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Study on Advancements in Dielectric Testing in High Voltage Applications and Assessment of Effects of Ageing on Dielectric Properties

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Abstract

The reliability of a power system relies heavily on the performance of insulation or dielectric materials used in various equipment like power cables, transformers, generators, switch gears, capacitors, reactors, and arresters. However, dielectrics can degrade over time due to various factors, including electrical stress, temperature, humidity, and other environmental conditions. The degradation or failure of insulation can lead to equipment malfunction, power outages, or even a catastrophic failure. Therefore, a periodic assessment and monitoring of insulation health and integrity through proper dielectric testing mechanisms serves as an essential tool for the safe and sustainable operation of an electrical power system. This paper also addresses the development of aging models and predictive tools for assessing the remaining life of dielectric materials in high-voltage applications, valuable insights into the long-term performance and reliability of dielectrics, enabling improved maintenance strategies and design guidelines for high-voltage systems.

Keywords: Aging, Accelerated Aging, Breakdown Voltage, Dielectrics, Dielectric Properties, High Voltage Applications, Insulation Resistance, Partial Discharge, Reliability, Testing

1. Introduction

In high-voltage applications, dielectric materials play a critical role in ensuring the safe and efficient operation of electrical systems. Dielectric testing is a fundamental aspect of assessing the insulation properties of these materials, enabling engineers to identify potential weaknesses and predict their performance under various operating conditions[1]. With the ever-increasing demand for more reliable and robust power systems, continuous research and advancements in dielectric testing methods have become imperative[5].

This work aims to study the recent advancements in dielectric testing techniques used in high voltage applications, focusing on the assessment of the effects of ageing on dielectric properties. Ageing is a natural phenomenon that affects the performance of dielectric materials over time, primarily due to thermal, electrical, and environmental stresses[3]. Understanding the degradation mechanisms and quantifying the impact of ageing on dielectric properties is crucial for ensuring the long-term reliability and safety of power systems[2].

To establish a comprehensive understanding of the subject, this study builds upon existing literature and research in the field of dielectric testing and ageing of insulating materials.

2. Dielectric Materials

2.1 Overview

Dielectric materials are essential components of insulation systems in high-voltage applications. They prevent electrical current flow and facilitate the storage and transfer of electric energy. Understanding the properties and behavior of dielectric materials is vital for accurate testing and assessment.

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2.2 Types of Dielectric Materials

Dielectric materials encompass a wide range of substances, including solid, liquid, and gas forms. Common types include polymers, ceramics, oils, and composite materials. Each type possesses unique electrical and physical properties, which affect their dielectric performance.

2.3 Properties of Dielectric Materials

Dielectric properties, such as permittivity, dielectric strength, and dielectric loss, determine the behavior of materials in electric fields. These properties play a crucial role in dielectric testing and assessment of insulation system integrity.

3. Dielectric Testing Techniques

3.1 Conventional Testing Methods

Conventional dielectric testing methods, such as insulation resistance measurement and dielectric breakdown testing, have been widely employed for evaluating the condition of dielectric materials. These methods provide valuable information about insulation resistance and the breakdown strength of materials.

3.1.1 Insulation Resistance Measurement

Insulation resistance measurement is a simple and effective technique for assessing the insulation integrity of electrical systems. It involves applying a DC voltage and measuring the leakage current to determine the quality of the insulation.

3.1.2 Dielectric Breakdown Testing

Dielectric breakdown testing involves subjecting dielectric materials to high voltages until electrical breakdown occurs. This method provides information about the dielectric strength and ability to withstand high electric fields.

3.2 Advanced Testing Methods

Advancements in dielectric testing have led to the development of advanced techniques that offer greater sensitivity and accuracy in assessing dielectric properties.

3.2.1 Partial Discharge Detection

Partial Discharge (PD) detection is a non-destructive testing technique used to detect and measure localized electrical discharges within insulation systems. PD activity indicates the presence of defects, such as voids, air gaps, or impurities within the insulation material, and can help predict potential failures.

3.2.2 Frequency Response Analysis

Frequency Response Analysis (FRA) is a diagnostic tool that measures the dielectric response of insulation systems across a range of frequencies. It provides valuable insights into the condition of the insulation, identifying changes in capacitance, inductance, and resistance.

3.2.3 Dielectric Spectroscopy

Dielectric spectroscopy involves subjecting dielectric materials to an AC electric field at different frequencies and measuring the complex dielectric permittivity. The complex dielectric permittivity, also known as the complex relative permittivity or complex dielectric constant, is a quantity that characterizes the electrical response of a material to an applied electric field at a given frequency.

$$\varepsilon^* = \varepsilon' - j\varepsilon''$$

It consists of a real part (ε’) and an imaginary part (ε”), which represent the material’s ability to store electric energy (polarization) and dissipate energy (conduction), respectively. This method provides detailed information about molecular interactions and the effects of aging on dielectric properties.

4. Effects of Ageing on Dielectric Properties

Aging refers to the gradual changes that occur in a material over time due to various factors such as temperature, humidity, exposure to radiation, mechanical stress, and chemical interactions. These changes can lead to alterations in the dielectric properties of the material, including its capacitance, dielectric constant, dielectric strength, and loss tangent. Here are some effects of aging on dielectric properties.

4.1 Effects of Aging on Dielectric Properties

4.1.1 Capacitance

Aging can cause changes in the physical structure and chemical composition of a material, which can lead to an increase or decrease in its capacitance. This change is often attributed to the modification of the material's surface, the presence of impurities, or the formation of conductive pathways within the dielectric. These changes can affect the performance of electronic components and circuits.

4.1.2 Dielectric Constant

Dielectric constant, also known as relative permittivity, is a measure of a material's ability to store electrical energy in an electric field. Aging can alter the intermolecular forces and molecular orientation within a dielectric material, resulting in changes to its dielectric constant. For example, polymers may experience a decrease in their dielectric constant over time due to molecular relaxation or diffusion of small molecules within the polymer matrix.

4.1.3 Dielectric Strength

Dielectric strength is the maximum electric field a material can withstand without experiencing electrical breakdown. Aging can lead to a decrease in the dielectric strength of a material due to the degradation of its chemical structure, the presence of defects or impurities, or the accumulation of stress within the material. This can result in an increased risk of electrical breakdown and failure in insulation systems.

4.1.4 Loss Tangent

The loss tangent represents the dissipation of electrical energy as heat within a dielectric material. Aging can cause an increase in the loss of tangent due to the formation of conductive pathways, the presence of moisture or contaminants, or the breakdown of polymer chains. An increased loss tangent indicates higher energy losses within the material, leading to reduced efficiency in electrical systems.

Effects of aging on dielectric properties can vary depending on the material type, environmental conditions, and aging mechanisms involved. Therefore, it's important to consider these factors when assessing the long-term reliability and performance of dielectric materials in various applications.

4.2 Aging Mechanisms

Various aging mechanisms contribute to the degradation of dielectric materials over time. Thermal stress, electrical stress, and moisture are among the key factors affecting the dielectric properties of materials.

4.2.1 Thermal Stress

Thermal stress occurs due to temperature variations, resulting in material expansion and contraction. It can cause changes in molecular structure, leading to reduced dielectric performance.

4.2.2 Electrical Stress

Electrical stress refers to the application of high electric fields, which can result in insulation breakdown, localized heating, and chemical changes within dielectric materials.

4.2.3 Moisture

Moisture ingress and the presence of water in dielectric materials can lead to increased conductivity, reduced breakdown strength, and accelerated aging. Moisture is a significant factor in the degradation of insulation systems.

4.3 Influence of Aging on Dielectric Properties

4.3.1 Breakdown Voltage

Ageing reduces the breakdown voltage of dielectric materials, indicating a decreased ability to withstand high electric fields without electrical breakdown.

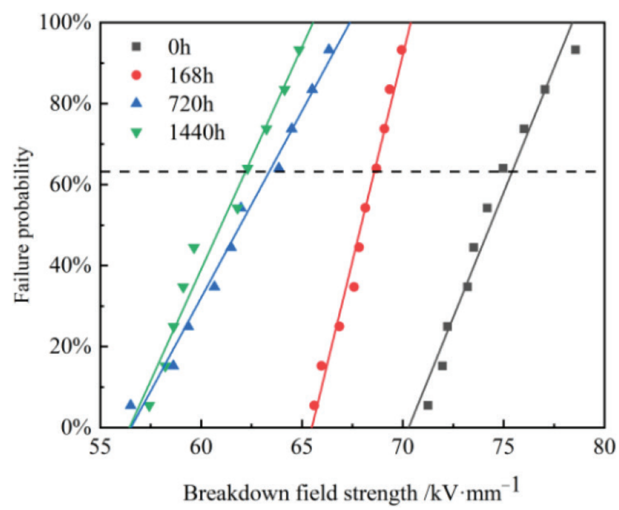

Figure 1. Variation law of breakdown field strength of insulation layer under different aging times[7].

4.3.2 *Permittivity*

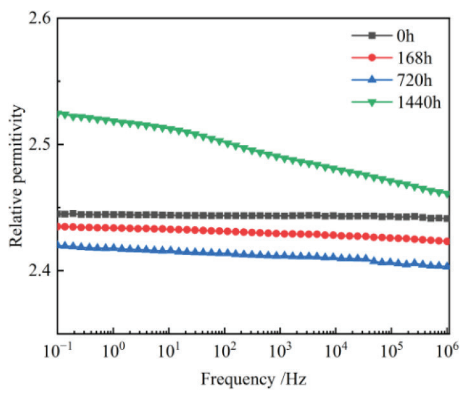

Figure 2. Variation of Relative permittivity of the insulation layer under different aging times[7].

4.3.3 *Dielectric Loss*

Aging can lead to increased dielectric loss, representing energy dissipation within the material due to dielectric and conductive losses.

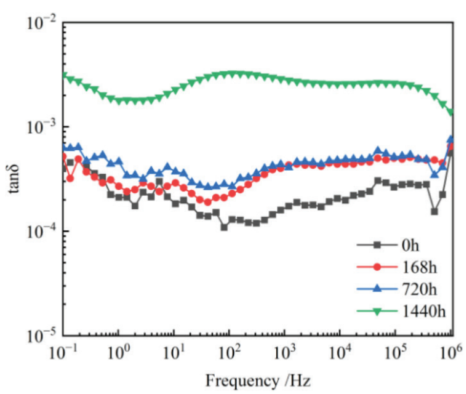

Figure 3. Variation of dielectric loss of the insulation layer under different aging times[7].

4.4 Overcoming Dielectric Ageing

In order to delay aging we can opt for newly reengineered dielectric materials, well-suited for high-voltage engineering applications such as polymer composites, nanocomposites, advanced ceramics, nanodielectrics, multilayer structured dielectrics, and synthetic ester-based dielectric fluids in place of mineral oils which have enhanced thermal stability, mechanical strength, flexibility, resistance to chemicals and radiation, and environmental friendliness. Apart from material improvements, we can also have process enhancement for material production along with the use of AI for equipment manufacturing and quality control. AI assists in detecting defects and ensuring quality control in dielectric material production by analyzing imaging data (e.g., microscopy or X-ray images) to identify and classify defects, thereby ensuring the use of materials that meet desired quality standards.

5. Experimental Results

An experimental setup was arranged to assess the dielectric properties of 50 MVA, 110/22/11 kV, 3-winding oil type transformer at BARC, Mumbai.

Figure 4. Testing of 50 MVA, 110/22/11 kV, 3 winding oil type transformer insulation at 100KV switchyard.

Insulations including Bushings, transformer oil, and winding insulation were tested for their dielectric properties. These Dielectric materials were subjected to electrical stress tests, insulation resistance tests, BDV, and tan delta assessment. The results are obtained below

5.1 Tan Delta Test

Tan Delta or Dissipation Factor, is a diagnostic method of testing cables to determine the quality of the insulation. This is done to try to predict the remaining life expectancy and in order to prioritize scheduled maintenance, replacement, or rejuvenation of the dielectric under test

Table 1. Tan delta test result and capacitance value of bushings

TAN DELTA & CAPACITANCE OF BUSHINGS

Test voltage = 5000 V   Oil temperature: 31°C

Bushing		Sl.No.	Capacitance (pF)	Tan delta (%)
123 kV Bushing	R	320208-3	332.13	0.2350
	Y	320208-2	333.56	0.2743
	B	320208-1	332.482	0.2817

Table 2. Tan delta test result and capacitance value of winding combination

TAN DELTA AND CAPACITANCE MEASUREMENT

Instrument used	:	Tan delta and capacitance meter
Make	:	OMICRON - CPC 100
Sl.No.	:	KF231R
Test voltage (V)	:	5000
Oil temperature (deg.C)	:	31°C
Reference std.	:	IS 2026

Winding combination		Tan delta (%)	Capacitance (pF)
HV - E	GSTg	0.2491	3711.48
MV - E	GSTg	0.2538	8147.90
LV - E	GSTg	0.2982	3029.82
HV - MV	UST	0.2428	3408.09
HV - LV	UST	0.2540	6070.47
MV - LV	UST	0.2490	8560.70

5.2 Insulation Resistance and PI Test

Table 3. Insulation resistance test result and PI values

M.O. No. 120746

MEASUREMENT OF INSULATION RESISTANCE WITH POLARIZATION INDEX

Instrument used :

Make	MEGGER
Sl.No.	101666899
Test voltage (V)	5000
Oil temperature (deg.C)	31.00
Reference std.	IS 2026

Winding combination	Insulation resistance (M.Ohm)			PI 600th/60th	Leakage current (ηA)
	at 15th sec.	at 60th sec.	at 600th sec.		
HV- MV, LV & E	1388	2520	5890	2.34	868
MV- HV, LV & E	722	1623	8840	5.45	579
LV- HV,MV & E	723	1486	7760	5.22	660
HV- MV	2480	4090	14150	3.46	362
HV- LV	1982	3800	13570	3.57	377
MV- LV	1142	2180	11890	5.45	430

5.3 Transformer Oil BDV Test

Table 4. Transformer oil BDV test result

MAKE	: TELK	LOCATION OF TRANSFORMER	: New Transformer
SR.NO.	: 120746	SAMPLED BY	: Customer
RATIO	: 110 KV/22 KV/11 KV	SAMPLING METHOD	: NA
RATING	: 50 MVA	DATE OF SAMPLE COLLECTED	: 10/05/2023
MFG.YEAR	: 2023	DATE OF SAMPLE RECEIPT	: 10/05/2023
SAMPLING POINT	: TOP (Before Charging) (After Filtration)	DATE OF SAMPLE TESTING	: 11/05/2023
OIL TEMP.	: 47°C		
RTTL -SAMPLE ID NO.	: OS -3138-2023		
CONDITION OF SAMPLE	: Good		

CONDITION DURING TESTING:		CONDITION DURING SAMPLING
I) TEMP-	26.6°C	I) TEMP- NA
II) HUMIDITY -	44%	II) HUMIDITY -NA
III) FREQUENCY OF TEST	50.03 Hz	

Sr. No.	Name of Test	Method of Test	Specified Limits as per IS:1866:2017	Results Derived	Conforms/ Not Conforms
A)	Physical Test:-		Table - 1		
1	Appearance	IS:335:2018	Clear , free from Sediments & matter	Clear, free from Sediments & suspended matter	Conforms
2	Interfacial Tension	ASTM D-971:2020	35 mN/m (Min)	41.5	Conforms
B)	Chemical Tests:-				
3	Water Content (PPM)	IS 13567:2018	10mg/kg (Max)	3	Conforms
C)	Electrical Tests:-				
4	Dielectric Dissipation Factor at 90°C Test Cell Type : SS Three Terminal Oil Cel Average voltage gradient : 250 V/mm.	IEC-60247:2004	0.015 (Max)	0.0012	Conforms
5	Resistivity at 90°C Test Cell Type : SS Three Terminal Oil Cel Average voltage gradient : 250 V/mm.	IEC-60247:2004	60 GΩ-m (Min)	370.2 GΩ-m	Conforms
6	Break DownVoltage(Electric Strength)	IS 6792:2017	60 kV (Min)	80	Conforms
	Electrode Type : Mushroom Shape S.S.	1 / 2 / 3	4 / 5 / 6		
	Oil Temp. :- 27.2°C	80 / 84 / 86	82 / 74 / 72		

6. Conclusion

In conclusion, this paper provides a comprehensive review of the various dielectric/insulation testing methods including both conventional as well as modern techniques used in high voltage industry. Also, various insulation degradation and failure mechanisms are analyzed which helps in the assessment of the remaining insulation life. At last, we applied various testing methods including insulation resistance, BDV, PI, and tan delta test for the assessment of the healthiness of dielectric/insulation of 50 MVA, 110/22/11 kV, 3 winding oil type transformer and it was found that the experimental results were in line and within range of recommendation by Indian standard 2026.

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