Figure 4.24. Medium/high voltage power cable structure. Cable image on the left: Okonite cables. ...................................................................................................... 74

Figure 4.25. (a) Electric field strength as a function of distance and (b) insulation damage detection at 20 m for different thicknesses of the semiconducting layer. (c) Moving a damage to 10 m for better detection when \( t_{semi} = 2 \text{mm} \). \( (\varepsilon_r, semi = 20, \sigma_{semi} = 5 \text{ S/m}.) \) .................................................................................................................... 77

Figure 4.26. (a) Electric field strength as a function of distance, and (b) insulation damage detection for different permittivity and conductivity of the semiconducting layer when \( t_{semi} = 1.5 \text{ mm} \). ............................................ 78

Figure 5.1. (a) The SWL proposed in chapter 4 when mounted on a cable. Simulated H-fields on a plane perpendicular to the launcher at 8 GHz when cable diameter is (b) 3 mm and (c) 24 mm ................................................................. 82

Figure 5.2. Illustrating conformal surface wave launcher on cable. ............................................. 84

Figure 5.3. (a) Layout of conformal surface wave launcher array with \( N = 4 \) (\( w = 8\text{mm}, l_1 = 7\text{mm}, l_2 = 8.5\text{mm}, d = 15.5 \text{ mm}) \), and (b) simulated \( S_{11} \) when the launcher is mounted on a 3m long cable. (c) Attenuation in surface waves between two launchers mounted on two ends of a cable with varying length.
(Cable conductor diameter, $d_c = 8.2$ mm, insulation thickness, $t_{ins} = 5.8$ mm and $\varepsilon_r = 2.5$).

Figure 5.4. Insulation damage detection using conformal array launchers with $N = 2$, 4, and 8 spaced uniformly throughout the cable circumference (outer diameter (OD) = 19.8 mm, insulation thickness = 5.8 mm, relative permittivity = 2.5). Red circles refer to array elements.

Figure 5.5. Insulation damage detection using conformal array launchers with $N = 4$, spaced non-uniformly throughout the cable circumference (outer diameter (OD) = 19.8 mm, insulation thickness = 5.8 mm, relative permittivity = 2.5). Red circles refer to array elements.

Figure 5.6. Insulation damage detection (a) at 1, 2 and 4 m distances for various cable lengths and (b) at 1 m distance with variable damage width. (c) Narrow longitudinal slit-like crack detection with variable width at 1 m distance. ($d_c = 8.2$ mm, $t_{ins} = 5.8$ mm and $\varepsilon_r = 2.5$).

Figure 5.7. Effect of cables in proximity when a cable is under test. $d_c = 8.2$ mm, $t_{ins} = 5.8$ mm and $\varepsilon_r = 2.5$. Nearby cables have no damage.

Figure 5.8. Effect of insulation damage in nearby cables. ($d_c = 8.2$ mm, $t_{ins} = 5.8$ mm and $\varepsilon_r = 2.5$).

Figure 5.9. Fabricated surface wave launcher, experimental setup, and the cable construction.

Figure 5.10. Experimental results of EPR insulation and CSPE jacket damage detection on Okonite cables (a) without semiconductor layer at 0.65 m (OD = 21 mm, $t_{ins} = 1.9$ mm, $t_{jac} = 1.6$ mm), and with semiconductor layer at (b) 0.5 m and (c) 1.0 m distance (OD = 21.3 mm, $t_{ins} = 3.18$ mm, $t_{jac} = 2.03$ mm).

Figure 5.11. Experimental results of insulation and jacket damage detection for RSCC Firewall 3/C 2 AWG cable with CSPE.
jacket and XLPE insulation. OD: 25.15mm, jacket thickness: 2.03 mm, XLPE insulation thickness: 0.76 mm.

Figure 5.12. Detection of water-trees in a EPR cable with semiconducting layer. (OD = 21.3 mm, \( t_{ins} = 3.18 \) mm, \( t_{jac} = 2.03 \) mm).

Figure 5.13. Insulation aging detection scenarios simulated in HFSS.

Figure 5.14. Accelerated aging of Okoguard Aerial Jumper cable specimens in heat chamber.

Figure 5.15. (a) Insulation removed from 3 cm length on a 1.5 m long unaged cable, (b) accelerated aged 3 cm long EPR insulations for different duration, (c) placement of aged insulation on the 1.5 m long unaged cable, (d) detection of aged section using proposed conformal launcher.
CHAPTER 1
INTRODUCTION

1.1 BACKGROUND

1.1.1 PERSPECTIVES ON CABLE CONDITION MONITORING

Most of today’s power plants and grids were built in the 1950s and 1960s when the cables had a life expectancy of 40-50 years [1]. For instance, a nuclear power plant (NPP) has greater than 1000 km of power, control, and instrumentation cables [2]. Almost all commercial NPPs in operation in the United States are applying for, or have already received, license renewal permission from the Nuclear Regulatory Commission (NRC). As a result, the nuclear industry is concentrating its efforts on assuring the safe and reliable operation of NPPs’ many operating components, including the thousands of kilometers of power and signal cables that connect complex plant systems. Due to the prohibitive cost of wholesale replacement of aged cables, in-situ techniques for checking the condition of installed cables are crucial to detect concerns such as wiring insulation failures which is a precursor to failure or unreliability.

Wiring insulation failures in safety critical components can have catastrophic impacts on critical systems of power plants (both nuclear and non-nuclear), aircraft, industrial, municipal, and military installations. A major reason for cable or wiring failure is the degradation and/or physical damage to the cable’s polymer insulation and/or jacket materials. Environmental and operational stressors, such as high current, heat, pressure,
humidity, and radiation, contribute to cable insulation and jacket polymer material degradation [3]-[5]. Change in the electrical properties such as dielectric strength, permittivity and loss tangent of the insulation polymer is a consequence of such degradation. Mechanical factors such as friction, vibration, and bending can cause additional stress leading to insulation polymer fretting, cracking, and tearing [6]-[7]. The effects of some or all of these may cause the insulation or jacket material to go missing from various places on the cable. Different forms of insulation degradation are illustrated in Figure 1.1. In addition to the risk of electrical shorts, arc flash or breakdown failure from the exposed live conductors, missing insulation can lead to corrosion of the conductor, affecting long-term system performance. For safety-critical cables, non-destructive condition monitoring methods are commonly applied to ensure reliable and uninterrupted system operation [8]-[12].

![Figure 1.1. Example of cable insulation degradation: (a) water-tree formation [13], (b) cracks due to high mechanical stress [14], and (c) corrosion of cable insulation [15].](image)

1.1.2 CABLE CONDITION MONITORING TECHNIQUES

Condition monitoring for electric cables involves detection or measurement of various types of phenomena such as open or short circuit faults, insulation missing over an area, change in dielectric properties of the insulation polymer, formation of water-tree, and partial discharge [16]-[20]. The data from condition monitoring aids in the effective
management of aging and degradation in electric cables, or other accessories in a cable system, before they reach the point of failure or degraded performance, which could compromise the safe and reliable operation of the associated components and systems.

Electric cable condition monitoring techniques are basically divided into two categories: destructive and non-destructive methods (see Figure 1.2). While selecting a condition monitoring technique for a specific application, the following features must be considered.

**Destructive vs. non-destructive:** The cable specimens under test are destroyed when destructive methods are employed. For example, elongation at break (EAB) test is destructive which measures the ratio between changed length and initial length after breakage of the test specimen [21], [22]. Partial discharge (PD) test launches high voltage pulse to detect PD location which may potentially damage the insulation permanently [23]-[26].

**Intrusiveness:** The term ‘intrusive’ refers to the fact that the cables must be unplugged from their regular service prior to testing. Intrusive methods do not allow online
monitoring of live cables. The reflectometry methods are intrusive by default. Non-intrusive methods include interdigitated capacitor (IDC) sensor [27], [28], intender modulus test [29], [30], infrared thermography (IRT) [31], [32] and visual inspection.

**Local sensing vs. remote detection:** Some techniques can only monitor the cable condition where the sensors are located (e.g., IDC) or where the test is carried out (e.g., IRT). Reflectometry techniques, on the other hand, can monitor cable condition at a distance from the testing point.

**In-situ vs. ex-situ:** Some tests such as IDC sensing and reflectometry are performed at cables’ location while some are performed on cable specimen in laboratory such as EAB testing.

Our work primarily focuses on in-situ reflectometry methods. Some of the methods are described in brief.

1.1.2.1 **TIME DOMAIN REFLECTOMETRY (TDR)**

A stepped signal or a time limited pulse is launched along a cable through a direct electrical connection between the cable and the testing device [33]-[38]. While traveling along the cable, a reflection is generated when the signal finds any discontinuity such as open/short circuit faults and insulation aging/damage as shown in Figure 1.3(a). The distance of the discontinuity is determined using the time lag between the incident and reflected pulses (see Figure 1.3(b)). The magnitude of the reflected pulse indicates the extent of the discontinuity. The efficacy of the method is limited by the distortion in pulse due to noise, attenuation, and dispersion. A pulse generator and an oscilloscope are the primary components of TDR system. Partial discharge (PD) testing [34] employs TDR which focuses on electrical discharge detection initiated from small voids present within
the insulation at a very low frequency (<60 Hz), which could be a good forecaster for future water-tree formation.

![Frequency Domain Reflectometry (FDR) principle and conceptual illustration of TDR.](image)

**1.1.2.2 Frequency Domain Reflectometry (FDR)**

Frequency domain reflectometry utilizes band limited swept frequency signal as input signal [39]-[43]. The response of the cable segment (reflection coefficient or impedance) at each frequency is measured. This frequency domain response is converted to time domain using inverse Fourier transform (IFT) (see Figure 1.4). Then result in time domain is interpreted similarly as TDR. It is less accurate than TDR in terms of location detection. This accuracy is limited by the signal bandwidth. However, FDR is inherently better at noise suppression than TDR.

There are other reflectometry methods that are derived from TDR and FDR such as time-frequency domain reflectometry (TFDR) [44], [45], spread spectrum TDR (SSTDR)
sequence TDR (STDR) [49], line resonance analysis (LIRA) [50], [51], broadband impedance spectroscopy (BIS) [52], [53] and so on.

1.1.2.3 **INTERDIGITATED CAPACITOR (IDC) SENSOR**

IDC based monitoring is a non-intrusive approach that measures the change in insulation permittivity due to aging. Aging causes the permittivity of the insulation to change, which is reflected as a change in the capacitance measured by the sensor (see Figure 1.5) [54]-[56]. However, the IDC can only measure the insulation aging directly beneath its surface because the electric fields established by its electrodes are localized under the sensor and cannot propagate beyond. IDC sensors are consequently of little value...
in cases where the sensor is located at position A, the insulation damage is at position B, and A and B are separated by a significant distance.

1.1.3 **Existing Works on Cable Insulation Degradation Monitoring**

In terms of cable insulation damage detection, Fantoni et al. [57] presented an intrusive FDR-based line resonance technique that could detect cuts or gouges on the jacket and insulation at 24 m distance on two and three conductor wires. Ohki et al. [58] applied an intrusive FDR-based technique to detect removed insulation and polymer sheath over a length of 10 cm at 10 m distance in a duplex cable with 2 mm² cross-section conductors, 0.8 mm thick insulation, and 1.5 mm thick jacket. In another report [59], using the same method, they detected a vented water tree (a 3 mm diameter hole in the insulation filled with NaCl solution) at 20 m distance on a coaxial cable (8.5 mm outer diameter). Glass et al. [60] introduced an FDR-based intrusive technique to locate a 38 mm long gouge on the jacket, outer conductor, and insulation at 15 m distance on a coaxial cable (4.95 mm outer diameter). In addition, they also detected the jacket removal over a length of 89 mm at 15 m distance on a 600V triad cable. All the works discussed above used direct-contact reflectometry to locate the insulation and/or jacket damage. Also, the frequencies used were around 200 MHz for FDR. In [61], Shin et al. reported their work on the detection of open and short circuit faults and ‘damage’ locations in coaxial cables using TFDR at up to 40 m distance. They emulated ‘damage’ by a failure of the external shields exposing the internal dielectric over 1 cm. In [62], the application of TFDR was focused on accelerated aging detection over 1 m length at 5-6 m distance in two-conductor ethylene-propylene rubber (EPR), cross-linked polyethylene (XLPE) and silicone rubber (SiR) insulated cables.
Motivation and Objectives

Majority of the existing insulation condition monitoring methods are primarily based on offline or intrusive techniques where the cables need to be disconnected from their usual service prior to testing. This approach cannot be used for real-time online monitoring. Also, for cables without a shield (whether single to multiconductor) transverse electromagnetic (TEM) wave type signal injection and reflectometry is very challenging because of the lack of two conductors forming a TEM type line. For both real-time online monitoring and for cables without a return signal path (e.g., non-coaxial) non-conductor contact method of cable NDE is highly desirable.

Among non-conductor-contact cable NDE techniques, inductive or capacitive signal couplers along with reflectometry methods have been proposed to detect open and short circuit faults [82], [83]. These have been applied to single conductor systems without the need for a return path. These methods can be suitable for online real-time monitoring provided they do not lead to interference to the intended signal. In [82], Wu et al. proposed a capacitive signal probing mechanism that could locate open-circuit faults on 18-gauge aircraft wires at different distances using a TDR-based technique. Gao et al. [83] reported a non-conductor-contact inductive coupling method for cable fault diagnosis. Their work demonstrated open and short circuit fault detection at 15.1 m distance on 1.6 mm diameter wires using spread spectrum TDR (SSTDR) technique.

In earlier work from our research group Alam et al. [84]-[85] proposed a non-conductor-contact surface wave technique which when combined with TDR could detect the presence of open circuit faults on a cable. A broadband surface wave reflectometry (SWR) approach was introduced that allowed a TDR signal to be launched on an
unshielded power cable without direct contact to the cable conductor. The proposed surface wave sensor with TDR operating at a center frequency of 250 MHz was able to detect an open-circuit fault at 9.45 m distance from the sensor on an 18 mm diameter power cable.

It is clear from the above discussions that only very limited works have been reported on non-conductor contact cable NDE of which most including our own group’s work focused on short or open circuit fault location detection.

The non-conductor-contact cable NDE approaches reported in [82] and [83] focused only on detecting open or short circuit faults. There is no evidence that these techniques would be effective in detecting insulation damages. As well known, for open or short circuit faults, the magnitude of the reflected signal is very high allowing relatively easy detection even from a large distance which is not the case for insulation damage detection. For the latter, the magnitude of the reflection coefficient would be small and would largely depend on the damage size, damage location, cable insulation type, insulation thickness and cable type.

Therefore, surface wave techniques that rely on GHz frequency waveforms with substantial bandwidth could be more appropriate to detect such damage. That is the primary focus of this dissertation. This dissertation introduces a novel surface wave based cable NDE reflectometry technique that can be effectively used to detect cable insulation and/or jacket damage on a variety of cables with varying diameters, lengths, insulation property, insulation thickness, damage size, and damage distance. To the best of our knowledge this has not been done before.

In contrast to the TDR-based surface wave cable NDE method reported by our own group [84], [85] which used a 250 MHz TDR signal to detect open circuit faults in this
work we propose both a 1 GHz and a 8 GHz surface wave based cable NDE technique that can be used to detect insulation damages on thick and thin cables, respectively. We show that higher frequencies allow detection of damages with smaller resolution while lower frequencies allow detection over longer distances especially for large diameter cables.

The key innovation proposed for insulation damage detection is to use a surface wave launcher (SWL) operating at high enough frequency (GHz range) that has sufficient bandwidth and that can ensure high EM energy localization within the insulation material. As shown in Figure 1.6 a non-conductor-contact surface wave launcher consisting of a cylindrical monopole and a ground plane is connected to a testing device which is a vector network analyzer (VNA) in this case. A sinusoidal swept frequency broadband signal with appropriate frequency range is excited between the monopole and the ground plane which causes the generation of surface waves that propagate along the length of the cable. The surface waves, upon reaching the location of the damaged insulation are reflected and then subsequently picked up by the SWL. The results are measured by a vector network analyzer (VNA) as complex $S_{11}$ as function of frequency. Further signal processing is performed on the $S_{11}$ to determine the location of the insulation damage. Later, a surface wave launcher array is proposed which has a conformal ground and it is demonstrated to detect much smaller damages such as cracks in the insulation and insulation aging.

Applied electromagnetics-based study of cable insulation aging or damage detection is a significant research area with a vast scope of work. Microwave sensors that monitor cable insulation non-intrusively have great potentials where full-length cables are not visible or physically accessible. Non-intrusive approaches for various sorts of cables, such as single and multi-conductor cables, cables of various diameters and insulation
thicknesses, cables with semiconducting screens, multiple wire carrying conduits, and so on, must be investigated. Detecting age-related deterioration, water-tree development, and small fractures or wears in cable insulation is just as critical as detecting larger cable defects. The object detection capability external to the cable such as ice formation around cables, tree branches fallen on overhead cables etc. may be considered as a valuable feature for a cable condition monitoring system.

The major thrust of this research is on microwave sensors and sensing techniques for aging or damage detection on cable insulation. In addition to the above, a conformal surface wave based non-intrusive reflectometry technique is also introduced that can detect mm-size insulation damages and track their growth on unshielded wires and cables. The sensor may be uniquely and practically implemented on live cables as a non-intrusive method since it may be applied to the outer insulation/jacket of a cable and requires no direct contact to the conductor. The feasibility study of surface wave reflectometry is presented for different type of cables such as single and multi-conductor cables, thin

Figure 1.6. Proposed non-intrusive technique for cable insulation damage and aging detection.
control and instrumentation cables, thick power cables, cables with semiconducting screen, and so on.

1.3 Organization

This dissertation is organized as follows. Before embarking on non-conductor contact method of cable NDE Chapter 2 presents a preliminary simulation study of insulation damage/aging detection for coaxial cables using direct-contact TFDR. The purpose is to explore and understand the various simulation studies to be undertaken and to understand the scope of reflectometry methods for simpler direct-contact configurations. Chapter 3 describes the fundamentals of surface wave propagation on an insulated conductor. Chapter 4 presents the proposed non-conductor-contact surface wave reflectometry for cable insulation damage detection. It includes simulation and experimental results. This chapter also delineates further studies on multi-conductor cables and cables with semiconductor screening. Chapter 5 presents a wideband planar surface wave launcher that allow minute insulation damage detection on variety of cable types and sizes. This chapter shows simulation and experimental results on insulation damage and aging detection. Chapter 6 summarizes the contributions of this dissertation and suggests some possible future works.
CHAPTER 2
DIRECT-CONTACT TIME-FREQUENCY REFLECTOMETRY

2.1 INTRODUCTION

Although the primary focus of this dissertation is cable insulation and jacket damage and degradation detection using non-conductor-contact technique preliminary studies to gain understanding on reflectometry thru direct-contact technique based on Ansys High Frequency Structure Simulator (HFSS) and circuit based Keysight Advanced Design System (ADS) co-simulations seemed necessary. Since cable damage/aging detection involves long lengths of cables a segmentation approach is considered to minimize computational load. To gain fundamental understanding on HFSS/ADS co-simulation we consider direct-contact time-frequency domain reflectometry (TFDR) [44], [45], [63], [64]. Nevertheless, as we will show in subsequent chapters frequency domain reflectometry (FDR) can also be used when appropriate signal processing methods are used in conjunction with that. It has been demonstrated that real-life field aging of cable under operating and environmental conditions causes the relative permittivity of the insulation and the jacket to change [3], [56]. In our studies, insulation aging is simulated by changing the permittivity of the insulation material while insulation damage is simulated by removing a small section of the insulation over a length of the cable.

TFDR was first proposed by Shin et al. [63]. Time domain reflectometry (TDR), FDR, and TFDR reference signals are schematically shown on a time frequency plane in
Figure 2.1. TDR compares the incident and the reflected signals in the time domain alone. TDR employs a pulse with a limited time span and compares the reference and reflected signals in the time domain only. As a result, TDR is unable to assess the signal in the frequency domain since the energy of an ideal step pulse is dispersed across a wide range of frequencies at the instance of the impulse. FDR, on the other hand, employs a range of sinusoidal signals with a defined frequency bandwidth and examines just the signal's change in the frequency domain. As a result, it is not possible to utilize FDR to evaluate a signal in the time domain since a pure sinusoidal signal, which serves as a reference signal in FDR, has an unlimited time duration in theory. TFDR signal can be investigated in both time and frequency domain since it is limited in both domains as shown in Figure 2.1.

![Schematic comparison of TDR, FDR, and TFDR](image)

Figure 2.1. Schematic comparison of TDR, FDR, and TFDR [63].

In this chapter, TFDR is applied to study the progression of insulation aging and physical damage over a small area in an XLPE coaxial cable based on a proposed
simulation scheme consisting of full-wave HFSS simulation and circuit based Keysight ADS simulation. Attenuation due to conductor and dielectric losses as well as effects of multiple reflections are considered. Cables containing physical damage are compared with undamaged cables. Also, cables with a section where the insulation permittivity changed is compared with cables that do not have any permittivity change. HFSS results come in the form of scattering (S) parameters as function of frequency which are exported from HFSS in the form of touchstone data. These simulated S-parameters are then imported within ADS in the form of a circuit block. To perform TFDR analysis a chirplet is launched in the ADS model that includes the S-parameter date from HFSS. Once a reflection ensues either due to insulation damage or aging the reflected signal is retrieved from ADS. Further analysis using continuous wavelet transform (CWT) is performed on the ADS results which delineate the location and extent of the physical damage or aging.

2.2 MATERIALS AND METHODS

2.2.1 FINITE ELEMENT MODELING AND HFSS SIMULATION

Cable models in HFSS were developed by cascading multiple sections of 50Ω RG58 coaxial cable segments, of which one of several sections was considered as a test case. To monitor cable insulation aging simulations, the relative permittivity of the insulation material for a small cable section was varied. To detect the location of insulation or jacket damage to the jacket, outer conductor, and insulation were created on a small section of the cable.

In HFSS, a 25 cm long undamaged cable section consisting of original parameters i.e., no damage or aging was first modeled and simulated to use it as a building block to create models of the two undamaged portions of a long cable (see Figure 2.2). A separate
simulation model of a separate 25 cm long cable section was created where either the relative permittivity of the insulation was varied, or a damage was created. This section is shown using red color in Figure 2.2. For instance, Figure 2.2 shows how a 20.25 m long cable simulation model was constructed using one 25 cm long test cable (red) section and eighty undamaged (blue) sections (each 25 cm long) of the cable.

The above approach was adopted to save HFSS simulation time. The cable considered had the following parameters: diameter of inner conductor = 0.91 mm, insulation thickness = 1.02 mm, thickness of outer conductor = 0.28 mm, and jacket thickness = 0.72 mm. The relative permittivity, $\varepsilon_r$ and loss tangent of the insulation material were 2.30 and 0.002, respectively, for the undamaged cable sections. The cable cross-section is shown in Figure 2.3(a).

![Figure 2.2. Construction of a 20.25 m long cable using multiple 25 cm long undamaged sections and one aged or physically damaged cable section.](image)

Each 25 cm long section was modeled and simulated in HFSS as a 2-port module. The excitation within the simulation model was created as shown in Figure 2.3(b). The inner conductor of the cable was made 1 mm shorter than the insulation at each end which created a feed gap (green color). A metal disk was placed at each end. A lumped 50 $\Omega$ gap excitation was created on each end to construct a 2-port simulation model. S-parameter simulations were performed within the frequency range of 1 to 250 MHz.
A Gaussian windowed linear chirp waveform was generated in MATLAB with a center frequency, $f_c = 100$ MHz, bandwidth, $BW = 80$ MHz, and time spread, $T = 100$ ns using (2.1) - (2.4) based on [65].

$$y(t) = \cos(2\pi f(t)t) \times \exp\left(-\frac{(t - t_0)^2}{2\sigma^2}\right) \quad (2.1)$$

$$f(t) = \frac{m}{2}t + f(0) \quad (2.2)$$

$$f(0) = f_c - \frac{BW}{2} \quad (2.3)$$

$$m = \frac{BW}{T} \quad (2.4)$$

Here, the parameters are time center, $t_0 = T/2$, standard deviation of this Gaussian window, $\sigma = t_0/4$, and the chirp rate, $m = BW/T$. Figure 2.4 shows the incident waveform in both (a) time and (b) frequency domains.
HFSS-simulated S-parameter data for each cable section were exported from HFSS and imported into ADS. In ADS, the 2-port HFSS-simulated S-parameter data were represented as SnP (n-port S-parameter file) blocks, as illustrated in Figure 2.5. A total of 81 SnP blocks were used to simulate the 20.25 m long cable. Each of the first 40 and the last 40 of the SnP blocks (color blue) contained S-parameters of the undamaged or un-aged cable section, while the red one at the center contained the S-parameters of the test cable section. At the end of this 20.25 m length, an open circuit was modeled by placing a 50
MΩ resistor. At the input of the circuit model in Figure 2.5, a signal generator was created to launch the chirplet waveform into the cable. This voltage source block was loaded with a waveform file exported from MATLAB.

2.3 Simulation Results

2.3.1 Insulation Aging Detection by Permittivity Variation

Researchers have demonstrated by capacitance measurement conducted on cable specimens that had undergone accelerated aging tests that the relative permittivity of the insulation and the jacket materials generally increase with aging [56]. Accelerated aging conducted using the modified Arrhenius equation represents real-life field aging that reflect certain operating temperature and age. For example, accelerated aging (140°C for 35 days) of cable sections has shown insulation relative permittivity increase by more than 30% for Okoguard®-Okolon® cables with EPR insulation [56].

In the HFSS simulations, the relative permittivity of the insulation of the test cable section, $\varepsilon_{r, aged}$ was increased by 13%, i.e., ($\varepsilon_r = 2.3$ in the beginning which was increased to 2.6). Small changes in relative permittivity were particularly the focus of this investigation because those are more likely to occur in service [56]. Figure 2.6 shows an example of the resulting waveform (V1 in Figure 2.5) from ADS that contains both the incident and the reflected signals when the relative permittivity increases to $\varepsilon_{r, aged} = 2.60$. Especially to be noted is the waveform labeled as “Reflection from aged section” which occurred because the relative permittivity of the insulation increased from 2.30 to 2.60 in the test section.
A built-in MATLAB function “cwt ()” was used to perform the CWT using an analytic Morse Wavelet. The CWT output variable is a 2-D matrix where each column of the data is for a certain time instant, and each row is for a certain frequency. Figure 2.7 shows the time-frequency scalogram for un-aged cable (Figure 2.7(a)) and for \( \varepsilon_{r, \text{aged}} = 2.60 \) (Figure 2.7(b)) at aged section.

For each value of relative permittivity, the dominant frequency at which the CWT peak occurred in the above magnitude scalogram was determined. That frequency was the same for each case, 102 MHz. At 102 MHz, the CWT magnitude, \( z(d) \) as a function of distance, \( d \) was found using (2.5) as follows.

\[
d = \frac{c \times vf \times t}{2}
\]

where \( c = 3 \times 10^8 \frac{m}{s} \) and velocity factor, \( vf = 1 / \sqrt{\varepsilon_r} = 0.66 \) in this case.

The CWT magnitude for each permittivity \( (\varepsilon_{r, \text{aged}}) \) variation is plotted in Figure 2.8(a), which shows the location of the peak to be 10.125 m. As expected, the magnitude of the peak increases as \( \varepsilon_{r, \text{aged}} \) increases with almost a linear slope of \( \approx 0.029/0.3 = 0.1 \).
The CWT magnitudes relative to the un-aged baseline, $z_{rel}(d)$ case is plotted in dB in Figure 2.8(b) using (6).

$$z_{rel}(d) = 10 \log(z(d)_{aged} - z(d)_{baseline}) \text{ dB}$$

(3.6)

Figure 2.7. CWT in time-frequency domain for (a) un-aged cable and (b) $\varepsilon_{r, aged} = 2.60$ at aged section.

Figure 2.8. Normalized CWT magnitude and (b) Relative CWT magnitude of reflected signal at dominant frequency, 102 MHz for $\varepsilon_{r, aged}$ variation.

This relationship shows that a change in $\varepsilon_{r, aged}$ from 2.35 to 2.40 causes a 4 dB change in the relative CWT magnitude.

The spread, $\delta$ of the peak in spatial (distance) domain can be calculated using (2.7).

$$\delta = \frac{c \times v_f \times T}{2}$$

(2.7)
For $T = 100$ ns, $\delta = 9.9$ m according to (7).

### 2.3.2 Physical Damage Detection on Cable

A simulation model consisting of a physical damage can be seen from Figure 2.9 where the jacket, the outer conductor, and the insulation were all removed from half of the circumference over a small length of the test cable section. The length of the damaged section was varied from 1 cm to 10 cm. Figure 2.9 shows the relative CWT magnitude in dB for each variation considering the undamaged cable as the reference. The peak relative CWT magnitude changes linearly with damage length with an initial rate of around 2.5 dB per cm. The rate of change decreases to as low as 0.7 dB per cm as the damage length increases beyond 7 cm.

![Figure 2.9](image)

Figure 2.9. Relative CWT magnitude of reflected signal at dominant frequency, 102 MHz for damage length variation.

### Effect of Attenuation on Physical Damage Length

A 50.25 m long cable was simulated to investigate the effect of attenuation on the proposed physical damage detection method. A 10 cm long physical damage was created first at 15.125 m on a 50.25 m long cable. Then it was moved to 35.125 m. Figure 2.10
shows the results. As apparent, the CWT magnitude decreases by about 2.2 dB for the latter case (peak at 35.125 m distance) due to attenuation.

![CWT Magnitude Plot](image.png)

Figure 2.10. Effect of cable attenuation on physical damage detection.

**Two Sections with Physical Damage**

Simulations of a 50.25 m long cable containing two sections with physical damage were conducted, considering the distance between them as the parameter. Figure 2.11 shows the CWT magnitude plots for various cases. When the distance between two consecutive reflections is $< \delta$, which is 9.9 m, the corresponding peaks start to overlap (see Figure 2.11(b)). When the distance is $< \delta/2$, differentiating the two peaks becomes difficult (see Figure 2.11(c)).

**2.4 Conclusion**

A direct-contact HFSS/ADS co-simulation technique of cable insulation aging and damage detection using TFDR is introduced. The presented results reveal that small changes in the relative permittivity of the insulation material, reflective of cable service aging, can be detected in the CWT magnitude from the analysis. The same is the case concerning physical damage location detection. The effect of attenuation and detection of more than one physical damage location are also presented.
Detection two 10 cm long consecutive physical damages in a 50.250 m long cable at (a) 10 m, (b) 5 m, and (c) 2 m apart.
CHAPTER 3
SURFACE WAVE FUNDAMENTALS AND ANALYSIS

3.1 INTRODUCTION

The primary focus of this dissertation is to develop devices, methods, and techniques to launch, propagate and then retrieve (upon reflection) electromagnetic (EM) surface waves (SW) along unshielded insulated wires and cables to detect insulation damage and aging on such cables/wires. Successful launch and propagation of EM surface waves will require using cables as waveguides. The fundamentals of SW waveguides are discussed in this chapter including solution of wave equations for such waveguides, surface wave energy, and the effects of various parameter variations such as SW frequency, conductor diameter, insulation thickness and insulation material permittivity.

Along with more well-known commonly used transmission lines and waveguides e.g., microstrip lines, coaxial lines, and rectangular/circular closed waveguides, there exists a class of open-boundary structures, which can guide EM wave propagation as surface waves. Dielectric-coated conducting planes or rods, conducting rods with finite conductivity or corrugated surface, and cylindrical dielectric rods fall under this category. These types of electromagnetic waves travel along the interface between two different media and thus they are called surface waves (SW). The structures capable of guiding such waves are called surface waveguides [66]. Figure 3.1 shows some typical surface waveguides [67].
Surface waves propagate along the axis of these types of structures. EM fields of surface waves are closely bound to the interface and decay exponentially away from the interface. As there is only one or no conductor (for conductor type SW waveguides) present here, TEM mode of propagation cannot exist for these types of structures. Hence the mode of propagation is Transverse Magnetic (TM) or Transverse Electric (TE) [68]. Higher order hybrid modes also exist for the surface waveguides which have both electric and magnetic field components in the direction of propagation [68], [69].

3.2 SURFACE WAVES ON A SINGLE CONDUCTOR

The study of surface waves dates back many years. Surface wave propagation was first theoretically investigated by Sommerfeld [70] and then Zenneck [71]. In 1899, Sommerfeld published a theoretical paper on wave propagation on the surface of a cylindrical wire with finite conductivity, which has much lower attenuation than a coaxial cable. The key points from his work are [72]:

- A cylindrical conductor with finite conductivity can support infinite number of propagating modes. The amplitudes of these modes depend on the nature of the sources.
• Fundamental TM$_{00}$ mode has the lowest attenuation. Higher order modes with higher cutoff frequencies have higher attenuation.

• Conductivity of the conductor may be high but must be finite. If the conductivity increases, the radial field spread increases. Therefore, at some point when conductivity is increased indefinitely the power carried by a wave of finite amplitude would be infinite which is not feasible in practical sense.

Due to large radial field spread, such propagation was subject to considerable loss of power by radiation at any discontinuity such as bend or kink or obstacles. This is another reason why it was not practically suitable for long distance communication.

In 1907, Zenneck published his work on surface wave propagation on an infinitely large plane interface between a conductor and a dielectric, which also had low attenuation. He showed theoretically that surface waves were non-radiating but remained concentrated near the surface. Figure 3.2 shows a conceptual illustration of surface wave propagation.

![Field Strength decreasing with distance](image)

Figure 3.2. Surface wave propagation along the interface of two dissimilar media.

However, both the Sommerfeld and Zenneck waves largely remained theoretical exercises since the problem of providing a finite power source capable of generating either
of these waves seemed difficult for practical implementation [73]. In 1950, Goubau [74] introduced a practical approach of exciting surface waves on a conductor. The conclusions from Goubau’s work are [72]:

- Surface waves could propagate along a conductor independent of conductivity if the phase velocity of the wave can be reduced suitably by modifying the surface of the conductor.
- Goubau proposed the use of a conducting rod with threaded surface and a conducting rod with dielectric coating as surface wave transmission line. The latter is known as G-Line after his name which is illustrated in Figure 3.3.
- Coated surface or threaded surface of the G-line makes the radial fields more concentrated near the surface compared to which is possible for a Sommerfeld guide.
- The G-Line has higher loss compared to the theoretical Sommerfeld guide. It includes ohmic loss (also present in Sommerfeld guide), dielectric loss due to coating and loss due to the limited efficiency of the launchers.

![Figure 3.3. Communication over Goubau line.](image)
• The Poynting vector integrated over a plane perpendicular to the direction of propagation yields a finite power density output which allows practical application consideration.

3.3 Analysis of Surface Waves on an Insulated Conductor

3.3.1 Derivation of the Wave Equations

Figure 3.4 shows the structure of a surface wave transmission line or a Goubau line. It has a conductor with radius $a$ and insulation with thickness, $t$. Outer radius of this line is, $a' = a + t$. The relative permittivity of the insulation is greater than that of air or vacuum ($\varepsilon_r > 1$). The direction of propagation is $+Z$.

Since cylindrical geometry is involved, it is appropriate to employ cylindrical coordinates. The wave equation is first solved for $E_Z$ or $H_Z$ and the transverse fields in cylindrical coordinates can be derived from $E_Z$ or $H_Z$ field components for TM or TE modes respectively using (3.1) - (3.4) [67].

$$E_\rho = \frac{-j}{k_c^2} \left( \beta \frac{\partial E_Z}{\partial \rho} + \omega \mu \frac{\partial H_Z}{\partial \phi} \right)$$ (3.1)

$$E_\phi = \frac{-j}{k_c^2} \left( \beta \frac{\partial E_Z}{\partial \phi} - \omega \mu \frac{\partial H_Z}{\partial \rho} \right)$$ (3.2)

$$H_\rho = \frac{j}{k_c^2} \left( \omega \varepsilon \frac{\partial E_Z}{\partial \phi} - \beta \frac{\partial H_Z}{\partial \rho} \right)$$ (3.3)
\[ H_\phi = \frac{-j}{k_c} \left( \omega \varepsilon \frac{\partial E_Z}{\partial \rho} + \frac{\beta}{\rho} \frac{\partial H_Z}{\partial \phi} \right) \] (3.4)

Here, cut-off wave number: \( k_c^2 = \varepsilon_r k_0^2 - \beta^2 \), \( k_0 = (2\pi/\lambda_o) \) is the wave number in the air, \( \lambda_o \) is the wavelength in air, and \( \beta \) is the propagation constant. \( e^{-j\beta z} \) propagation is assumed. TM\(_{00}\) is the mode of interest in this report. For TM mode, \( H_Z = 0 \). Therefore, the second parts after the plus signs in (3.1) - (3.4) will be zero and \( E_Z \) will provide the solution to the wave equation,

\[ \nabla^2 E_Z + k^2 E_Z = 0 \]

Surface waves propagate in both the air and dielectric regions. If \( E_Z(\rho, \phi, z) = e_Z(\rho, \phi)e^{-j\beta z} \), the above equation can be expressed in cylindrical coordinates as

\[
\left( \frac{\partial^2}{\partial \rho^2} + \frac{1}{\rho} \frac{\partial}{\partial \rho} + \frac{1}{\rho^2} \frac{\partial^2}{\partial \phi^2} + k_c^2 \right) e_Z(\rho, \phi) = 0 \quad a \leq \rho \leq a' \quad (3.5)
\]

\[
\left( \frac{\partial^2}{\partial \rho^2} + \frac{1}{\rho} \frac{\partial}{\partial \rho} + \frac{1}{\rho^2} \frac{\partial^2}{\partial \phi^2} - b^2 \right) e_Z(\rho, \phi) = 0 \quad a' \leq \rho \leq \infty \quad (3.6)
\]

Here, \( k_c^2 = \varepsilon_r k_0^2 - \beta^2 \) is the cut-off wavenumber in dielectric and \( b^2 = \beta^2 - k_0^2 \) is the cut-off wavenumber in air. The sign on \( b^2 \) has been selected in anticipation of an exponentially decaying result for \( \rho > a' \). The same propagation constant, \( \beta \) is considered for both regions to achieve phase matching of the tangential fields at \( \rho = a' \) interface for all values of \( z \). General solution of (3.5) and (3.6) are respectively,

\[ e_Z(\rho, \phi) = [A_1 J_n(k_c \rho) + B_1 Y_n(k_c \rho)] \times [C_1 \sin(n \phi) + D_1 \cos(n \phi)] \]

where \( a \leq \rho \leq a' \) \hfill (3.7)

\[ e_Z(\rho, \phi) = [A_2 I_n(b \rho) + B_2 K_n(b \rho)] \times [C_2 \sin(n \phi) + D_2 \cos(n \phi)] \]

where \( a' \leq \rho \leq \infty \) \hfill (3.8)
\( J_n \) and \( Y_n \) are the Bessel function of the first and the second kind, respectively and \( I_n \) and \( K_n \) are the modified Bessel’s function of the first and the second kind, respectively. \( A_i, B_i, C_i \) and \( D_i \) are constants which depend on the source. For the TM_{00} mode, \( n = 0 \). In (4.8), the \( I_n \) function rises exponentially with \( \rho \) while fields decay exponentially with \( \rho \) after \( \rho > a' \). Therefore, \( A_2 = 0 \). Finally, (3.7) and (3.8) becomes,

\[
e_Z(\rho, \phi) = \begin{cases} 
AJ_0(k_c \rho) + BY_0(k_c \rho) & a \leq \rho \leq a' \\
CK_0(b \rho) & a' \leq \rho \leq \infty 
\end{cases} \tag{3.9}
\]

where \( A, B \) and \( C \) are new constants. It is clear that, \( \partial e_Z / \partial \phi = 0 \). Thus, from (3.2) and (3.3), it is found that, \( E_\phi = 0 \) and \( H_\rho = 0 \). Hence using (3.4), it is found that,

\[
h_\phi(\rho, \phi) = \begin{cases} 
-j\omega \varepsilon_0 \varepsilon_r [AJ_1(k_c \rho) + BY_1(k_c \rho)] & a \leq \rho \leq a' \\
j\omega \varepsilon_0 [CK'_0(b \rho)] & a' \leq \rho \leq \infty 
\end{cases} \tag{3.10}
\]

where \( J'_0, Y'_0 \) and \( K'_0 \) are derivatives of the zeroth order functions \( J_0, Y_0 \) and \( K_0 \).

From Bessel function properties it is known that,

\[
J'_0(x) = -J_1(x) \\
Y'_0(x) = -Y_1(x) \\
K'_0(x) = -K_1(x)
\]

Therefore, (3.10) becomes,

\[
h_\phi(\rho, \phi) = \begin{cases} 
-j\omega \varepsilon_0 \varepsilon_r [AJ_1(k_c \rho) + BY_1(k_c \rho)] & a \leq \rho \leq a' \\
-j\omega \varepsilon_0 [CK_1(b \rho)] & a' \leq \rho \leq \infty 
\end{cases} \tag{3.11}
\]

**Boundary conditions:** At metal-dielectric interface \( \rho = a \), \( e_Z = 0 \). Using (3.9), it can be written that,

\[
AJ_0(k_c a) + BY_0(k_c a) = 0
\]
\[ B = -\frac{A J_0(k_c a)}{Y_0(k_c a)} \quad (3.12) \]

Tangential electric and magnetic fields \( E_z \) and \( H_\phi \) are continuous in the interface at \( \rho = a' \). From (3.9), it can be written that,

\[ A J_0(k_c a') + B Y_0(k_c a') = C K_0(b a') \quad (3.13) \]

Using (3.12) and (3.13), it can be written that,

\[
\frac{C}{A} = \frac{J_0(k_c a')Y_0(k_c a) - J_0(k_c a)Y_0(k_c a')}{K_0(b a')Y_0(k_c a)} \quad (3.14)
\]

And applying boundary condition in (3.11), the following is found.

\[
\frac{\varepsilon_r}{k_c} [A J_1(k_c a') + B Y_1(k_c a')] = -\frac{1}{b} [C K_1(b a')] \quad (3.15)
\]

The following can be written using (3.12) and (3.15).

\[
\frac{C}{A} = \frac{\varepsilon_r b}{k_c} \left[ J_0(k_c a)Y_1(k_c a') - J_1(k_c a')Y_0(k_c a) \right] \quad (3.16)
\]

Combining (3.14) and (3.16), the eigenvalue equation can be written as in (3.17).

\[
\frac{K_1(b a')}{b K_0(b a')} = \frac{\varepsilon_r}{k_c} \times \frac{J_0(k_c a)Y_1(k_c a') - J_1(k_c a')Y_0(k_c a)}{J_0(k_c a')Y_0(k_c a) - J_0(k_c a)Y_0(k_c a')} \quad (3.17)
\]

(3.17) is used in Subsection 3.2.2.3 along with some other equations to determine the relationship analytically between the surface wave power concentration and different parameters such as frequency, insulation thickness, conductor diameter etc.
3.3.2 POWER IN A SW TRANSMISSION LINE

3.3.2.1 POWER TRANSMITTING THROUGH AIR

Poynting vector corresponding to the surface wave propagation is defined as: \( \vec{S} = \vec{E} \times \vec{H} \). Since \( E_{\phi} = H_{\rho} = H_z = 0 \), the z-component of \( \vec{S} \) is a function of \( E_{\rho} \) and \( H_{\phi} \) which contributes to the wave propagation along the insulated conductor.

The amount of power transmitted through air can be calculated using the following equation.

\[
P_{air} = Re \left( 2\pi \int_{\alpha'}^{\infty} \rho E_{\rho}H_{\phi}^* d\rho \right) \quad (3.18)
\]

Here, \( E_{\rho}(\rho, \phi, z) = e_{\rho}(\rho, \phi)e^{-j\beta z} \) and \( H_{\phi}(\rho, \phi, z) = h_{\phi}(\rho, \phi)e^{-j\beta z} \). \( e_{\rho} \) can be found using (3.1) and (3.9).

\[
e_{\rho} = \frac{j\beta}{b} CK_1(b\rho), \quad \alpha' < \rho < \infty \quad (3.19)
\]

Using (3.18), (3.19) and (3.11), the following equation is formed.

\[
P_{air} = -C^2 \frac{2\pi\omega\varepsilon_0\beta}{b^2} \int_{\alpha'}^{\infty} \rho[K_1(b\rho)]^2 d\rho \quad (3.20)
\]

If a hypothetical cylinder with radius \( R_p \) is considered around the surface wave transmission line, power transmitting in air within that hypothetical cylinder can be determined using (3.20).

\[
P_{R_p,air} = -C^2 \frac{2\pi\omega\varepsilon_0\beta}{b^2} \int_{\alpha'}^{R_p} \rho[K_1(b\rho)]^2 d\rho \quad (3.21)
\]

\[
\frac{P_{R_p,air}}{P_{air}} = \frac{\int_{\alpha'}^{R_p} \rho[K_1(b\rho)]^2 d\rho}{\int_{\alpha'}^{\infty} \rho[K_1(b\rho)]^2 d\rho} \quad (3.22)
\]
3.3.2.2 POWER CONFINED IN INSULATION

The power transmitted within the dielectric coating is determined as follows,

\[ P_{\text{ins}} = \text{Re} \left( 2\pi \int_{a}^{a'} \rho E_{\rho} H_{\phi} \ast d\rho \right) \] (3.23)

If current, \( I \) is assumed to be flowing in the line, \( E_{\rho} \) and \( H_{\phi} \) are as follows.

\[ E_{\rho} = \frac{\beta I}{2\pi \omega \varepsilon_{0} \varepsilon_{r} \rho} \]

\[ H_{\phi} = \frac{I}{2\pi \rho} \]

Hence,

\[ P_{\text{ins}} = I^2 \frac{\beta}{2\pi \omega \varepsilon_{0} \varepsilon_{r}} \int_{a}^{a'} \frac{1}{\rho} d\rho = \frac{\beta I^2}{2\pi \omega \varepsilon_{0} \varepsilon_{r}} \ln \frac{a'}{a} \] (3.24)

At \( \rho = a' \), using (3.11), it can be written as follows.

\[ (H_{\phi})_{\rho=a'} = \frac{I}{2\pi a'} = -\frac{j \omega \varepsilon_{0}}{b} [CK_{1}(ba')] \]

\[ -\frac{j}{C} = \frac{2\pi a' \omega \varepsilon_{0} K_{1}(ba')}{b} \] (3.25)

The ratio of power transmitted in dielectric layer to the power transmitted in air can be determine using (3.20), (3.24) and (3.25).

\[ \frac{P_{\text{ins}}}{P_{\text{air}}} = \frac{a'^2 [K_{1}(ba')]^2}{\varepsilon_{r} \ln \frac{a'}{a}} \times \frac{\ln \frac{a'}{a}}{\int_{a}^{a'} \rho [K_{1}(b\rho)]^2} \] (3.26)

Therefore, total power is \( P_{\text{air}} + P_{\text{ins}} \). Fractional power confined in the insulation (\( \%P_{\text{ins}} \)) and within hypothetical cylinder with radius \( R_{p} \) (\( \%P_{R_{p}} \)) can be calculated using (3.26) and (3.27).
\[
%P_{ins} = \frac{P_{ins}}{P_{air} + P_{ins}} \times 100\% = \frac{P_{ins}}{P_{air}} \times 100\%
\] (3.27)

\[
%P_{rp} = \frac{P_{rp,air} + P_{ins}}{P_{air} + P_{ins}} \times 100\% = \frac{P_{rp,air}}{P_{air}} + \frac{P_{ins}}{P_{air}} \times 100\%
\] (3.28)

3.3.2.3 Effect of Parametric Sweep on Surface Wave Power

As shown in the previous discussions, the power density near the conductor depends on few important parameters: frequency, insulation thickness, insulation permittivity, and conductor diameter. In this dissertation, cable insulation condition monitoring is the focus where cables with different diameters, different insulation material and different insulation thicknesses will be studied at different frequencies. Therefore, analytical knowledge of these parameter variations is imperative.

For accurate analytical investigation of the effect of these parameters, a cable with 8.2 mm diameter conductor, 3 mm thick insulation of \(\varepsilon_r = 3\) and frequency of 8 GHz is considered. Figure 3.5(a), (b) and Figure 3.6-3.8 are plotted using data generated from Matlab that used equations (3.17), (3.22) and (3.26) - (3.29). The velocity of surface waves, \(v_{sw}\) is calculated as follows.

\[
v_{sw} = \frac{2\pi f}{\beta}
\] (3.29)

Figure 3.5(a) shows that fractional power confined in the insulation and the fractional power in air near the conductor increases as the frequency increases. This is a very important observation which will be described in the following chapters. Since the fractional power inside the insulation increases surface wave velocity decreases with
frequency. At a very low frequency, the velocity is close to the one in free space as shown in Figure 3.5(b).

The illustration in Figure 3.6 should clarify the role of surface wave frequency further. The fractional power density per unit volume plotted as a function of radial distance, $\rho$ for 1, 8 and 12 GHz after normalizing (with respect to the highest magnitude at 12 GHz) using (3.30) and (3.31).

$$\frac{P_{\delta\rho}}{P_{\text{air}}} = \frac{\left(\int_{\rho}^{\rho+\delta\rho} x[K_1(bx)]^2 dx\right)}{\int_{a'}^{\infty} x[K_1(bx)]^2 dx}$$

(3.30)
\[
P_{\text{den}} = \frac{P_{\delta\rho}}{\rho} \frac{\rho}{P_{\text{air}} + P_{\text{ins}}}
\]  

(3.31)

Here, \(P_{\delta\rho}\) is the fractional power confined between to hypothetical cylinder with radius of \(\rho\) and \(\rho + \delta\rho\), and \(\delta\rho\) is very small. \(P_{\text{den}}\) is the fractional power density per unit volume at distance \(\rho\).

The fractional power density is higher at higher frequency at \(\rho = a'\) which is right outside the insulation. But it decreases at a faster rate for higher frequency as one moves away from the cable. This observation indicates that the radial spread of the surface wave is narrower at higher frequency but more concentrated and vice versa.

![Diagram](image)

Figure 3.6. Fractional power density vs. radial distance from the cable.

Similar results were observed when the insulation thickness increased. Thicker insulation can confine more EM power; hence the wave velocity decreases as shown in Figure 3.7. Insulation permittivity variation has a very minimal effect on the fractional power inside insulation specially when \(\varepsilon_r > 5\) as shown in Figure 3.8(a). When \(\varepsilon_r < 5\),
confined EM power in insulation decreases while the fractional power within $R_p$ increases as the permittivity increases. This observation indicates that EM power density in air increases. As expected, the wave velocity decreases as the permittivity increases as shown in Figure 3.8(b). Figure 3.9(a) shows that fractional power confined in the insulation decreases as the conductor diameter gets larger. However, the fractional power in air increases. Figure 3.9(a) and 3.7(a) indicate that when insulation thickness to conductor diameter ratio, $t/a$ increases, more fractional power is confined in the cable insulation. As shown in Figure 3.9(b), the wave velocity increases as the conductor diameter increases.

![Figure 3.7](image1.png)

Figure 3.7. (a) Confined power in dielectric and in air, and (b) surface wave velocity as a function of insulation thickness.

![Figure 3.8](image2.png)

Figure 3.8. (a) Confined power in dielectric and in air, and (b) surface wave velocity as a function of insulation permittivity.
3.3.2.4 The Case of Very Thin Coating ($t \ll a$)

In contrast to the above analysis, Goubau [74] and Collin [66] considered $t \ll a$, such as paint coating on the conductor, to simplify the calculations. This assumption becomes invalid when $a$ and $t$ are comparable which is generally the case for power cables. When $t \ll a$, (3.17) is reduced to (3.32) [66].

$$
\varepsilon_r b^2 a' \ln(0.89 b a') \approx -(\varepsilon_r - 1) k_0^2 t 
$$

(3.32)

The following small-argument approximations and Taylor series expansion were used to derive (3.30) where $x < 0.3$.

$$
K_0(x) \rightarrow -\ln(0.89 x) \\
K_1(x) \rightarrow \frac{1}{x} \\
J_0(b a) = J_0(b a') - \frac{dJ_0(b a')}{d\rho}(a' - a) = J_0(b a') + bJ_1(b a')t
$$

Figure 3.10(a) and 3.10(b) shows that, when $t/a < 0.2$, the exact eigenvalue equation (3.17) and the approximated equation (3.32) produce very close results. Beyond
that, (3.32) overestimates the fractional power and hence underestimates the phase velocity. Here, \( a = 5 \text{ mm} \) and \( \varepsilon_r = 10 \).

Figure 3.10. Exact and approximated eigenvalue equation comparison: (a) Fractional power inside insulation and the hypothetical cylinder and (b) surface wave velocity when insulation thickness is varied.

Figure 3.11. Fractional power inside insulation and the hypothetical cylinder for (a) \( t = 0.1 \text{ mm} \), and (b) \( t = 3 \text{ mm} \) when \( a = 5 \text{ mm} \).

Figure 3.11 and Figure 3.12 show the comparison between the exact eigenvalue equation (3.17) and the approximated one (3.32) for \( t = 0.5 \text{ mm} \) and \( t = 3 \text{ mm} \), when frequency is varied from 2 to 4 GHz. When \( t = 0.5 \text{ mm} \), the calculated power and wave...
velocity are very close using both equations unlike the case of \( t = 3 \) mm. It is observed that, when the frequency increases, the deviation becomes smaller for both power and velocity calculation. It indicates that, at much higher frequency, the wavelength will become shorter and comparable to the insulation thickness, hence the thin insulation thickness cannot be neglected anymore.

![Wave velocity vs Frequency graph](image)

Figure 3.12. Surface wave velocity for (a) \( t = 0.1 \) mm, and (b) \( t = 3 \) mm when \( \alpha = 5 \) mm.

### 3.3.3 HFSS Simulation of TM\(_{00}\) Surface Waves

An insulated conductor or cable was simulated in HFSS for visual demonstration of the surface wave propagation and the electric and magnetic fields surrounding the cable where \( \alpha = 1 \) mm, \( t = 0.5 \) mm, and \( \varepsilon_r = 3.5 \). The cable was simulated as waveguide by defining wave-port at the two ends of the cable. The cable and the insulation were modeled as cylinders with hexagonal cross-section to reduce the computational load. Figure 3.13 shows the electric and magnetic fields and Poynting vector around/along a dielectric coated conductor.
Figure 3.13. (a) E field magnitude on a plane along a conductor, (b) E field vector around the conductor, (c) H field vector on a plane along the direction of propagation, (d) H field vector around the conductor, and (e) Poynting vector indicating the energy flow along the conductor.

Figure 3.14 shows the E-field strength in V/m in the insulation and in the surrounding air at 0.2, 1, 4, and 8 GHz. The E-field becomes strong near the conductor as
the frequency increases. The velocity of the surface waves decreases as well with the increase in frequency as shown in Table. 3.1.

<table>
<thead>
<tr>
<th>Frequency, $f$ (GHz)</th>
<th>Evaluated Wavelength in HFSS, $\lambda_{sw}$ (mm)</th>
<th>Surface Wave velocity from HFSS, $v_{sw} = f \times \lambda_{sw}$ (m/s)</th>
<th>Surface Wave velocity (Analytical) (m/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.2</td>
<td>1420</td>
<td>$2.84 \times 10^8$</td>
<td>--</td>
</tr>
<tr>
<td>1</td>
<td>280</td>
<td>$2.80 \times 10^8$</td>
<td>$2.85 \times 10^8$</td>
</tr>
<tr>
<td>4</td>
<td>66.5</td>
<td>$2.66 \times 10^8$</td>
<td>$2.71 \times 10^8$</td>
</tr>
<tr>
<td>8</td>
<td>29.9</td>
<td>$2.39 \times 10^8$</td>
<td>$2.52 \times 10^8$</td>
</tr>
</tbody>
</table>

Figure 3.14. E-field magnitude on a plane perpendicular to the cable axis at 4 different frequencies simulated in HFSS.

### 3.3.4 Higher Order Modes

Higher order TM and TE modes exist alongside the fundamental mode [66], [75]-[77]. In [75], the following equations were derived based on asymptotic approximation of Bessel functions to calculate the cut-off frequencies of higher order TM$_{0m}$ and TE$_{0m}$ mode. Here, $m>0$.  

43
\[ f_{cutoff}(TM_{0m}) = m \times \frac{1}{2t} \times \frac{c}{\sqrt{\varepsilon_r \mu_r - 1}} \]  

(3.33)

\[ f_{cutoff}(TE_{0m}) = \left( m + \frac{1}{2} \right) \times \frac{1}{2t} \times \frac{c}{\sqrt{\varepsilon_r \mu_r - 1}} \]  

(3.34)

These higher order modes have very high cutoff frequencies which may be in the THz. For example, TM\(_{01}\) and TE\(_{01}\) mode have 189 GHz and 285 GHz cutoff frequencies, respectively when \( t = 0.5 \) mm, \( \varepsilon_r = 3.5 \) and \( \mu_r = 1 \). Since surface waves with such high frequency are complicated to excite and suffer from huge loss, TM\(_{00}\) mode is considered in this dissertation which has a zero-cutoff frequency.

### 3.4 Existing Surface Wave Launchers

Although higher order wave modes can exist, TM\(_{00}\) wave is the point of interest as it can be excited using e.g., a horn type structure and use it for different applications. The concept of surface wave propagation in a Goubau line has been recently employed for a variety of applications.

The horn type conical launcher that Goubau originally proposed for microwave communication is shown in Figure 3.15(a). As shown, the outer conductor of the coaxial line is connected to the shell of the conical launcher and the inner conductor is connected to the conductor of the G-line.

Elmore [78]-[79] designed a conical shaped slotted wave launcher, which could be mounted on an existing stranded aluminum overhead power line as shown in Figure 3.15(b). Elmore’s objective was to demonstrate the feasibility of communication over power line. For a transmitter and receiver placed 18 m apart, he demonstrated that a bandpass transmission centered at nearly 2 GHz could be achieved.
Sharma et al. [80] presented a coplanar Vivaldi-style launcher for uninsulated single-wire transmission line in order to provide broadband communication channel at ultrahigh and microwave radio frequency (0.81-2.29 GHz). They demonstrated very low loss transmission of only 0.19 dB/m at 1.5 GHz. Moreover, this launcher was claimed to be more convenient than Goubau’s conical launcher in terms of ease of installation. This launcher is shown in Figure 3.16. It excites surface waves through direct physical contact with the transmission line.

A vertical wire monopole launcher was introduced by Alam et al. [81]. The concept was extended to design a wide monopole launcher that wraps around the surface wave transmission line. A novel conformal surface wave launcher was proposed that can excite surface waves along unshielded cable non-intrusively. It can be placed anywhere on the line as an add-on; no physical connection was needed. The proposed application was for open-circuit fault detection in a power line. Figure 3.17 illustrates the structure of such conformal surface wave launchers.
Figure 3.16. Vivaldi-style surface wave launcher proposed by Sharma et al. [80].

Figure 3.17. Conformal surface wave launcher for non-intrusive surface wave excitation [81].
3.5 Conclusion

This Chapter focuses on the analyses of EM surface waves. Analytical model of surface wave transmission line is established in this chapter which led to parametric study of surface wave propagation. The effect of surface wave frequency, insulation thickness and permittivity and conductor diameter on fractional power confinement in the cable insulation and in air are studied. The eigenvalue equations were solved numerically in Matlab. Due to the limitation of the solution function of Matlab, the equations could not be solved for certain ranges of frequency, insulation thickness or the conductor diameter.
CHAPTER 4

PROPOSED SURFACE WAVE REFLECTOMETRY TECHNIQUE

4.1 INTRODUCTION

The major thrust of this dissertation is to propose and study non-intrusive cable NDE techniques to monitor cable insulation condition which do not require direct electrical connection to the cable conductor and the sensor can be placed on the outer surface of live wires and cables. Only limited works have been reported on non-conductor contact cable NDE of which most works are focused on short or open circuit fault location detection. Different NDE cable diagnosis methods are summarized in Table 4.1.

The most significant innovation is to use a surface wave launcher (SWL) operating at high enough frequency (GHz range) that has sufficient bandwidth and that can ensure high EM energy localization within the insulation material. As shown in Figure 4.1, a non-conductor-contact surface wave launcher consisting of a cylindrical monopole and a ground plane is connected to a vector network analyzer (VNA). A sinusoidal swept frequency broadband signal with appropriate frequency range is excited between the monopole and the ground plane which causes the generation of surface waves that propagate along the length of the cable. The surface waves, upon reaching the location of the damaged or missing insulation are reflected and then subsequently picked up by the SWL. The results are measured by the VNA as complex S11 as function of frequency. After applying a specific window (Kaiser window) on the complex S11, the inverse fast
Fourier transform (IFFT) is performed to determine the location of the insulation damage.

The proposed surface wave-based technique employs FDR because of its relative immunity to noise and electromagnetic interference (EMI) enabled by available filtering and noise lowering algorithms [9]. In addition, to launch/receive 5.5-8.5 GHz surface waves, TDR
devices must be rated at least 17 GSPS according to Nyquist theorem. Such high frequency TDR devices may not be readily available, and they are excessively expensive compared to equivalent FDR devices. Therefore, FDR is preferable than TDR at microwave frequencies.

4.2 Surface Wave Launcher and Frequency Choice

4.2.1 Launcher Geometry

The proposed technique considers a surface wave launcher (SWL) that is of the non-intrusive type (Figs. 4.1 and 4.2(a)) as introduced in our earlier work [74], [79], [80]. Considering Figure 4.2(a), the surface wave launcher consists of a conductive monopole on a conductive ground plane, both containing slits. For placement of the SWL on a cable, please see Figure 4.1.

![Figure 4.2](image)

Figure 4.2. (a) Surface wave launcher and (b) HFSS simulation model (cable not shown).

For simplicity of numerical analysis, it was considered for the time being that the monopole and the ground plane do not contain any slit as shown in Figure 4.2(b). It will be shown in Section 4.4.3 that this simplification has negligible effect in terms of performance. Also, since this approach considers the launch and propagation of a broadband waveform the HFSS simulation of an SWL and a cable with circular cross-section can be computationally intensive especially on a desktop computer. To circumvent
this challenge the SWL and the cable were modeled using hexagonal cylinders as shown in Figure 4.2(b).

### 4.2.2 Frequency Range of Interest

By selecting and designing an SWL with appropriate length and diameter a signal of a certain frequency or frequency range can be launched on a dielectric-coated conductor. For low frequency surface waves only a small fraction of the EM energies will remain confined to the dielectric as expected. To ensure a larger fraction of EM energy confinement into the dielectric material higher frequencies should be selected. However, higher frequencies will cause higher levels of attenuation.

Let us assume the case of a thin dielectric coated wire, referred to here and onwards as ‘thin wire’ (conductor radius, $a = 1.025$ mm, insulation thickness, $t = 0.5$ mm, $a' = a + t = 1.525$ mm, insulation relative permittivity, $\varepsilon_r = 3.5$, and loss tangent, $\tan\delta = 0.002$). Like Goubau [74], consider an imaginary cylinder with radius, $R_p$ that surrounds this insulated conductor (see Figure 4.3(a)). Consider that only $P\%$ of the surface wave energy is confined within this imaginary cylinder. Then the $P\%$ energy confinement inside $R_p$ can be represented as a function of surface wave frequency, $f_{sw}$ using (5.1) - (5.4) as shown in Figure 4.3(b) for $P=50\%$.

\[
P = 1 - \frac{F(bR_p)}{F(ba')} \tag{4.1}
\]

where $F(x) \approx \frac{8}{\pi^2} (-\ln 0.89x - 0.5)$ for $x < 0.3 \tag{4.2}$

\[
G(ba') = -\left(\frac{ba'}{2\pi}\right)^2 \ln 0.89ba' \tag{4.3}
\]
\[ f_{sw} \approx \frac{c}{a} \left[ \frac{1}{G(ba')} \ln \left( \frac{a'}{a} \right) \frac{(\varepsilon_r - 1)}{\varepsilon_r^2} \right]^{-\frac{1}{2}} \]  

(4.4)

Here \( G(ba') \) is Goubau’s function, \( a \) is the radius of the conductor, \( t \) is the thickness of the insulation \((a' = a + t)\) and \( b^2 = h^2 - k^2 \), where \( h \) is the propagation constant \((\alpha - j\beta)\), \( k \) is the wavenumber, and \( c \) is the velocity of light.

If the intent is to confine as much of the EM surface wave energy into the dielectric, then surface waves must be concentrated near the conductor. As the surface waves concentrate more towards the conductor, \( R_p/a' \) decreases which indicates that the frequency must increase as shown in Figure 4.3(b).

Previously, surface wave-based open circuit fault detection on a cable [84] was reported where 50% of the surface wave energy confined within the imaginary cylinder with \( R_p/a' = 10 \). Since the objective of this work is insulation damage detection on dielectric coated wires or cables with insulation/jacket, a smaller \( R_p/a' \) with 50% or more energy confinement inside that hypothetical cylinder must be chosen.
For further investigation, 6 and 3 was considered as the upper and the lower value of ratio $R_p/a'$ for insulation damage detection which correspond to 4 GHz and 15 GHz respectively for the thin wire as shown in Figure 4.3(b).

### 4.2.3 Transmission Properties for Different Launchers

To understand the surface wave propagation (loss) for several cases HFSS simulations of two surface wave launchers on the two ends of the thin wire with length 2 m (Figure 4.4) were conducted. Four cases were simulated for different launchers with four different design frequencies: 4, 8, 12 and 16 GHz, the last one causing the most concentrated surface waves among others. For each case, simulations were performed over a bandwidth. An SWL of the type shown in Fig 4.2(b) with length,

$$L_{SWL} = 0.23\lambda$$

(4.5)

where $\lambda = c/f$, f is the design frequency in free space was considered. This length is slightly shorter than the quarter wavelength because of the launcher’s finite diameter and it not being made of an infinitesimally thin wire [87].

Figure 4.4 shows the $|S21|$ results as function of frequency for the above four cases which indicate surface wave propagation over a wide frequency band for each case. The wideband nature of the surface wave propagation is apparent from the bandpass-type response in the $|S21|$. As expected, attenuation is higher for the higher frequency launcher e.g., 12 GHz vs. 4 GHz. The ripples in the S-parameter indicate the reflection of the launched signal between two ends of the cable. For higher frequency surface wave launcher, reflected signal gets weaker due to higher attenuation. Figure 4.4 also shows that for a specific launcher the transmission is higher at higher frequency. This phenomenon
happens due to the higher energy concentration near the wire at higher frequency as shown in Figure 4.5(a) and (b).

Figure 4.4. Simulated $|S_{21}|$ dB for two SWLs spaced at 61 cm on the thin wire. $w_{gn}$ = 1.33$\lambda$. Distance between the ground and the launcher was 0.08$\lambda$. Launchers 1 and 2 are identical.

Figure 4.5. E-field magnitude along the wire at (a) 5 GHz and (b) 8 GHz where $L_{SWL}$ = 8.625 mm.
4.3 Surface Wave and FDR Based Insulation Damage Detection

To detect the location of missing insulation or insulation damage on a cable using surface wave reflectometry only a single SWL is needed as shown in Figure 4.6(a). The complex reflection coefficient vs. frequency data at the launcher ($S_{11}$ here because there is only one port) can be used and further processed using IFFT to detect the location of the insulation damage. Because of the finite bandwidth of measurement system, the $S_{11}$ measurement in the frequency domain is truncated abruptly at the start and stop frequencies. Such abrupt cut-off at the edge frequencies creates high-level sidelobes on both sides of the main impulse when converted to time domain (seen as a $\sin(x)/x$ shape). As a result, low-level responses from minute insulation damages are buried within the sidelobes of nearby higher-level responses [88]. To circumvent this problem, a windowing technique was applied to the frequency domain response prior to the time domain conversion which tends to reduce the sharpness of the original $S_{11}$ response at edge frequencies. There are a variety of windowing techniques available for this purpose, including Kaiser, Hanning, Hamming, and Blackman windows.

4.3.1 Windowing the Frequency Domain Data and IFFT

Consider the case of a 3 m long thin insulated wire (3.05 mm diameter) where there is an insulation damage (10 mm long) at 2 m from the input side. Using previously described 8 GHz SWL, yields in the S11 response shown in Figure 4.6(b). A Kaiser windowing technique (a bandpass complex window) when employed on the complex S11 prior to the application of IFFT ensures clear detection peak(s) for the discontinuities that result from insulation damage. A Kaiser window can be defined using the frequencies at the band edges, the passband magnitude, and the stopband attenuation. Figure 4.6(c) shows
a complex Kaiser window response applied to the 8 GHz SWL $S_{11}$ on the 3 m long insulated wire. The IFFT results obtained from the windowed $S_{11}$ can be seen in Figure 4.6(d). The time domain results of Figure 4.6(d) can also be plotted as function of the cable length using the wave velocity, $v_{SW}$. In Figure 4.6(d) the peak corresponding to the open-end on the other side of the SWL occurs at Time = 21.561 ns. Considering the round-trip travel being 6 m, $v_{SW} = 2.78 \times 10^8$ m/s. The abscissa in (seconds or nsec) will then need

Figure 4.6. (a) Illustration of surface wave reflection phenomenon. (b) Magnitude and phase of $S_{11}$ response, (c) Magnitude and phase of Kaiser Window (d) Transformation of the $S_{11}$ frequency response to the t-domain signal for a 3 m long thin wire with insulation missing at 2 m.
to be converted to distance or length as: \( \text{Distance} = \frac{v_{sw} \times \text{Time}}{2} \), since round-trip travel of the wave is considered.

The accuracy of the damage location detection depends on the spatial resolution (SR) defined using (5) [60].

\[
SR = \frac{2 \times B}{v_{sw}} \quad (4.6)
\]

where \( B \) is the IFFT frequency range. For the case in Figure 5.6, \( B = 3 \) GHz is the difference between 5.5 and 8.5 GHz. Therefore, \( SR = 21.58 \) samples/m. Detected location of any damage may differ from actual location by up to \( 1/\text{SR} \) or 4.64 cm. Any damage closer than \( 2/\text{SR} \) or 9.27 cm from the launcher or the open-end may not be detected. Also, the minimum distance between two consecutive damage locations should be at least \( 2/\text{SR} \) for successful detection.

Performance of other windowing techniques were investigated as well. Hanning and Blackman windows performed similarly as Kaiser window while Hamming window resulted in poorer performance as shown in Figure 4.7.

![Figure 4.7. Performance comparison between different windowing techniques prior to IFFT.](image)

Figure 4.7. Performance comparison between different windowing techniques prior to IFFT.
4.3.2 Impedance Matching Between the Launcher and the Cable

The effect of impedance matching between the launcher and the cable on the proposed insulation damage detection technique was studied. In the initial simulations, the launcher and the cable were not matched, and the average $|S_{11}|$ was around -5 dB (see black curve in Figure 4.8(a)). To improve the matching, some approaches were studied using the 8 GHz launcher and the thin wire. Since the launcher was broadband, resistive loading was considered. Instead of copper, a highly resistive material with conductivity, $\sigma = 100$ S/m was used for launcher design using HFSS simulation. Although the reflection decreased with this approach, damage detection performance deteriorated i.e., it resulted in a less sharp and low amplitude IFFT peak at the location of the damage. Note that, the priority is better detection of insulation damage rather than the impedance matching. Another approach by making the launcher wall thinner to increase the launcher resistance led to a poorer detection performance as well. The next approach was to make a multiwavelength structure e.g., flaring the launcher open like a conical antenna. This approach also improved the impedance matching at a cost of poor damage detection performance as the simulations proved. This observation suggests that the launcher must touch the cable insulation surface for better surface wave excitation.

Interestingly, the role of the distance, $h$ (see Figure 4.8(b)) between the ground and the launcher was found to be significant for improving both impedance matching and damage detection performance. In the initial simulations, $h$ was 0.5 mm. It was observed in HFSS simulations that the reflection was minimum when $h = 3$ mm. Unlike previous approaches, the IFFT peak amplitude got higher when the reflection was reduced. At $h = 3$ mm, the average $|S_{11}|$ was around -15 dB as shown in Figure 4.8(a), and the IFFT peak
increased by 5 dB in amplitude for a damage at 2 m distance as shown in Figure 4.8(b). Therefore, for the 8 GHz launcher, $h = 3$ mm (0.08$\lambda$) is optimum to achieve better matching between the launcher and the cable, and better performance of insulation damage detection.

Figure 4.8. Effect of $h$ on (a) reducing reflection coefficient ($S_{11}$) and (b) on insulation damage detection performance for insulation missing over 10 mm length at 2 m of a 3 m long thin wire.

### 4.3.3 IFFT Damage Response vs. Launcher Frequency Range

IFFT damage response vs. launcher frequency range was studied for all four launchers e.g., 4, 8, 12, and 16 GHz. The previously simulated 3 m long thin insulated wire was used to perform these studies where a 10 mm long damage was created at 2 m distance. Figure 4.9 shows some results. As seen, the 8 GHz launcher shows strong IFFT peaks at the location of the damage. The 4 GHz launcher exhibits reduced IFFT peak amplitude at damage location due to less energy confinement within insulation layer. For the 12 GHz launcher, the IFFT response at the damage location also shows reduced amplitude because of the higher attenuation. For the 16 GHz launcher, the signal was so attenuated that the IFFT peak was buried below noise threshold (consider -30 dB) and could not be identified distinctively.
The 8 GHz surface wave launcher was used to conduct more in-depth investigations of insulation damage on a thin cable by considering damage location, type, size, and permittivity variation. The first case among these includes the results shown in Figure 4.10, representing insulation missing at various locations along the length of a wire. The damage size for each case was 10 mm. The damage locations were at 1.7 m on a 3.0 m long wire, 2.7 m on a 4.5 m long wire, 4.0 m on a 6 m long wire, and 6.5 m on an 8 m long wire, respectively. Simulations for wire lengths greater than 8 m at 8 GHz could not be successfully run using a desktop computer with 64 GB of RAM.

As the damage went further along the cable, the amplitude of the IFFT peak became reduced as seen in Figure 4.10, approximately at a rate of 2.8 dB/m. At this rate, IFFT peak corresponding to insulation missing over 10 mm length will be buried below noise threshold approximately after 8 m, using an 8 GHz launcher. To achieve an extended detection range, the damage must be larger and/or the surface wave frequency must be lower. The minimum size of a detectable damage depends on its distance from the launcher,
the energy confinement in the insulation at the frequency in use, and the attenuation at that frequency.

The efficacy of the proposed technique on detecting insulation damage with varying size, e.g., 1, 3, 5, and 10 mm were investigated. The results may be seen in Figs. 4.11(a) and (b). Full circumferential or ‘Type-I damage’ and half circumferential or ‘Type-II damage’ were considered. As expected, for both types of damage, the magnitude of the IFFT peak at the damage location increases with increasing damage length. Interestingly, even Type II damage of as small as 1 mm can be detected. In practical cases, the circumferential damages may be less than half, for example, in an angle of 30 or 60-degree. Figure 4.11(c) shows that for an angle as small as 30-degree, the proposed method is effective. In some circumstances, the cable conductor may not be fully exposed. Figure 4.11(d) shows that when the insulation is corroded by only 0.1 mm, it is detectable at 2 m distance on a 3 m long thin wire.

Figure 4.10. Simulation results of damage detection at 1.7, 2.7, 4, and 6.5 m respectively in 3, 4.5, 6, and 8 m long thin wires. Detected damages are marked with black arrows.

The efficacy of the proposed technique on detecting insulation damage with varying size, e.g., 1, 3, 5, and 10 mm were investigated. The results may be seen in Figs. 4.11(a) and (b). Full circumferential or ‘Type-I damage’ and half circumferential or ‘Type-II damage’ were considered. As expected, for both types of damage, the magnitude of the IFFT peak at the damage location increases with increasing damage length. Interestingly, even Type II damage of as small as 1 mm can be detected. In practical cases, the circumferential damages may be less than half, for example, in an angle of 30 or 60-degree. Figure 4.11(c) shows that for an angle as small as 30-degree, the proposed method is effective. In some circumstances, the cable conductor may not be fully exposed. Figure 4.11(d) shows that when the insulation is corroded by only 0.1 mm, it is detectable at 2 m distance on a 3 m long thin wire.
Also, it is clear from these figures that the magnitude of the IFFT peak relative to the baseline can track the growth of the damage if it progresses from a small size over time. This feature is very relevant if real-time online monitoring will be considered.

The effect of ground plane size and shape on insulation damage detection performance was investigated as well for the case of 8 GHz launcher and thin wire. Like monopole antennas, the performance of the proposed surface wave launcher is affected by the finite size of the ground plane. Larger ground planes direct more surface waves towards the wire. Damage detection performance degrades as the ground plane size decreases.

Figure 4.11. Simulation of insulation damage detection in 61 cm long thin wires. Tracking the growth of (a) a Type-I damage and (b) a Type-II damage at 30.5 cm. (c) Tracking the growth of a 10 mm long damage along the circumference. (d) Full circumferential damage with varying insulation depth over 10 mm section at 2 m on a 3 m long thin wire.
When the ground plane is a square with 30 mm sides, the response from a 10 mm long full circumferal damage is hidden in the noise (see Figure 4.12). In terms of detecting insulation damage, there are no discernible differences between a circular and a square ground plane with similar length and diameter, respectively.

![Figure 4.12. Effect of ground plane size and shape on damage detection performance.](image)

Figure 4.12. Effect of ground plane size and shape on damage detection performance.

In some circumstances, a larger diameter launcher may have to be placed on small diameter cables creating an air-gap between the launcher and the cable. In order to

![Figure 4.13. Effect of an air-gap between the launcher and the cable on insulation damage detection.](image)

Figure 4.13. Effect of an air-gap between the launcher and the cable on insulation damage detection.
investigate the effect of the air-gap, 8 GHz launchers with diameters larger than the thin wire’s diameter were considered. As shown in Figure 4.13, the proposed launcher most effectively excites surface waves when there is no air gap, according to simulation data. A small air gap, such as 1 mm, has no significant effect on detecting insulation damage. It's worth noting that the launcher itself is quite inexpensive. Also, since the launcher itself does not contain any complicated parts multiple launchers with differing lengths and diameters can be fabricated and used to suit various cable diameters.

4.3.5 EFFECT OF INSULATION THICKNESS ON DAMAGE DETECTION

Insulation thickness variation between 0.25-0.75 mm was studied using simulations for the thin wire. Thicker insulation confines more surface wave energy and hence shows a greater signature at the damage location as shown in Figure 4.14(a). Cable insulation permittivity usually varies between 2 to 3.5. Small decrease in detection performance was observed when the relative permittivity reduced to 2.3 from 3.5 as shown in Figure 4.14(b).

Figure 4.14. Insulation damage detection for thin wire with different (a) insulation thicknesses and (b) insulation permittivity.
4.3.6 Insulation Damage Detection on a Thick Cable

Thin or moderately thin cables may avail the surface wave launchers described above that operate in the 7-10 GHz frequency range. Extremely thin cables may necessitate the use of even higher frequencies while moderately thick cables, e.g., 5-10 mm diameter instrumentation or control cables, may require somewhat lower than 7 GHz frequencies. Thick power cables (greater than 15 mm diameter) will require even lower frequencies. The smallest size of insulation or jacket damage that can be detected will increase with decreasing frequency.

To investigate the efficacy of insulation damage detection on a ‘thick power cable’ a scale model 1 GHz surface wave launcher was designed that can be placed on a 16.4 mm diameter cable with 4 mm thick XLPE insulation ($\varepsilon_r = 3.5$, tan $\delta = 0.002$). The length of the surface wave launcher was $L_{SWL} = 69$ mm. A type-I damage of length 40 mm was created at 40 m distance on a 50 m long cable. Simulated magnitude of the IFFT response for this embodiment can be seen from Figure 4.15 (a). The damage located at 40 m distance can be clearly identified. Figure 4.15(b) and (c) show that growth of full and half circumferential insulation missing can be tracked. A half-circumferential damage as small as 10 mm was detected at 4 m distance on a 6 m long cable. Here the launcher operates between 0.7-1.1 GHz. Therefore, $SR = 2.86$ samples/m. Detected location of any damage may differ from actual location by up to $1/SR$ or 0.35 m. Any damage closer than $2/SR$ or 0.7 m from the launcher or the open-end may not be detected. Also, the minimum distance between two consecutive damage locations should be at least 0.7 m for successful detection.
4.4 EXPERIMENTAL RESULTS

4.4.1 EXPERIMENTAL SETUP

To check the validity of the simulation results the case for the 8 GHz surface wave launcher on the thin copper wire (2.05 mm diameter conductor and 0.5 mm thick nylon-coated PVC insulation) was considered.

Figure 4.15. Simulation of insulation damage detection in a thick cable. (a) Detection of a 40 mm Type-I damage at 40 m distance in a 50 m long thick cable. Detection of (b) full-circumferential and (c) half-circumferential damage with varying width at 4 m on a 6 m cable. \( f = 1 \text{ GHz}, w_{\text{gnd}} = 1.33\lambda \) and \( h = 0.08\lambda \).
A photograph of the 8.6 mm long launcher is shown in Figure 4.16(a) with Figure 4.16(b) showing the launcher being placed on the test wire. A piece of copper sheet measuring 50 mm by 50 mm was placed on a rigid plastic sheet to form the launcher ground plane. As seen, a subminiature co-axial (SMA) connector was used to connect the launcher to the VNA.

Figure 4.16. Experimental validation of the proposed method. (a) Fabricated launcher, and (b) frequency response measurement of the launcher along with a wire sample, and artificially created damage. Photographs of Type-I and Type-II damages are inset.

4.4.2 EXPERIMENTAL RESULTS

Figure 4.17 shows the magnitudes of the IFFT containing 10 mm long Type-I damages at distance of 30.5 cm on a 61 cm long wire. The response from the experiment was very close to the simulated response. Noise threshold was considered -20 dB for the experiment.

Experimental results of Type I and Type II damage with the damage length as the parameter can be seen in Figs. 4.18(a) and (b). As before with simulation, the peak of the IFFT response at the damage location gradually decreases as the damage length decreases. Nevertheless, the experiments show that 2.5 mm long damages can be detected.
Finally, two 10 mm long Type-I damages were created on a 6 m long wire at 1.425 m and 4.475 m distance. The measured magnitude of the IFFT response shown in Figure 4.19 indicate that the locations of these damages are at 1.4309 m and 4.4933 m. The measured magnitudes clearly illustrate the locations of these damages at 1.4309 m and 4.4933 m, respectively which are close to the manually measured damage locations of
1.425 m and 4.475 m, respectively. The small difference (0.4%) is attributable to the slightly shorter physical measured distance (caused by bends).

![Graph](image)

Figure 4.19. Experimental results demonstrating detection of two Type-I insulation damages at 1.425 m and 4.475 m in a 6 m long wire (marked with arrows).

### 4.4.3 Modified Design with Slits in the Launcher and the Ground

A non-intrusive sensor must have the capability to be installed on live wires or cables without interrupting their operation. Such provision can be made by creating slits along the monopole and the ground place. This modification signifies the potential of the proposed technique for field applications. However, the slit must be as thin as possible in order to achieve uniform surface wave excitation throughout the circumference and good mechanical stability.

A 0.5 mm wide slit in the monopole and a 5 mm wide slit in the ground were created, as shown in Figure 4.20(a). Measurement was performed on this modified launcher and a 61 cm long wire sample with a 10 mm long Type-I damage at 30.5 cm. Figure 4.20(b) shows the successful detection of this damage. The results indicate that even with the slit, the modified launcher is as effective as the baseline design.
In contrast to previous study, this section presents an investigation of cable insulation and jacket damage detection on multi-conductor cables and detection of water-leak inside the cable jacket. The feasibility of surface wave propagation on multiple insulated conductors is established. Multiple scenarios involving a 4 GHz surface wave launcher and a 2 m long three conductor cable with an 8 mm outer diameter were simulated using the Ansys high frequency structure simulator (HFSS). Different types of insulation and jacket damage and a water leak were simulated at 1 m distance from the launcher and detected.

4.5.1 Feasibility of Surface Wave Propagation on Multiconductor Cable

A three-conductor cable is considered which is shown in Figure 4.21(a) along with the specifications. The relative permittivity of both the insulation and jacket are considered to be 3.5. Underneath the jacket, there may be foam-like material to support the inner conductors (relative permittivity close to 1). To reduce the computational load, the

Figure 4.20. Design and experimental results for a modified launcher and AW 541201 wire ($a = 1.05$ mm and $t = 0.5$ mm). (a) Photograph of a fabricated slitted SW launcher, (b) Comparison between slitted and base SW launcher.
monopole and the cable were modeled using dodecagon cylinders (cross-section is a polygon with 12 sides instead of circular). For simplicity of numerical analysis, let us assume the launcher and the ground plane have no slits which may have negligible effect on surface wave reflectometry.

In the previous studies, it was observed that for a 3.05 mm diameter cable, 8 GHz surface waves confined sufficient surface wave energy. Also, for a 24.4 mm diameter single conductor cable, 1 GHz surfaces waves confined enough surface wave energy within the insulation for cable insulation damage detection. For the three-conductor cable, the frequency of 4 GHz was considered, which was consistent with the previous findings. Using equation (4.5), the length of the launcher = 17.25 mm was determined.

Figure 4.21. (a) Cross-section of a three-conductor cable and (b) Surface wave electric field magnitude along the cable axis at 4 GHz (Scale: 0-1000 V/m).
Figure 4.21(b) shows the electric field magnitude on a plane along the cable axis, which validates the propagation of surface waves on a multi-conductor cable. From the field magnitude plot, the wavelength was found to be 71.5 mm at 4 GHz which led to $v_{sw} = 2.86 \times 10^8 \text{ m/s}$ where $v_{sw}$ is the surface wave velocity.

### 4.5.2 INSULATION AND JACKET MISSING DETECTION

Multiple simulations were performed to conduct in-depth investigations of insulation and jacket damage detection on the three-conductor cable using the 4 GHz surface wave launcher. Different types of insulation damage were simulated at 1 m on a 2 m long cable by removing cable insulation and jacket from above on one, two and three conductors over 20 mm length. An example simulated cable damage is shown in Figure 4.22(a). Figure 4.22(b) shows that the damaged areas are located at 1 m distance from the launcher as proposed. Furthermore, the extent of the damage is determined, which helps

![Graph](image)

Figure 4.22. (a) Insulation and jacket removed from top of two conductors, (b) Detecting insulation and jacket damage at 1 m distance on a 2 m long three-conductor cable.
track its growth. This is a very important feature if real-time cable condition monitoring is considered. The minimum size of detectable damage depends on its distance from the launcher and the frequency of the surface waves.

4.5.3 WATER-LEAK DETECTION

In some multi-conductor cables or in cable conduits, the space between the jacket and the inner wires (colored grey in Figure 4.21(a)) is empty. In some circumstances, there may be a tear in the jacket or conduit wall, which is too small to detect using the proposed method. However, water or other liquid can leak through to the empty space and the presence or absence of liquid can be detected depending on the extent of the leak. Such a scenario was simulated using HFSS. A water leak was simulated by adding water in the empty space over a 20 mm length at 1 m distance from the launcher. The relative permittivity of water was considered to be 81. The leak was detected using the proposed method and the result is shown in Figure 4.23.

![Figure 4.23. Detection of water-leak through the jacket at 1 m distance on a 2 m long cable.](image-url)
4.6 EFFECT OF SEMICONDUCTING LAYER ON CABLE INSULATION DAMAGE DETECTION

The core of medium or high voltage power cables are made up of multiple stranded conductors. Since the surface of the stranded core is not smooth, small air-filled cavities emerge between the conductors and the insulation, causing nonuniform electric field distribution. As a solution, a semiconducting layer or screen is often introduced on top of the conductor strands as shown in Figure 4.24 to round up the conductor surface. This layer prevents air-filled cavities from forming and reduces voltage stress between metal conductors and the dielectric due to nonuniform field distribution, preventing electric discharges and jeopardizing the insulation material [89]. From the standpoint of electronics, this semiconducting material is not a 'semiconductor.' It is in fact a poor conductor or poor dielectric made up of a mix of conducting carbon black particles and dielectric material, with the ratio determining the conductivity and permittivity. Some cables with an exterior metallic shield may have a second semiconducting layer underneath that shield. In this chapter, the cables that have the inner semiconducting layer are the topic of interest, as shown in Figure 4.24.

![Medium/high voltage power cable structure](image)

Figure 4.24. Medium/high voltage power cable structure. Cable image on the left: Okonite cables.

However, the presence of a semiconducting layer between the conductor and the insulation, which is common in medium or high voltage power cables, could pose a
challenge in terms of the distance over which insulation damage can be detected due to increased attenuation. Hasheminezhad et al. [90] theoretically analyzed the impedance of the semiconductor layer, wave velocity, and signal attenuation for varied layer thicknesses and frequencies for the purpose of partial discharge detection in power cables. Paludo et al. [91] adjusted the traditional circuit model of a power line to account for attenuation due to the semiconductor layer and validated the model by comparing simulated and measured TDR results for underground cables. Both studies focused on transverse electromagnetic (TEM) wave propagation, which is different from surface waves in that TEM waves are excited by direct contact with the cable conductor.

In contrast to the previous works, this section investigates the feasibility of surface wave propagation along a cable with a semiconducting layer present between the conductor and the insulation. Furthermore, an in-depth study of the effect of this semiconducting layer on the performance of surface wave reflectometry is presented. The role of various parameters pertinent to the study, such as the permittivity and conductivity of the semiconducting material, thickness of the semiconducting layer, and the distance of insulation damage from the surface wave launcher are investigated. In this study, a 1 GHz surface wave launcher that is 6.9 cm long is considered. Each side of the ground plane is 40 cm.

4.6.1 Effect of the Presence of Semiconducting Layer and its Thickness

In order to speed up the analysis, the conductor core and semiconducting layer were considered as smooth cylindrical structures in the simulations. Cable specifications are: conductor core diameter = 16.4mm, insulation (EPR, $\varepsilon_r = 3.5$) thickness = 4mm, semiconducting layer thickness varies from 1mm to 2mm. In [92], the authors observed
that for higher frequencies the relative permittivity is lower, typically in the range of 10-100 at 500 MHz, and the conductivity may vary between 1-10 S/m at similar frequency. In this section, relative permittivity, \(\varepsilon_{r,\text{semi}} = 20\) and conductivity, \(\sigma_{\text{semi}} = 5\) S/m for 1 GHz were considered.

A semiconducting layer of varying thicknesses was introduced to the cable in the HFSS simulation. In practice, the thickness of this layer may vary around 1-1.5 mm [91]. In this study, the thickness, \(t_{\text{semi}} = 1, 1.5, \text{ and } 2\) mm were considered for a 30 m long cable with insulation damage at 20 m distance from the surface wave launcher. The damage was simulated by removing insulation from the full cable circumference over a 4 cm length.

Figure 4.25(a) shows the change in electric field magnitude as a function of distance. It can be observed that the surface waves are more attenuated when the semiconducting layer is introduced, and the signal decays faster as the layer gets thicker. When the thickness is 2 mm, the electric field fades away after approximately 30 m.

The field strength decays at an exponential rate: \(\exp \left( -\alpha d \right)\) where \(\alpha\) is the rate of attenuation. From Figure 4.25(a), \(\alpha\) was calculated to be: \(\alpha = 0.02, 0.03, 0.07, \text{ and } 0.10\) m\(^{-1}\) for \(t_{\text{semi}} = 0, 1, 1.5, \text{ and } 2\) mm, respectively, using a curve fitting algorithm. Therefore, the surface waves are attenuated 5 times faster when a 2 mm thick semiconducting layer is present. The increased attenuation, in turn, results in poorer performance in insulation damage detection. Figure 4.25(b) shows that the amplitude of the IFFT peak at the damage location (20 m) decreases when the semiconducting layer is thicker. If -30 dB is considered as the noise threshold, the damage response for \(t_{\text{semi}} = 2\) mm is buried in the noise because the associated field is very weak at 20 m. If the damage is brought closer to 10 m, it is clearly identified as shown in Figure 4.25(c) since the
associated field is stronger at that distance. $v_{sw}$ also changes with the thickness of the semiconducting layer. It was calculated as $2.75 \times 10^8$, $2.71 \times 10^8$, $2.66 \times 10^8$, and $2.60 \times 10^8$ m/s when $t_{semi} = 0$, 1, 1.5, and 2 mm respectively.

Figure 4.25. (a) Electric field strength as a function of distance and (b) insulation damage detection at 20 m for different thicknesses of the semiconducting layer. (c) Moving a damage to 10 m for better detection when $t_{semi}=2$ mm. ($\varepsilon_{r,semi} = 20, \sigma_{semi} = 5 S/m$.)
4.6.2 Electrical Properties of the Semiconducting Layer

The most important electrical properties of the semiconducting layer are the relative permittivity ($\varepsilon_{r, semi}$) and the conductivity ($\sigma_{semi}$) which are studied in this section. Two more cases were simulated. Relative permittivity was changed to 10 in one simulation and conductivity was changed to 20 S/m in another simulation.

The effect of changing the permittivity was negligible as shown in Figure 4.26(a) and (b). However, when the conductivity was increased, a drastic drop in electric field strength was observed. It almost faded away at 20 m. Hence, no IFFT peak was observed at 20 m in Figure 4.26(b). Since the semiconducting layer is in fact a dielectric material doped with carbon black particles, its dielectric loss increases as its conductivity increases [92]. If the damaged section is located closer to the launcher, it is more likely to be detected.

![Figure 4.26](image.png)

Figure 4.26. (a) Electric field strength as a function of distance, and (b) insulation damage detection for different permittivity and conductivity of the semiconducting layer when $t_{semi}$=1.5 mm.

4.7 Conclusion

This chapter introduces a novel non-intrusive surface wave-based method of insulation and/or jacket material damage detection on cables. The sensor may be
implemented on live cables as an NDE method since it may be applied to the outer jacket/insulation and requires no contact to the conductor. A broadband monopole surface wave launcher that can confine a considerable portion of the EM energy within the insulation layer accomplishes this goal. However, most of the surface waves travel through air, which is a non-dispersive medium. Hence, the effect of the dispersive nature of the cable insulation is minimal. High wave velocity (0.92c) of surface waves, hence the effective permittivity of 1.1815 supports this argument.

Simulation results show that the magnitude of the peak of the IFFT response that is obtained by post-processing the complex reflection coefficient vs. frequency characteristics measured by the launcher can identify the location of damage. This method is adaptable to thin, moderately thick, and thick cables. The launcher and its operating frequency need to be designed accordingly, e.g., for thin wires shorter launcher and higher frequency vs. for thick cables longer launcher and lower frequency will be needed. Design guidelines for the surface wave launcher are provided. It was observed that when the launcher length was roughly 2-3 times the cable diameter, the IFFT peak at the damage location had maximum amplitude. The ground plane with width equal to or greater than the wavelength (in free space) resulted in sharper IFFT peak with higher amplitude as found in further simulations. Examples of damage location and severity detection on a thin cable (2.1 mm diameter wire with 0.5 mm thick insulation) is given using an 8 GHz launcher. The damage severity can be used as a feature or signature for damage that evolves over time and can be monitored using an online system. The example of a 1 GHz surface wave launcher shows insulation damage detection at 40 m on a 50 m long power cable with 24.4 mm diameter.
In the proposed scheme the parameter SR defines the minimum required distance between the damage location and the launcher, and the minimum distance between two consecutive damage locations.

This chapter also investigates how the presence of the semiconducting layer in medium/high voltage power cables affects the surface wave propagation and surface wave reflectometry for varying thickness and electrical properties of the layer. The semiconducting layer causes increased attenuation which increases further as the layer becomes thicker. As a result, the range over which the surface wave reflectometry method can locate damaged insulation sections decreases. Attenuation increases when the conductivity of the layer increases due to higher dielectric loss. Changes in relative permittivity of a moderate magnitude have a minor effect.

For practical applications, it may be necessary to adapt to a monopole launcher that is not a whole cylinder but has a cut so that the sensor can be wrapped around or placed more easily on a cable. The ground plane may be redesigned to make it more conformal or shaped to suit a particular application. Additionally, configurations without ground planes may be designed and developed. Cases of live current or signal carrying conductor may be considered. The use of a VNA may also not be a deterrent for a technology as the one proposed here since low-cost handheld miniature VNAs have been becoming available lately [93], [94].
CHAPTER 5
CONFORMAL SURFACE WAVE LAUNCHER FOR SMALL INSULATION DAMAGE/AGING DETECTION

5.1 INTRODUCTION

In Chapter 4, an electromagnetic (EM) surface wave-based technique was introduced that had the ability to confine significant EM energy in the cable’s insulation allowing detection of degradation or damage in the cable insulation. The launcher for the thin wire had operating frequency range of 5-8 GHz. However, when applying this technique to a thicker power cable, the frequency range was needed to be reduced to 0.7-1.1 GHz which reduced the resolution of the damage to be detected. Insulation damage over a length of 40 mm was detected at 40 m distance on a 50 m long power cable with 24 mm diameter. Although the distance over which the detection could be made was much longer, the size of a detectable damage was larger because of the reduced frequency. There are two factors here: (1) smaller amount of confined energy in the insulation, and (2) smaller electrical length/width of the damage (compared to the wavelength) at a lower frequency. It was clear from studies that to detect smaller defects such as cracks and tears on power cable insulation, surface wave frequency significantly higher than 1 GHz would be needed. Previously reported cylindrical monopole launchers simply failed to excite such high frequency waves on thick power cables due to the following reasons explained below. Surface waves propagate in transverse magnetic TM\(_0\) mode along an insulated conductor.
where \( z \) and \( \rho \) components of magnetic field, \( H \) are absent \((H_z = H_\rho = 0)\), considering \( z \)-directed surface wave propagation in a cylindrical coordinate [66]. Considering a cylindrical monopole launcher operating in the 5-8 GHz frequency range, if the launcher diameter is substantially larger than its length (the case of a thick power cable), it does not allow launching TM\(_0\) surface waves because \( H_z \neq H_\rho \neq 0 \). This can be explained with the help of Figure 5.1.

![Diagram](image_url)

Figure 5.1. (a) The SWL proposed in chapter 4 when mounted on a cable. Simulated H-fields on a plane perpendicular to the launcher at 8 GHz when cable diameter is (b) 3 mm and (c) 24 mm.
Figure 5.1(a) shows the geometry, placement, and orientation of a cylindrical surface wave launcher on a cable. Figure 5.1(b) shows successful surface wave launch ($H_z = 0$) at 8 GHz on a thin cable where the launcher diameter is 3 mm, and the length is 8.6 mm. By contrast, Figure 5.1(c) shows no surface waves launched when the launcher diameter is 24 mm, and its length is 1.08 mm also operating at 8 GHz.

For the thick power cable, the previously reported cylindrical monopole launcher with 0.7-1.1 GHz frequency range has a significantly large and protruded ground plane which measures 40 cm by 40 cm (see Figure 5.1(a)). Due to the narrower frequency range of 0.7-1.1 GHz, the spatial resolution of that launcher, which is 2.86 samples/m, is insufficient. A wideband launcher can increase spatial resolution, allowing it to identify damages closer to the launcher or damages in close proximity.

Given the challenge presented by a cylindrical monopole launcher when placed on a large diameter cable a new conformal surface wave launcher array (Figure 5.2) is proposed. The proposed SWL consists of planar monopole arrays that can be easily placed on a cable and that does not require a ground plane orthogonal to the monopole’s axis. With the proposed concept, it is demonstrated that the smallest size of a detectable damage decreases and the spatial resolution on thick power cables improves significantly because of the launcher’s ability to excite and use 6-11 GHz surface waves. For example, insulation loss over half of the circumference for only 1 mm length is detected successfully at 1 m distance on a 19.8 mm diameter cable. Experimental results on cables with cross-linked polyethylene (XLPE) and ethylene-propylene rubber (EPR) insulation, with and without chlorosulphonated polyethylene (CSPE) jacket, with and without semiconducting layer, and single and multiconductor cables are presented.
In terms of conformal launcher, Alam et. al. introduced a cylindrical monopole launcher with folded ground plane in [84] for cable open-circuit fault diagnosis. Gatti et al. [95] presented the study of a surface wave probe-array on a 1.2 m long 254 mm diameter metal pipe to detect damage and circumferential gaps in the acrylic coating at 0.9 m distance.

The geometry of the proposed broadband planar monopole array launcher is illustrated in Figure 3, which is printed on a 0.5 mm thick flexible substrate ($\varepsilon_{r,subs} = 2.2$). The element-to-element spacing for this N-element array is $1/N^{th}$ the circumference of the cable. As shown, the array elements are excited using a corporate-feed arrangement with the primary feed for each element being 50 Ohms. All design and analyses were carried out using Ansys HFSS where the cables were modeled as cylinders with hexagonal cross-section in order to reduce the computational load. Simulated magnitude of the $S_{11}$ vs frequency characteristics for this array with $N = 4$ are shown in Figure 3(b) which illustrate broadband operation (6-11 GHz) within $|S_{11}| < -10$ dB.

The transmission between two identical conformal launchers with $N = 4$ was studied as well. Two launchers were mounted on the two ends of a cable with varying
length and the attenuation for different lengths were plotted as shown in Figure 5.3(c). The surfaces waves are attenuated at a rate of approximately 2 dB/m with a linear approximation. When the length is zero, the linear approximation gives a value of 10.5 dB which indicates that the coupling between the cable and each launcher is around -5.25 dB.

![Figure 5.3](image)

Figure 5.3. (a) Layout of conformal surface wave launcher array with N = 4 (w = 8mm, l₁ = 7mm, l₂ = 8.5mm, d = 15.5 mm), and (b) simulated S₁₁ when the launcher is mounted on a 3m long cable. (c) Attenuation in surface waves between two launchers mounted on two ends of a cable with varying length. (Cable conductor diameter, dᵦ = 8.2mm, insulation thickness, tᵣᵢᵣ = 5.8 mm and εᵣ = 2.5).

### 5.3 SIMULATION OF MINIATURE INSULATION DAMAGE

The method employed to detect insulation damage is described in Chapter 4 which involves Kaiser windowing and IFFT. Since the conformal launcher allows more of the surface waves to propagate through the insulation, the wave velocity is \( v_{sw} = 1.83 \times 10^8 \)
m/s which is significantly smaller than $2.8 \times 10^8$ m/s which was reported in Chapter 4. Because of the wide frequency range (5 GHz), the spatial resolution after IFFT is 54.6 samples/m which is more improved than that in the Chapter 4. In the simulation studies, a power cable with outer diameter (OD) = 19.8 mm, insulation thickness = 5.8 mm, relative permittivity = 2.5 was considered.

5.3.1 **Effect of Number of Array Elements**

Number of array elements, $N$ is a very important design parameter. Launching surface waves requires uniform excitation throughout the cable circumference. Therefore, the array elements are equally spaced. From an antenna point of view, the optimum distance between array elements should be roughly half-wavelength [87] which is 15 mm at 10 GHz. For $N = 2$, 4, and 8, the element-to-element distances are 31.1 mm, 15.5 mm, and 7.8 mm respectively in free space. It is observed that the optimum distance can nearly be achieved when $N = 4$. Figure 5.4 illustrates the comparison between the damage detection performances for $N = 2$, 4, and 8. A 1.5 m long piece of the 19.8 mm diameter cable with a 5 mm wide half-circumferential insulation damage at 1 m was considered as the cable under test in the simulations. The IFFT peak magnitude at the damage location is maximum when $N = 4$.

Figure 5.5 illustrates a scenario when the array elements are not uniformly distributed throughout the circumference of a similar cable for $N = 4$. The distance between the array elements is reduced so that they are concentrated at one side of the cable circumference leaving the side empty. It is evident from Figure 5.5 that, non-uniformly spaced array elements excite weaker surface waves hence the damage detection performance becomes poorer.
5.3.2 Insulation Damage Detection

Figure 5.6(a) shows the demonstration of the proposed concept where the feasibility of missing insulation detection at different locations on a cable with varying lengths was shown. The locations of missing insulation were detected at 1m distance on a 1.5m long cable, at 2m distance on a 3m long cable and at 4m distance on a 5m long cable. The
scenario of missing insulation was modeled by removing insulation from over half of the circumference over \( w_d = 5 \text{ mm} \) width. As seen from Figure 5.6(a), the proposed approach can detect missing insulation on cables at various distances. The IFFT peak at the location of the missing insulation decreases at an approximate rate of 2.5 dB/m as the location of the damage along the cable was shifted. At this rate, the corresponding IFFT peak will be buried under noise after 5 m for this cable. The damage must be larger and/or the surface wave frequency must be lower to attain a longer detection range. The effectiveness of the proposed launcher in detecting half-circumferential insulation missing over a very small width \( (w_d) \), e.g., 1, 3 and 5 mm at 1m distance was also studied. As shown in Figure 5.6(b),

Figure 5.6. Insulation damage detection (a) at 1, 2 and 4 m distances for various cable lengths and (b) at 1m distance with variable damage width. (c) Narrow longitudinal slit-like crack detection with variable width at 1 m distance. \((d_c = 8.2 \text{ mm}, t_{ins} = 5.8 \text{ mm and } \varepsilon_r = 2.5)\).
insulation missing on as small as 1mm area was detected successfully. As expected, the magnitude of the IFFT peak at the damage location increases with damage growth. When considering real-time online monitoring, this feature will be very relevant because the IFFT peak will then reveal the growth of damage over time. A second important concern for example, is insulation damage that may of the shape and size of a narrow slit or crack e.g., along the cable’s axis. Such a case was also studied as shown in Figure 5.6(c), which shows that insulation damage like a narrow slit with width as small as 2 mm over 10 mm length can be detected. Further reduction in the damage width to 1 mm is not detectable because of system noise.

5.3.3 Multiple Cables in Proximity

In many practical applications, cables may reside next to other cables e.g., within a cable bundle, harness, or cable tray. Since a significant fraction of surface wave energy can propagate in the air and in the vicinity of the cable it is important to investigate the efficacy of the proposed approach when other cables are in proximity. Figure 5.7 illustrates such a scenario where three 1.5 m long cables reside next to each other with a gap of $s$ in between them. The cable under test contains a 5 mm long half-circumferential insulation damage at 1 m distance. The magnitude of the IFFT peak in Figure 5.7 clearly shows the effectiveness of the proposed approach even when cable to cable separation is only about 0.5 mm (minimum gap due to 0.5 mm thick launcher substrate).

Considering similar circumstances Figure 5.8 illustrates the case of two cables side by side where each contains a 5 mm long half-circumferential damage with damage locations being different e.g., 1 m and 0.6 m, respectively. If the intended damage to be detected is the one at 1m distance, then the results of the IFFT peak reveal that for cable-
to-cable separation distance of 20 mm or larger the damage location determination is unambiguous. As the separation between the cables decreases, two IFFT peaks start to appear indicating both damages. Since the magnitude of the IFFT peak at 0.6 m is smaller than the one at 1 m distance one can easily infer it must be coming from a second cable. In the case of more than two cables and all having damages multiple surface wave launchers can be used such as in a cable bundle and an algorithm can be developed to identify all or most damages.

Figure 5.7. Effect of cables in proximity when a cable is under test. $d_c=8.2$ mm, $t_{ins}=5.8$ mm and $\varepsilon_r=2.5$. Nearby cables have no damage.

Figure 5.8. Effect of insulation damage in nearby cables. ($d_c=8.2$ mm, $t_{ins}=5.8$ mm and $\varepsilon_r=2.5$).
5.4 EXPERIMENTS WITH MINIATURE INSULATION DAMAGE

5.4.1 EXPERIMENTAL SETUP

Conformal surface wave launchers were fabricated on 0.5 mm thick flexible Duroid 5880 substrate as shown in Figure 5.9. An Agilent E5071C vector network analyzer (VNA) was used to measure the $S_{11}$ vs frequency response. Photographs of the experimental setup are shown in Figure 8. Three types of cables were used: cables with EPR insulation and with and without semiconducting layer, and a three-conductor cable with XLPE insulation. All the cables had CSPE jackets. The cable was supported by Rohacell HF-71 foam structures which are electromagnetically transparent (Dielectric constant = 1.07).

Figure 5.9. Fabricated surface wave launcher, experimental setup, and the cable construction.

5.4.2 EXPERIMENTAL RESULTS OF DAMAGE DETECTION

Figure 5.10(a) shows the experimental results involving an EPR cable with 21 mm outer diameter (OD) and no semiconducting layer. Half-circumferential insulation and jacket damage over a length as small as 3 mm was detected successfully at 0.65 m distance.
As shown in Figure 5.10(b), a 3 mm damage was detected at 0.5 m on an EPR cable with OD = 21.3 mm with semiconducting layer. Same 3 mm damage was not detected at 1m distance due to increased attenuation introduced by the lossy semiconducting layer as shown in Figure 5.10(c). Figure 5.11 shows the results of insulation and jacket damage detection on a three-conductor cable with ground wires (OD = 25.15 mm). The 3 mm wide half circumferential damage was detected at 1 m on the 1.5 m long cable. In all cases, the magnitude of the peak of the IFFT increases with the damage size.

Figure 5.10. Experimental results of EPR insulation and CSPE jacket damage detection on Okonite cables (a) without semiconductor layer at 0.65 m (OD = 21 mm, $t_{ins} = 1.9$ mm, $t_{jac} = 1.6$ mm), and with semiconductor layer at (b) 0.5 m and (c) 1.0 m distance (OD = 21.3 mm, $t_{ins} = 3.18$ mm, $t_{jac} = 2.03$ mm).
5.4.3 Simulated Water-tree Detection

Water-treeing is a primary degradation factor in power cables, resulting in a shorter lifespan [96]. In the EPR cable with semiconducting layer, artificial water-tree was created by drilling 20 of 1.5 mm diameter holes in the jacket and insulation and filling them up with water. Figure 5.12 illustrates the successful detection of water-trees at 0.5 m distance on a 1.5 m long cable. Presence of water increases the average permittivity of the affected area, hence a reflection of surface waves with higher amplitude is generated from that area.
5.5 Aging Detection of Cable Insulation

Insulation aging is a different phenomenon compared to insulation damage or missing insulation. The term ‘aging’ in this dissertation refers to the fact that when insulation is aged or severely degraded, it stays in situ, which is the primary distinction between insulation aging and insulation missing. The dielectric properties of the insulation, such as relative permittivity, change with age and are used to identify insulation aging. Since the relative permittivity of the insulation and jacket normally increases with aging the growth of such parameters over time could serve as indicators of material aging.

Under normal service working conditions, power cables have an average lifetime of 50-60 years. The usual operating temperature of Okoguard jumper cable with EPR insulation is 60-70°C [56], [97]. Insulation aging happens uniformly across the cable at usual operating temperature due to heat caused by current flow. Reflectometry, which works on the principle of wave reflection from a location of rapid impedance mismatch due to a discontinuity, is not ideal for detecting such phenomena. While IDC sensing and EAB testing are well-suited for measuring the extent of uniform aging of a cable specimen at usual operating temperature, reflectometry techniques can be used to locate sudden insulation degradation or aging in a small segment in a long cable due to excessive heat generated by nearby machineries, heavy external pressure, cable bend, severe chemical or radiation exposure, water-tree formation, and, as previously discussed, missing or corrosion of insulation.

The detection of change in insulation permittivity due to aging using reflectometry requires highly sensitive technique. The monopole launcher proposed in chapter 4 proved to be unsuccessful in that endeavor. This section focuses on the feasibility of insulation
aging detection using surface wave reflectometry by employing the conformal array launcher since it is more sensitive to detecting small changes in parameters or discontinuities.

5.5.1 Simulation of Aging Detection in HFSS

As shown in Figure 5.13(a), using HFSS, an aged section with length \( L_{aged} \) was created at 1 m distance from the launcher in a 1.5 m long cable with OD = 19.8 mm, \( t_{ins} \) = 5.8 mm and \( \varepsilon_r = 3 \). According to [56], when insulating material is aged, its relative permittivity increases depending on the aging temperature and duration (considering accelerated aging). Considering \( L_{aged} = 3 \) cm, the relative permittivity of the aged section, \( \varepsilon_{r,aged} \) was varied to 3.1, 3.2, 3.3 and 3.5. Figure 5.13(b) shows the magnitude of the IFFT peak increasing as function of the increase in the relative permittivity of the aged section. As the section ages more and more the magnitude of the IFFT peak grows as well indicating

![Aged insulation (\( \varepsilon_{r,aged} \))](image)

(a)

![Relative Permittivity of aged insulation, \( \varepsilon_{r,aged} \)](image)

(b)

![Length of aged section, \( L_{aged} \)](image)

(c)

Figure 5.13. Insulation aging detection scenarios simulated in HFSS.
the progression of insulation aging. An interesting case of the growth of the length of the section getting aged can be seen in Figure 5.13(c). This figure shows the results as the length of the aged section varies while $\varepsilon_{r,\text{aged}}$ is 3.5. The increase in length of the section over which aging is prevalent can also be detected using the proposed method. The latter can be useful in locating sections which may be more prone to aging due to environmental conditions.

5.5.2 ACCELERATED AGING MECHANISM

Accelerated aging is a well-known technique that is used by many researchers in different disciplines to artificially age materials in a laboratory by exposing them to a temperature higher than usual over a short period of time [98]-[100]. It is popular among researchers working on NDE cable testing. In [56], accelerated aging of cable specimens in a heat chamber was carried out on an EPR cable at 160°C for 224 hours to simulate the actual aging of 60 years at regular service temperature of 70°C. The authors of [56] used interdigital capacitor (IDC) sensors to measure the extent of material aging. In contrast to [56], this study focuses on locating smaller but severely aged areas on a power cable which occurs due to intense external factors such as very high temperature, say 90°C which is maximum rated temperature for Okoguard EPR jumper cable, over 50-60 years. Unlike previous studies in this dissertation, the aged or degraded insulation remains in its place, hence, does not expose the conductor. The launched surface waves will see a change in the dielectric properties of the insulation in the aged area and a reflection will ensue. Since the insulation is not missing, the reflection will be smaller than the previous cases which makes it harder to detect.
The accelerated aging time and temperature can be correlated to the real time and temperature using the modified Arrhenius equation [101] as follows.

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

(5.1)

Here, \( T_a \) = accelerated aging temperature (K), \( T_r \) = temperature in reality (K), \( t_a \) = total duration of accelerated aging, \( t_s \) = total duration of real aging, \( E_a \) = activation energy of the insulating material (eV), and \( k \) = Boltzmann’s constant which is \( 0.8617 \times 10^{-4} \) eV/K.

The activation energy, \( E_a \) is considered 1.1 eV for EPR insulation [102], [103]. To replicate 60 years (\( t_r \)) of real-life aging at 90°C (\( T_r = 363 \) K), the accelerated aging in laboratory needs to be done for \( t_a = 917 \) hours at 170°C (\( T_a = 443 \) K). Although accelerated aging at a lower temperature such as 140°C is likely better from a material degradation point of view carrying out such experiments in an academic laboratory will be prohibitively long and expensive.

### 5.5.3 Experiments with Accelerated Aging

The accelerated aging of medium voltage Okoguard aerial jumper cable with EPR insulation was considered in this study. Between the insulation and the stranded conductor resides a semiconducting screen. The outer diameter of the cable is 23.3 mm, while the thickness of the EPR insulation is 5.94 mm. A total of 5 cable examples were prepared, each measuring roughly 8 cm in length. The specimens were heated at 170°C for varying amounts of time in a Test Equity Model 115 temperature chamber. The five specimens were heated for a total of 176, 336, 504, 691, and 887 hours, respectively. After the specific time period, each specimen was removed from the chamber. The accelerated aging was carried out for 60 days, with 14 to 15 hours of heating every day. A total of 887 hours at
170°C is equivalent to 58 years of aging at 90°C according to (5.1). Figure 5.14 shows the accelerated aging setup in the temperature chamber.

![Temperature Chamber](image_url)

Figure 5.14. Accelerated aging of Okoguard Aerial Jumper cable specimens in heat chamber.

Surface wave reflectometry was performed on a 1.5 m long cable. Insulation was removed completely from that cable at 1 m distance over a length of 3 cm as shown in Figure 5.15(a). On the other hand, 3 cm long insulation was also cut from the aged cable specimens as shown in Figure 5.15(b) which could fill in the gap in the 1.5 m long cable piece (see Figure 5.15(c)). The conformal launcher was placed on the cable at 1 m distance from the aged section. As shown in Figure 5.15(d), the aged section was detected, and the IFFT peak magnitude increases as the duration of aging increases.
This chapter introduces a unique concept of non-intrusive insulation damage and aging monitoring for power cables. The proposed sensor launches surface waves of several GHz frequency enabling the detection of miniature damages in insulation and/or jacket that might be precursors of serious incidents. The efficacy of the proposed approach was demonstrated by multiple simulations and experiments on a variety of cables. The slight inaccuracy in damage location detection observed in the experiments was caused by the errors in length measurement using manual tape-measures that were difficult to precisely employ due to cable bending. Although utilization of microwave frequencies limits the

**5.6 CONCLUSION**

Figure 5.15. (a) Insulation removed from 3 cm length on a 1.5 m long unaged cable, (b) accelerated aged 3 cm long EPR insulations for different duration, (c) placement of aged insulation on the 1.5 m long unaged cable, (d) detection of aged section using proposed conformal launcher.
distance over which the proposed method is effective, its ability to detect miniature cracks or damages and aging without making any electrical connection to the conductor makes it an excellent candidate for future cable NDE applications including on-line and live-wire monitoring. The purpose of the accelerated aging study was to investigate and explore the feasibility of insulation permittivity change detection using surface wave reflectometry. There is scope for more in-depth investigation on this particular topic, especially if specimens can be aged at a lower temperature and for longer duration in a laboratory setting.
CHAPTER 6
CONCLUSION AND FUTURE WORKS

This dissertation focuses on the application of electromagnetic principles in the design and development of non-intrusive microwave surface wave sensors for NDE cable health monitoring. The focus of this dissertation was on studying and developing a non-intrusive insulation damage detection method using surface wave reflectometry for a variety of cables, including thin and thick cables/wires, single and multi-conductor cables, cables with and without semiconductor layer, and cables with and without jacket. Below is a summary of the contributions. In Section 6.2, the direction of prospective future research in this area is outlined.

6.1 SUMMARY OF CONTRIBUTIONS

From the standpoint of cable diagnosis, the behavior of electromagnetic surface waves on electrical cables with various diameters, insulation thicknesses, and relative permittivity was studied analytically. The study revealed that the fractional microwave power confined in the cable insulation increases with frequency. While intuitive, this understanding was essential to comprehend the need for higher frequencies to detect insulation damage on cables as compared to sub-GHz frequencies that had been proposed and used in the past for open-circuit type fault detection.
Starting from Goubau’s analyses a broadband 5.5-8.5 GHz frequency range was selected and a surface wave signal was effectively launched on a thin cable using a monopole type launcher. The reflected signal from insulation damage was measured in the form of $S_{11}$ which when further processed (windowing and IFFT) clearly delineated the location and the extent of the damage. Simulation results show that the magnitude of the peak of the IFFT response that is obtained by post-processing the complex reflection coefficient vs. frequency characteristics measured by the launcher can identify the location of damage. This method is adaptable to thin, moderately thick, and thick cables. The launcher and its operating frequency need to be designed accordingly, e.g., for thin wires shorter launcher and higher frequency vs. for thick cables longer launcher and lower frequency will be needed.

Insulation damage at various distances, full circumferential, half-circumferential, and other types of damages were effectively detected. Under our proposed approach even a 1 mm wide insulation gap on a 3.05 mm diameter thin wire was detected. It was demonstrated that insulation damage of the shape of partial insulation removal over an area which may occur due to minor corrosion is also detectable. Insulation missing from over a 30° circumferential angle was detected. The effect of airgap on the efficacy of this approach was studied. Experimental results demonstrated the simulated findings.

The efficacy of insulation damage detection for various insulation thicknesses and permittivity was investigated. Finally, by applying a 0.7-1.1 GHz surface wave signal on a relatively large diameter 50 m long power cable (diameter 2.44 cm) a 4 cm long circumferential insulation damage was detected at 40 m distance.
It was clear from these studies that surface waves of higher frequencies, such as 8-10 GHz would be needed to detect damages of smaller size. This is analogous to radar. The higher the resolution requirement the higher should be the frequency and the bandwidth. Nevertheless, the cylindrical monopole type launchers shrink in length as the frequency increases. At some point, the length to circumference aspect ratio becomes such that they fail to launch surface waves. This bottleneck was solved by designing and developing a conformal planar monopole type surface wave launcher array. With this proposed approach, insulation damages with various sizes and shapes were detected on a power cable with 19.8 mm diameter and 5.8 mm thick insulation. For example, a 1-2 mm wide crack of 10 mm length was detected at 1m distance on a 2m long cable. Experimental results validated the simulated findings. The proposed methodology and approach were successful when applied on cables containing semiconducting screens although over a shorter distance due to increased attenuation. The technique when applied on a multiconductor cable was able to detect insulation damage at a distance. The proposed approach was found to be effective in the presence of other cables even when they are as close as within 0.5 mm from each other as long as they do not contain damages. It was observed that for multiple cables with damages innovative algorithms along with multiple launchers may need to be developed in order to identify and tag each damage separately.

Finally, the idea of a certain cable section that may have suffered aging more than the rest of the cable was investigated using the proposed approach and conformal surface wave array launcher. Since cable polymer aging results in material degradation and hence permittivity change it was hypothesized that the proposed approach may succeed in detecting such aging.
Simulations and experiments were performed to investigate the feasibility of localized insulation aging detection on a power cable. Simulation results clearly show the feasibility of the proposed approach. When the method was applied on specimens of EPR insulation specimens that had undergone accelerated aging for 887 hours at 170°C it demonstrated successful aging detection.

6.2 Future Works

In Chapter 5, a conformal surface wave launcher was used to detect localized insulation aging on a long cable. The cable specimens were subjected to accelerated aging at 170°C for 887 hours. Because of the high temperature aging the material became somewhat brittle. In the future accelerated aging at lower temperatures such as 140°C can be considered.

Since under our proposed approach surface waves are injected non-intrusively that should be applicable to live cables or wires which will simultaneously allow the flow of power or other types of signals on the cable as well as EM surface waves. It is expected that surface waves operating at microwave frequencies will likely have no effects on power line signals carrying currents at 50-60 Hz. Nevertheless, studies on electromagnetic interference (EMI) should be carried out to eliminate the possibility of EMI. Another area of EMI could be from other radiating sources like Wi-Fi which also needs to be studied.

One of the primary obstacles in reflectometry approaches in terms of field use is the bulky size and/or expense of the testing instruments. Even cheap 1-4 GHz VNAs cost several thousand dollars. Furthermore, traditional reflectometry approaches rely on TDR sensors that can only work in the 100-200 MHz frequency range. Microwave-capable TDR devices, which are necessary for the proposed surface wave reflectometry, are not easily
accessible on the market. At microwave frequencies, digital signal generators, analog-to-digital converters (ADC), digital-to-analog converters (DAC), and other components are exceedingly expensive. A hybrid technology combining frequency modulated continuous wave (FMCW) radar and surface wave reflectometry could provide a solution to this problem [104]-[106].

It is evident from the observation in Chapter 4 and 5 that no single launcher can simultaneously detect a very small insulation damage like an extremely small crack or slit and simultaneously detect damage at a long distance. The 0.7-1.1 GHz launcher in Chapter 4 offers longer range but poor damage resolution on a power cable. In contrast, the 6-11 GHz launcher can detect a very narrow slit in the insulation since energy concentration inside insulation increases and the electrical length/width of the damage becomes larger at higher frequency. However, the detection range becomes shorter because of the increased attenuation.

A new type of surface wave launcher may be developed which can operate at two or more different frequency bands. It may offer a scenario where it can detect very small damages at close range and can detect large damages at a much longer range. Frequency reconfigurable launchers or multiband launchers may be designed. The new challenges presented by such launcher may include impedance matching and designing the feedline at multiple frequencies, algorithm development to combine responses at different frequencies to achieve resolution and range coverage.
REFERENCES


