

A Study of the Eroding Dry-Band Arcing on Silicone Rubber Insulation Using Ultra-High Frequency Detection Technique

by

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Author's Declaration

I hereby declare that I am the sole author of this thesis. This is a true copy of the thesis, including any required final revisions, as accepted by my examiners.

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Abstract

Erosion of silicone rubber housing material is a major cause of failure in outdoor insulators used on overhead power distribution and transmission networks. Dry-band arcing, resulting from leakage currents on the insulator surface, is the main culprit of the erosion of silicone rubber housing material. The inclined plane tracking and erosion test, standardized in IEC 60587 and ASTM D2303, has been a key tool for testing outdoor insulating materials under dry-band arcing at the material development stage, enabling efficient material ranking for field applications. Extensive research on the erosion mechanism of silicone rubber has been carried out in the standard test, and accordingly, the reliable assessment of erosion has facilitated the development of formulations with acceptable performance for outdoor insulation applications. The degree of erosion of silicone rubber varies depending on the severity of dry band arcing during the inclined plane test, with highly severe arcing—referred to as critical or eroding dry-band arcing—often leading to deep erosion.

The two inclined plane test standards specify different testing methods, range of test voltages, and failure criteria for the assessment of erosion on silicone rubber. However, the testing methods specified in the standards have often been used interchangeably in different studies, and there is no general agreement on which method is most appropriate for the reliable evaluation of erosion on silicone rubber. In addition, there are wide discrepancies in the selection of test voltages, and no unified agreement exists on the most suitable voltage level for testing silicone rubber materials, leading to inconsistencies in test outcomes. Another crucial aspect of the inclined plane test in evaluating the performance of insulating materials is identifying erosion failure, for which different criteria are specified in the two standards. However, the failure criteria specified in the standards are also applied inconsistently across various studies, with different criteria being used. While some criteria may be effective for certain materials, they are not always applicable to SR—particularly under DC voltages. These inconsistencies in testing methods, voltage selection, and failure criteria largely stem from a

limited understanding of the erosion failure mechanisms of silicone rubber, highlighting a critical research gap that needs to be addressed.

Additionally, the erosion mechanism of silicone rubber has been extensively studied in the inclined plane test based on leakage current techniques. While these methods correlate leakage current with dry-band arcing severity during the test, the onset of erosion or material failure could not be reliably detected with these techniques. In particular, no significant focus has been given to the erosion failure mechanisms on silicone rubber insulation under the eroding dry-band arcing. Consequently, the underlying physics of the eroding dry-band arcing driving erosion failure of silicone rubber remains inadequately understood, presenting a critical technical gap. This highlights the critical need for a reliable detection method of the eroding dry-band arcing to identify deep erosion failure during the inclined plane test.

This thesis provides a mechanistic understanding of the erosion failure mechanisms of silicone rubber particularly through a reliable detection of the eroding dry-band arcing in the inclined plane test. To achieve this, ultra-high frequency detection of the eroding dry-band arcing is introduced as a reliable technique to identify erosion failure of silicone rubber in the AC and DC inclined plane tests. This detection method will serve as a foundation for improving the elucidation of the mechanisms of eroding dry-band arcing that drive erosion failure in silicone rubber. Moreover, it is a critical step towards improving the standards by introducing a clear erosion failure criterion for silicone rubber in the inclined plane test.

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Dedication

To my beloved mother and my father,
for their endless love, support, and encouragement.

To my dear brothers, Adil, Adeel, and Afaq,
for their companionship and unwavering belief in me.

To my beloved wife,
whose love and joy inspire me every day.

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List of Acronyms and Symbols

Acronyms

AC	Alternating Current
ASTM	American Society for Testing Materials
ATH	Alumina Tri-Hydrate
ATR	Attenuated Total reflection
CV	Coefficient of Variation
DC	Direct Current
DBA	Dry-Band Arcing
DTG	Derivative Thermogravimetry
DTA	Differential Thermal Analysis
EM	Electromagnetic
FRP	Fiberglass-reinforced polymer
FTIR	Fourier Transform Infrared
GIS	Gas-Insulated Switchgear
IPT	Inclined Plane Tracking and Erosion Test
IR	Infrared
IEC	International Electrotechnical Commission
IEEE	Institute of Electrical and Electronics Engineers
LC	Leakage Current
MRA	Multiresolution Analysis
PDMS	Polydimethylsiloxane
PD	Partial Discharge
RTV	Room Temperature Vulcanizing
rms	Root Mean Square
RM	Residue obtained from non-eroded regions on sample
RE	Residue obtained from eroded regions on sample
RF	Radio Frequency
SR	Silicone Rubber
TGA	Thermogravimetry Analysis
UHF	Ultra-High Frequency
A30	Room Temperature Vulcanized Silicone Rubber+30 wt% Alumina Tri-Hydrate
A50	Room Temperature Vulcanized Silicone Rubber+50 wt% Alumina Tri-Hydrate

S30	Room Temperature Vulcanized Silicone Rubber+30 wt% silica
S50	Room Temperature Vulcanized Silicone Rubber+50 wt% silica

Symbols

Si-O	Siloxane Bond
CH ₃	Methyl side groups
CH ₄	Methane Gas
+DC	Positive Polarity Direct Current
-DC	Negative Polarity Direct Current
wt%	Percentage Weight
%	Percent
°C	Degrees Centigrade
V	Volt
kV	Kilovolt
Ω	Ohm
kΩ	Kilo Ohm
mA	Milliamper
Hz	Hertz
kHz	Kilohertz
MHz	Megahertz
GHz	Gigahertz
kW	Kilowatt
kVA	Kilo volt-ampere
m	Meter
s	Second
cm	Centimeter
min	Minute
ml	Millilitre
ms	millisecond
μs	Microsecond
ns	Nanosecond
mm	Millimeter
μm	Micrometer
mg	Milligram
mV	Millivolt
mS	Milli siemens

dB	Decibel
GS	Giga Samples
cm ⁻¹	Inverse Centimeter
N ₂	Nitrogen
O ₂	Oxygen
NH ₄ Cl	Ammonium Chloride
T _h	Maximum surface temperature
KBr	Potassium Bromide
ZnSe	Zinc Selenide
S	Shannon Entropy
P(x)	Probability distribution of the UHF signal values
σ	Standard Deviation
μ	Mean of the entropy values
Σ	Summation

Chapter 1

Introduction

1.1 Context and Research Motivation

Polymeric outdoor insulators have been adopted to replace conventional porcelain and glass insulators, mainly due to their lighter weight and better performance in wet and polluted environments. The reliable performance of polymeric outdoor insulators is crucial to maintaining the smooth operation of the power system with minimal disruptions. The reliability of these insulators depends on the performance of the insulator's housing material under the polluted conditions of the outdoor environment. Among all polymer materials in use, silicone rubber (SR) is widely favored for insulator housing due to its excellent performance in polluted environments. However, in harsh weather conditions, contaminant films can wet the SR housing, leading to leakage currents that may progress into sustained dry-band arcing (DBA). The DBA-induced heat gives rise to erosion of SR housing, which may result in insulator failure and subsequent power supply disruptions.

The inclined plane tracking and erosion test (IPT), standardized in IEC60587 [1] and ASTM D2303 [2], has been widely used as a screening test to evaluate the erosion performance of insulating materials under DBA for outdoor applications. Its widespread use in both industry and research is due to its short conduction time, allowing for efficient ranking of insulating materials suitable for field applications. The IPT has also been used to extensively study the erosion mechanisms of silicone rubber insulation, leading to the development of improved housing formulations suitable for outdoor applications. IEC 60587 and ASTM D2303 standards outline testing methods, voltage levels, and failure criteria for erosion under AC voltages, while IEEE Std. 2652 [3] provides guidelines for testing under DC voltages. Two standard IPT test methods are available applying different testing voltages to insulating materials. However, there is no consensus on the most appropriate testing method for evaluating SR erosion, as the standard-defined methods have been used interchangeably across different studies, resulting in inconsistencies in test outcomes. One of the key aspects of the

IPT has been the selection of the test voltage, which varies depending on the amount of filler loading in SR, influencing its resistance to erosion. Despite the availability of two standards, significant discrepancies remain in selecting the most suitable test voltage that would induce eroding DBA on the material surface, ensuring a reliable evaluation of erosion performance.

Another crucial aspect of the IPT is identifying material failure due to erosion, based on the failure criteria defined by the IEC 60587 and ASTM D2303 standards. One of the standard failure criteria for SR in the IPT is the formation of a 1-inch erosion path on the surface [1,2]. However, this criterion may not be applicable when evaluating SR formulations under DC voltages, which tend to cause deep and instantaneous erosion rather than progressive surface erosion. Another failure criterion specified in IEC 60587 is the measurement of a 60-mA LC on the material surface as an indicator of failure [1]. However, this criterion may not always be useful for lower equivalent DC voltages compared to standard AC_{rms} voltages, as materials tested under DC may fail the IPT earlier due to combustion or deep erosion before reaching the 60-mA LC threshold. The failure criterion found useful for testing under DC is the formation of deep erosion holes, material puncture, or sample ignition during the IPT. However, measuring the erosion depth during the test is not feasible, so relying on this criterion may not always yield reproducible test outcomes. This challenge was encountered during round-robin testing in the development of IEEE Std. 2652 for the DC IPT. Therefore, the existing failure criteria in IEC 60587 and ASTM D2303 are not feasible for clearly identifying erosion failure during the IPT. The use of different testing methods, test voltages, and failure criteria in evaluating silicone rubber materials has led to inconsistencies in test outcomes, as a result of a lack of understanding of their erosion failure mechanisms. This highlights a critical research gap that needs to be addressed.

To date, the erosion mechanism of SR insulation has been extensively studied in the IPT using existing LC-based techniques, such as third harmonic analysis [4] and wavelet transform [5]. These techniques have demonstrated a correlation between the LC and DBA severity but have not clearly identified the inception of erosion or material failure during the test. Notably, little attention has been given to studying the erosion failure mechanisms of SR

insulation under the eroding DBA in the IPT. In other words, the underlying mechanism of the eroding DBA contributing to erosion failure of SR is still not well understood, presenting a significant technical gap. This gap needs to be bridged by developing a reliable detection technique of the eroding DBA to improve the understanding of the erosion failure mechanisms of SR insulation. Addressing this need is particularly important for DC inclined plane test methods, given the limited experience, knowledge, and baseline data available for material performance under DC voltages compared to AC voltages.

1.2 Research Objectives

The objectives of this thesis are as follows:

- Develop a reliable technique to detect the eroding DBA and identify erosion failure of SR during the IPT.
- Understand the erosion failure mechanisms of SR insulation by elucidating the physics of eroding DBA that contributes to failure of SR in the IPT.

1.3 Thesis Organization

This thesis is organized to begin with this introductory chapter, followed by four additional chapters. A summary of the content in these chapters is provided below:

- Chapter 2: This chapter provides the essential background and literature review to contextualize the research. It begins with an overview of polymeric high voltage outdoor insulators and the use of SR housing material in outdoor insulation, along with key information about the IPT. The chapter then presents a summary of the current state of knowledge regarding the erosion mechanisms on SR insulation under both AC and DC voltages in the IPT. It highlights the limitations of existing practices in

evaluating the erosion of SR and in identifying erosion failure under standard IPT procedures. Additionally, the chapter explores literature on ultra-high frequency (UHF) electromagnetic detection methods as applied to outdoor insulators. The chapter concludes by outlining the research aims and how this study addresses the identified gaps.

- Chapter 3: This chapter outlines the methodology for investigating the erosion failure mechanisms of SR through UHF detection of the eroding DBA. It covers the research approach, including sample preparation, experimental setup, variables, testing procedures, and the measurements and analyses conducted on SR tested in IPT. The measurements taken in this study include leakage current, UHF signals, surface temperature, and erosion depth, all of which are critical for analyzing the erosion failure mechanisms of SR. Temperature measurements are analyzed to correlate the thermal erosion mechanism with the eroding DBA. UHF signal analysis is performed, enabling UHF detection to identify the onset of eroding DBA and potential indicators of erosion failure in IPTs. Material characterization tests are conducted to establish correlations with IPT results and other measurements on SR during IPT. TGA-DTA is used to identify the thermal degradation mechanisms of SR in relation to surface temperature changes during IPT, while FTIR analysis investigates the chemical changes on the SR surface affected by varying severity levels of the DBA.
- Chapter 4: This chapter presents experimental findings from the IPT and material characterization tests. The results include the eroded depth of the tested SR composites under both AC and DC voltages in the IPT, along with LC, temperature, and UHF measurements. Additionally, the chapter discusses the TGA-DTA and FTIR results. The presented results are analyzed to evaluate the effectiveness of the UHF technique in identifying erosion failure in SR, compared to leakage current-based techniques. A mechanistic understanding of the eroding DBA is established by correlating the IPT outcomes, material characterization results, and UHF measurements. Furthermore, an

analysis of UHF measurements is conducted to determine reliable indicators of erosion failure in SR during the IPT.

- Chapter 5: This chapter summarizes the key findings of this study and provides recommendations for future research related to the topics investigated.

Chapter 2

Background and Literature Review

2.1 Polymeric Outdoor Insulators

Outdoor insulators are considered one of the critical components of overhead power transmission and distribution networks. They provide essential mechanical support to high-voltage line conductors as well as the required insulation from the grounded towers. Ceramic insulators, commonly used for this purpose, are made from materials such as porcelain or toughened glass. However, these insulators are heavy and brittle, making them susceptible to fracture under forcible stresses, and prone to failure in highly contaminated conditions. Polymeric outdoor insulators replace ceramic insulators in many applications due to their advantages, including being lightweight, hydrophobic, and demonstrating high resistance to vandalism as well as superior electrical performance. These insulators are available in either post, tension or suspension type, depending on their specific application within the power system.

Polymeric insulators consist of a fiberglass-reinforced polymer (FRP) rod, metallic end fittings, and a polymer housing as shown in Figure 2.1 [6]. The FRP rod forms the core of the insulator, providing the mechanical strength required to support the weight of the conductor. The metallic end fittings connect the insulator to both the tower and the line conductor. The polymer housing comprises watersheds and a sheath that encapsulate the FRP core, protecting it against tracking that may take place under outdoor weathering conditions. During its service operation, the polymer housing is subjected to a combination of stress factors, including voltage, moisture, and contamination. These stressors can degrade the polymer housing, exposing the FRP core to outdoor contaminants and voltage gradients, leading to brittle fracture of the core and insulator failure. This may result in a power line drop that consequently interrupts the power supply, thereby compromising the reliability of the power grid

infrastructure. Thus, the reliability of outdoor insulators has become crucial for ensuring a reliable power grid.

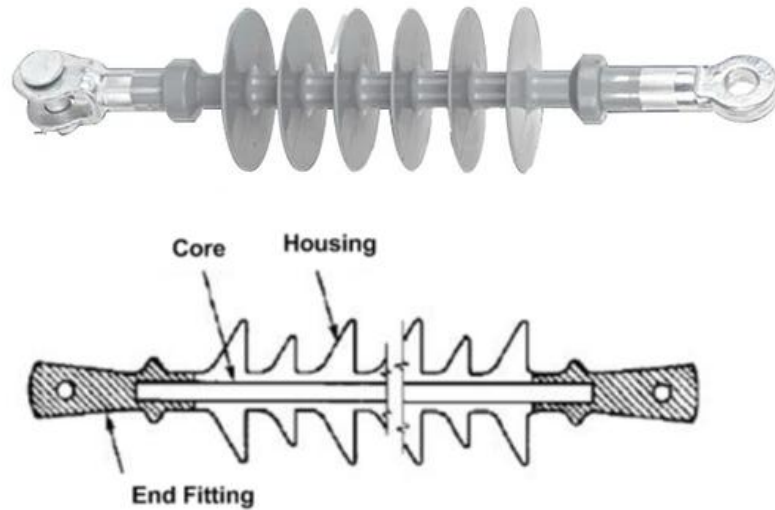


Figure 2.1. Schematic of a Polymeric outdoor Insulator [6]

2.2 Development of Dry-Band Arcing on Polymeric Insulators

Depending on the area where the insulator is installed, it may experience various contaminants and weathering conditions during its service life, which can significantly deteriorate the insulation housing. These conditions include exposure to moisture in salt environments, coastal regions, fog, and mist. Other sources of contamination include airborne dust particles in the surrounding atmosphere and industrial pollution [6]. Exposure to these conditions can temporarily reduce surface hydrophobicity, gradually making the surface hydrophilic. In the presence of moisture or fog, surface contaminants become easily wetted, forming conductive water filaments across the insulator surface which, in the presence of voltage stress, leads to the development of leakage current (LC). The non-uniform current density along the insulator surface causes joule heating and evaporation of the conductive layer

in regions of higher current density, forming dry bands where most of the voltage appears. Consequently, electrical discharges of relatively larger magnitude occur, dynamically bridging the dry bands—a phenomenon commonly referred to as dry-band arcing (DBA).

Depending on the magnitude of the leakage current and discharge duration, the heat released by DBA strikes the insulator surface and forms hot spots on the surface. The DBA may severely degrade the housing material, causing tracking and erosion, which can lead to insulation failure [7]. In some cases, the DBA may propagate to bridge the gap between the insulator ends, causing flashover and eventually the interruption of the power supply.

2.3 Tracking and Erosion of Silicone Rubber Housing

Among the polymer housing materials in use, silicone rubber (SR) is widely employed for polymeric insulators in overhead power transmission and distribution networks, due to its superior hydrophobicity and better performance in polluted environments [6, 8]. While experience with SR insulators has been promising worldwide, the degradation of the housing material, leading to insulator failure, remains a concern. Continuous wetting can destroy the hydrophobicity of SR insulators, making the housing material susceptible to DBA, which leads to tracking and erosion. Surface tracking refers to the formation of conductive tracks, either fully or partially, across the insulator surface due to the formation of carbonized residue, which may cause an irreversible loss of insulation properties [9, 10].

Erosion, on the other hand, refers to the heat ablation of the housing material caused by sustained DBA, resulting in permanent loss of insulation mass. Erosion may expose the fiberglass core to voltage and moisture, conditions that are conducive to tracking failure of the FRP rod, thereby leading to insulator failure. Figure 2.2 illustrates the erosion mechanism of SR, highlighting the stages of LC development leading to DBA-induced heat. The DBA heat and localized surface hot spots accelerate thermal degradation and erode the SR housing material [11].

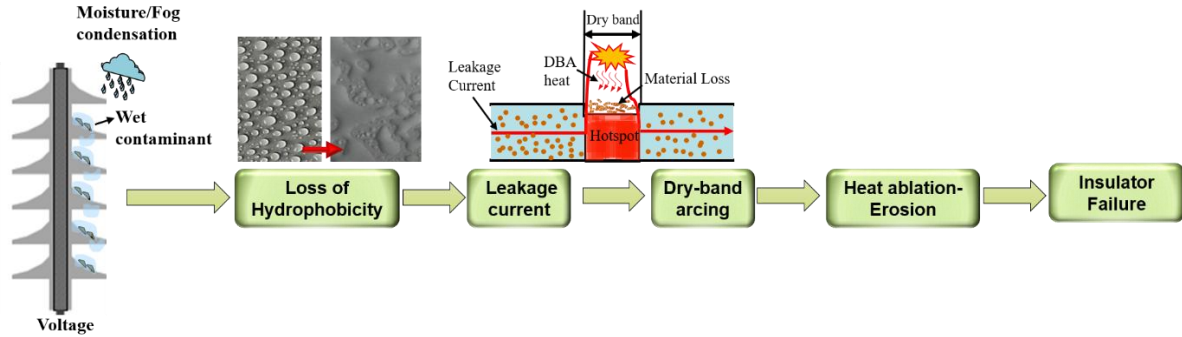


Figure 2.2. Erosion mechanism of SR housing leading to insulator failure.

SR is an elastomeric polymer with a backbone chain composed of alternating silicon and oxygen atoms, known as the siloxane (Si-O) chain. The molecular structure of SR consists of repeating siloxane units, with methyl (CH₃) side groups attached, forming polydimethylsiloxane (PDMS), as shown in Figure 2.3. Compared to other organic polymers used in outdoor insulation, SR has an inorganic backbone with low carbon content, making it more resistant to carbonization and tracking failure. Unlike other polymers, SR does not promote the formation of significant carbonized residue on its surface under the effect of DBA [12]. Analysis of the surface residue formed on SR under DBA revealed only 1 wt% elemental carbon, found as amorphous carbon, graphite, and hydrocarbon, which was considered insignificant to promote tracking failure in SR [12]. Rather than promoting tracking failure, silicone rubber primarily fails due to erosion under the effect of the eroding DBA, a key concern for SR in outdoor insulation.

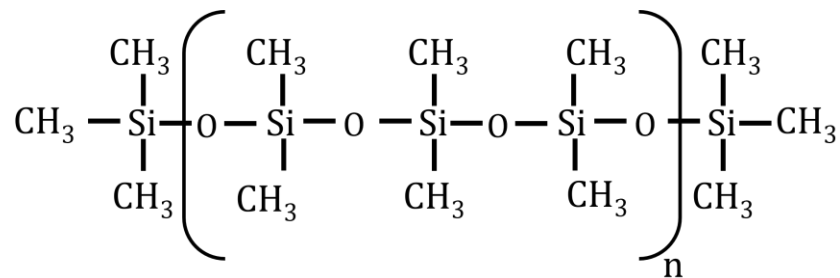


Figure 2.3. Molecular structure of PDMS SR

Significant improvements have been made to suppress erosion by incorporating inorganic fillers into polymer housing materials. Initially, these fillers were introduced to suppress tracking by reducing the organic polymer content but were later used to suppress erosion in tracking-resistant materials such as SR. Inorganic fillers, known for their flame-retardant properties, have been shown to provide various effects that play a key role in suppressing SR erosion, including both volume and physical effects [13-21]. The volume effect improves the thermal properties of the SR composite, including heat capacity, thermal conductivity, and thermal stability. The physical effect, on the other hand, involves a surface-cleaning mechanism driven by the release of water of hydration from hydrated fillers. Additionally, water of hydration is released during the thermal decomposition of hydrated fillers, stimulating the internal oxidation of the SR side chains. This mechanism produces inert gases that dilute the DBA plasma, thereby reducing the polymer's flammability and suppressing erosion [14, 18, 21, 22]. Moreover, another flame-retardant mechanism is the formation of an inert residue layer, which acts as a shield against heat influx and oxygen diffusion into the polymer [19, 21, 23]. These studies have identified the type and amount of inorganic fillers as important factors in suppressing erosion. As a result, several SR housing formulations have been developed utilizing the two commonly employed fillers in outdoor insulation applications: silica and alumina tri-hydrate (ATH). Accordingly, SR housing formulations for outdoor applications must be verified for acceptable erosion performance under DBA using the IPT, in compliance with IEC 60587 or ASTM D2303 [1,2].

2.4 Thermal Degradation of Silicone Rubber

The thermal degradation mechanisms of SR have been widely studied in the literature. Heat generated by DBA can depolymerize SR by breaking siloxane bonds, resulting in the formation of cyclic volatile oligomers. Three possible mechanisms have been identified for SR depolymerization: unzipping, random scission, and externally catalyzed reactions as shown in Figure 2.4 [24, 25]. The unzipping mechanism occurs in SR with silanol end groups. Upon

heating, these silanol groups facilitate intramolecular redistribution reactions, forming cyclic oligomers [25]. This volatilization shortens the siloxane chains, thereby degrading the silicone polymer. In the random scission mechanism, siloxane bonds break at various points along the chain, producing shorter siloxane chains and cyclic oligomers. This process continues until the chains become too short to form cyclic oligomers. The oligomers formed undergo thermo-oxidation, resulting in the formation of an inert silica residue [25]. Random scission is the dominant mechanism for depolymerization in SR, and its rate is influenced by the flexibility of the siloxane chains and the polarity of the siloxane bond [26]. The externally catalyzed mechanism is triggered by additives and polar impurities in the polymer network, which catalyze the scission of Si-O bonds. For example, hydrolysis of siloxane bonds by hydroxyl anions can occur, producing methane (CH_4) and silicone oligomers [25-28].

Thermal degradation of PDMS SR has been widely studied [25-27], with several factors affecting its behavior, including heating rate, testing environment (inert or air), and the nature of the composition. The degradation in an oxidative (air) atmosphere differs from that in an inert (N_2) atmosphere. According to G. Camino et al. [26], oxidative degradation in an air atmosphere occurs at lower temperatures to form mixtures of oligomers compared to an inert atmosphere, due to catalytic role of oxygen. In inert atmosphere, degradation typically begins around 400°C , with a significant increase in the degradation rate at around 540°C [25-28]. The byproducts of inert degradation are cyclic silicone oligomers, while oxidative degradation yields water, carbon dioxide, and silica in addition to the oligomers. At lower heating rates, oxidative degradation takes place in two distinct stages, occurring at around 240°C and 400°C . In contrast, at higher heating rates, the oxidative degradation typically takes place in a single stage at elevated temperatures. Other studies have shown that at high heating rates, different residuals form at temperatures exceeding 600°C , such as stable silicon carbide or oxycarbide [26, 27]. During inert degradation, small amounts of black residue (around 4wt% [26,27]) are typically identified as silicon carbide, whereas only trace amounts (around 1wt% [25]) of black residue are formed during oxidative degradation, confirming that erosion of SR is more dominant than tracking under the influence of DBA heat.

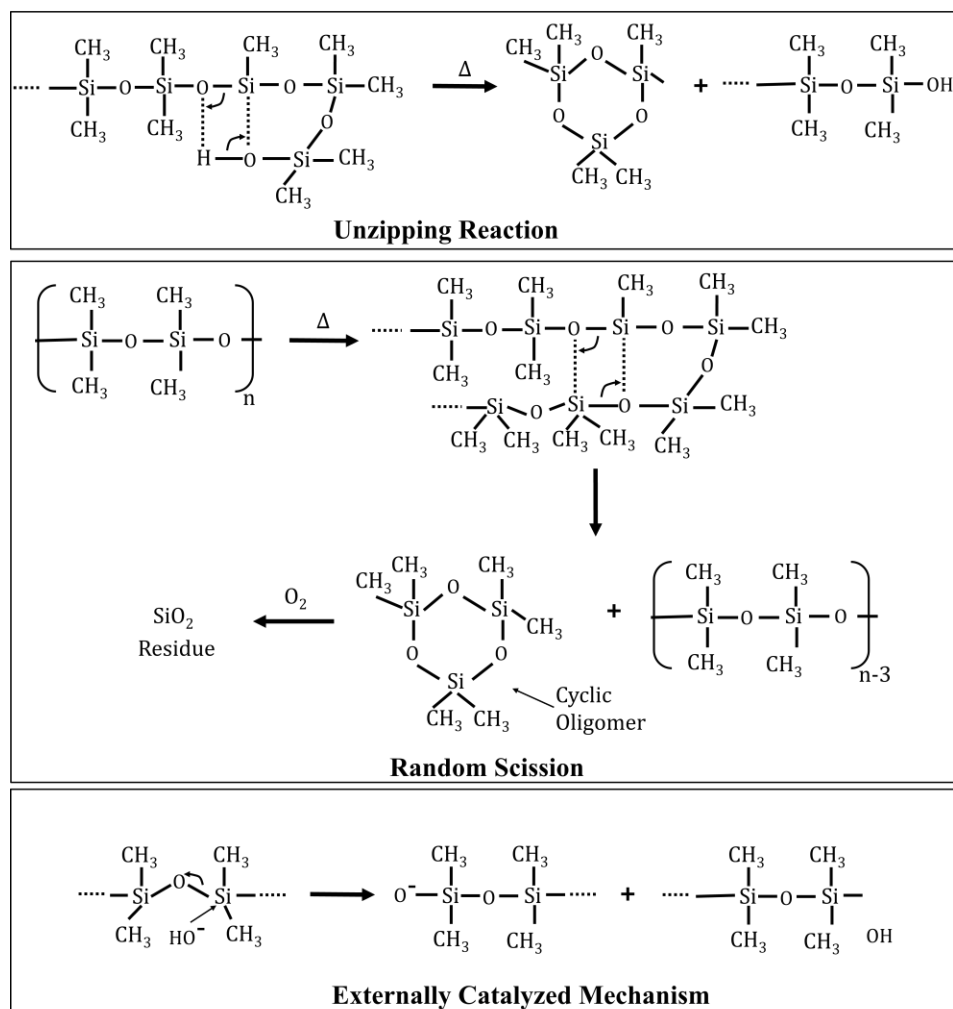


Figure 2.4. Depolymerization of SR through three different mechanisms [24]

2.5 The Standard Inclined Plane Tracking and Erosion Test

The IPT was developed by Mathes et al. to produce a continuous DBA rooted at the bottom electrode, thereby enables accelerated and reproducible aging of insulating materials [7]. IPT is standardized in IEC60587 [1] and ASTM D2303 [2] and has been widely used to evaluate the tracking and erosion resistance of outdoor polymeric insulating materials under AC voltages. It facilitates testing across different voltage ranges, allowing the evaluation of a

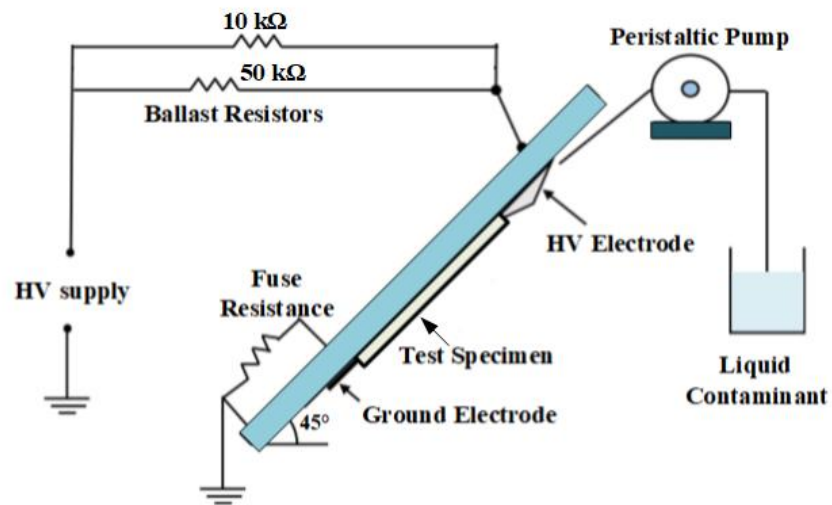
broad spectrum of materials with varying tracking and erosion performance. This test was initially developed as a tracking test but was later adopted for evaluating the erosion of tracking-resistant materials such as SR [29].

Figure 2.5 depicts the schematic circuit of the standard IPT setup, as per ASTM D2303, along with the laboratory arrangement of the samples under test. In this setup, the two electrodes connect the test samples to the high-voltage power source through ballast resistors, which stabilize the discharge activity on the surface. A liquid contaminant is applied to the sample surface at a controlled rate through a peristaltic pump. When the test is energized, the liquid contaminant establishes a conductive path between the top and bottom electrodes. This path allows LC to flow, leading to the formation of dry bands and the initiation of continuous DBA, resulting in material degradation.

The AC test standard specifies the contaminant flow rate, voltage level, and ballast resistance to test the material under DBA. The voltage is selected based on the test parameters to ensure that the evaporation rate of the liquid contaminant matches its flow rate, thereby inducing continuous and effective DBA. The AC test is adapted for testing under DC voltages (both -DC and +DC), with modified test parameters specified in IEEE Std. 2652 for the DC IPT [3]. It follows that the equivalent DC voltages can be determined with respect to the corresponding standard AC_{rms} voltages, using the same test parameters and conditions selected for AC.

According to ASTM D2303 and IEC 60587, both the stepwise voltage (or initial tracking voltage) and the constant voltage test methods can be applied during IPT. In the initial tracking voltage method, the voltage is applied in three steps, with each step lasting one hour and increased by 250 V at each successive step. This method is used to determine the initial tracking voltage at which the test material fails no later than the third step. On the other hand, both standards use the constant voltage method, which allows testing under a fixed voltage level for a few hours with fixed test parameters, such as contaminant conductivity and flow rate. Both standards define material failure as the test endpoint when a 1-inch track or erosion path is formed from the ground electrode. Additional failure criteria, as per IEC 60587, include

measuring a 60 mA LC and observing deep erosion holes or sample ignition. Under both standards, the erosion depth or area is measured at the end of the test to identify material failure.



(a)



(b)

Figure 2.5. Standard IPT test setup (a) Schematic diagram (b) Samples under test in the laboratory

2.6 Literature Review

2.6.1 Studies on Silicone Rubber Erosion Under AC/DC Voltages

The effect of DBA on SR under AC and DC voltages was initially studied by Gorur et al. [30], where SR demonstrated the lowest tracking and erosion performance in salt fog test under -DC compared to +DC and AC. Numerous studies have compared SR erosion under AC and DC using the constant voltage method in the IPT, with +DC being identified as the most severe voltage, followed by -DC and AC [31-34]. Gustavson et al. also confirmed the severity of +DC voltage in field aging tests on various SR formulations [35]. Other studies have focused on comparing SR erosion under AC and DC using the time-to-track method, where inferior performance was indicated by the shortest tracking time, which was always observed under -DC across various contaminant types and conductivities [32, 36].

Later, the magnitude and duration of the discharge current have been identified as key factors governing the extent of erosion on SR. Gorur et al. [37] and Moreno et al. [38] reported that higher magnitudes and longer durations of the discharge current lead to greater damage under DC compared to AC. Similar findings were reported in [35], which pointed out that the test voltage is the determining factor, regardless of the voltage type. Sarathi et al. showed that longer discharge durations led to earlier failure of SR under -DC, attributed to the higher energy of the discharge under -DC compared to +DC [36]. Bruce et al. conducted LC measurements in the DC IPT and found more intermittent discharges under +DC [31], with LC magnitude and degree of intermittency identified as the key factors leading to severe erosion on SR under +DC. Rowland et al. verified these findings through image analysis and reported a higher LC under +DC, but with a shorter discharge period compared to -DC [39].

The electrolytic corrosion of the anode under +DC has been proposed to increase contaminant conductivity by liberating metallic ions, leading to a higher LC magnitude and consequently greater erosion severity [31, 33]. Other studies have shown that LC magnitudes are higher under +DC than -DC, implying that DBA power dissipation can influence the degree of erosion [40, 41]. However, experimental studies on SR under both DC and AC have not

identified electrode corrosion as the dominant factor, as the linear resistance of the DBA under +DC is comparable to that under AC [41]. Another factor proposed to contribute to the LC magnitude is the electro-hydrodynamic effect of voltage on the liquid contaminant [31]. It has been shown that despite the inclusion of a wetting agent in the contaminant, the wettability of the sample surface affects SR erosion under DC [39]. Ghunem et al. [42] showed that electrowetting of the contaminant is influenced by DC voltage polarity, with fewer droplets expelled under +DC, resulting in relatively higher contaminant conductance and LC compared to -DC and AC.

Chrzan et al. demonstrated that intense and concentrated discharges severely erode SR housing in both laboratory and field conditions, despite the low DBA currents [43]. Zhang et al. [44] proposed that severe and deep erosion of SR insulators occurs more rapidly under a stable DBA, as opposed to the gradual erosion resulting from intermittent DBA. The deep and instantaneous erosion was attributed to the effect of wind or gravity on the electrolyte, which allows the onset of a compressed DBA with increased arc severity and energy density. Ghunem et al. [22, 42] demonstrated that the DBA length is influenced by voltage polarity, being shorter under +DC compared to both AC and -DC, which leads to more localized heating over smaller areas and causes greater erosion severity. Kumagai et al. proposed a critical IPT test voltage level, i.e. 4.5 kV, to produce a stable DBA that causes severe erosion of SR [14]. Critical voltages have been rather shown leading to deep and instantaneous erosion under the effect of a stable and intense DBA, as opposed to gradual erosion [14, 22, 45]. Moreover, DBA has been found to be more stable and intense under DC than AC, leading to deep and reproducible erosion, as reported in another study [42].

In addition to the basic characterization of the DBA, the underlying physical mechanism driving erosion has also been studied, particularly the development of surface residue on SR. Residue formation has been identified as an important factor, promoting a stable DBA, thereby increasing the erosion severity of SR [5, 30, 37]. Gorur et al. emphasized that residue accumulation on SR during salt fog tests contributes to the formation of a stable DBA, leading to earlier failure [30, 37]. The residue was identified as conductive deposits resulting

from contaminant evaporation [30], whereas Kumagai et al. reported the residue of SR to be predominantly non-conductive in nature [12]. The residue reported in [30] may be attributed to equipment-related factors rather than originating from the sample itself. Mathes et al. [7] suggested that surface residue occurs under the influence of electrostatic forces and reported no evidence of conductive deposits, indicating no biased effect in the IPT. Ghunem et al. showed that this residue develops during intermittent DBA which promotes the eroding DBA, leading to induction of hotspots ($>400\text{ }^{\circ}\text{C}$) and eventually the initiation of deep erosion under DC [5]. In addition, the study emphasized that the erosion of SR only takes place in the presence of eroding DBA, characterized by stable and intense discharges.

Although erosion severity under DC is greater than under AC, selecting DC voltages corresponding to AC_{rms} voltages was crucial to eliminating experimental bias when comparing erosion under DC to AC. Since DBA-induced erosion is an energy-driven process [5, 46], the power approach was commonly used to determine equivalent DC voltages, defined as those producing the same DBA power as the corresponding standard AC_{rms} voltages. A key step in effectively utilizing the power approach was acquiring only the DBA power component responsible for heat ablation of the material while disregarding the dissipated power associated with Joule heating and the evaporation of the contaminant that forms dry bands [42]. The power approach was applied using the acquired LC waveforms, with DBA power correlated to the coefficient of variation or by observing nonlinearity in the LC waveform [42, 47]. The equivalent DC voltages were determined to be 70% and 90% of the corresponding standard AC voltages for +DC and -DC, respectively [42, 48]. Round-robin tests on SR indicated that these levels result in reproducible outcomes in the IPT [3, 47].

Despite the availability of two standard IPT methods, wide discrepancies remain in the selection of the most suitable IPT voltage. Meyer et al. compared ground silica and ATH-filled SR composites for their erosion performance using the stepwise voltage method of the IPT, under a 2 kV starting voltage [15]. Indistinct difference in the erosion resistance was reported between the tested ATH- and ground silica-filled SR composites under this method. On the other hand, the significance of using the critical IPT voltage has been reported in [14, 45], and

Ghunem et al. reported superior erosion resistance of ATH-filled over silica-filled composites at 50 wt% loading level under the critical IPT voltage using the constant voltage method [20]. However, in another study [48], no significant difference was found between ATH and silica in suppressing erosion under the critical IPT voltage. Ansorge et al. showed SR filled with high loading levels of surface treated ATH passing the IPT under 6 kV, which might suggest that 6 kV can be applied as the critical IPT voltage [49]. In addition, testing under 6 kV was shown leading to repeatable outcomes. The above-cited studies show inconsistent test outcomes due to the use of different testing methods and test voltages for evaluating SR erosion in the IPT. This shows that there is no clear agreement on the most suitable method or voltage to test track-resistant SR, highlighting the need for further research.

2.6.2 Leakage Current Indicators and Thermal Analysis of the Eroding Dry-Band Arcing

The characteristics of the DBA leading to SR erosion in the IPT have been investigated through LC analysis. The LC as a useful indicator of DBA has been analyzed under both AC and DC voltages, correlating with the extent of erosion on SR. Attempts have been made to measure the third harmonic component of LC under AC voltages and establish its correlation with the occurrence of DBA [4, 51, 52]. Accordingly, the DBA energy has been correlated with the severity of erosion and hotspots on SR, both of which gradually increase over time during the IPT [50]. In another work, a correlation has been established between the energy of the LC harmonics, obtained through wavelet-based multiresolution analysis (MRA), and the erosion of SR in the IPT [53, 54]. Moreover, Mathes et al. [10] correlated DBA energy with the eroded mass of SR, while the rate of energy absorption was proposed as an indicator of erosion [46].

The analysis of LC on SR under DC has been conducted in the context of comparing erosion between AC and DC, as well as between the two polarities of DC. Sarathi et al. utilized the conventional wavelet transform to analyze spectral energy over time, comparing the time-

to-track of SR under +DC and -DC [36]. The rising trend in average LC over time, and thus the degree of intermittency, was found to correlate with the damage to SR tested in the DC IPT [36]. Bruce et al. also highlighted the degree of intermittency in the LC as a key indicator of erosion severity under DC [31]. The LC profile was fitted to a normal distribution curve [31], and the coefficient of variation (CV) was suggested as an indicator for comparing DBA severity to AC. Ghunem et al. [42] verified the CV by employing the initial tracking voltage method of the IPT, which was also identified as a useful indicator of DBA energy under DC. Rowland et al. identified DBA current and wetting current as the two main components in the LC pulses under DC, with DBA current contributing to erosion and wetting current not contributing to heat ablation [39].

Numerous studies have reported that SR erosion results from a heat-driven degradation process due to DBA [31, 42, 46, 50]. Thus, analyzing DBA characteristics as a heat source can provide insights into the erosion of SR. An analytical model was proposed in [30] to determine the SR surface temperature in salt fog, accounting for the heat transfer between the DBA plasma and the test material through conduction and convection. Meyer et al. [15] described a correlation between the thermal conductivity and erosion resistance of SR, highlighting that enhanced thermal conductivity, achieved through the addition of ATH or silica filler, significantly reduces erosion. Based on experimental findings and modeling, Kim et al. also identified heat conduction as the dominant mechanism driving surface temperature [55]. Another approach for investigating eroding DBA is the concurrent measurement of LC and surface temperature, where LC analysis reveals DBA characteristics, and temperature monitoring helps detect erosion severity. Meyer et al. analyzed DBA energy using the third harmonic power of LC and correlated it with the highest surface temperature to determine the severity of SR erosion in the IPT [50]. Ghunem et al. established a correlation between discharge periods and hotspots leading to erosion under DC using short-time statistical analysis, proposing statistical parameters of DBA current as useful indicators of significant erosion [56]. Although these indicators have demonstrated a correlation between LC and the gradual erosion of the surface, they were not effective in identifying deep erosion failure of

SR, which occurs over much shorter periods under critical (eroding) DBA, particularly under DC voltages.

Based on the above cited literature, the erosion mechanism of SR under DBA was divided into two main stages based on the severity of the arcing: intermittent (mild) DBA and eroding DBA. In the early stage of IPT, DBA exhibits an intermittent behavior characterized by a pulsating LC waveform with a significant occurrence of non-conducting periods [31]. During the intermittent DBA, the heat generated raises the surface temperature to approximately 200°C, causing thermal oxidation of SR. This results in residue formation, primarily silica, as explained by the Andrinov mechanism [57]. No significant hotspots or erosion occur under mild DBA, but the residue formation plays a crucial role in the progression of the intermittent DBA to the eroding DBA. The residue formed during the intermittent DBA promotes the transition to a stable and more intense DBA phase i.e. eroding DBA. The transition to a stable DBA was identified as being marked by a notable decrease in non-conduction periods within the LC waveform [31]. The statistical analysis of the LC further supported the inception of the stable DBA, as a similar trend was observed in both the mean and the LC approximation [56].

Bruce et al. [31] conducted an extensive analysis of the development of intermittent DBA on SR, while the eroding DBA has been described in [30]. However, no clear explanation of the relationship between the eroding DBA and erosion failure mechanism was provided. Ghunem et al. [5] established a strong correlation between the occurrence of hotspots on SR and the development of eroding DBA, as opposed to intermittent DBA. The detection of hotspots was particularly linked to the evolution of the third detail component of the LC, and a significant reduction in non-conducting periods within the approximate LC waveform. Both components were extracted through wavelet-based MRA applied to the LC waveforms, as detailed in [5]. Alqudsi et al. [58] highlighted that LC waveforms measured in the IPT showed less randomness and low variance in the distribution of LC values during the stable DBA.

Hotspots exceeding 400°C can occur during the eroding DBA stage and were hypothesized to contribute to significant erosion on SR due to the thermo-oxidative

degradation of SR, which generates exothermic heat [14]. It follows that erosion initiates with SR depolymerization through the random scission of siloxane (Si-O) bonds of silicone rubber at around 400 °C, which yields cyclic volatile oligomers [14]. In addition to the hotspots generated by the DBA, silicone oligomers undergo combustion in the gas phase, providing feedback heat into the DBA plasma impacting the surface [14, 22]. Ghunem et al. reported a significant increase in the intensity of the stable DBA associated with the detection of random supplementary current pulses superimposed on the main LC waveform, thereby indicating supplementary ionizations [5, 59]. Similarly, Kumagai et al. [14] ascribed the increased DBA intensity to ionizations taking place in the DBA plasma during the combustion of silicone oligomers at elevated temperatures. Therefore, a reliable technique to detect ionizations in the eroding DBA plasma is needed, as it will form the basis for understanding the physics of eroding DBA and its contribution to the erosion failure of SR.

2.6.3 Studies on Failure Criterion of Insulating Materials in Standard Test

The IPT standards have defined the formation of a 1-inch erosion path as the failure criterion for tracking-resistant materials such as SR. The erosion test method in ASTM D2303 recommends testing under a constant voltage of 2 kV for a specified duration, eventually leading to measurable erosion depth or volume [2]. However, modern outdoor insulating materials are commonly loaded with high levels of inorganic fillers (up to 60 wt%) and have demonstrated an outstanding erosion performance during the IPT under mild voltages such as 2 kV [22]. Test voltages higher than 2 kV were therefore required to properly test, rank, and select materials with high resistance to erosion for outdoor insulation applications. The importance of applying critical test voltages, such as 4.5 kV AC_{rms}, has been emphasized in numerous studies, where it has been shown leading to material puncture [14, 45], and is specified in IEC 60587 as a failure criterion [1].

Observing a 1-inch erosion path as a test end point may not be useful to apply when evaluating SR formulations particularly under DC voltages, which lead to deep erosion rather than progressive erosion over the surface during the test. Measuring a LC magnitude of 60 mA or higher on the surface is another failure criterion specified in the IEC 60587 as an indicator of material failure [1]. However, this criterion may not be always useful when testing materials under the lower equivalent DC voltages as compared to the standard AC_{rms} voltages, as tested materials under DC may fail earlier due to combustion or deep erosion before a LC level of 60 mA is reached [59]. A test end point that has been found useful for DC is the formation of deep erosion holes, material puncture or sample ignition during the test. For this reason, a common practice has been to stop the test and consider the material under test failed when the erosion depth reaches half the thickness of the sample, which is widely accepted to denote erosion failure [20, 45]. Moreover, the IPT is not meant to be flammability test, thus sample ignition is also regarded as an end point for the test.

However, identifying material failure in terms of erosion depth is not feasible or practical, thus relying on this criterion may not always lead to reproducible test outcomes. Such a challenge was experienced during round-robin testing in the development of the IEEE Std. 2652 for the DC IPT [3]. Techniques based on visual observations have also been used to identify deep erosion. Image analysis was utilized to distinguish periods of conduction versus dry-band arcing (DBA) during the IPT [39], and deep learning was applied to images of tested materials in the IPT to evaluate erosion [60]. However, these techniques were not useful to clearly identify deep erosion during the test in the presence of a continuous contaminant flow, surface residue, and a continuous DBA activity impinging on the surface. Numerous techniques have been applied to analyze LC waveforms measured on the surface of SR insulation, such as third harmonic analysis [4], and wavelet transform [5], which established a correlation between LC and the DBA severity, but these methods do not clearly identify material failure or the test end point. This also highlights a critical need for a reliable method to detect eroding DBA and accordingly identify erosion failure of SR during the IPT.

2.6.4 Ultra-High Frequency Electromagnetic Detection Method for Outdoor Insulators

Extensive research has explored the use of the Ultra-high frequency (UHF) method for detecting electromagnetic (EM) emissions and identifying defects in critical power components, such as gas-insulated switchgear (GIS) and transformers [61-65]. However, the application of this method to outdoor insulators is relatively limited. The UHF electromagnetic detection technique has demonstrated outstanding performance in detecting and localizing discharges from partial discharge (PD) defects in GIS and transformers, owing to its high detection sensitivity, and high signal-to-noise ratio [66, 67]. PD results in several physical quantities, one of which is the propagation of radio frequency electromagnetic emissions within the UHF range (300 MHz-3 GHz), which can be detected by the radiofrequency (RF) sensor. UHF techniques rely on EM waves generated by very fast current pulses during PD activity. From an EM perspective, wave propagation takes place when electric and magnetic fields are produced. This phenomenon can occur due to the rapid movement and acceleration of electrical charges under an applied electric field. During PD events within an insulating medium, charges undergo rapid acceleration, producing high-frequency, broadband current pulses. These pulses emit EM waves that radiate in all directions into the surrounding space.

The PD current at the discharge location typically exhibits a rise time in the nanosecond range, producing EM waves with a frequency spectrum that extends into the RF region, often above 200 MHz [68]. The intensity of the emitted electromagnetic radiation is directly related to the rate of change of the current, making it a reliable indicator of PD activity. These characteristics provide a basis for UHF-based PD detection methods, which leverage the high frequencies of the emitted EM waves for detection and localization of defects in various power equipment. The UHF-based detection technique is typically categorized into two types: narrow-band detection and wide-band detection. In narrow-band detection, the signal resolution is narrowed with a spectrum analyzer, while in wide-band detection, the electromagnetic wave is analyzed in the time domain using an oscilloscope with a wide band-pass filter. Defect detection and localization based on UHF measurements have been achieved

with a considerable degree of accuracy using both frequency and time domain approaches in various high-voltage power apparatus [61, 63, 64].

The UHF-based EM detection method for outdoor insulators, particularly polymeric insulators, is still relatively nascent, even though the detection and localization of PDs using UHF measurements is now a well-established technique in GIS and transformers [61, 62]. However, this technique has shown potential for online PD detection in outdoor insulation, which is a key indicator of defects in insulators, offering similar advantages to those observed in GIS and transformers. In ceramic insulators, the primary forms of physical damage are internal voids or cracks [6, 69], whereas in polymeric insulators, the most severe form of physical damage is the erosion of the housing material [6]. Defects in these insulators can initiate PDs, generating EM waves that can be detected using an RF antenna tuned to appropriate bandwidth. Additionally, the RF antenna can detect other types of discharges, such as corona or surface discharges, caused by hardware defects or pollution accumulation.

The RF noise interference caused by PD on high-voltage lines have been long realized to span a wide frequency range, from below 100 kHz to several GHz [70]. In fact, the presence of distinctive RF components associated with discharge activity has been confirmed by RF antenna in polymeric and porcelain insulator samples under laboratory conditions [71]. A promising aspect of these findings was the distinct RF spectra observed for ceramic and polymer samples, suggesting that differences in the frequency content of the discharge signal could be used to distinguish various discharge types in outdoor insulators [71]. In another attempt [72], an RF antenna was installed on top of a vehicle to detect PD activities and locate defects in overhead line insulation by analyzing the time delay between signals received by an array of four antennas. It was noticed that low-level RF emissions from the defective line insulator interfere with radio and TV reception. Another study investigated the use of the RF sensor for detecting and classifying discharges on wet SR insulation sample [73]. The discharges were classified according to their sources, such as surface discharges due to contamination and/or corona discharges from energized ends, using an artificial neural network

trained with features derived from the spectral and statistical analysis of the electromagnetic signals.

Studies show that discharge collisions generate high-frequency waves up to several GHz, with intense UHF emissions (1–6 GHz) used as early indicators of plasma inception within a discharge [74-76]. As such, thermal ionizations have been reported to intensify stable DBA during the combustion of SR oligomers [5, 14, 22, 59], transitioning it into an intense plasma characteristic of eroding DBA. Since discharge collisions generate these intense UHF emissions, the eroding DBA plasma produces electromagnetic radiation detectable in the UHF range. Understanding the physics of these UHF emissions from the eroding DBA plasma could provide crucial insights into the erosion failure mechanisms of SR in the IPT.

2.7 Summary: Aim of the Present Work

As demonstrated in the literature, several shortcomings have been identified that require further investigation. A major shortcoming is the significant inconsistency in the use of test methods, test voltages, and failure criteria, which introduces uncertainties in verifying the erosion failure of SR during the IPT. These uncertainties arise from an inadequate understanding of the underlying mechanisms of eroding DBA that lead to the erosion failure of SR. Accordingly, a key research objective is to investigate the erosion failure mechanisms of SR under eroding DBA. Another limitation is the lack of a reliable method for detecting eroding DBA during the IPT. Therefore, another objective is to develop a reliable UHF-based detection technique of the eroding DBA to identify erosion failure of SR during the IPT.

Chapter 3

Research Methodology

The focus of this research is to provide a comprehensive understanding of erosion failure mechanisms of SR through UHF detection of the eroding DBA. This chapter outlines the methodology employed to achieve the research objectives, including sample preparation, experimental setup and variables, testing procedures, measurements, and analysis conducted on SR. The AC and DC IPTs are conducted on SR composites to facilitate the detection of the eroding DBA using a UHF sensor. During the IPTs, temperature measurements are taken and analyzed to correlate the thermal mechanism of erosion with the eroding DBA. The measured LC data is analyzed, and erosion depth is recorded at the end of each test. UHF measurements and analysis are performed, enabling UHF detection to correlate with the inception of eroding DBA and to identify potential indicators of erosion failure in IPTs. Material characterization tests were conducted to establish correlations with IPT outcomes, as well as with various measurements and analyses performed on SR during IPT. TGA-DTA is performed to identify the thermal degradation mechanisms of SR related to the evolution of surface temperature in the IPT, while FTIR analysis is conducted to analyze the surface affected by varying severity levels of the DBA. The block diagram in Figure 3.1 summarizes the research methodology, highlighting the tests and measurements performed and the corresponding analyses undertaken in this research.

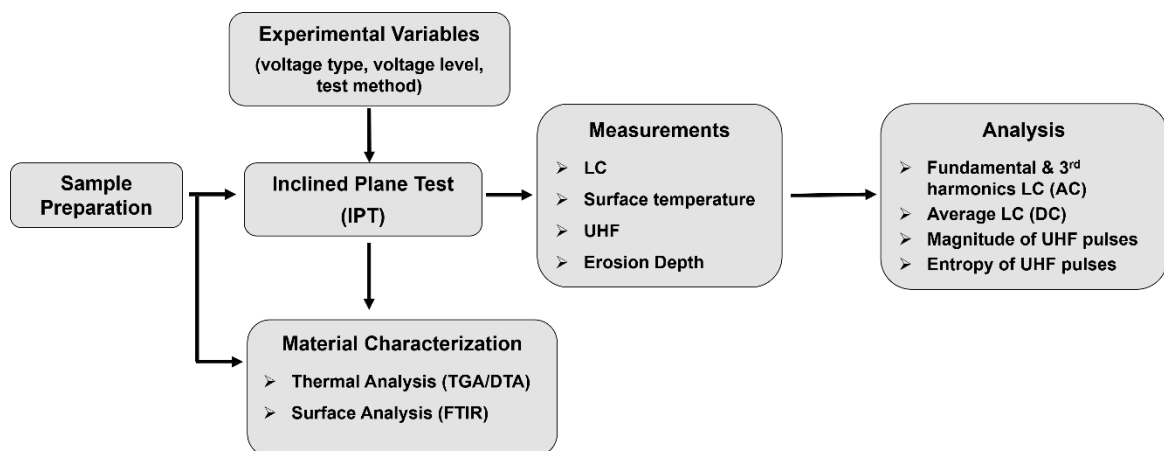


Figure 3.1. Research methodology illustrating the tests, measurements, and corresponding analyses conducted in this study.

3.1 Material Samples Preparation

In this study, SR composite samples were prepared in the laboratory using a commercial two-component base polymer—room temperature vulcanized SR (RTV615), along with ATH and ground silica fillers. The base polymer, RTV615, was procured from Newark (Momentive Performance Materials). It is a transparent, low-viscosity vinyl-polydimethylsiloxane (PDMS) SR, composed of approximately 70% vinyl-PDMS and 30% vinyl resin, with no reinforcing fillers added. Micronized Min-U-Sil silica, supplied by U.S. Silica, was selected due to its high chemical purity (> 99%) and narrow particle size distribution. A commercial grade of ground ATH, sourced from Huber Engineered Materials, was also chosen due to its high purity and precise particle size distribution. The selected ATH grade is surface-treated with vinyl functional groups to enhance compatibility with the polymer matrix.

Composite mixing was carried out using a high shear ROSS laboratory mixer (model HSM-100LSK) equipped with a 16 mm diameter blade. The mixing process began at 1500 rpm to allow for the wetting of filler particles, after which the speed was increased to 4500 rpm to facilitate uniform dispersion. The mixing time was determined based on an empirical

formula provided by the manufacturer to ensure optimal dispersion of fillers. The RTV615-A SR was mechanically mixed with fillers at appropriate filler loading (30 wt% and 50 wt%), followed by mixing with a curing agent (RTV615-B) in a 10:1 weight ratio. For a 100 g batch of composite formulation with 50 wt% fillers, the mixture consisted of 50 g of filler (ATH or silica) and 50 g of SR, comprising 45.45 g of Part A and 4.55 g of Part B. In the case of a 30 wt% filler formulation, 30 g of filler were combined with 70 g of SR, consisting of 63.64 g of Part A and 6.36 g of Part B.

The prepared mixture was subsequently degassed under vacuum, transferred into the sample molds, and then left to vulcanize at room temperature for 24 hours. The composites were then post-cured at 85 °C in an oven for additional 4 hours to achieve optimum properties. The sample dimensions for testing in IPT were selected as 12.5 cm in length, 5 cm in width, and 0.6 cm in thickness according to ASTM D2303. Prior to testing, all sample surfaces were sanded with fine-grit sandpaper under running tap water, followed by rinsing with distilled water and final cleaning with isopropyl alcohol. Figure 3.2 illustrates the preparation process of the SR composite samples, while Table 3.1 presents the details of the composite formulations, including the specifications of the fillers used and the identification names of the samples.

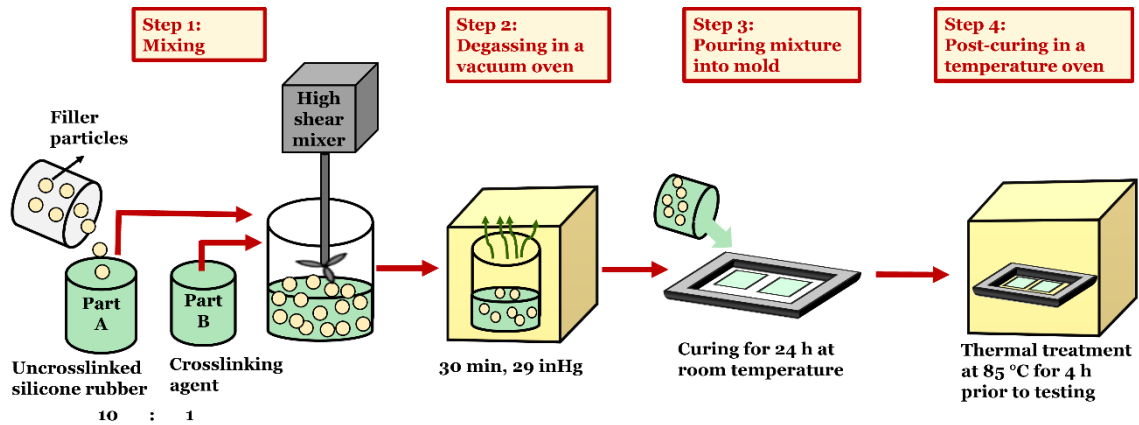


Figure 3.2. Preparation process of SR composite samples used in this study

Table 3.1. Description of SR composite samples and fillers used

Sample identification	Fillers				
	Type	Grade	Median particle size (μm)	Loading Level (wt%)	Specific Gravity (g/cm^3)
A50	ATH	Hymod M632 SP	3.5	50	2.42
A30				30	
S50	Silica	Min-U-Sil10	3.6	50	2.65
S30				30	

3.2 Experimental Setup

Figure 3.3 illustrates the schematic diagram of the IPT setup utilized in this study which was built as per the guidelines of the ASTM D2303 standard. For the DC IPT, a Glassman® regulated DC power supply (5 kV, 1 kW) is used, having a ripple of less than 5% of the rated voltage under full load conditions. For AC IPT, a 75 kVA distribution transformer rated at 8 kV is used, with the applied voltage controlled via a variac. The liquid contaminant was prepared using an aqueous solution containing 0.1 wt% ammonium chloride (NH_4Cl) and 0.02 wt% Triton X-100 wetting agent, resulting in a conductivity of 2.60 mS/cm [2]. Both constant voltage and stepwise voltage testing methods of the IPT were adopted to test SR composites samples under both AC and DC voltages.

The LC waveforms were acquired using a data acquisition (DAQ) device, National Instruments USB-6001, via the Analog Input Recorder App in MATLAB, at a sampling frequency of 20 kHz. For DC IPT, a window of 512 samples per second was stored for data analysis and a moving average window of 300 samples was applied to derive the average trendline of the LC using MATLAB. In the case of AC IPT, Fast Fourier Transform (FFT) was performed every second on a 100 ms data window acquired during the test, and the AC_{rms}

values for the 60 Hz fundamental and third harmonic components of the LC were recorded. Maximum surface temperature (T_h) was measured during the AC and DC IPT tests using a FLIR T650sc high-resolution infrared (IR) camera, and T_h was captured at a sampling frequency of 1 Hz. To analyze trends, the acquired AC LC and T_h waveforms were smoothed respectively using a 200-sample and a 30-sample moving average window for LC and T_h . The erosion depth on SR composite samples was evaluated after each test using a Mitutoyo 571-200 digital micrometer.

To ensure accurate surface temperature measurements, the IR camera was calibrated through a controlled procedure. Samples were placed in a laboratory oven for two hours to reach thermal equilibrium. A thermocouple recorded the actual temperature, while the camera was focused on the sample surface. The emissivity parameter in the camera software was adjusted until the temperature reading matched the thermocouple measurement. Following this procedure, an emissivity value of 0.97 ± 0.01 was determined, with negligible variation observed across different samples.

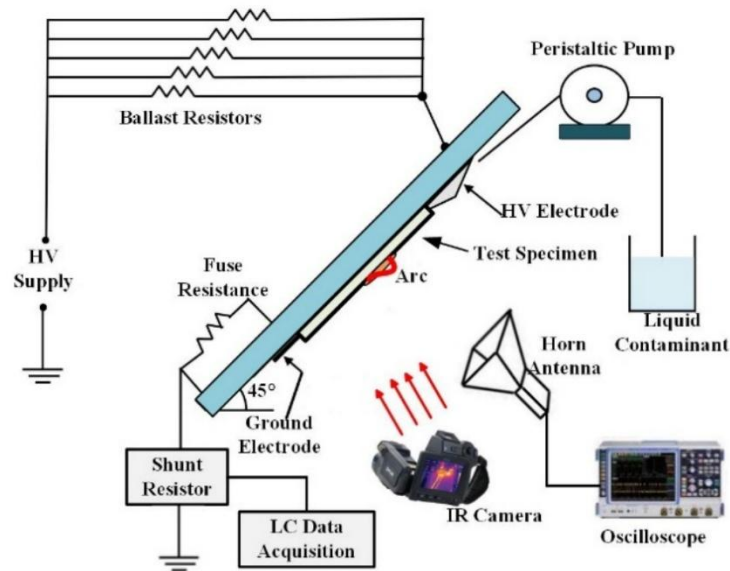


Figure 3.3. Experimental setup used in this study

3.3 Ultra-High Frequency Sensor Selection and Measurements

Horn antennas are widely utilized for measurements within the UHF range (300 MHz to 3 GHz) due to their advantages, including high gain, low voltage standing wave ratios, and high bandwidth [77, 78]. Rectangular horn antennas are commonly employed, using a rectangular waveguide feed to transmit or receive EM waves. The horn acts as a transition between the waveguide mode and the free-space mode of the EM wave. The construction of horn antennas varies depending on the direction of flaring. Rectangular horn antennas are categorized into three types based on the flaring direction: (a) E-plane horn antennas, flared only in the elevation plane (E-plane); (b) H-plane horn antennas, flared only in the horizontal plane (H-plane); and (c) pyramidal horn antennas, flared in both the E and H planes. The flare is typically linear; however, circular and exponential flare designs are also employed in specific applications. Figure 3.4 shows the typical E-plane, H-plane, and pyramidal horn antennas [77].

As shown in Figure 3.5, E-plane and H-plane horn antennas focus their radiation patterns primarily in the E and H planes, respectively [78]. The pyramidal horn antenna combines the features of both, as it is flared in both the E and H planes, resulting in radiation characteristics that are a hybrid of the E-plane and H-plane sectoral horns. Figure 3.5 also illustrates the radiation pattern of the pyramidal antenna, where the significant overlap of the two patterns confirms that it focuses the radiation in both planes [78]. This makes the pyramidal horn antenna particularly well-suited for applications where radiation needs to be captured from all directions. As a directional antenna, the pyramidal horn is more effective at radiating or receiving electromagnetic waves in specific directions.

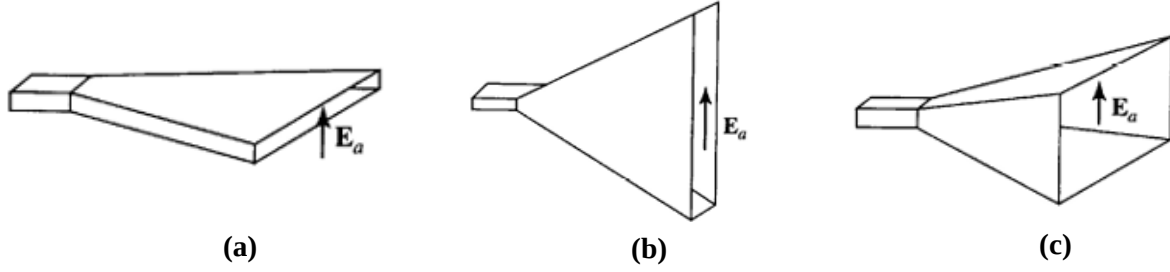


Figure 3.4. Various configurations of rectangular horn antenna (a) H-plane sectoral horn (b) E-plane sectoral horn (c) Pyramidal horn antenna [77]

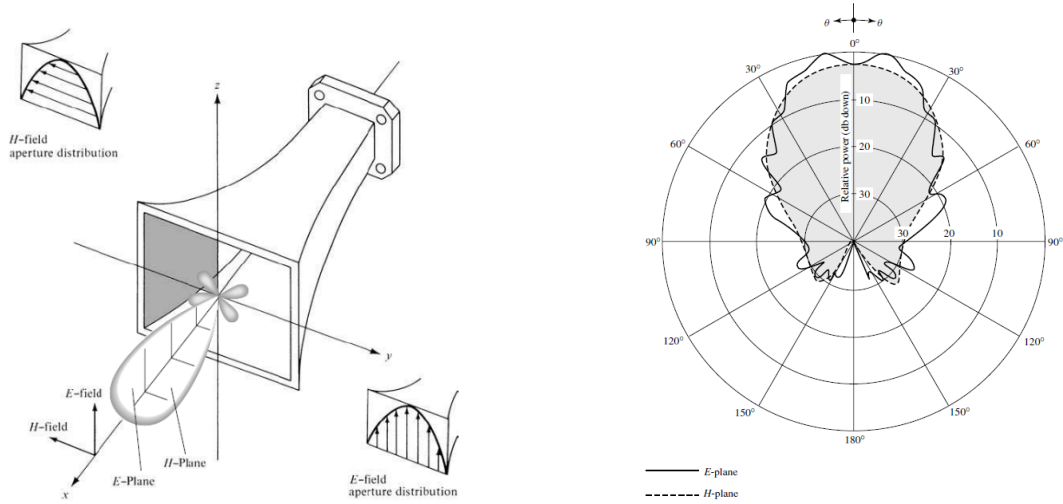


Figure 3.5. Radiation patterns for a pyramidal horn antenna [78]

In this study, an octave pyramid-type horn antenna was used to measure UHF signals radiated from the eroding DBA on the test samples, as shown in Figure 3.6a. Figure 3.6b shows the frequency response of the UHF antenna, which has a bandwidth of 1-2 GHz and a corresponding gain of 14.5-18 dB. The antenna was positioned at 1 m from the test sample. A digital Rohde & Schwarz oscilloscope with a 2 GHz bandwidth (10 GS/s) and 50 Ω input impedance was used for data acquisition. The oscilloscope was connected to the antenna through a shielded coaxial cable with 50 Ω characteristic impedance to capture the UHF signals with high fidelity. Ten 1- μ s signal windows per minute were captured using the oscilloscope

and concatenated to evaluate the DBA during the test. Each window comprised 2000 samples, recorded with a time resolution of 0.5 ns per sample. The captured UHF signals were subsequently transferred to a computer for further processing and analysis. To confirm the absence of any partial discharge (PD) activity—whether background noise or from the experimental setup (e.g., electrodes, DC source)—preliminary dry IPT test runs were conducted by applying the full test voltage without introducing any liquid contaminant. No discharge activity was detected by the horn antenna during these runs, ensuring that any captured UHF signal during the IPT originates solely from the DBA plasma.

It is important to note that, according to IEC TS 6478 [79] and IEC TS 61934 [80], calibration of electromagnetic detection methods for apparent charge values is not feasible. Sensitivity check can be alternatively performed, which is specific to different applications such as GIS, transformers and rotating machines, etc. For laboratory tests, sensitivity check essentially entails testing for the frequency spectrum and signal level detected due to real PD defects. In this study, laboratory tests are performed to detect DBA while only relying on the frequency band criteria (low vs high frequency) and not the signal level. The frequency spectrum of the used antenna used in this study has been verified over more than a decade of research in numerous publications including [61, 69, 81].

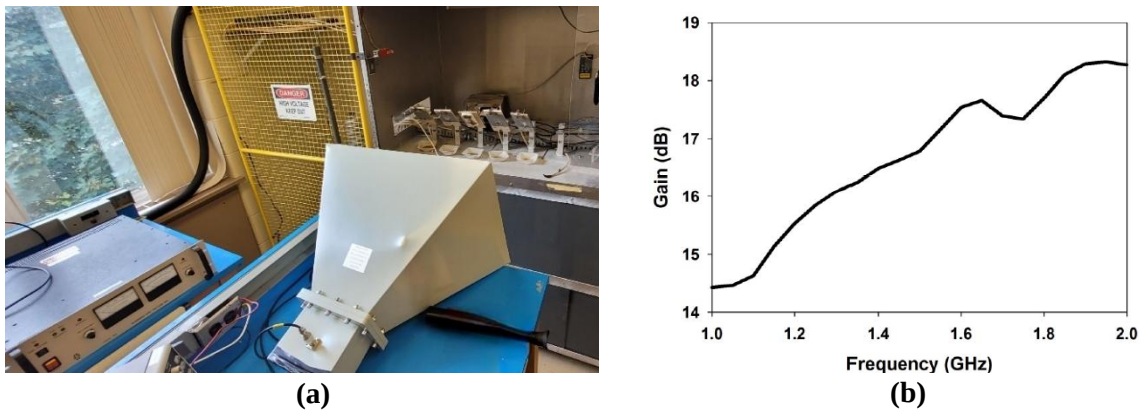


Figure 3.6. Octave horn Antenna used in this study along with its frequency response [69].

3.4 Material Characterization Tests

3.4.1 Thermogravimetric and Differential Thermal Analysis

The simultaneous thermogravimetric and differential thermal analyses (TGA-DTA) were conducted on the SR samples under both air and nitrogen (inert) atmospheres to elucidate T_h and identify thermal degradation mechanisms of SR associated with the evolution of T_h in the IPT. The SR samples (10-15 mg) were heated in an SDT Q600 instrument from TA® at a rate of 25 °C/min, within a temperature range of 80 °C to 800 °C. The TGA outcomes typically show the sample's weight loss as a function of temperature, indicating the thermal degradation of SR. The DTA curve reveals the thermal degradation mechanism associated with sample weight loss, exhibiting endothermic dents and exothermic humps. The exothermic hump indicates thermo-oxidation, while the endothermic dent corresponds to the thermal decomposition of the SR composite samples.

3.4.2 Fourier Transform Infrared Spectroscopy

Fourier transform infrared (FTIR) spectroscopy was employed to identify chemical changes taking place on tested SR samples under both mild (intermittent) and eroding DBA. The residue obtained from the non-eroded region affected by mild DBA and the eroded regions impacted by eroding DBA was analyzed using attenuated total reflection (ATR) FTIR. ATR-FTIR spectra of the residues, along with reference spectra of SR, were acquired using a Bruker Alpha II spectrometer equipped with KBr beam splitter and temperature controlled DTGS (deuterated triglycine sulphate) detector. All experiments were carried out with a ZnSe ATR crystal with 100 scans at a spectral resolution of 4 cm^{-1} . Background reference spectra were recorded with the same acquisition parameters prior to loading of samples onto the ATR crystal. For ATR-FTIR measurements, all samples were directly placed on the ATR crystal and compressed with the gauge to form intimate contact with the ZnSe crystal.

3.5 Study Approach

3.5.1 Effect of the Voltage Level on Silicone Rubber Degradation in Inclined Plane Test

Experiments were conducted to investigate the impact of DBA severity on the degradation of SR composite samples in the AC and DC IPT. This investigation was carried out because of the wide inconsistencies in selecting the most suitable test voltage for IPT that would produce critical (eroding) DBA, leading to deep erosion and failure of SR in the IPT. A systematic experimental approach was followed, involving the testing of different SR formulations under three AC voltage levels: 2.5 kV, 3.5 kV, and 4.5 kV of the constant voltage method. These voltage levels were selected to generate mild DBA and eroding DBA on SR composite samples. Samples of A30, A50, S30, and S50 were tested in AC IPT. The contaminant flow rate was accordingly selected for each applied test voltage, as specified in ASTM D2303 guidelines [2]. The flow rate of the contaminant was set at 0.15 ml/min for 2.5 kV, 0.30 ml/min for 3.5 kV, and 0.60 ml/min for 4.5 kV, while maintaining a conductivity of 2.60 mS/cm as shown in Table 3.2. For the DC IPT, only A50 and S50 samples were tested. Following the procedures outlined in [3], two +DC voltages, +2.25 kV and +3.5 kV, were selected corresponding to 3.5 kV AC_{rms} and 4.5 kV AC_{rms} voltages.

To identify various forms of degradation, the A50 and S50 samples were also tested in both AC and DC IPT using the stepwise voltage method. This method was applied with a starting voltage of 3.75 kV AC_{rms} for AC IPT and +3.75 kV for DC IPT. The contaminant flow rate was initially set to 0.30 mL/min at the starting test voltage and increased to 0.60 mL/min at higher voltage steps (Table 3.2). Figure 3.7 illustrates the IPTs performed on SR under both AC and DC test voltages, employing two testing procedures: the constant voltage method and the stepwise voltage method.

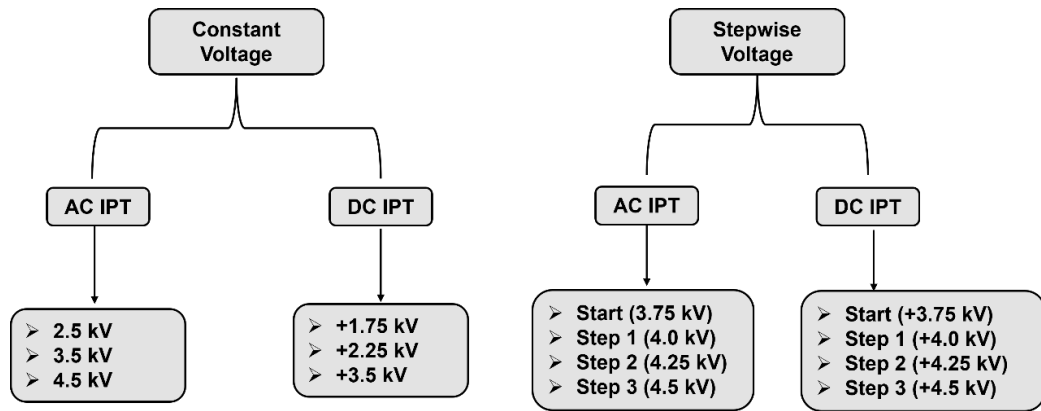


Figure 3.7. IPTs conducted on SR composite samples under AC and DC voltages using both constant voltage and stepwise voltage methods.

Table 3.2. Test parameters

Test Voltage (kV)	Flow Rate (mL/min)	Conductivity (mS/cm)
1.0-1.75	0.075	2.60
2.0-2.75	0.15	
3.0-3.75	0.30	
4.0-4.75	0.60	

3.5.2 Ultra-High Frequency Detection of the Eroding Dry-Band Arcing and Erosion Failure in AC and DC Inclined Plane Tests

As described in Section 2.6, thermal ionizations resulting from the combustion of silicone oligomers during SR depolymerization give rise to intense DBA plasma [5, 12, 22, 59], and the detection of intense UHF emissions has been shown as an early indicator of the

onset of plasma [76]. Therefore, the second part of the investigation focused on the UHF-based monitoring of eroding DBA in DC IPT, which was then applied to detect eroding DBA in AC IPT. As illustrated in Figure 3.7, tests were first performed on A50 samples under three different DC test voltages using the constant voltage method: +1.75 kV, +2.25 kV, and +3.5 kV, while conducting LC, surface temperature, erosion depth and ultra-high frequency measurements. Similarly, three different AC_{rms} voltages were selected for testing the A50 samples in AC IPT: 2.5 kV, 3.5 kV, and 4.5 kV as shown in Figure 3.7. TGA-DTA and FTIR spectroscopy were conducted to correlate with IPT outcomes and support the temperature and UHF measurements and analyses performed on SR during the test.

The third part of the investigation extends the second, which aimed to demonstrate the effectiveness of using UHF monitoring of the eroding DBA to identify erosion failure of SR in both AC and DC IPTs. To achieve this, AC and DC IPTs were performed on A50 and S50 samples, while conducting LC, temperature and UHF measurements. The acquired UHF pulses from each test were analyzed to determine possible indicators of erosion failure. The stepwise voltage method was applied, starting at 3.75 kV AC_{rms} for AC IPT and +3.75 kV for DC IPT as shown in Figure 3.7.

Additionally, the UHF pulses were analyzed within five discrete magnitude ranges: 1–2 mV, 2–4 mV, 4–6 mV, 6–8 mV, and 8–10 mV. The number of UHF pulses within each magnitude range was computed for each captured window.

Entropy of the UHF signal was another parameter used in this study. Shannon entropy for a discrete distribution measures the level of disorder or randomness in a system. A more chaotic or random UHF signal results in a higher entropy value, and vice versa. For a UHF signal $[x_1, x_2, x_3, \dots, x_N]$, entropy (S) was calculated using Equation (1):

$$S = - \sum_{i=1}^N p(x_i) \log_2 p(x_i) \quad (1)$$

Where $p(x_i)$ represents the probability distribution of the signal values across the histogram bins. The entropy of each UHF signal window was calculated and stored as a single value. The steps involved in calculating the entropy of the UHF signals are detailed in Appendix A.1. The entropy values for both A50 and S50 samples were fitted to a normal distribution curve.

Chapter 4

Results and Discussion

This chapter begins by presenting the results of the AC and DC IPTs conducted on SR composites, illustrating how the severity of the DBA under varying test voltages impacts the degradation of SR composites. Next, the chapter presents the results of the analysis of LC, temperature, erosion depth, and UHF measurements taken during the AC and DC IPTs, along with TGA-DTGA and FTIR results, all of which support the effectiveness of the proposed UHF technique for detecting the eroding DBA. Finally, the results of the tests conducted on SR composites using UHF detection of the eroding DBA are presented, with a focus on determining reliable indicators of erosion failure during the IPT.

4.1 Impact of Dry-Band Arcing Severity on Silicone Rubber Degradation

Figure 4.1 shows the degradation patterns obtained on the tested A50 and S50 samples under 2.5 kV AC_{rms} in the IPT, without evident signs of erosion. This observation could be attributed to the mild test voltage level applied, producing a DBA with insufficient power to initiate depolymerization and hence erosion. Under 2.5 kV, the DBA was observed mainly to be mild and intermittent. The intermittent DBA was reported causing thermo-oxidation of SR during the IPT at temperatures below 200 °C but was not found severe enough to stimulate thermal degradation mechanisms of SR at temperatures exceeding 400°C, i.e. depolymerization or radical-based crosslinking [5]. However, the tested composites somewhat showed a tendency to form black residue near the bottom test electrode, which gradually progressed towards the upper test electrode. Similarly, insignificant erosion was observed on both A50 and S50 samples during the IPT under 3.5 kV as shown in Figure 4.2. It is important to note that the IPT test is meant to produce a continuous DBA that leads to material

decomposition. Therefore, evaluating the erosion resistance of such highly loaded SR with fillers under relatively mild voltages may not be useful in IPT.

Figure 4.3 shows the degradation patterns obtained for the tested A50 and S50 samples in the IPT under 4.5 kV. Under this test voltage level, the tested SR composites showed a tendency for erosion under the effect of the eroding DBA. All A50 samples passed the IPT, whereas three out of five S50 samples failed due to the formation of an erosion path accompanied by combustion, as indicated by the presence of white ash on the surface. Comparable outcomes were reported in [82]. It has been reported that ATH releasing water of hydration may have an additional influential erosion suppression effect as compared to ground silica [20]. The dehydrated water may promote an internal oxidation mechanism that dilutes the SR in gas phase and suppresses failure under DBA during the IPT. It should be noted however that DBA under 3.5 kV and 4.5 kV started at one specific location, stopped at some point during the IPT and then re-started again at different location on the sample under test, which may affect the repeatability of the test outcomes. It is worthwhile to mention that in order to assess erosion resistance of SR, the development of a continuous DBA at a certain location near the bottom electrode is necessary for repeatable test outcomes [7].

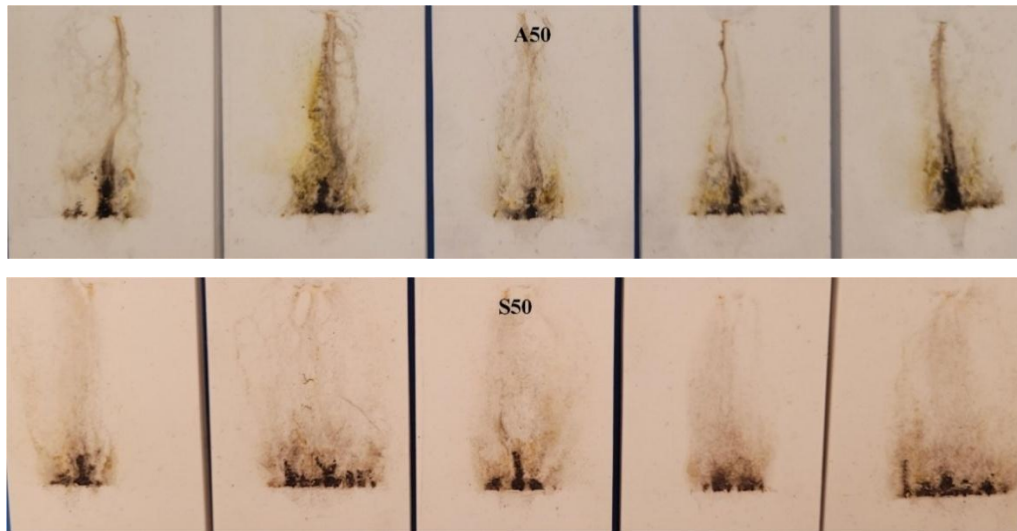


Figure 4.1. Degradation patterns on tested A50 and S50 samples under 2.5 kV in AC IPT

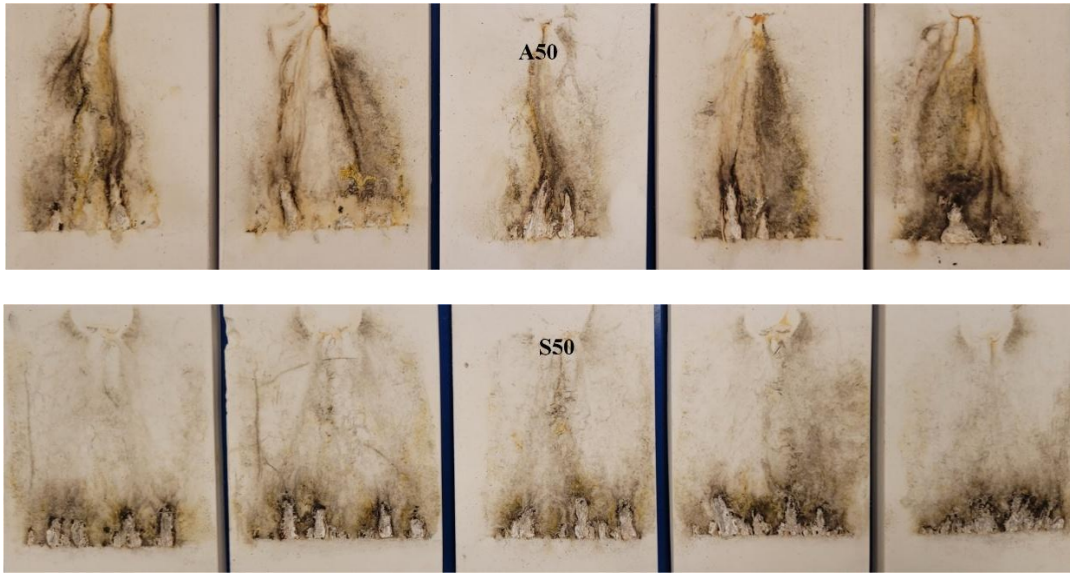


Figure 4.2. Degradation patterns on tested A50 and S50 samples under 3.5 kV in AC IPT

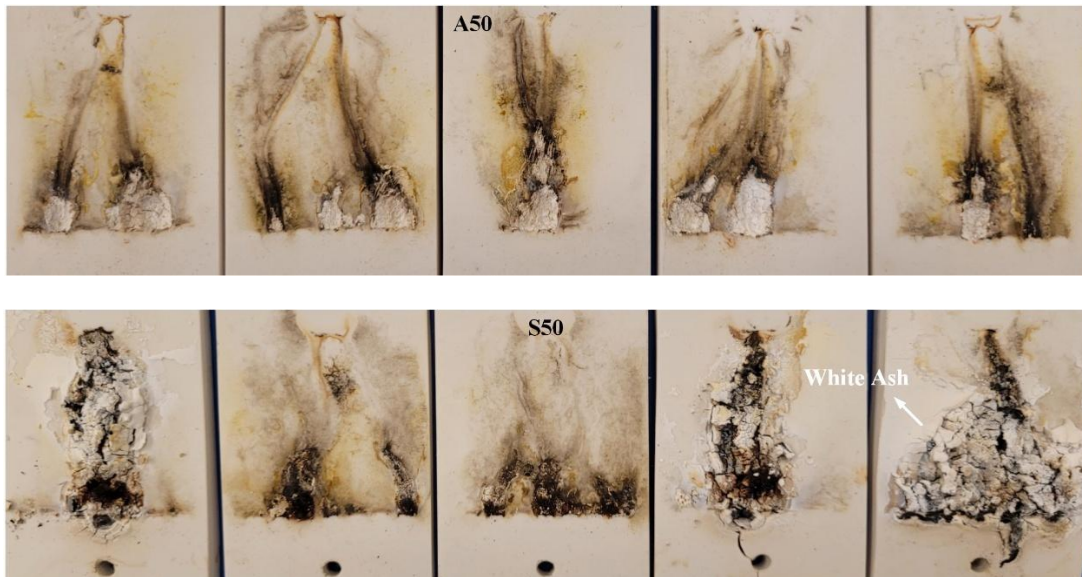


Figure 4.3. Degradation patterns on tested A50 and S50 samples under 4.5 kV in AC IPT

Figures 4.4-4.6 show the degradation patterns observed on the A30 and S30 after the IPT. As speculated for the A50 and S50 samples, the tested A30 and S30 composites under 2.5 kV showed a tendency to form black residue possibly because of thermo-oxidation under an intermittent DBA. On the other hand, erosion started on the A30 and S30 under 3.5 kV, leading to failure as shown in Figure 4.5. Three out of five A30 and S30 samples failed the IPT under 3.5 kV. In addition, all the A30 and S30 samples were combusted during the IPT under the effect of DBA produced with 4.5 kV test voltage applied, resulting in deep holes as shown in Figure 4.6. It should be noted that less voltage level than 4.5 kV, i.e. 3.5 kV, was required to cause erosion during the IPT on a relatively weak SR material (A30 and S30). In addition, eroding DBA under the 4.5 kV seemed to be too severe to be applied for the 30 wt% filled SR, as leading to material combustion. This finding suggests the dependency of the critical voltage on the amount of filler added to SR.

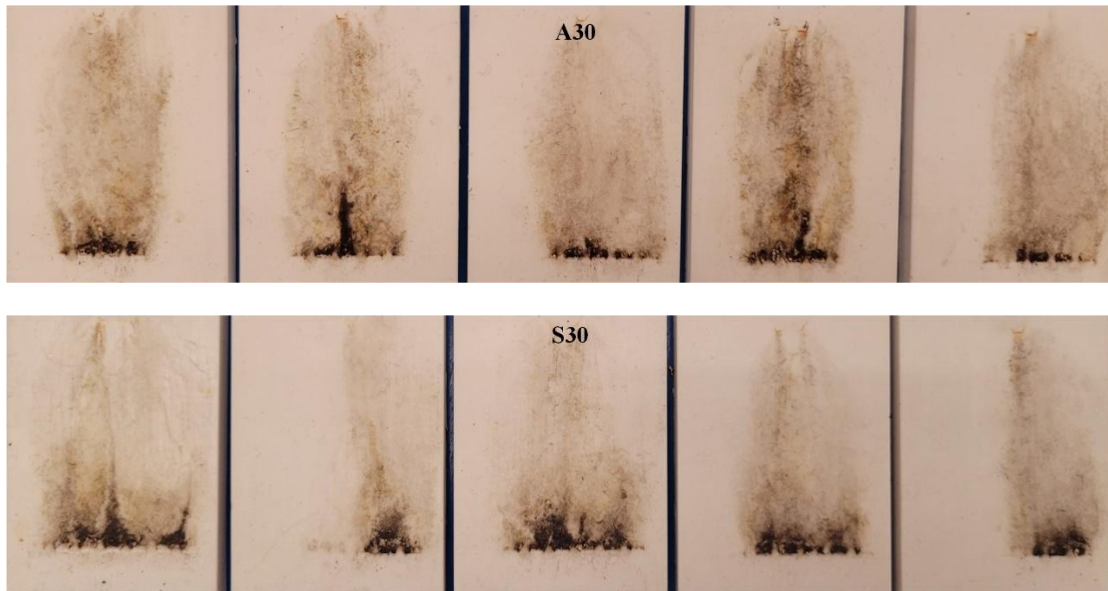


Figure 4.4. Degradation patterns on tested A30 and S30 samples under 2.5 kV in AC IPT

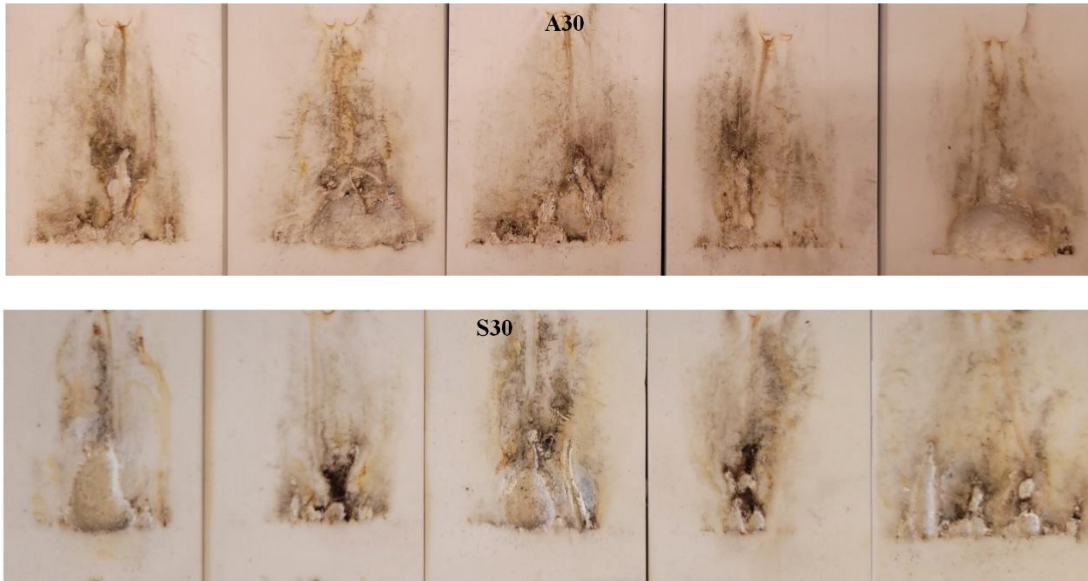


Figure 4.5. Degradation patterns on tested A30 and S30 samples under 3.5 kV in AC IPT

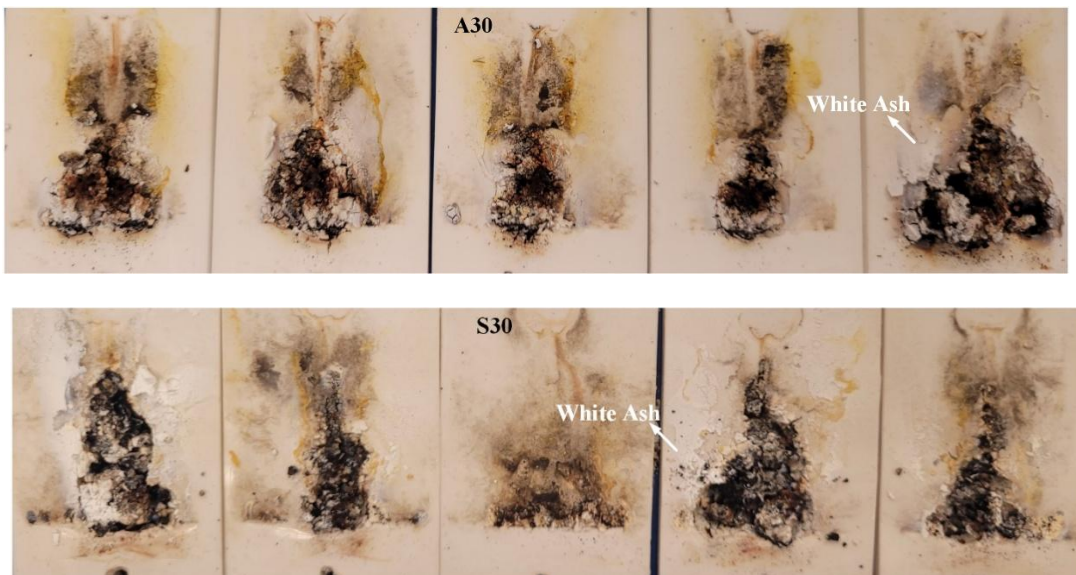


Figure 4.6. Degradation patterns on tested A30 and S30 samples under 4.5 kV in AC IPT

Figure 4.7 illustrates the degradation patterns observed in the tested A50 and S50 samples, showing erosion under +2 kV in the DC IPT, along with black residue near the ground electrode. No significant difference in surface damage was observed between the A50 and S50 samples under +2 kV in the DC IPT. While the tested composites showed some tendency to erode under +2 kV in the IPT, no erosion failure (1-inch path) was observed in any of the samples. Figure 4.8 shows the degradation patterns of the tested A50 and S50 samples in the IPT under +3.5 kV (critical voltage). At this voltage level, four out of five A50 samples failed due to deep erosion and combustion, as indicated by white ash traces on the surface. As the DBA transitioned into a stable state during the test, hotspot temperatures triggered depolymerization, eventually leading to deep erosion and combustion. In contrast, all tested S50 samples failed the DC IPT due to the propagation of an erosion path under the effect of the eroding DBA induced at +3.5 kV (critical voltage). The failure of S50 samples was associated with combustion caused by the eroding DBA, leading to deep erosion holes or material puncture. These observations highlight the need to consider deep erosion as a failure criterion in the IPT.

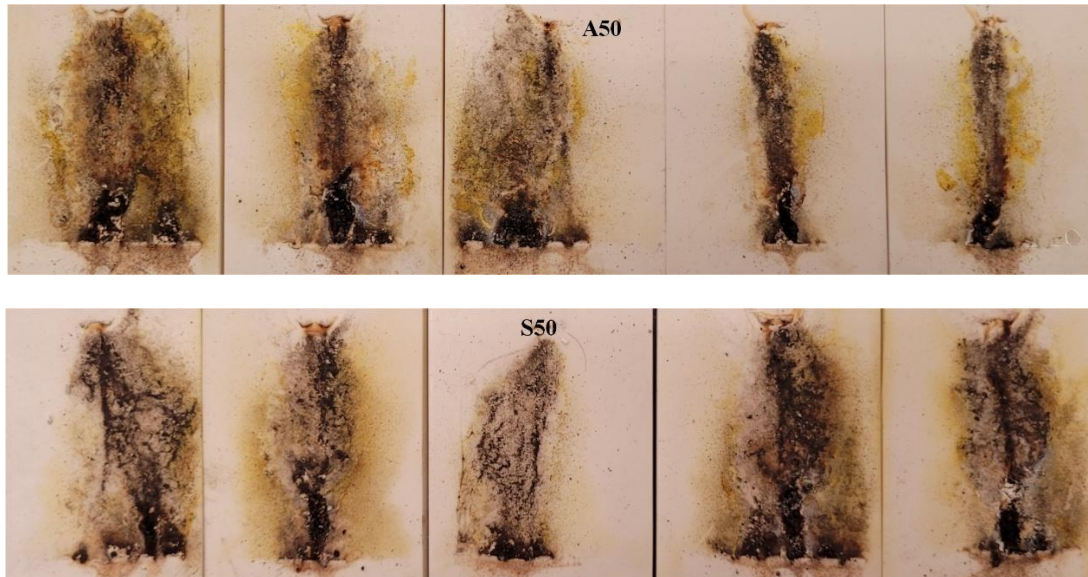


Figure 4.7. Tested A50 and S50 samples under +2.25 kV in DC IPT

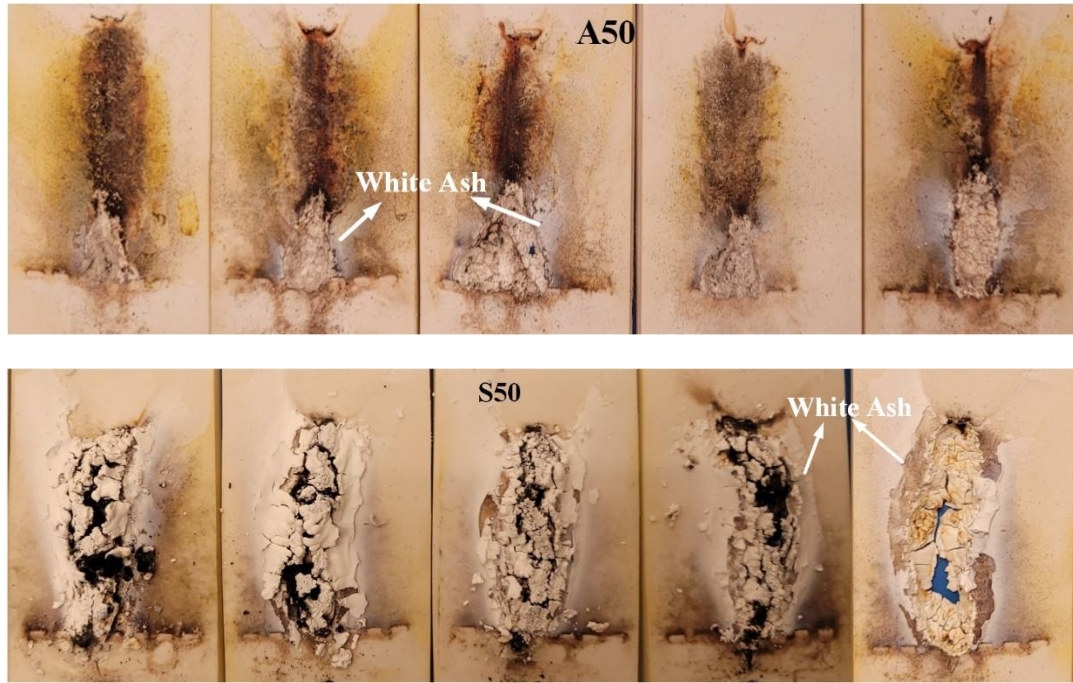


Figure 4.8. Tested A50 and S50 samples under +3.5 kV in DC IPT

Additionally, different forms of degradation under varying DBA severity were also identified using the stepwise voltage test method of the DC IPT. Figure 4.9 shows different levels of surface damage observed on A50 and S50 samples as the test progressed. Similar forms of degradation were also observed during the AC IPT, with the A50 sample passing the test, showing only surface erosion. Mild surface damage was observed under mild and intermittent DBA, and the residue formed led to stable DBA on the sample surface during the test [5]. When DBA impinging the surface became stable, erosion due to SR depolymerization occurred under the effect of hotspots exceeding 400°C [59]. Over time, the increasing severity of DBA transitioned into an eroding DBA plasma, further elevating the surface temperature and leading to the combustion failure of A50 and S50 samples in the DC IPT. These observations are further discussed in correlation with T_h and UHF measurements in Section 4.5 of the thesis.

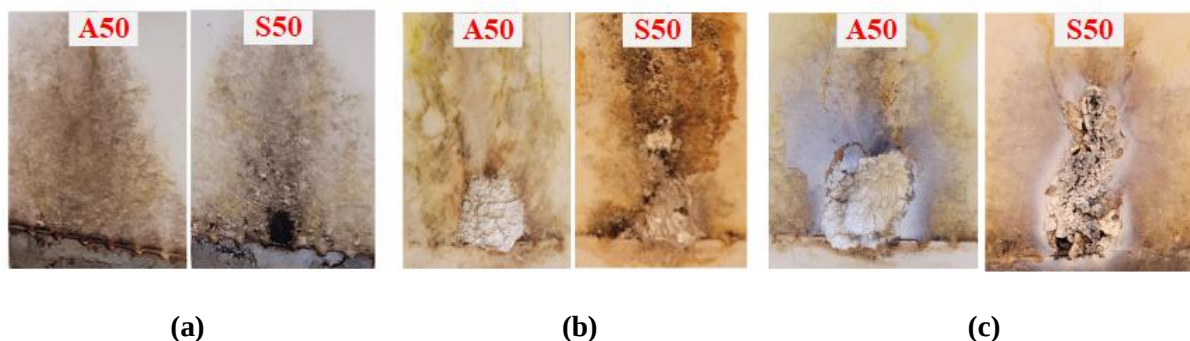


Figure 4.9. Obtained different surface damage levels on A50 and S50 samples tested in the stepwise voltage method of the DC IPT (a) Mild damage (b) Erosion (c) Erosion failure with combustion.

4.2 Ultra-High Frequency Detection of the Eroding DC Dry-Band Arcing

Figures 4.10a and 4.10b show the average LC and T_h measured on A50 samples during the DC IPTs, respectively. The applied +1.75 kV voltage produced a mild DBA throughout the entire test that led to mild or negligible erosion (Fig. 4.11a), whereas the +2.25 kV and +3.5 kV tests led to deep erosion (Fig. 4.11b and 4.11c). Notable temperature rise throughout the test was clearly detected under +2.25 kV and +3.75 kV as compared to +1.75 kV, confirming the distinct difference reported in the severity of erosion. The measured temperature exceeded 400°C during the +2.25 kV and +3.5 kV tests and was found to remain below 200°C during the +1.75 kV test. Depolymerization of SR was reported to start at about 400°C [22, 27], thus deep erosion would be expected to take place under the effect of hotspots exceeding 400°C in temperature. The TGA curves in Fig. 4.12 showed weight loss starting for the tested materials at 400°C in both nitrogen and air atmospheres indicating depolymerization [5, 14, 22]. Note that the DBA was severe enough to raise the surface temperatures to levels exceeding 1000°C. Similar findings were reported for the DBA produced under critical voltages of the IPT, leading to hotspot temperatures approaching 1200°C [5, 14, 17].

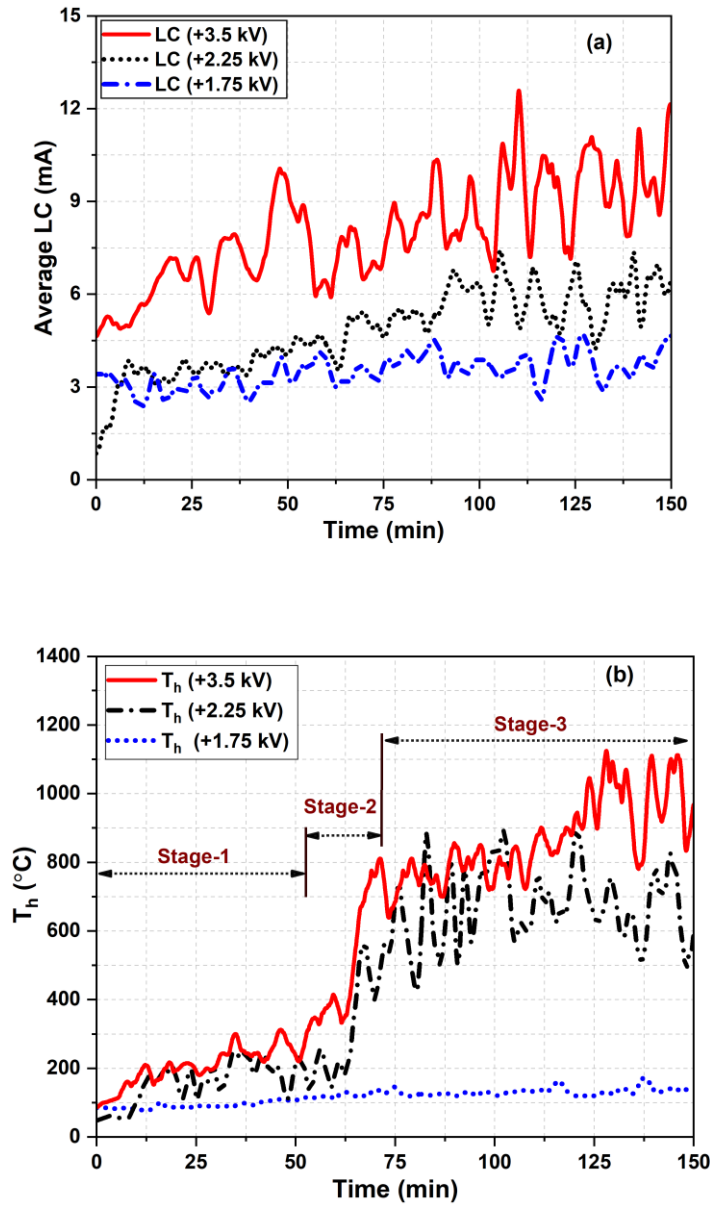


Figure 4.10. Average LC and T_h measured on A50 samples tested under +1.75 kV, +2.25 kV, and +3.5 kV in DC IPT

On the other hand, the trend of the average LC measured on A50 samples (Figure 4.10a) under all voltages were comparable and did not correlate with the distinct difference reported in the severity of the erosion after the test or temperature measurements throughout the test.

The reason is the acquired LC waveforms during the test would constitute not only the eroding DBA component, but mostly the wetting current that does not contribute to heat ablation of the surface [22, 31, 39]. It is clear that identifying the eroding DBA based on LC measurements would require a sophisticated type of analysis in order to distinguish between the wetting current and the DBA current [31]. Thus, average LC measurement may not be a reliable technique to detect deep erosion failure during the DC IPT.

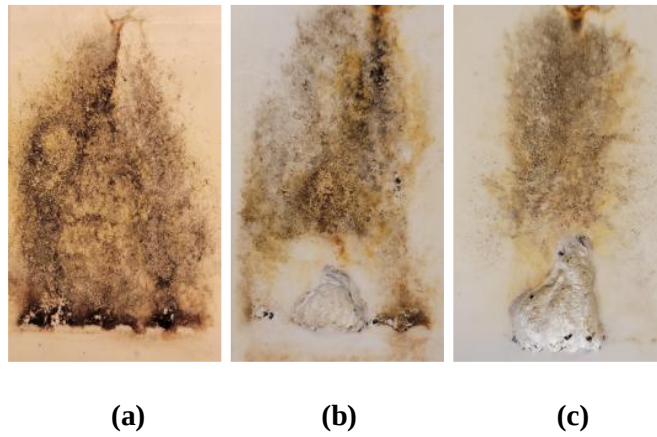


Figure 4.11. Obtained degradation patterns on tested A50 samples in the IPT (a) under +1.75 kV (b) +2.25 kV (c) +3.5 kV.

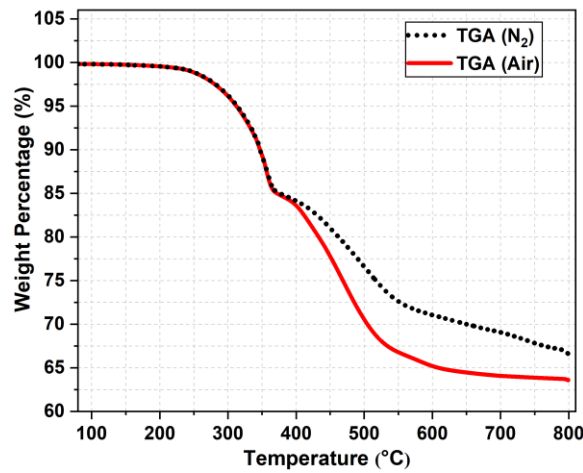


Figure 4.12. TGA performed on A50 samples in air and N₂.

Throughout the test, the detection of surface temperatures exceeding 400°C was correlated with the detection of UHF signals. Three distinct stages were identified during the test based on surface temperature measurements, TGA curves and the corresponding UHF detection. After identifying the stages, multiple UHF signals were systematically recorded at various time points, with measurements taken every minute within each stage. The signals showed a consistent pattern across all recorded data for each stage. Therefore, only a representative 10µs snapshot is provided for each stage at each voltage level, as it captures the characteristic behavior observed. The erosion depth measured on tested samples under +2.25 kV and +3.5 kV in the IPT is shown in Figure 4.13.

Figures 4.14a-4.14c depict three snapshots of the measured UHF signals from the tested A50 samples under +1.75 kV, which were captured at the early (stage 1), middle (stage 2), and late stages (Stage 3) of the test, respectively. It is evident from Figure 4.14a-4.14c that the UHF detection remained flat throughout the test, with negligible amount of UHF pulses detected. This was attributed to the mild DBA, which did not cause a significant rise in T_h , as the temperature remained below 200°C and did not produce an intense DBA plasma that could lead to deep erosion. Only black residue formed on the sample surface was formed with no visible signs of deep erosion, as shown in Figure 4.11a.

Figures 4.14d-4.14f show typical snapshots of the measured UHF signals captured for tested A50 samples under +2.25 kV, at three different stages of the IPT as indicated in Figure 4.10b. In stage 1, as shown in Figure 4.14d, no UHF pulses were detected, indicating a mild DBA. Over time, the DBA became stable and the test sample showed a remarkable jump in T_h during stage 2 (Figure 4.10b). At that moment the horn antenna began to capture a train of UHF pulses as shown in Figure 4.14e, indicating the onset of the eroding DBA due to the development of an intense plasma. A further increase in T_h was reported ($T_h > 800^\circ\text{C}$) in stage 3 (Figure 4.10b). During stage 3, a more intense UHF detection was obtained, as depicted in Figure 4.14f. Such an increase in the intensity of the UHF detection was associated with deep erosion on the test samples, as depicted in Figure 4.11b.

Similarly, Figure 4.14g shows no UHF detection during stage 1 in the +3.5kV test, indicating a mild DBA. However, UHF detection was obtained at stage 2 during the stable and intense DBA as shown in Fig 4.14h. The T_h curve showed a concurrent increase in temperature to 800°C (Figure 4.10b) along with the development of the stable and intense DBA. Figure 4.14i demonstrates a more intense UHF detection during stage 3 as compared to stage 2, indicating a more intense DBA plasma and deep erosion as depicted in Figure 4.11c. More intense UHF detection indicating a more intense DBA plasma and deeper erosion was obtained with higher applied voltages. This finding was in line with the higher erosion depth measured on the SR sample under +3.5 kV compared to +2.25 kV (Figure 4.13).

A statistical analysis of the UHF signals was conducted to compare stages 2 and 3, with results provided in Appendix A.2. The skewness and kurtosis of the UHF signal windows from each stage were evaluated at different voltage levels. As shown, no significant differences were observed in the statistical characteristics between the stages, aside from variations in pulse magnitude and repetition rate—both of which were higher during stage 3 due to more intense thermal ionizations.

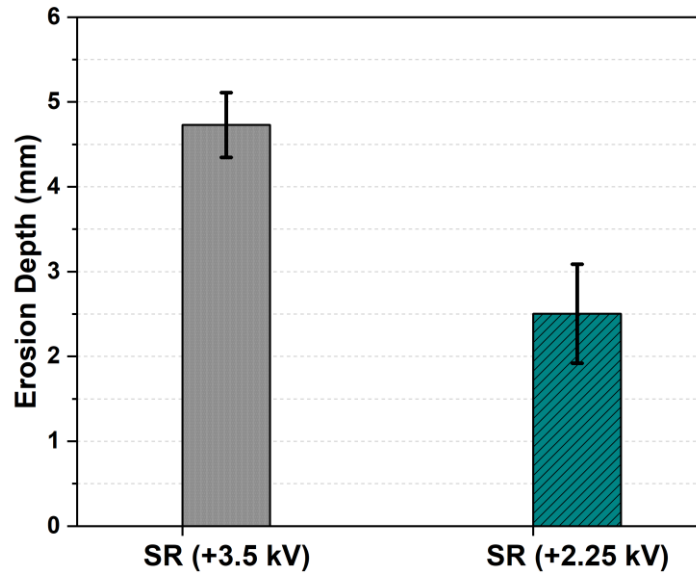


Figure 4.13. Erosion depth measured on A50 samples under +2.25 kV and +3.5 kV in the IPT.

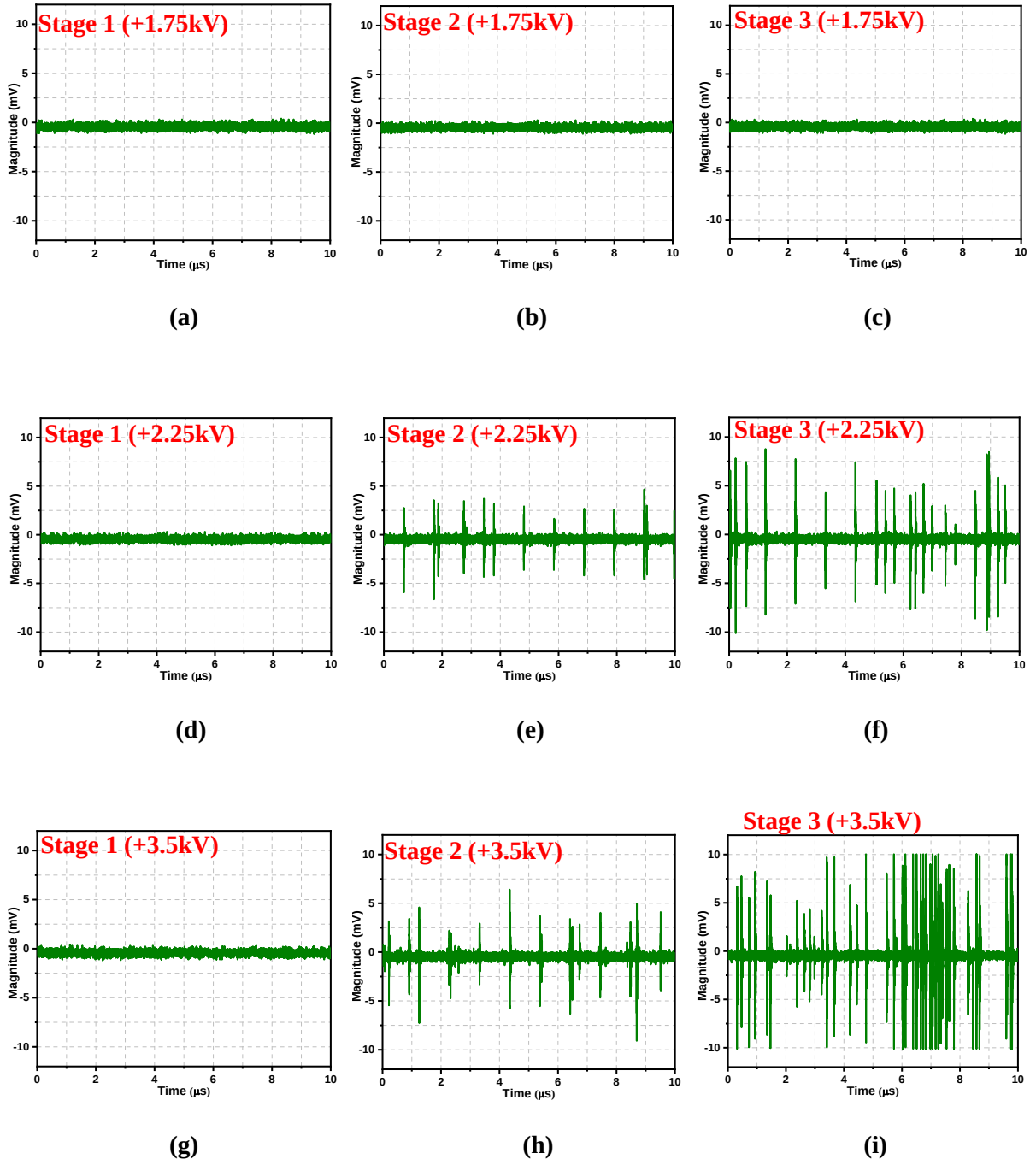


Figure 4.14. Typical 10 μs snapshots of UHF signals measured at three stages (1, 2, and 3) during tests conducted on A50 samples at +1.75 kV, +2.25 kV, and +3.5 kV.

4.3 Ultra-High Frequency of the Eroding AC Dry-Band Arcing

Figures 4.15-4.17 show the fundamental LC, third harmonics LC, and T_h measured over time on A50 samples during the AC IPTs, respectively. The DBA produced under 2.5 kV was mild throughout the test, resulting in minimal or negligible erosion (Figure 4.18), whereas the tests conducted at 3.5 kV and 4.5 kV resulted in deep erosion (Figure 4.18). A notable increase in temperature was clearly detected under 3.5 kV and 4.5 kV compared to 2.5 kV (Figure 4.17), confirming the distinct difference in the severity of erosion (Figure 4.18). The measured temperature remained below 300°C during the 2.5 kV test, while the T_h exceeded 400°C during the 3.5 kV and 4.5 kV tests. Depolymerization of SR was reported to start at around 400°C [22, 27], thus deep erosion would be expected to occur under the effect of hotspots exceeding 400°C. The erosion depth measured on tested samples under 3.5 kV and 4.5 kV in the AC IPT is shown in Figure 4.19.

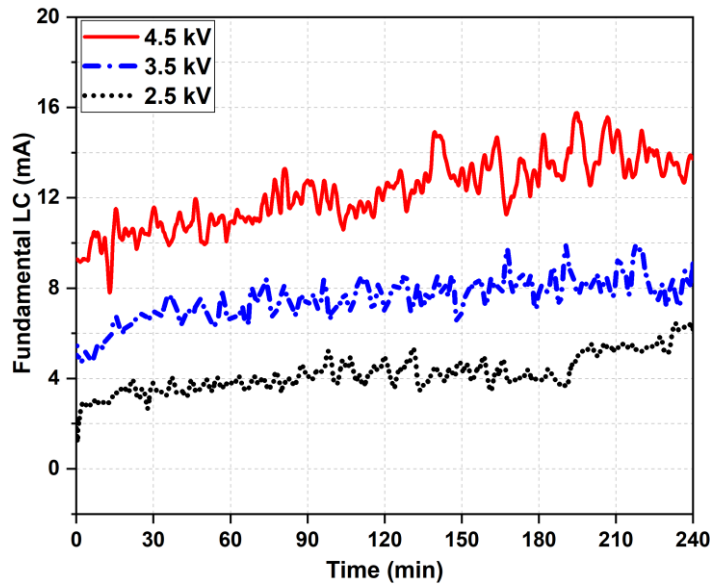


Figure 4.15. Fundamental LC measured on A50 samples under 2.5kV, 3.5kV, and 4.5kV in AC IPT.

It is evident from Figure 4.15 that the magnitude of the measured fundamental LC increased with higher applied voltages. Under each applied voltage, the fundamental LC showed an increasing trend over time. The third harmonic also demonstrated an increasing trend over time under the three applied voltages (Figure 4.16). While it is well-known that DBA is correlated with the third harmonics LC, it remains unclear when deep erosion takes place during the test. In other words, it was not possible to identify the inception of deep erosion by only relying on LC without observing the surface condition of the samples during the test.

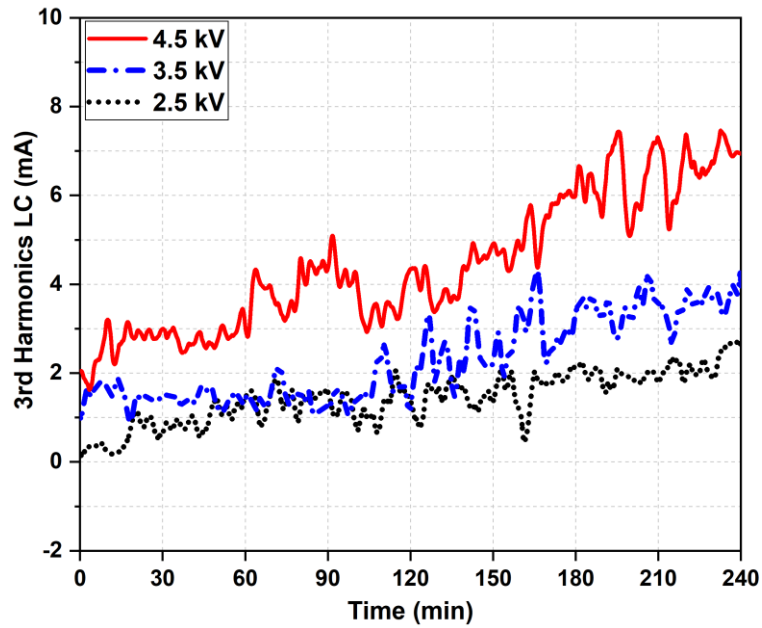


Figure 4.16. Third harmonics LC measured on A50 samples under 2.5kV, 3.5kV, and 4.5kV in AC IPT.

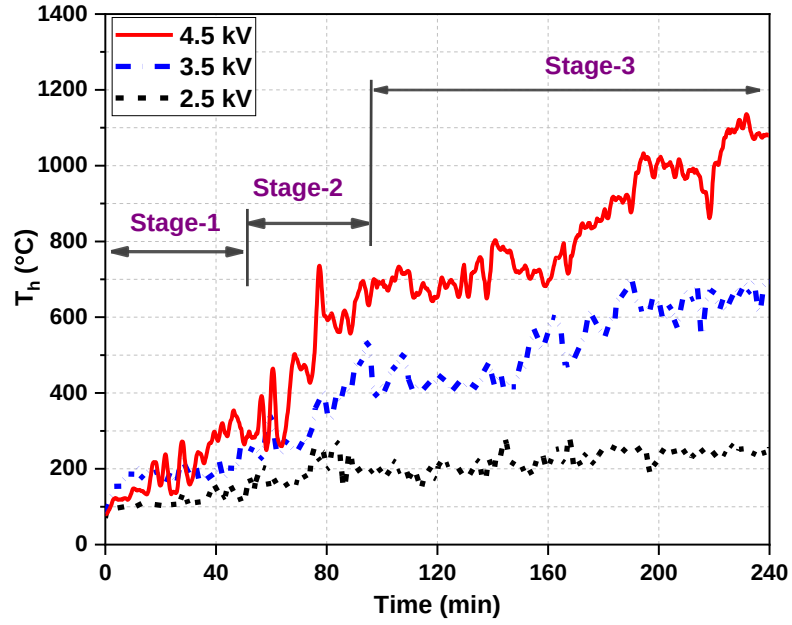


Figure 4.17. Measured surface temperature of A50 samples under 2.5kV, 3.5kV, and 4.5kV in AC IPT.

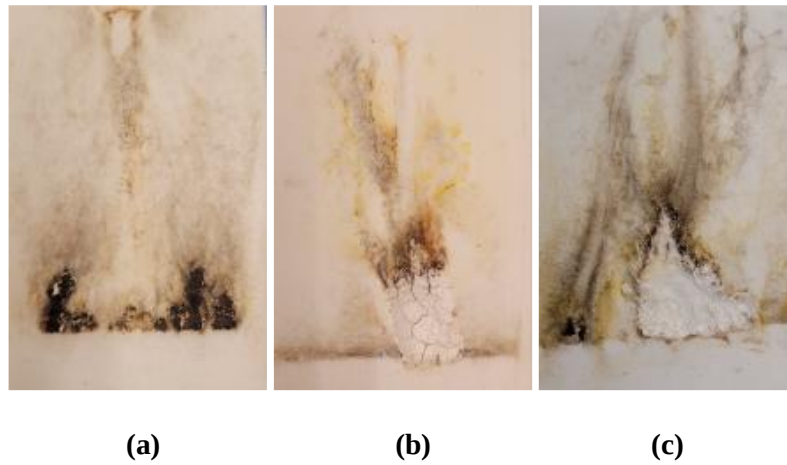


Figure 4.18. Tested A50 samples under three different voltages in AC IPT (a) 2.5kV (b) 3.5kV (c) 4.5kV

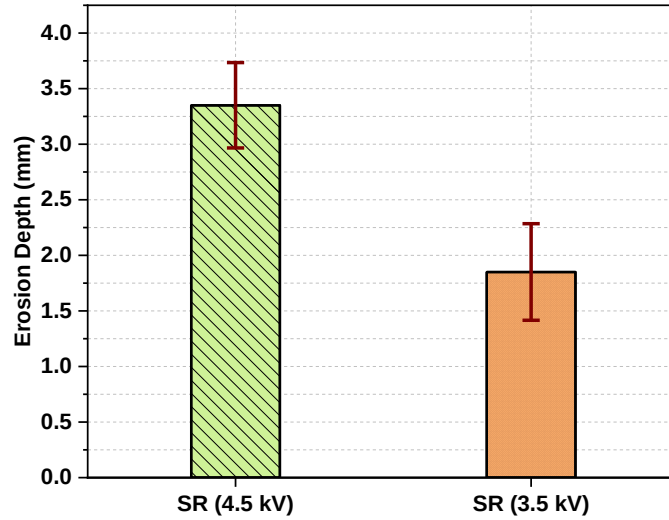


Figure 4.19. Erosion depth measured on A50 samples in the AC IPT under 3.5KV and 4.5kV.

Figures 4.20a-4.20c show the UHF measurements from the test A50 samples under 2.5 kV, with three windows of the UHF signals captured at the early, middle, and late stages of the test with respect to the level of observed damage on the surface. No UHF pulses were detected throughout the 2.5 kV test, ascribed to the mild DBA which did not cause a significant increase in T_h ($<300^\circ\text{C}$) (Figure 4.17). The mild DBA did not produce intense DBA plasma that could lead to deep erosion. Instead, only black residue was formed on the tested surface with negligible erosion, as shown in Figure 4.18a.

Figures 4.20d-4.20f show the progression of the measured UHF signals from the test samples during the 3.5 kV test. Three windows of UHF signals were captured at different stages of the IPT, as indicated in Figure 4.17. It is evident that no UHF signals were detected during stage 1. As the DBA stabilized overtime, the test samples showed a significant rise in temperature during stage 2. At that moment, a train of UHF pulses was captured by the horn antenna, indicating the onset of eroding DBA due to the formation of intense plasma. During stage 3, a further increase in temperature ($T_h > 600^\circ\text{C}$) was reported (Figure 4.17). More intense UHF pulses were detected in stage 3, as shown in Figure 4.20f. This increased intensity

of the UHF detection was associated with deep erosion obtained on test samples, as shown in Figure 4.18b.

Similarly, Figure 4.20g shows no detection of the UHF pulses during stage 1 in the 4.5kV test, indicating a mild DBA. However, UHF pulses were detected during stage 2 as depicted in Figure 4.20h. The DBA became stable and intense during stage 2 and the test sample showed a remarkable jump in T_h to 700°C (Figure 4.17). Figure 4.20i shows an increased intensity of UHF detection in stage 3 compared to stage 2, indicating a more intense DBA plasma and deeper erosion, as shown in Figure 4.18c. A further increase in T_h exceeding 1000°C was reported during stage 3 (Figure 4.17). Higher applied voltages resulted in more intense UHF radiation, indicating a more intense DBA plasma and deeper erosion. This finding is in line with the greater erosion depth recorded on the sample tested at 4.5kV compared to 3.5kV (Figure 4.19). Based on the results, it can be concluded that the magnitude of UHF pulses correlates with the amount of thermal ionization detected and thus the intensity of DBA plasma. Additionally, the intensity of UHF detection was found to be relatively higher under DC voltages compared to corresponding AC voltages.

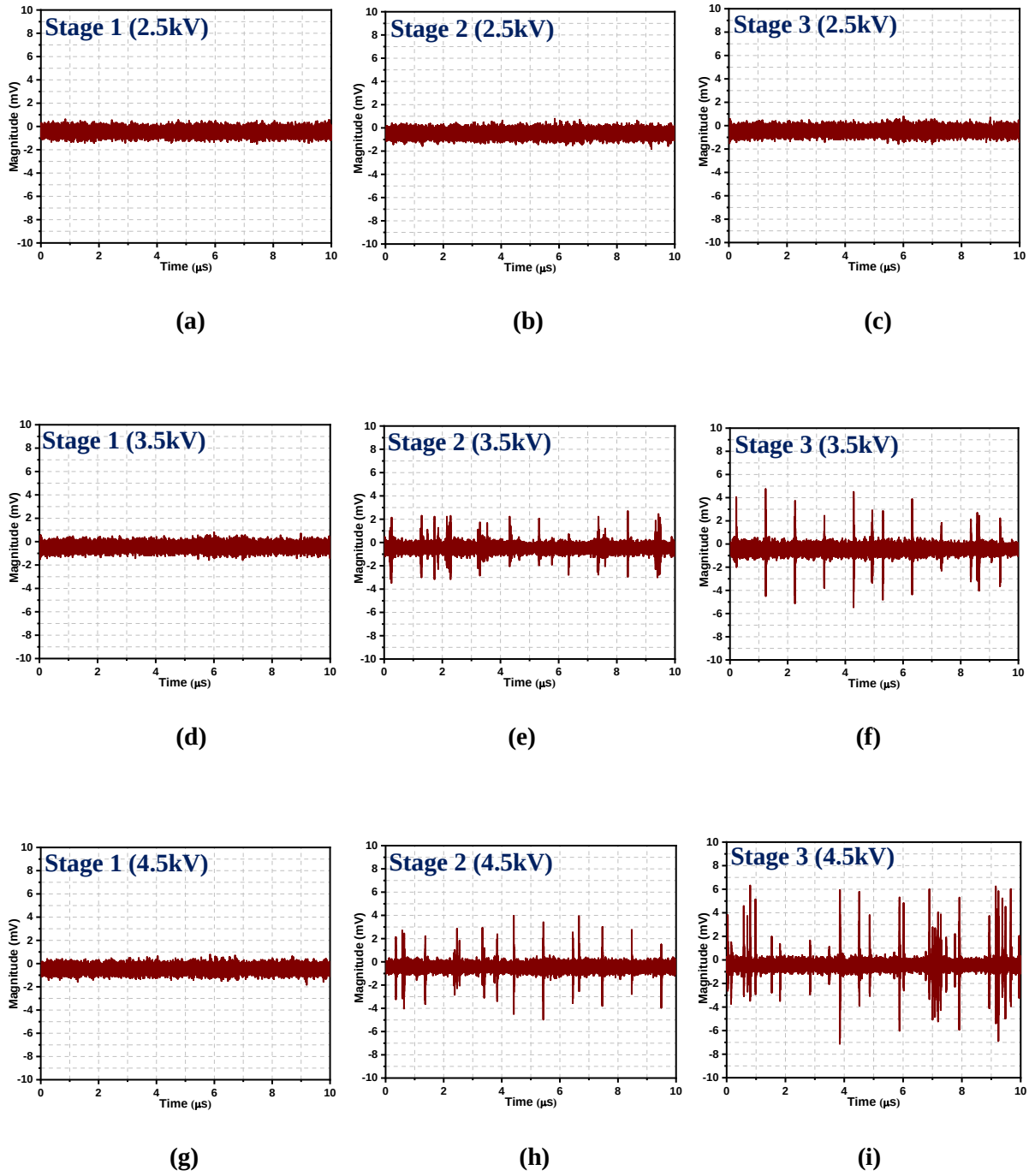


Figure 4.20. Typical 10 μs snapshots of UHF signals measured with horn antenna at three stages (1, 2, and 3) during AC IPTs conducted on A50 samples at 2.5 kV, 3.5 kV, and 4.5 kV.

4.4 Chemical Analysis of Silicone Rubber Surface Under the Eroding DBA

Figure 4.21 shows the ATR-FTIR spectra obtained for an unaged (reference) A50 sample, while Table 4.1 identifies the important infrared (IR) absorption bands [28]. Figure 4.22 compares the FTIR spectra of residues obtained from non-eroded regions of A50 that were impinged by a mild DBA (RM) and residues obtained from eroded regions that were impinged by the eroding DBA (RE) during the DC IPT. The Si-O-Si peak broadened, and its intensity decreased in the FTIR spectra of RE as compared to RM, possibly as a result of the Si-O bond scission taking place during depolymerization during the eroding DBA.

A noticeable reduction in absorption intensities for C-H, Si-CH₃, and Si-(CH₃)₂ was evident in RE as compared to RM with a more evident reduction obtained in the absorption intensities at 788 cm⁻¹, 1260 cm⁻¹, and 1410 cm⁻¹ for RE as compared to RM measurements. In the spectra of RM, the absorption peaks observed at 2800-3200 cm⁻¹, which corresponded to C-H stretching vibrations, were observable in RM. However, these peaks were nearly diminished in RE, indicating a greater loss of C-H bonds in RE as compared to RM. These notable changes in the absorption spectra of RE as compared to RM may have resulted from the eroding DBA heat causing the scission of side dimethyl chains of SR, thereby initiating a radical-induced crosslinking [83].

Radical-based crosslinking has been reported to occur at a temperature higher than the onset depolymerization temperature of SR as exceeding 500°C during the eroding DBA [20]. The DTGA conducted in Nitrogen and air (Fig. 4.23) showed a second tiny peak taking place as approaching 500°C, indicating the occurrence of a radical-based crosslinking [20, 22, 83]. Such a finding was in line with the FTIR findings reported in this study.

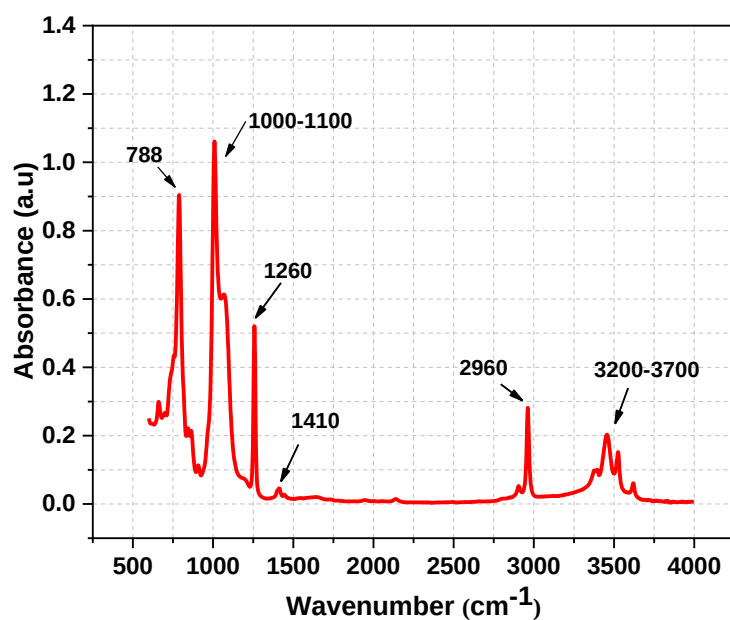


Figure 4.21. FTIR spectra obtained for an unaged A50 (reference) sample.

Table 4.1. Characteristics IR absorption bands for A50 [28]

Chemical Bond	Wavenumber (cm ⁻¹)
Si-(CH ₃) ₂	788
Vibration of Si-O-Si	1000-1100
Si-CH ₃ (Asymmetric stretching in CH ₃)	1260
C-H	1410
C-H in CH ₃ (Symmetric stretching)	2960
OH in ATH	3200-3700

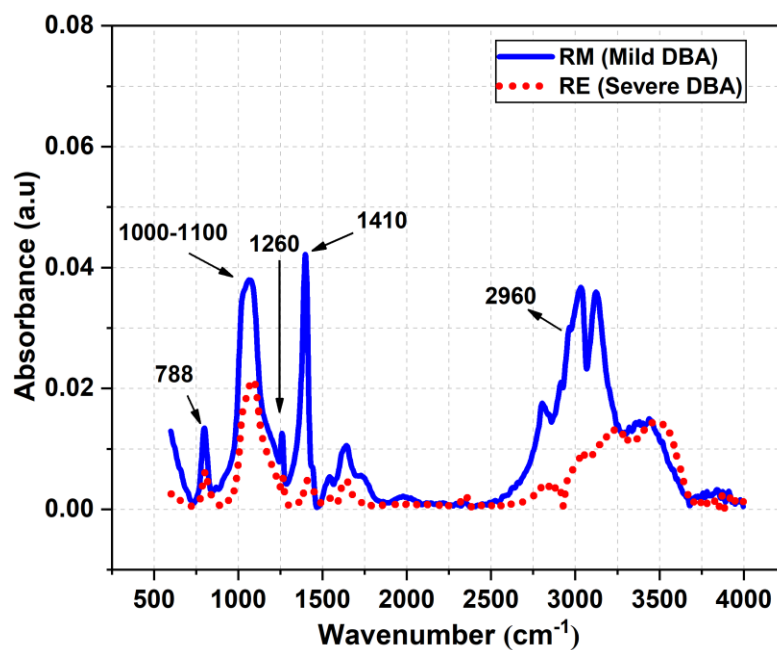


Figure 4.22. Comparison of FTIR spectra of the residue obtained from the non-eroded region affected by mild DBA and the eroded region impacted by severe DBA on A50.

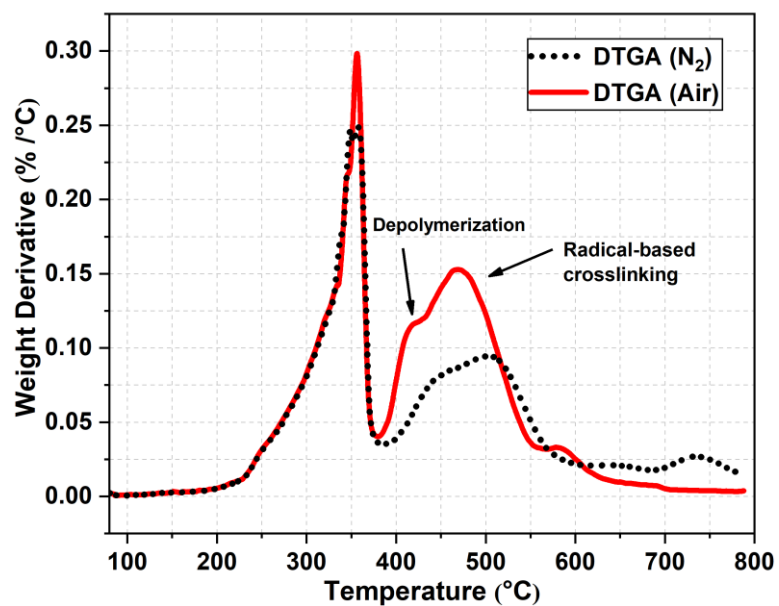


Figure 4.23. DTGA conducted on A50 samples in air and N₂.

4.5 Deep Erosion Failure Mechanism

The main objective of this research was to develop the UHF-based detection technique of deep erosion as a failure criterion for the IPT. Such an objective could be achieved by detecting the critical (eroding) DBA leading to deep erosion. Based on the cited literature, the critical voltage of the IPT has been reported leading to hotspot temperatures exceeding 400°C. Consequently, deep erosion occurs as soon as the DBA impinging the surface becomes stable and intense. Whereas, mild erosion has been shown to occur at the early stage of the test when the DBA is dominantly intermittent. It should be noted that residue formed on the surface under the effect of the intermittent or mild DBA establishes for the transformation to a stable DBA. The TGA curves (Figure 4.24) indicate that SR depolymerizes at around 400°C, producing volatile silicone oligomers in the gas phase. Therefore, deep erosion takes place under the effect of the hotspots exceeding 400°C in temperature.

In addition to the hotspots generated by the eroding DBA, these volatile oligomers combust in the gas phase during the SR depolymerization [14, 22]. This combustion process provides feedback heat into the DBA plasma that significantly increases the surface temperature, leading to deep erosion failure — a recognized failure criterion that often leads to the production of flames. Moreover, studies have shown a noticeable increase in the intensity of stable DBA, which is attributed to ionizations occurring in the DBA plasma [5, 14, 22, 59]. These ionizations have been reported to be promoted by the reduction of the dielectric breakdown strength of the gas phase. This reduction in the dielectric strength has been shown to be resulted by the release of volatile silicone oligomers during the depolymerization of SR under the effect of the stable DBA [5, 14, 22, 59]. The DTA conducted in air as compared to nitrogen (Figure 4.24) clearly shows an exothermic hump associated with depolymerization of SR, indicating the thermo-oxidation (combustion) of SR. It is possible that oxygen reacts with the solid state of silicone rubber, contributing to greater mass loss — as indicated by the lower residue observed in the air atmosphere compared to nitrogen in the TGA curve (Figure 4.12). Beyond its catalytic role, oxygen may also act as a reactant, further contributing to SR erosion.

Throughout the test, the detection of surface temperatures exceeding 400°C was consistently found to coincide with the detection of UHF signals. The thermal ionizations occurring in the DBA plasma increase the DBA intensity and generate UHF emissions, which are detected by the UHF antenna. Intense UHF emissions in the frequency range of 1–6 GHz were also reported as early indicators for the inception of an intense plasma within a discharge [76]. Therefore, this study utilized UHF measurements to detect intense plasma development during stable DBA as an indicator of deep erosion failure in the IPT. The block diagram in Figure 4.25 summarizes the proposed approach for UHF detection of deep erosion failure in the IPT.

The IEC 60587 [1] for AC IPT and IEEE Std. 2652 [3] for DC IPT also specify combustion on the surface of the material as one of the failure criteria for SR. The combustion of SR observed in both IPT and DTA highlights the need to consider deep erosion as a failure criterion for the IPT not only for proper evaluation of the erosion resistance, but also in order to avoid the occurrence of combustion of SR during the test. While the IPT has been developed as a tracking and erosion test, it is not intended as a flammability test [3, 7].

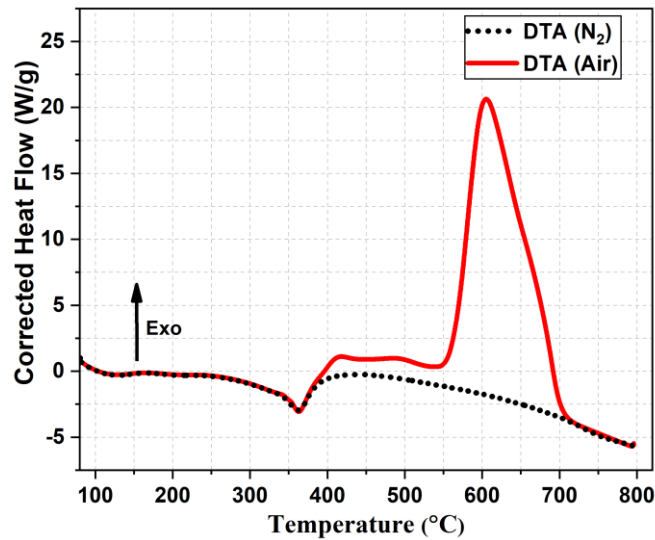


Figure 4.24. DTA conducted on A50 samples in air and N₂.

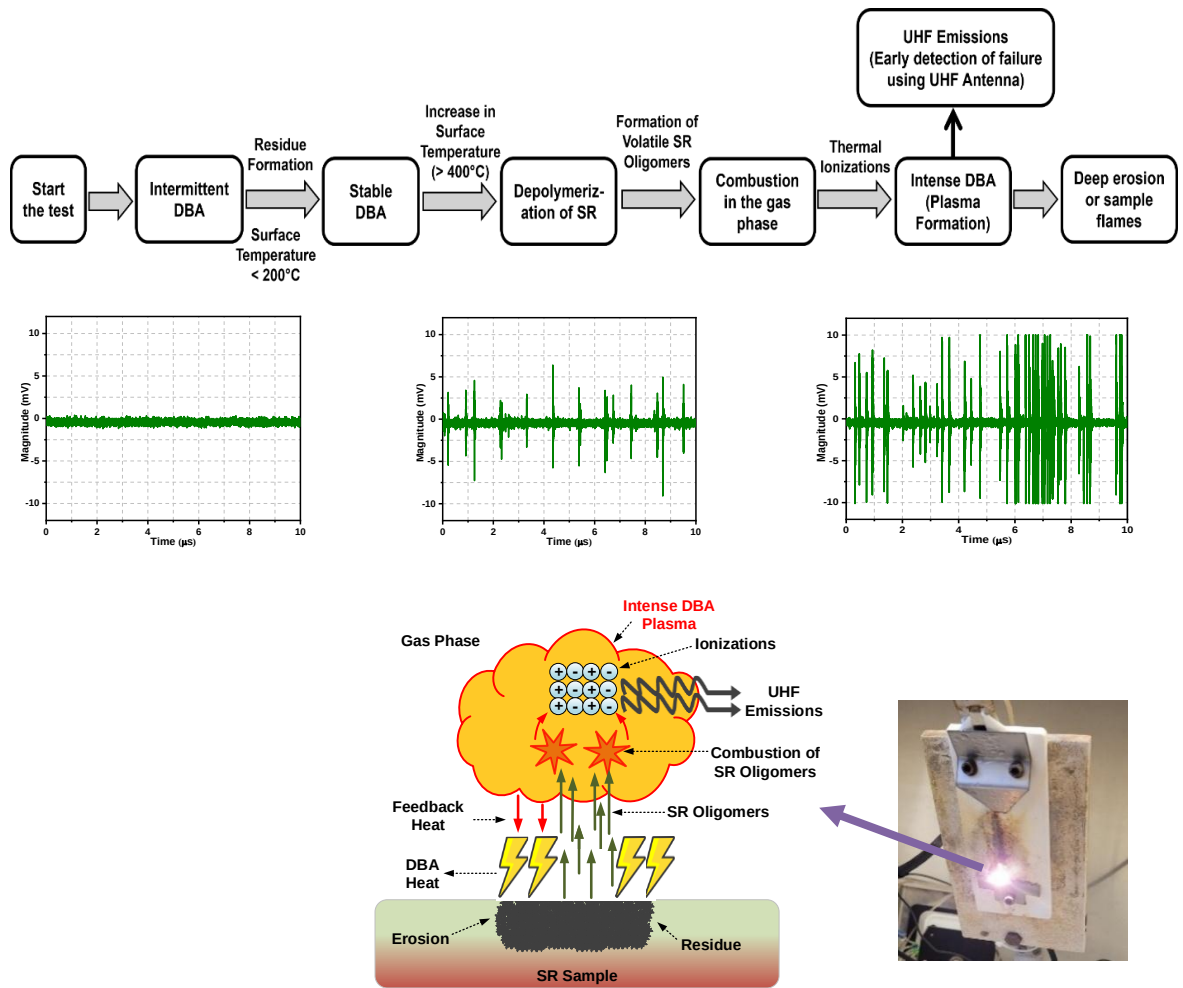


Figure 4.25. Proposed approach for UHF detection of deep erosion failure in IPT.

4.6 Ultra-High Frequency Detection of Erosion Failure of Silicone Rubber in the AC and DC Inclined Plane Tests

This section focuses on UHF detection of erosion failure of A50 and S50 samples tested in AC and DC IPTs using the stepwise voltage method. The stepwise voltage method was adopted with two primary objectives: first, to accelerate the progression of material damage from one stage to the next; and second, to demonstrate whether the UHF detection remains consistent with that observed in the constant voltage method. Figures 4.26 show the failed A50

and S50 samples tested under DC voltages, respectively. The S50 materials failed the DC IPT due to the formation of erosion path. A similar failure pattern has been observed for S50 in the AC IPT. The A50 composites failed the DC IPT due to deep erosion. Despite the difference in the failure mode between the A50 and S50 composites, material failure was always associated with combustion. Traces of white ash could be observed on the surfaces after the test (Figure 4.26). Note that A50 composites passed the AC IPT, thus are used as reference composites in this study.

A notable rise in temperature was clearly detected as the tested samples transitioned from erosion to combustion and failure (Figures 4.26 and 4.27), suggesting a distinct difference in the degree of damage (Figure 4.9). Note that the eroding DBA was severe enough to raise the surface temperatures to levels exceeding 1000°C during combustion and failure, whereas less hotspot temperatures were detected on the A50 samples which passed the AC IPT. This significant rise in temperature could be attributed to the feedback heat into the DBA plasma from the combustion of volatile oligomers, produced during the depolymerization of SR [22].

Figures 4.26 and 4.27 also show the average LC measured under DC and third harmonic LC measured under AC for the A50 and S50 samples during IPT. From the LC trend, the onset of erosion was associated with the increase in LC as the test voltage was increased leading to the onset of erosion. However, no distinct indicators of erosion failure could be obtained from LC measurement during both the AC and the DC IPTs. Note that the magnitude of the third harmonic LC for both S50 and A50 samples was comparable over the test, although they demonstrated distinct test outcomes (S50 failed and A50 passed the AC IPT). Therefore, the proposed UHF technique can be used to identify erosion failure by detecting combustion of the material under test.

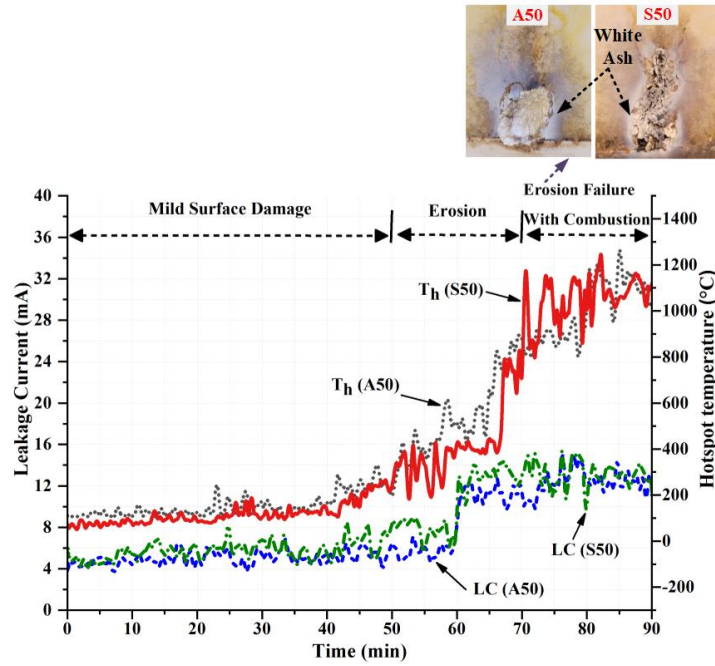


Figure 4.26. Surface temperature and average LC measured under DC for A50 and S50 samples in the stepwise voltage test method. The samples failed due to combustion are also shown.

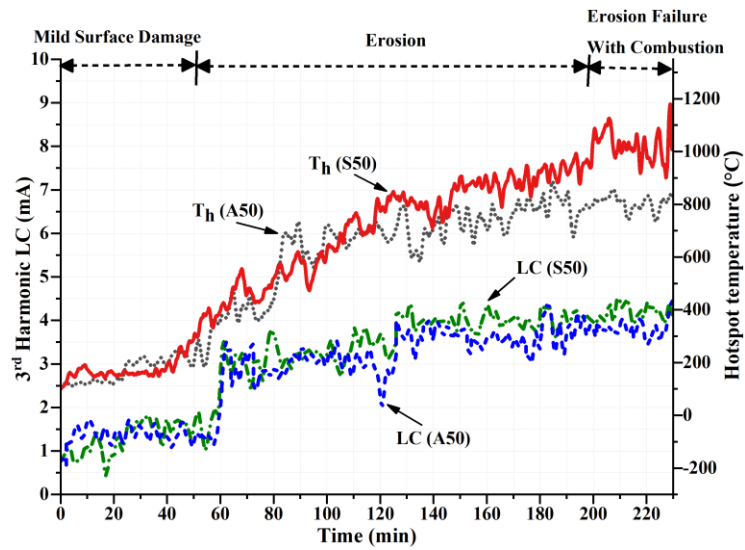


Figure 4.27. Surface temperature and third harmonic LC measured under AC for A50 and S50 samples in the stepwise voltage test method.

Figure 4.28 illustrates the distribution of the total voltage pulse counts acquired from the UHF antenna during testing of the A50 and S50 samples in the AC and DC IPTs. As has been explained in detail in [84], the pulse counts correlated with the level of thermal ionization detected and thus the intensity of the DBA plasma. In the erosion phase of S50 and A50 samples, UHF pulses were detected with magnitudes ranging from 1 mV to less than 8 mV, while no pulses in the 8–10 mV range were detected. For both composites, a higher number of UHF pulses were detected across all magnitude ranges during failure compared to the onset of erosion. More importantly, UHF pulses in the 8–10 mV range were exclusively detected during the combustion and failure phase of SR. This indicates that the intensity of UHF detection increased during combustion and failure, signifying a more intense DBA plasma due to a higher level of thermal ionization during combustion and failure as compared to the onset of erosion phase. The UHF pulses in the 8-10 mV were not detectable for the A50 samples which passed the AC IPT. Therefore, the combustion failure of the material in the IPT was indicated by the detection of UHF pulses in the 8-10 mV magnitude range.

Pulse counts for A50 were found to be lower than those for S50, indicating that a relatively lower level of ionization was detected for A50. This could be attributed to the internal oxidation of SR side chains which is stimulated by the release of the water of hydration in ATH, thus diluting the eroding DBA plasma by releasing inert gases. More details can be found in [22] about the dilution effect of ATH in the suppression of SR erosion. In contrast, the progressive dielectric breakdown in the gas phase for S50 samples indicates that more SR oligomers evolved and combusted during SR depolymerization compared to A50. This resulted in higher ionization being detected, leading to more intense UHF detection for S50.

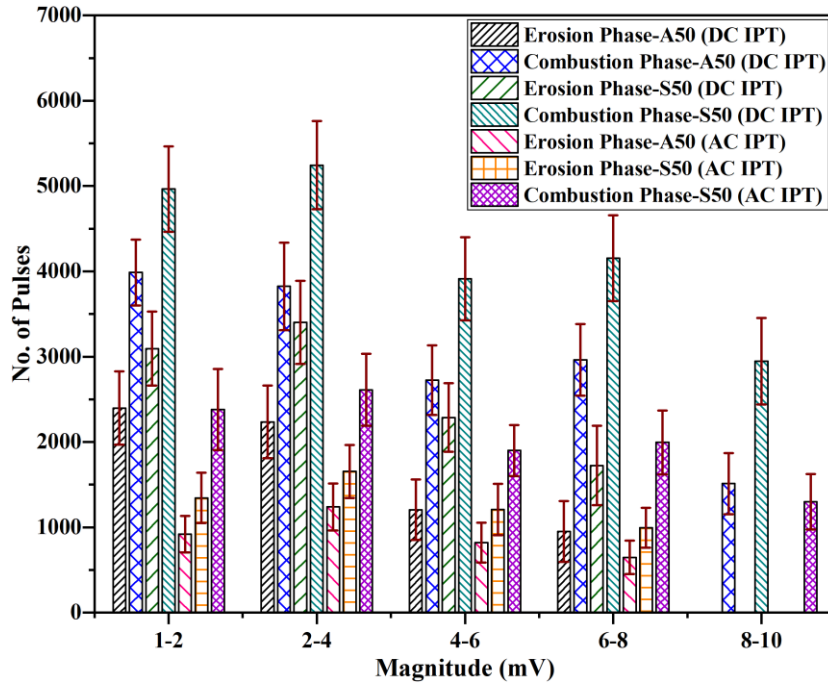


Figure 4.28. Distribution of total voltage pulse counts captured by the UHF antenna during the testing of A50 and S50 in the AC and DC IPTs.

Figure 4.29 shows the entropy distribution of UHF signals captured during the erosion and combustion phases of both A50 and S50 samples in the DC IPT, respectively. It is evident that the entropy values of the majority of UHF pulses captured during combustion are lower than those detected during the erosion of SR. With lower entropy values during combustion, the UHF pulses become less random, possibly indicating a more intense DBA. These findings align with previous work by Alqudsi et al. [58], where LC waveforms measured in the DC IPT showed less randomness and low variance in the distribution of LC values during stable DBA and towards the end of the test. Such a finding suggests that the entropy of the UHF pulses could be a reliable indicator of combustion and failure during the IPT.

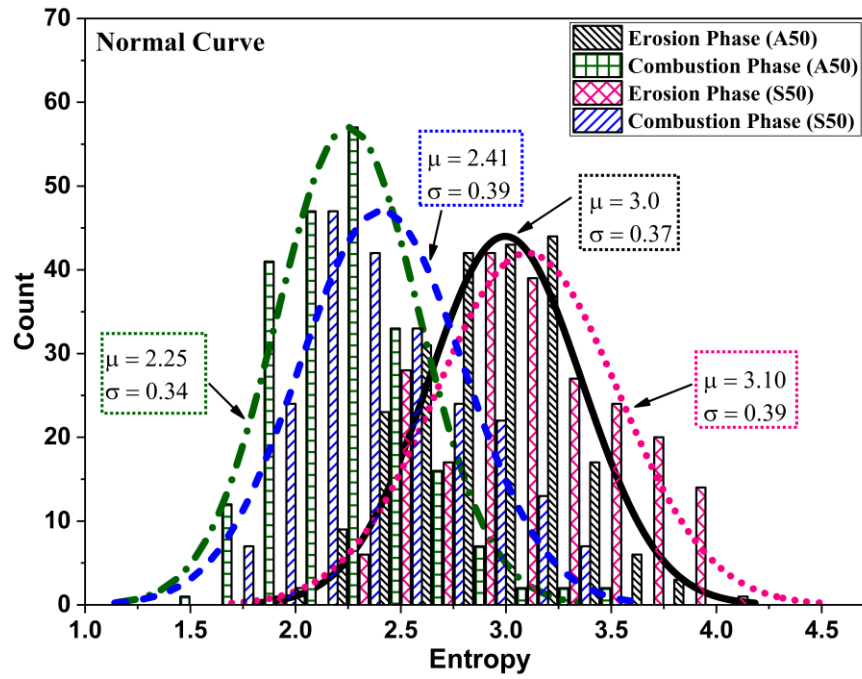


Figure 4.29. Entropy distribution of UHF signals captured during erosion and combustion phases of A50 and S50 in the DC IPT.

Chapter 5

Conclusions and Future Work

5.1 Summary and Conclusions

In this thesis, a mechanistic understanding of the erosion failure mechanisms of SR is achieved through UHF detection of the eroding DBA during the IPT. The thesis is structured into three parts. The first part presents a systematic experimental study on the impact of DBA severity on SR degradation under different test voltages in AC and DC inclined plane tests. The findings indicate that mild test voltages below the critical IPT voltage may not be severe enough to cause eroding DBA on SR. Under mild voltages, SR tends to decompose and form black residue without surface erosion, whereas deep erosion and failure become evident at critical test voltages. This suggests that the degradation behavior of SR during IPT depends on the test voltage level. The critical voltage is found dependent on the amount of the filler added to the SR under test. In addition, a severe voltage may lead to material combustion during the IPT, which should be avoided as the IPT has been developed to be a tracking and erosion test, but not a flammability test.

In the second part of the thesis, UHF detection of the eroding DBA is introduced as a reliable detection technique of erosion failure of SR during the IPT. AC and DC IPTs are performed on SR composites; while leakage current, surface temperature and UHF measurements were conducted using an IR camera and horn antenna respectively. No UHF detection is obtained during mild DBA, which does not lead to erosion on SR. Whereas, the detection is shown possible with the development of an intense DBA plasma, promoted by combustion of SR during depolymerization. Thermogravimetry, differential thermal analysis and Fourier Transform spectroscopy are conducted to elucidate temperature measurements and visual observations. The eroding DBA is shown leading to depolymerization of SR at 400°C, thereby leading to combustion and erosion failure, and stimulating a radical-based crosslinking reaction at temperatures exceeding 500°C. The intensity of ultra-high frequency detection is

also shown to be sensitive to the severity of the eroding DBA under both AC and DC voltages, increasing over time as the DBA transforms from mild to stable and intense DBA, as well as with higher applied test voltages.

The third part of the thesis extends the second part, demonstrating the effectiveness of UHF detection of the eroding DBA in identifying erosion failure of SR in both AC and DC IPTs. The UHF pulses captured during the tests are analyzed through pulse counts and entropy as indicators of erosion failure of SR. It is found that the magnitude of the UHF pulses signals detected during the test is shown to correlate with the level of thermal ionizations detected and thus the severity of the eroding DBA. In particular, it is shown possible to identify erosion failure using the magnitude and the entropy of the ultra-high frequency pulses detected during the test. The magnitude and entropy of UHF pulses are highlighted as potentially reliable indicators of combustion and failure during the IPT. It is also shown that the UHF detection intensity is lower for ATH-filled SR compared to silica-filled SR, highlighting the significance of the dilution effect caused by the released water of hydration in ATH in the erosion suppression of SR. Furthermore, the UHF detection remained consistent regardless of the test method or the type and level of the applied voltage (AC or DC).

While leakage current is found to correlate with DBA severity in both AC and DC IPTs, it does not provide distinct indicators for the onset of erosion or erosion failure. As a result, it remains ineffective in reliably detecting deep erosion and failure of SR during the test. Therefore, LC may not be a reliable technique for identifying deep erosion failure in IPT. Compared to LC-based techniques, the UHF detection offers the advantage to identify the inception of deep erosion failure under the critical test voltages of the AC and DC IPT. This proposed technique could potentially be implemented as a detection method to support realizing a reliable and automatic erosion failure criterion for the IPT.

5.2 Future Work

The results of this research demonstrate the potential of using UHF detection technique to identify erosion failure of SR in the IPT. However, there are several promising directions for future research that could enhance the applicability and reliability of this technique.

A key direction for future work is to extend the applicability of UHF detection to a broader range of polymeric insulating materials. This will help verify the reliability of this technique for detecting erosion failure in other types of materials used for outdoor applications. Such studies will ensure that the UHF method can be adapted for more general use in various insulation materials.

The current tests have been conducted under controlled laboratory conditions, which may not fully replicate the field conditions of the actual polymeric outdoor insulators. Therefore, extending the research to include real outdoor polymeric insulators is essential. Testing and verification of the proposed technique in field conditions is required which will provide insights into how the UHF technique can be employed for online monitoring of the eroding DBA and identify early indicators of insulator failure, potentially preventing catastrophic power outages and line drops.

Further analysis of the UHF signals can be carried out to explore the statistical and spectral characteristics of the UHF pulses. Detailed investigations into the frequency content of the UHF signals associated with thermal ionizations could provide deeper insights into the underlying mechanisms of the eroding DBA. Understanding these mechanisms better will facilitate the design of more accurate UHF sensors tailored for both SR and other polymeric materials used in outdoor insulation.

The presence of other sources of RF signals can impact the accuracy of UHF measurements. Future research should focus on identifying these interfering signals and developing effective filtering techniques to isolate the true UHF signatures of the eroding DBA. This would enhance the accuracy of failure detection and help in distinguishing the critical signals associated with the eroding DBA from background noise.

A potential avenue for future work is the integration of multiple sensor types, such as acoustic sensors alongside UHF sensors, to capture a more comprehensive range of signatures related to the eroding DBA. This approach could offer a more robust detection system, especially in identifying critical stages when the DBA transitions into a plasma state. In future, a comparative study could be proposed between UHF detection and other emerging non-intrusive methods, such as optical or acoustic emission techniques. This study would provide valuable insights into the strengths and weaknesses of UHF in various scenarios, helping to determine its suitability relative to other detection techniques for monitoring the erosion and failure of polymeric insulators.

One of the current limitations of UHF detection is the difficulty in correlating the intensity of the received UHF signals with the magnitude of the charge inside the discharge. This limitation arises due to the lack of information about the UHF signal's propagation path. Future work should focus on overcoming these calibration challenges by developing methodologies to calibrate UHF sensors more effectively, ensuring reliable and consistent measurements.

To enhance the efficiency of the UHF detection system, future research could focus on developing algorithms that automate the detection process. This could involve collecting and analyzing a larger volume of UHF data, thus covering a wider spectrum and obtaining more comprehensive readings. Automating this process for field insulators would help detect early signs of failure before catastrophic failures occur.

Future research could focus on advancing UHF sensor technologies to improve detection capabilities for polymeric outdoor insulators. One possible direction is to explore the use of different antennas with varying characteristics to develop low-cost, efficient, and compact sensors that can be easily deployed on real insulators. Work could be done using wideband antennas or antennas tuned to specific frequency bands to achieve maximum gain. Additionally, improving the radiation characteristics of the antennas could enhance the accuracy of UHF signal readings, providing more precise insights into the failure mechanisms.

These advancements in UHF detection technology will have significant implications for the diagnostic capabilities of polymeric insulators in power distribution and transmission systems. By improving the reliability and efficiency of failure detection, this research could lead to more effective and timely maintenance practices, reducing the risk of unexpected failures and enhancing the overall reliability of power systems.

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Appendix A

A.1 Shannon Entropy Calculation

The entropy of each UHF signal window captured from S50 and A50 samples tested in the DC IPT was computed using a MATLAB script. Each 1 μ s UHF signal window contained 2016 samples, and the computed entropy was stored as a single value. As a result, multiple entropy values were obtained for both the erosion and combustion phases. A sample entropy calculation for a single 1 μ s UHF signal window is described below.

$$S = - \sum_{i=1}^N p(x_i) \log_2 p(x_i)$$

Where:

- S is the Shannon entropy of the UHF signal window.
- $p(x_i)$ is the probability that a given signal sample falls within the i^{th} histogram bin.
- N is the total number of bins used to construct the histogram of the signal values; in this case, $N=50$.

The probabilities $p(x_i)$ are computed as:

$$p(x_i) = \frac{n_i}{\sum_{j=1}^N n_j}$$

Where:

- n_i is the number of signal values falling within the i^{th} bin.
- $\sum_{j=1}^N n_j$ is the total number of samples in the signal.

The entropy calculation was carried out using the following steps:

1. The signal samples in each window were divided into 50 equally spaced bins. The bin edges were automatically computed to span the full range of signal amplitudes. The number of samples in each bin was counted and stored as n_i .
2. The empirical probability distribution $p(x_i)$ was estimated by normalizing each bin count n_i by the total sample count across all bins.
3. The entropy S was computed by summing the product $(-p(x_i)\log_2 p(x_i))$ for all bins where $p(x_i) > 0$. Bins with zero probability were excluded to avoid undefined logarithmic values.

A.2 Statistical Analysis

The statistical characteristics of the UHF signals captured during stages 2 and 3 were analyzed by computing the skewness and kurtosis of 500 UHF signal windows from each stage using MATLAB®. The analysis was performed at each voltage level, all of which exhibited similar trends. For clarity, only the results from the +3.5 kV test are presented. Skewness and kurtosis were plotted in Figure A.1 to compare the statistical characteristics of the UHF signals between the two stages. Most of the data points are clustered in a similar region for both stages, indicating no significant difference in the statistical characteristics of the UHF signals, regardless of the voltage level or test stage. It is apparent from Figure 4.14 that the only difference between the stages lies in the pulse magnitude and repetition rate. This outcome was expected, as the phenomenon involves thermal ionizations, with the only variation being in the intensity of the UHF signal—higher during stage 3.

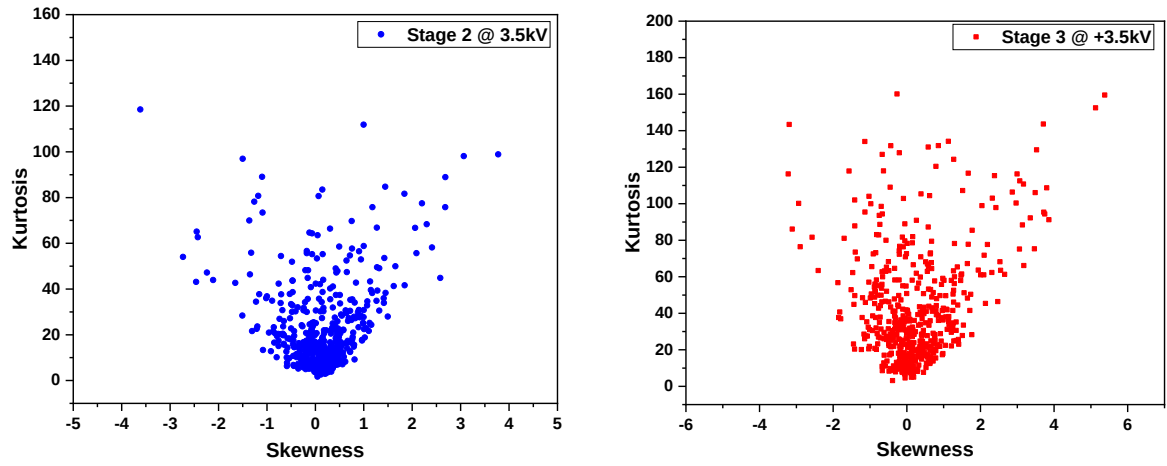


Figure A.1. Comparison of skewness and kurtosis of UHF signal windows captured during stage 2 and stage 3 in the +3.5kV test.

Appendix B

B1. List of Papers in Refereed Journals

- [1] **B. Mehmood**, R. A. Ghunem, A. El-Hag, and L. L. Tay, "UHF Detection of the Eroding DC Dry-Band Arcing on Silicone Rubber Insulation". *IEEE Transactions on Dielectrics and Electrical Insulation*, 2024 (Early Access) Available: <https://doi.org/10.1109/TDEI.2024.3510222>.
- [2] F. Z. Kamand, **B. Mehmood**, R. A. Ghunem, M. K. Hassan, A. El-Hag, L. Al-Sulaiti, and A. Abdala, "Self-healing silicones for outdoor high voltage insulation: mechanism, applications and measurements," *Energies*, vol. 15, no. 5, p. 1677, 2022. Available: <https://doi.org/10.3390/en15051677>
- [3] **B. Mehmood**, R. A. Ghunem, A. El-Hag, "UHF Detection of Erosion Failure on Silicone Rubber in the Inclined Plane Test," in *IEEE Transactions on Dielectrics and Electrical Insulation*. (Under Review)

B2. List of Papers in Refereed Conference Proceedings

- [1] **B. Mehmood**, R. A. Ghunem, A. El-Hag, M. K. Hassan, L. Al-Sulaiti, and A. Abdala, "Effect of Voltage Level on the Performance of Silicone Rubber in the Inclined Plane Tracking and Erosion Test. In *2022 IEEE Conference on Electrical Insulation and Dielectric Phenomena (CEIDP)*, Denver, CO, USA, Oct 30- Nov 2, 2022, pp. 515-518, IEEE. Available: <https://doi.org/10.1109/CEIDP55452.2022.9985319>
- [2] **B. Mehmood**, R. A. Ghunem, A. El-Hag, M. K. Hassan, L. Al-Sulaiti, and A. Abdala, "Assessment of ATH-Filled Silicone Rubber Under DC Dry Band Arcing," In *2023 24th International Middle East Power System Conference (MEPCON)*, Mansoura, Egypt, Dec 19-21, 2023, pp. 1-4, IEEE. Available : <https://doi.org/10.1109/MEPCON58725.2023.10462334>
- [3] **B. Mehmood**, R. A. Ghunem, A. El-Hag, "The Eroding DBA Detection in AC Inclined Plane Tracking and Erosion Test using UHF Antenna" In *2024 IEEE Conference on Electrical Insulation and Dielectric Phenomena (CEIDP)*, Auburn, Alabama, USA, Oct 6-9, 2023, pp. 1-4, IEEE.