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Effects of SiO_2 and TiO_2 Nano Fillers in Enhancing the Insulation Breakdown Strength of Epoxy Nano Composite Dielectric under Divergent Electric Fields

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Abstract: The proper mixing of nanoscale fillers in conventional dielectric materials leads to an enhancement in the breakdown strength and voltage endurance. In this study experimental investigations are carried out to compare the breakdown characteristics of epoxy nano-composites with that of a base epoxy resin under the influence of divergent electric fields so as to obtain inferences on its breakdown performances. This would in turn enable providing solutions to acquire more effective electrical insulation systems and explore the prospect of tapping the merits of utilizing the rapid strides made in field of fabrication of nano-dielectrics. The main objective is such studies are to enhance the electrical properties of the epoxy dielectric by employing nano-fillers such as SiO_2, TiO_2 etc. This research envisages the use of epoxy resin mixed with nano-fillers for ascertaining the ability of the nano-composite to be utilized as a dielectric/ insulator in power apparatus. The epoxy resin is mixed with appropriate proportion of SiO_2 and TiO_2 and experimentation is carried out under the influence of divergent electric fields. Classical breakdown voltage withstand tests such as AC power frequency, DC voltage, lightning impulse and switching impulse test is carried out on epoxy dielectrics (with and without nano-fillers) and the results are compared. In addition, a non-classical breakdown voltage test (high frequency high voltage) is also devised to analyze and ascertain the breakdown characteristics due to varying frequencies so as to investigate the possibility of utilizing such nano-composites in applications related to high speed switching devices.

Keywords: Epoxy resin, nano-fillers, Divergent electric fields

1. Introduction

In the field of power systems design, installation and operation, electrical insulation plays a major role. In recent years several high voltage application systems utilizes Epoxy based insulating materials with different operating conditions. The epoxy dielectric materials are frequently exposed to huge electrical stresses and during long run the dielectric will degrade and shorten the life span of the equipment. Hence the need of the hour is to develop insulating materials for High voltage electrical applications with better electrical and mechanical characteristics. The research article by Lewis [1], discusses the introduction of nano fillers in the dielectric material in enhancing the electrical and mechanical properties of the nano composite insulation. Further, improved manufacturing techniques due to the advent of nano-technology has resulted in renewal of focus among researchers to explore on the possibility of developing stronger yet compact dielectric/ insulation system pertaining to power apparatus. The research studies reported by Tanaka et. al., [2],[3], in the development of polymer nanocomposites shows the improvement in the electrical properties of the new class of nano dielectric materials.

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In this context, nano-dielectrics has emerged as new area in high voltage engineering which aims at development of a new class of insulation materials with improved mechanical and electrical properties which could have substantial commercial implications [3]-[4]. This aspect becomes all the more relevant, since cost of insulation is a substantial portion of the net cost of the power system. Hence, attempts to provide solutions for obtaining higher dielectric withstand strength (by mixing nano-fillers with the base polymer unlike the conventionally used bulk expensive fillers) at reduced cost [5]-[7] has become the main focus of challenge to researchers worldwide.

The use of nano-fillers instead of its expensive polymer-filler counterpart has proved to be most efficient in terms of cost and electrical performance. Further, failures reported in composite insulation system of large power apparatus attribute breakdown due to chemical, thermal and mechanical aspects also as precursors to electrical insulation collapse due to purely electrical stresses. The addition of nano-fillers has been found to improve the mechanical and chemical property.

In this research the main objective is to test epoxy resin based dielectric under divergent electric fields and assess its dielectric breakdown strength and comparing the same with epoxy resin dispersed with SiO_2 and TiO_2 nano-fillers. In most of the cases, failure of electrical insulation is often followed by the failure in mechanical and thermal property of the insulator. By adding the nano-fillers it is proposed that the mechanical strength as well as the thermal strength of the insulator increases. Increase in the aforementioned two properties ensures durability of the insulator i.e., even with less volume the insulator can with stand very high transmission voltages [8]. Hence, detailed studies and substantial analysis of insulation system comprising nano-fillers may provide innovative solutions to insulation system in a variety of applications such as outdoor insulators, switchgears, DC cables, electrochemical capacitors, and insulation for inverter-fed motors etc.

2. Epoxy Nano-composite Preparation Methodology

In this work first a mould of thickness 2mm is made using galvanized iron sheet. Epoxy resin [Poly(Bisphenol A- co-Epichlorohydrin)] of suitable quantity is taken in a glass beaker. The beaker containing the epoxy resin is heated by maintaining a temperature of 45°C in a hot plate apparatus. Due to the oxidation of the phenolic compound, the final product obtained becomes black in colour in the form of gel. This indicates the complete formation of the epoxy resin. Nano-fillers are added to 5% of the base (epoxy resin) material's weight. The complete dispersion of the nanofillers can be ensured by using a high speed mixer. Once the fillers are thoroughly dispersed, Triethylenetetramine (TETA) is added to the solution as a hardener, so that the resulting polymer is heavily cross-linked, and is thus rigid and strong. The prepared sample is poured into the mould without lowering the temperature of 45°C as epoxy is a thermosetting resin and hardens as soon as the temperature falls below the preparing temperature. Air bubbles appearing on the surface is removed by applying heat on the surface

Figure 1. Preparation of Epoxy Nano-dielectric

using a blow torch. The prepared sample is allowed to cool for the duration of 10 minutes. Fast cooling of the sample is avoided to make the sample less brittle.[9]-[14]. Figure. 1 shows the various stages of preparation of the epoxy nano-dielectric.

3. Experimental Test Setup

The sample is kept in a test cell which comprises a point-plane electrode configuration filled with transformer oil to avoid external flashover. The point-plane electrodes are utilized for studies since most practical insulation systems exhibit such electrode configuration and since this arrangement provides the necessary divergent electric field on the sample which is kept intact between them. The point electrode is made up of stainless steel with an apex angle of 45° and the diameter of the plane electrode is 2.5 cm. Figure. 2 depicts a snapshot of the test cell arrangement.

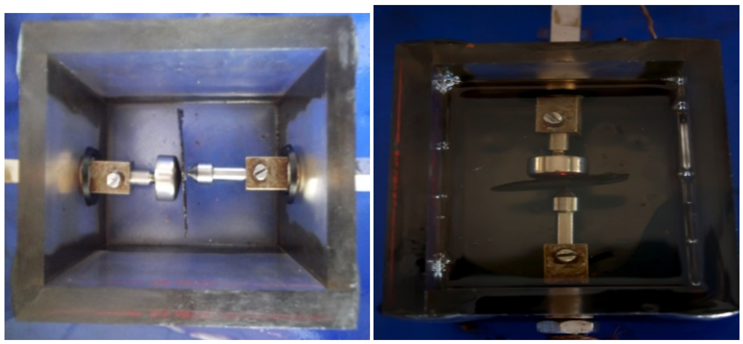

Figure 2. Test Cell containing the Epoxy Nano-dielectric

Figure. 3 and Figure.4 displays photographs of the test setup available in the High Voltage Laboratory, SASTRA University for conducting high voltage withstand tests pertaining to A.C power frequency, impulse voltages, and HVHF signals.

Figure 3. Experimental test set up for the power frequency and impulse voltage test

Figure 4. Experimental test set up for the High Voltage High Frequency test

4. Power Frequency and Impulse Voltage Test Setup

For the purpose of comparison, studies are carried out to determine the breakdown characteristics during classical test procedures namely the power frequency and impulse (lightning and switching) voltage setup. The power frequency voltage test setup utilizes a high voltage test transformer tunable to 100kV with appropriate voltage divider for further measurement and acquisition of waveforms. Figure 5 depict a typical test setup of the power frequency voltage test setup utilized during studies.

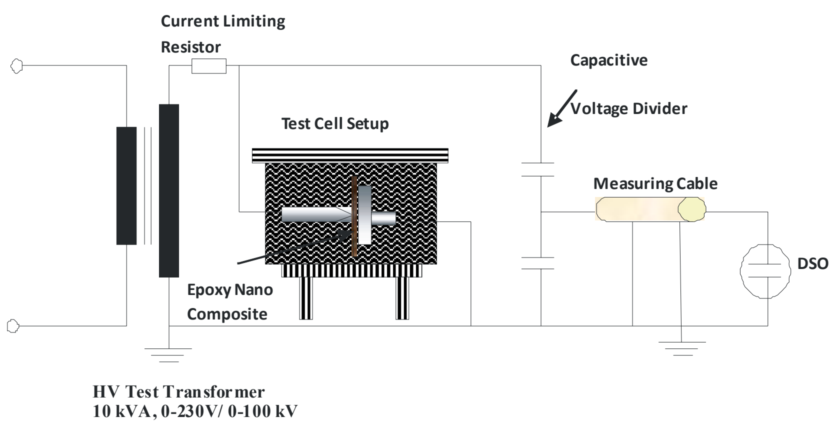

Figure 5. Power Frequency Test Setup for Epoxy didelectric Insulation Testing

A single stage Marx Impulse Voltage generator arrangement is setup to carry out impulse voltage testing due to the classical lightning (1.2/50 µs) and switching (250/2500 µs) transients. The test setup comprises a set of sphere gaps, a charging capacitor and appropriately chosen wave-shaping components for obtaining the standard lightning and switching wave shapes. Figure 6 indicates the Marx impulse generator circuit arrangement utilized for carrying out impulse studies on Epoxy dielectric samples.

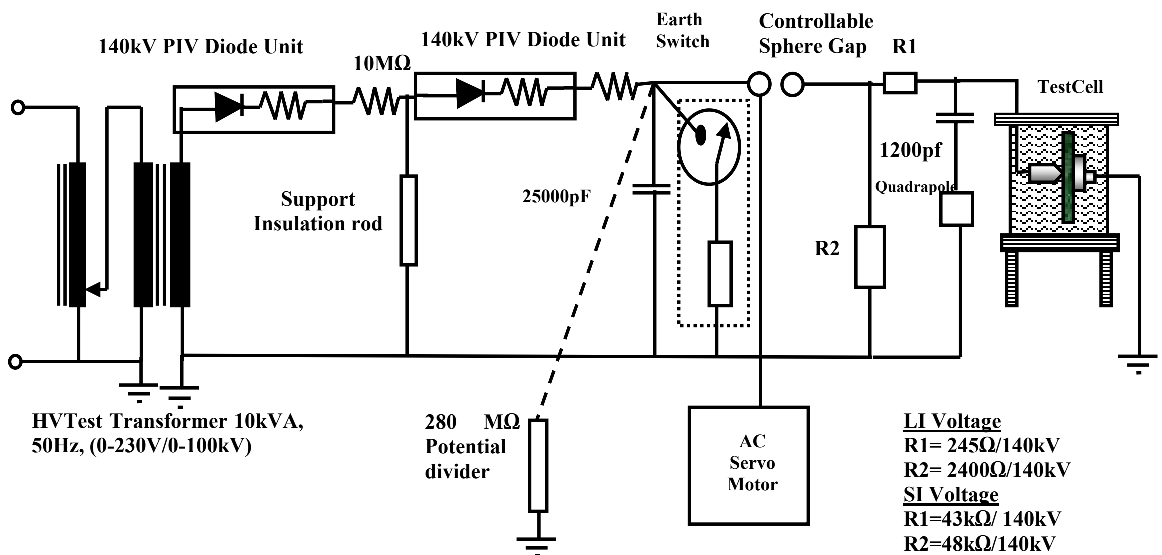

Figure 6. Experimental Test Setup for Impulse Voltage Breakdown Studies

Breakdown voltage corresponding to Lightning Impulse (LI) and Switching Impulse (SI) voltage is also noted. A comparison study is made between the breakdown due to power frequency, HFHV transients, LI/SI voltages in terms of the breakdown voltage and the number of cycles required to cause a breakdown in the Epoxy nano-dielectric samples.

5. DC Voltage Test Setup:

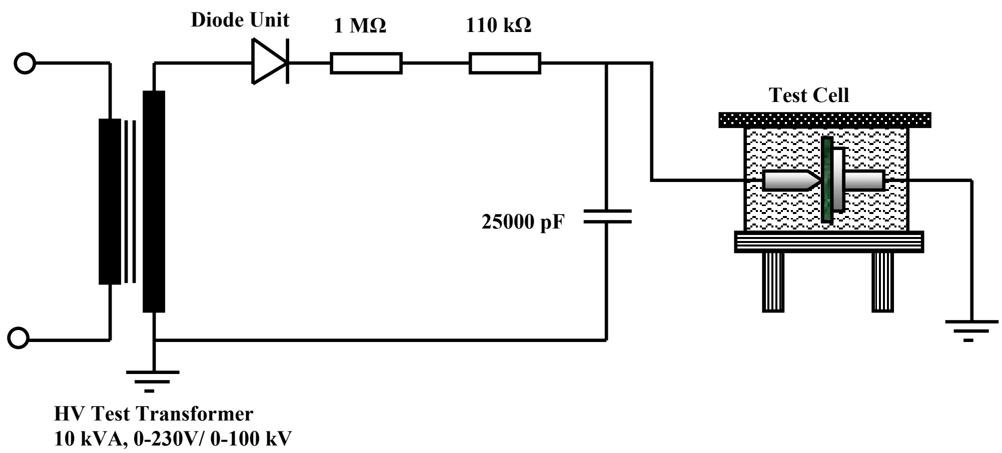

Figure 7. DC voltage test setup

In this test setup the H.V side of the transformer is fed directly to a half wave rectifier circuit to get a unidirectional flow of current.The d.c.input is given to the R-C combination for current limiting and the initially charged capacitor discharges through to the test cell.The electric field is created with the point-plane electrode configuration and the voltage stress is impressed on the specimen.The dielectric strength of the specimen is noted and the waveforms are obtained from the DSO.

5. High Voltage High Frequency (HVHF) Test Setup

The commonly used resonant transformer (Tesla coil) is designed for obtaining a doubly tuned resonant circuit in order to obtain better coil factor (voltage magnification) at resonant condition. The laboratory experimental test setup comprises a 10kVA, 230/100kV high voltage test transformer which is utilized to convert to produce a direct current output at condenser C1 utilizing the rectifier arrangement. A spark gap arrangement (G) is utilized with the aid for controlled trigatron (triggering) mechanism which forms a part of the control circuit of the sphere gaps for obtaining the desired voltage V1 which induces a high self-excitation in the secondary. The primary and secondary windings (L1 & L2) are wound on an air-cored arrangement which comprises the coil with facility to tap-off variable values of inductance. Tapping at various points of the coil provides an appropriate choice of inductance which in turn offers various choices of resonant frequencies. The two coil combinations are tuned to appropriate frequencies in the range of 40-150 kHz in conjunction with condensers C1 and C2. The output voltage is directly a function of the L-C combination (L1, L2, C1 and C2) and the mutual inductance of the coils. Since invariably the winding resistance is small it contributes only to the damping of the oscillations.[15]-[17].

Figure 8 represents the Equivalent circuit of the Double tuned resonant circuit used in this study.

Figure 9 represents the typical HVHF signal generated using the proposed circuit.

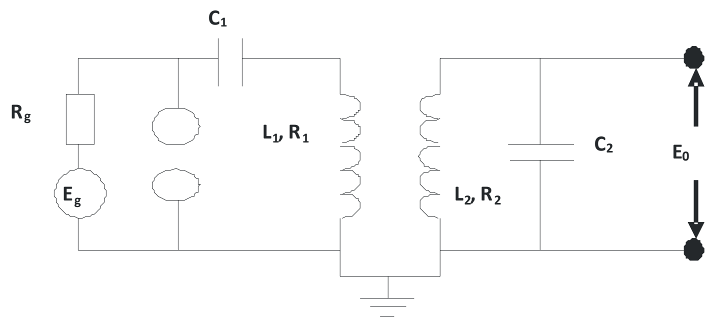

Figure 8. Equivalent Circuit

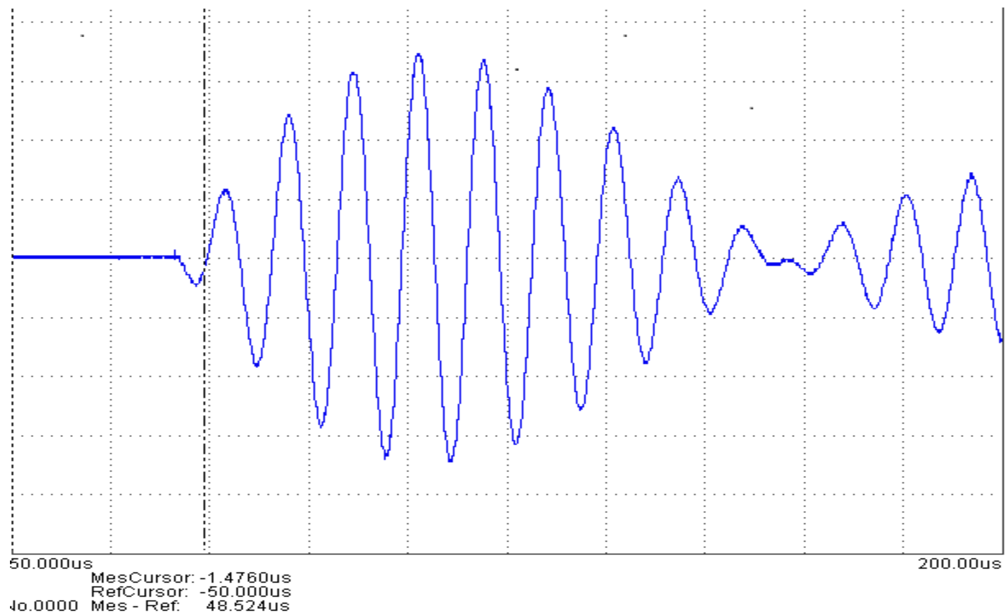

Figure 9. Typical HVHF Waveform from DSO

The primary and secondary circuits resonate at the same frequency, ω_r which is given by

$$\omega_r^2 = \frac{1}{L_1 C_1} = \frac{1}{L_2 C_2}$$

The corresponding Equations for the primary and secondary circuit can be written as

$$\left[R_g + R_1 + j\omega L_1 - \frac{j1}{\omega C_1}\right] I_1 - j\omega M I_2 = E_g$$

$$-j\omega M I_2 + I_2\left[R_2 + j\omega L_2 - \frac{j1}{\omega C_2}\right] = 0$$

At resonance both primary and secondary coils behave as purely resistive circuit. Hence at resonance $\omega_r L_1 - \frac{1}{\omega_r C_1} = 0$ and $\omega_r L_2 - \frac{1}{\omega_r C_2} = 0$

The equation for secondary current and output voltage at resonance can be written as:

Secondary current at resonance $$I_{2r} = \frac{j\omega_r M E_g}{R_1 R_2 + \omega_r^2 M^2}$$

Output voltage at resonance $$E_0 = \frac{\frac{M E_g}{C_2}}{R_1 R_2 + \omega_r^2 M^2}$$

Figure 10 illustrates a typical layout of the double tuned test setup utilized for HVHF testing of epoxy nano-dielectric.

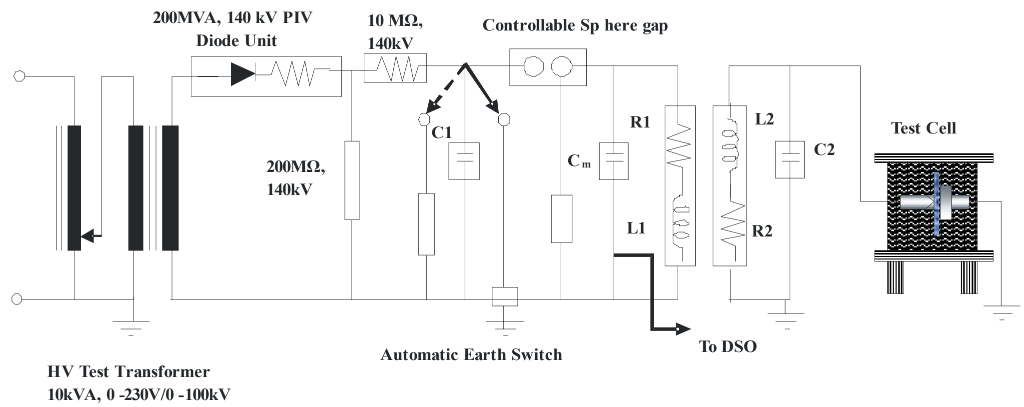

Figure 10. Typical Layout of Double Tuned Resonant Test Setup

Test set up comprises a tuned high frequency resonant oscillator, divider, measuring impedance connected to a 200 MHz, 200 MS/s DSO (DL 1620®). The selected range of high frequencies for the experiment varies from (40–115) kHz.[16] and [17]. This range has been selected since researchers who have carried out HFHV studies on similar such studies have chosen a comparable range of frequencies since a few reported incidents of failures has been observed to occurred at such frequencies[18],[19] and [20].

7. Comparison & Analysis of the Influence of Nano-fillers in Epoxy Resin

Initially high voltage 50Hz power frequency is applied on the epoxy resin without nano-filler and 5 samples are tested for dielectric breakdown test and the calculated average breakdown strength is observed to be 66.3 kV. Power frequency voltage at 50Hz is also applied on the epoxy resin with TiO_2 nano-fillers and Epoxy resin with SiO_2& TiO_2 nano-fillers and the calculated average breakdown strength is 76.5kV and 86.8 kV respectively. From the breakdown values it is evident that the addition of nano-fillers increases the dielectric strength of the material. Table 1 depicts the breakdown values of the samples tested under AC power frequency.

Table 1. High Voltage AC Power Frequency Voltage Breakdown Test

Test Samples	**Break down strength(kV)**				
	Sample 1	**Sample 2**	**Sample 3**	**Sample 4**	**Sample 5**
Epoxy resin without nanofillers	64.3 kV	65.7 kV	66.2 kV	68 kV	67.3 kV
Epoxy resin with TiO_2 nanofillers	74.4 kV	76.3 kV	75.5 kV	79 kV	77.5 kV
Epoxy resin with Sio2& Tio2 nanofillers	81.4 kV	83.7 kV	88.2 kV	91.3 kV	89.7 kV

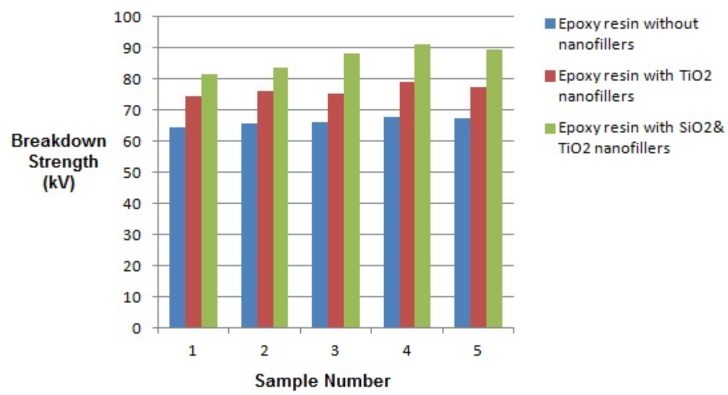

Figure 11. Comparison of Breakdown strength of Epoxy resin with and without Nanofillers under A.C Power frequency

A similar procedure is adopted for the DC voltage breakdown test. The average values of the breakdown strength of the epoxy resin without nano-filler, with TiO_2 nano-filler, with TiO_2 and SiO_2 nano-filler are observed to be 89.2kV, 101.1kV and 106.2 kV respectively. Hence the DC voltage withstanding capability of the nano-dielectric is higher than the AC voltage withstanding capability which may be attributed to frequency independent characteristic of polarization during DC testing. Table 2 depicts the various breakdown values of the samples tested under high voltage DC.

Table 2. High Voltage D.C. Voltage Breakdown Test

Test Samples	**Breakdown Strength (kV)**				
	Sample 1	**Sample 2**	**Sample 3**	**Sample 4**	**Sample 5**
Epoxy resin without nanofillers	85.6 kV	88.2 kV	91.6 kV	90.8 kV	89.9 kV
Epoxy resin with TiO_2 nanofillers	101.5 kV	93.6 kV	103.8 kV	104.5 kV	102.3 kV
Epoxy resin with Sio2& Tio2 nanofillers	105.7 kV	106.2 kV	102.5 kV	108.8 kV	107.9 kV

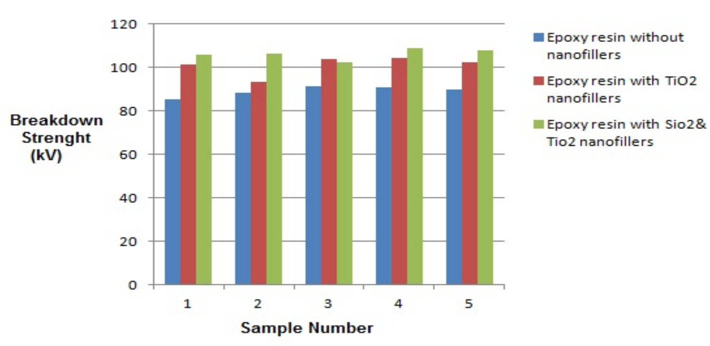

Figure 12. Comparison of Breakdown strength of Epoxy resin with and without Nanofillers under High voltage D.C

The prepared sample is also subjected to LI and SI breakdown tests. During lightning impulse test the average values of the breakdown strength of the epoxy resin without nano-filler, with TiO_2 nano-filler, with TiO_2 and SiO_2 nano-filler are found to be 74.4 kV, 85.3kV and 94.5kV respectively. During switching impulse test the average values of the breakdown strength of the epoxy resin without nano filler, with TiO_2 nano-filler, with TiO_2 and SiO_2 nano-filler are found to be 123.5kV, 124.2kV and 131.4kV respectively. The nano-dielectric hence withstands higher voltages during SI when compared to LI. Table 3 and Table 4 depicts the various breakdown values of the samples tested under lightning and switching over voltages.

Table 3. Lightning Impulse Voltage Breakdown Test

Test Samples	Break down strength (kV)				
	Sample 1	Sample 2	Sample 3	Sample 4	Sample 5
Epoxy resin without nanofillers	73.7 kV	74.2 kV	74.9 kV	73.8 kV	75.6 kV
Epoxy resin with TiO_2 nanofillers	84.6kV	85.3kV	86.7kV	84.8kV	85.3kV
Epoxy resin with SiO_2& TiO_2 nanofillers	94.6kV	92.8kV	93.4kV	95.4kV	96.6kV

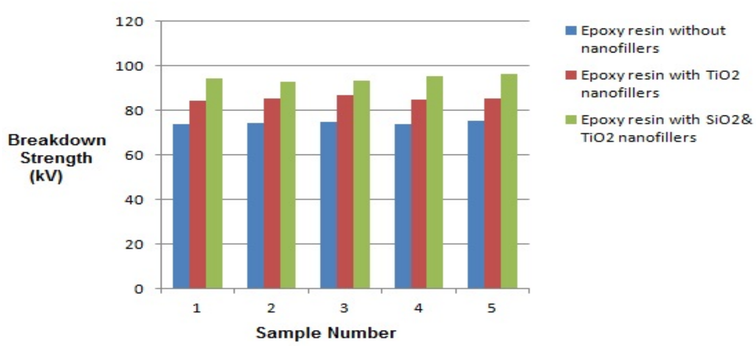

Figure 13. Comparison of Breakdown strength of Epoxy resin with and without Nanofillers under Lightning Impulse voltage

Table 4. Switching Impulse Voltage Breakdown Test

Test Samples	Break down strength (kV)				
	Sample 1	Sample 2	Sample 3	Sample 4	Sample 5
Epoxy resin without nanofillers	124.6 kV	119.2 kV	125.1 kV	120.3 kV	128.7 kV
Epoxy resin with TiO_2 nanofillers	124.6 kV	123.7 kV	122.6 kV	123.7 kV	126.4 kV
Epoxy resin with Sio2 & Tio2 nanofillers	128.6 kV	129.4 kV	135.8 kV	130.9 kV	132.3 kV

Table 5. High Frequency High Voltage (HFHV) Breakdown Test

Frequency of HFHV Transients	Double Tuned Circuit Parameters		Test Sample	Breakdown Strength kV		
	Parameters of Primary Circuit	Parameters of Secondary Circuit		Sample 1	Sample 2	Sample 3
43kHz	C1= 51200pF (25000pF|| 25000pF||1200pF) L1= 0.265mH	C2=1300pF (1200pF||100pF) L2= 10.10 mH	Epoxy resin without nanofillers	72.2kV	71.6kV	70.3kV
			Epoxy resin with TiO_2 nanofillers	83.4kV	84.5kV	80.5kV
			Epoxy resin with SiO_2& TiO_2 nanofillers	95.3kV	97.5kV	93.6kV
60kHz	C1= 25000pF L1= 0.265mH	C2 =2500pF (1200pF ||1200pF|| 100 pF) L2= 2.9 mH	Epoxy resin without nanofillers	51.5kV	55.6kV	53.4kV
			Epoxy resin with TiO_2 nanofillers	63.4kV	67.5kV	66.3kV
			Epoxy resin with SiO_2& TiO_2 nanofillers	72.4kV	70.2kV	74.5kV
86 kHz	C1= 26200pF (25000pF|| 1200pF) L1= 0.134mH	C2 =1200pF L2= 2.83 mH	Epoxy resin without nanofillers	78.4kV	76.4kV	76.4kV
			Epoxy resin with TiO_2 nanofillers	84.4kV	85.7kV	88.4kV
			Epoxy resin with SiO_2& TiO_2 nanofillers	95.6kV	93.2kV	99.4kV
111kHz	C1= 13700pF (12500pF|| 1200pF) L1= 0.14 mH	C2 =1200pF L2= 1.7 mH	Epoxy resin without nanofillers	141kV	142.5kV	143.6kV
			Epoxy resin with TiO_2 nanofillers	144.2kV	144.4kV	146.5kV
			Epoxy resin with SiO_2& TiO_2 nanofillers	148.1kV	146.3kV	147.3kV

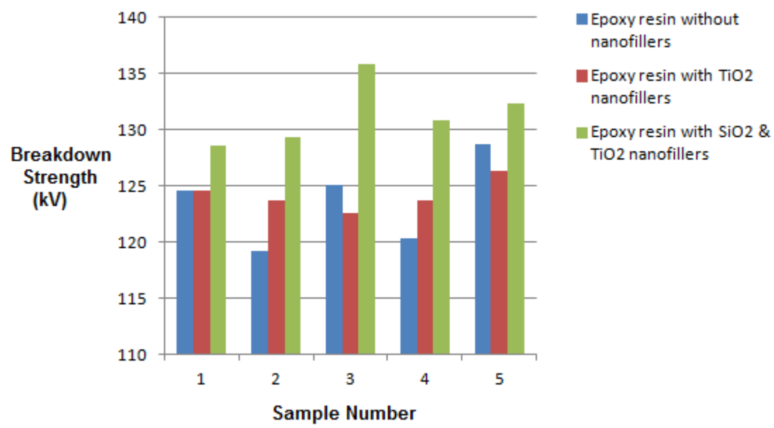

Figure 14. Comparison of Breakdown strength of Epoxy resin with and without Nanofillers under Switching Impulse voltage

Repetitive HFHV transients are applied and the specimens are observed for breakdown. If breakdown occurs, corresponding breakdown voltage for a particular frequency is noted else voltage is increased by 0.5kV. Table 5 depicts the studies conducted for epoxy nano-dielectric samples for wide range of HVHF transients.

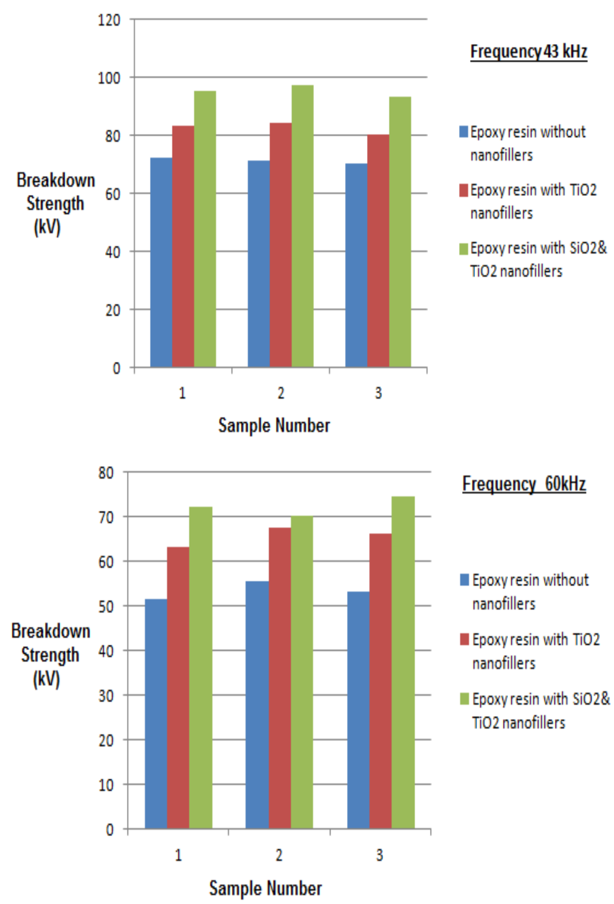

Figure 15. Comparison of Breakdown strength at 43kHz and 60kHz HFHV signal

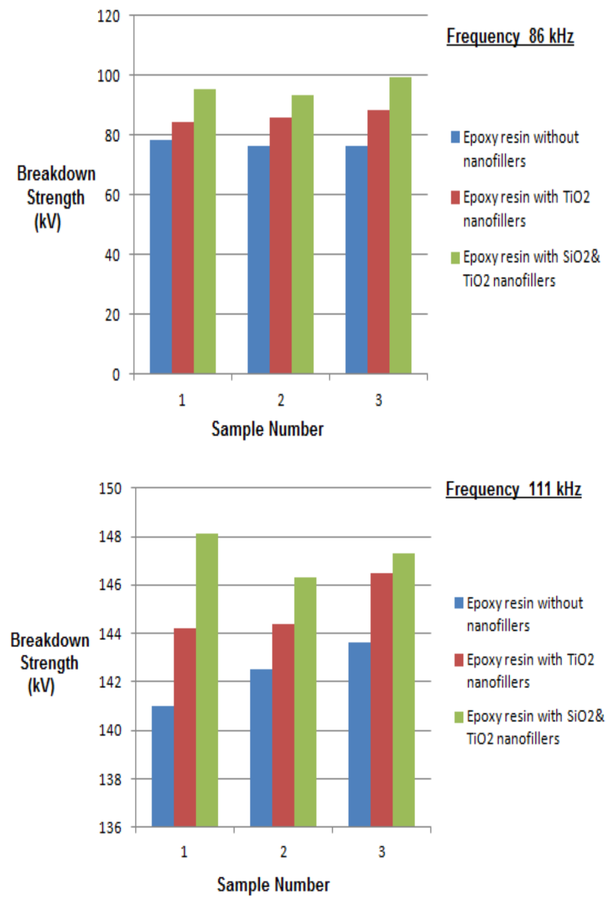

Figure 16. Comparison of Breakdown strength at 86 kHz and 111 kHz HFHV signal

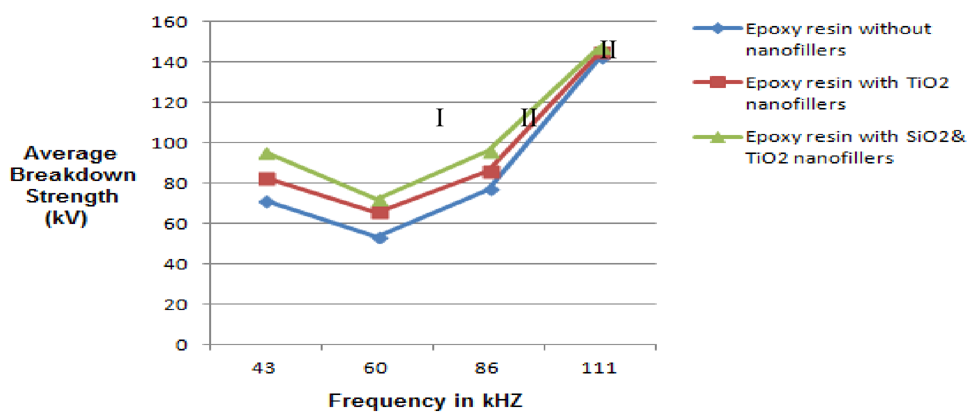

Figure 17. Frequency Vs Average Breakdown strength characteristics

In Zone I the Breakdown strength of the dielectric decreases with increase in frequency due to influence of volume charges and dielectric loss effect. It is also to be noted that the dielectric loss is a function of frequency ($P=V^2fC\tan\delta$). As the frequency increases the voltage required for breakdown decreases due to thermal agitation caused at higher frequency. This may be due to dipole spinning at different frequencies.

In Zone II and Zone III the virtual distances of travel for free electrons between electrodes increases as random velocity component increases with frequency. Hence the breakdown voltage increases as the frequency increases in these zones.

This aspect is also concurred by researchers as deliberated in [21]. Further investigation is required in this zone (Region 5) indicated in [21] to explore the physical behavior of the nano-dielectric at higher frequencies. Figure 18 and Figure 19 shows the breakdown waveforms which are recorded in DSO during LI, SI and HVHF testing.

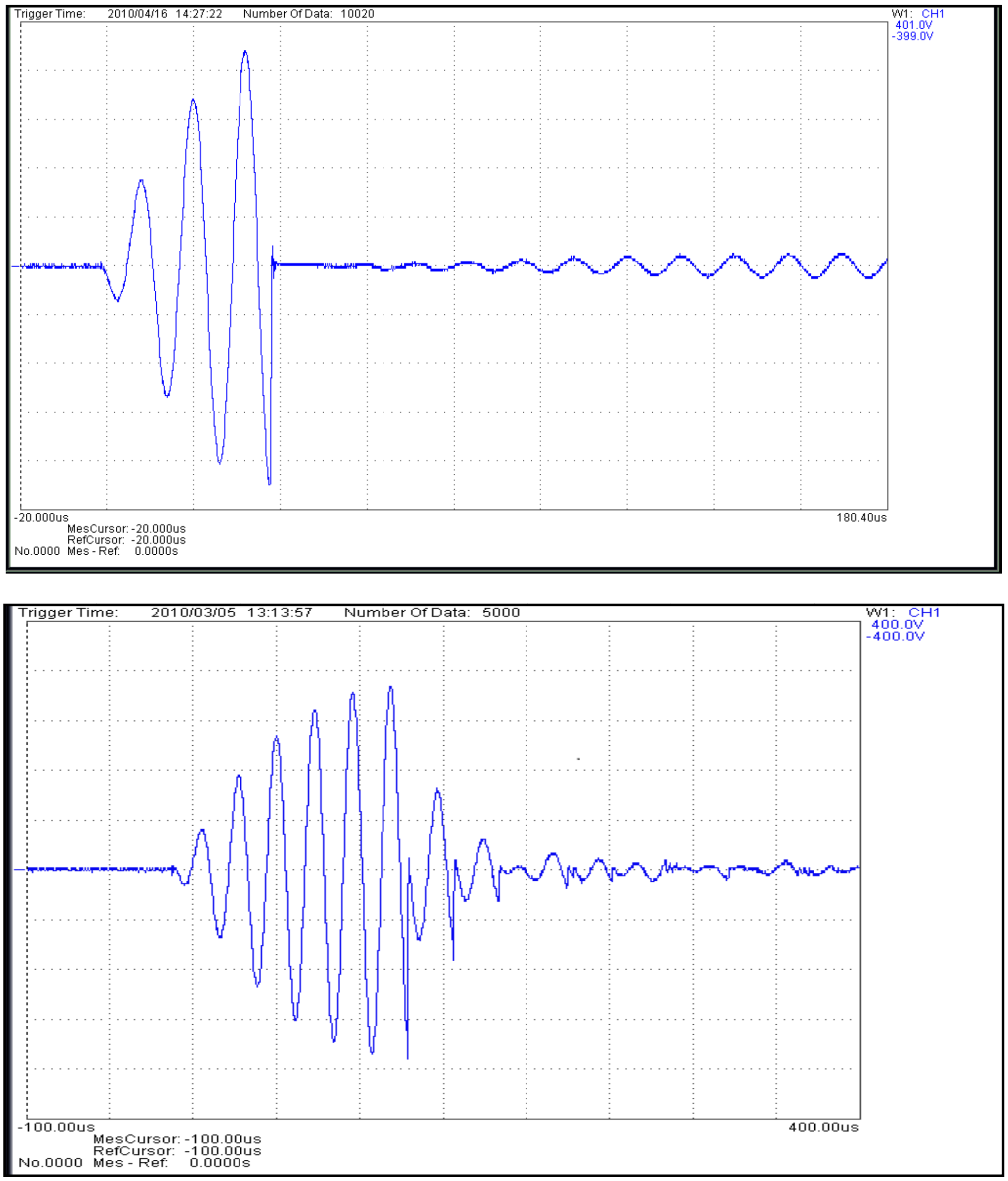

Figure 18. Breakdown voltage at 43kHz and 60 kHz HVHF Signals from DSO

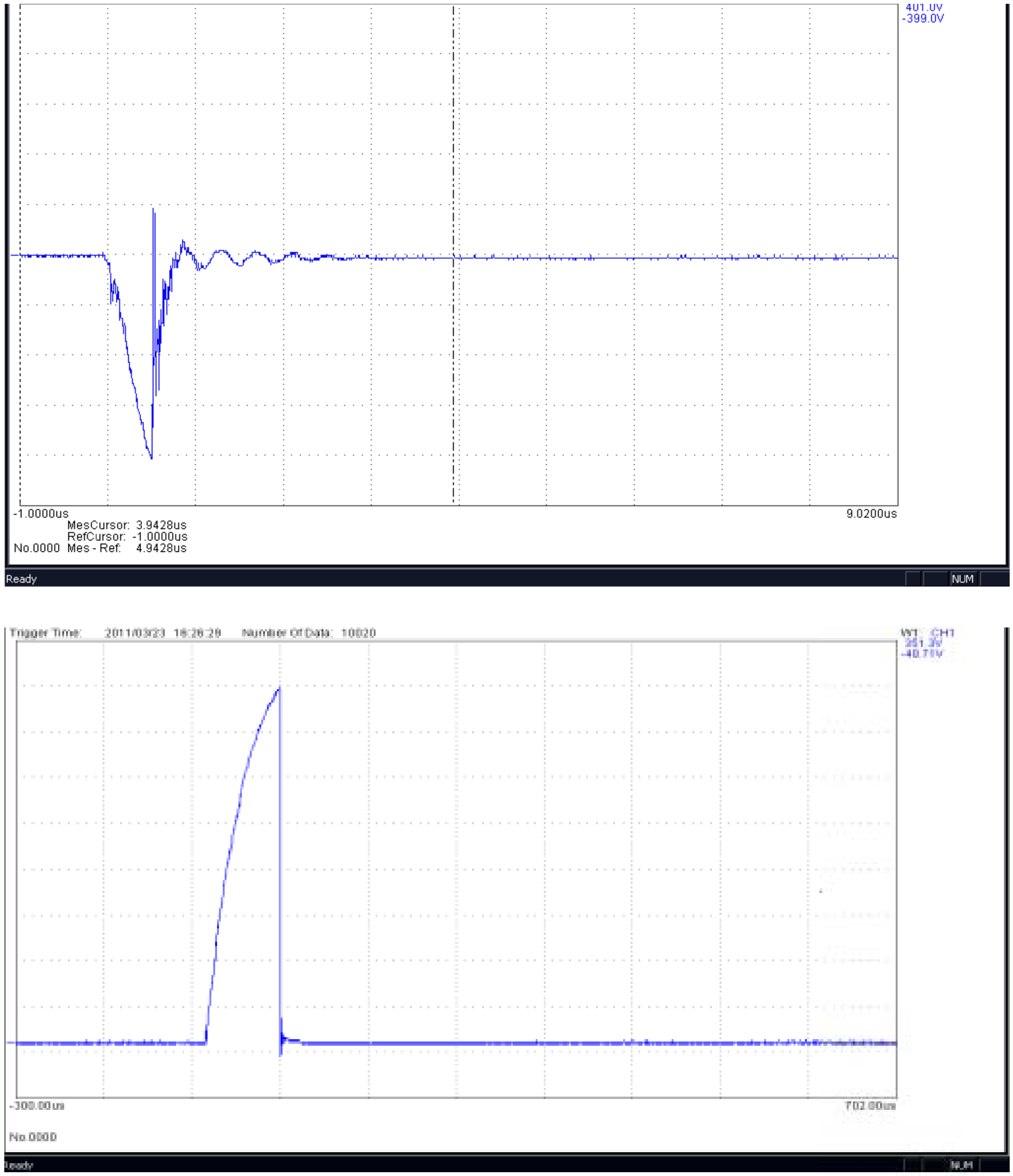

Figure 19. Breakdown voltage at Lightning and Switching Impulse voltages

Thus from the above observations it is evident that the use of nano-fillers mixed with the insulator material increases its electrical properties considerably. The addition of the nano-fillers not only increases the electrical properties but also increases its mechanical strength. The epoxy insulators designed without nano-fillers are found to be much brittle and breaks down at a lesser voltage when compared to the nano-composite epoxy insulators.

6. Conclusions

The epoxy resin mixed with nano-filler has better dielectric breakdown strength compared to that of the base epoxy specimen. The interfacial properties have to be taken care of which is facilitated by preparing the specimen & the quantity of the filler in calculated quantities, which plays a dominant role in deciding the dielectric behavior and the molecular configuration of the specimen. The test values obtained make it evident that the specimen could sustain more overvoltage, particularly lightning surges and may be stressed with additional overvoltage with better characteristics. The power frequency test results show that the specimen has better voltage endurance characteristics and the addition of nano-fillers has proved to be effective. Thus, it can be inferred that the nano-composite fabricated is effective and may serve as a plausible insulating material for power apparatus. Though further detailed studies may be essential to validate the possibility of utilizing these nano-composite materials it is envisaged by the authors of this research to take up future studies to carry out thorough studies to ascertain the possibility of fabricating and manufacturing power devices such as outdoor insulators, switches, tripping circuits etc.

7. Acknowledgement

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