# Understanding Surface Discharge and Surface Flash over Activity with Epoxy Silica glass fiber reinforced Nano composites

*A THESIS*

*Submitted by*

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*For the award of the degree*

*Of*

**MASTER OF TECHNOLOGY**

**DEARTMENT OF ELECTRICAL ENGINEERING**

**INDIAN INSTITUTE OF TECHNOLOGY MADRAS**

**MAY 2019**

*Dedicated to my Parents*

# THESIS CERTIFICATE

This is to certify that the thesis titled **Understanding Surface Discharge and Surface Flash over Activity with Epoxy Silica glass fiber reinforced Nano composites,** submitted by **Killi Krishna Mohan** to the Indian institute of technology Madras ,Chennai for the award of the degree of **Master of Technology** is a bonafied research work don by him under my supervision .The contents of thesis ,in full or in parts ,have not been submitted to any other institute or university for the award of any degree .

**Project Guide**


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# ACKNOWLEDGEMENTS

I wish to express my sincere thanks and deep sense of gratitude to Prof R.Sarathi, for his inspiration, tremendous support, vision and dedication to the successful completion of this work .His futuristic vision and realistic ideas have created an ever increasing zeal to work and explore many things .He has been a great source of inspiration to work with and I shall always cherish my association with him with immense pleasure.

I thank Prof Dr Shanti swaroop, Prof Dr Mahesh Kumar, Prof Dr Krishna vasudevan, Former Heads, Department of Electrical Engineering IIT Madras for providing me facilities to carry out my M tech project in Department of electrical engineering.

I wish to express my gratitude to Prof K Sethupathi for giving valuable suggestion in cryostat design and also motivated and encourage in my project work.

I wish to express my gratitude to my friends Srinivas, kiran, Avinash, phalgun, shiva, sushanth, Adhi, srinu for their unforgettable help during my project work.

I would never forget the company , encouragement and cooperation I had from mylabmates,PalashMishra,Nagaraju,Naresh,Sukesh,Yugandhar,Prem,Jeshurun,Vinod ,Amal, swathi, Soumya, Nelmani, Naveen, Thanga balan I am also Thankful to Malar madam and chandu sir helping me in lab while performing experiments.

**ABSTRACT**

*KEYWORDS* **-** Cryogenic insulation, epoxy nano composites , Surface discharges ,impulse and oscillating impulse break down.UHF signals.

The SDIV increases with increase in weight percent of silica in epoxy composite insulation. During surface discharge UHF signals are observed and its frequency contents 0.5-1.5 GHz. It is observed that the change of UHF signal formed is same irrespective of percentage of silica present in epoxy nano composite.

Breakdown chance of epoxy nano composite was carried under transient voltages especially in LIV and OIV. It is observed that negative impulse breakdown is much higher than positive impulse breakdown.

Dielectric parameters were studied using dielectric spectrum spectrometer and it indicates the permittivity and tan delta has high influence to different percentage of nano filler added to it.

## TABLE OF CONTENTS

**Title** **Page No**



### CHAPTER 1 INTRODUCTION



### CHAPTER 2 EXPERIMENTAL AND THEORETICAL STUDIES

## CHAPTER 3 RESULTS AND DISCUSSIONS



## CHAPTER 4 CONCLUSIONS

## LIST OF TABLES

***Title*** ***PageNo***

## LIST OF FIGURES

## ABBREVIATIONS

| | |
|---|---|
| AC | Alternating current |
| DC | Direct current |
| FFT | Fast Fourier Transform |
| GIS | Gas insulated system |
| HTS | High Temperature Super conductor |
| HFCT | High Frequency current Transformer |
| HV | High voltage |
| IEC | International Electro technical commission |
| LI | Lightening Impulse |
| LN2 | Liquid Nitrogen |
| SD | Surface Discharge |
| SA | Spectrum Analyzer |
| STFT | Short Time Fourier Transform |
| PD | Partial Discharge |
| RF | Radio Frequency |
| UHF | Ultra High Frequency |
| WOB | without barrier |

# CHAPTER 1

# INTRODUCTION

## 1.1 GENERAL

Bulk power transmission over longer distances at higher voltage has acquired considerable prominence in the recent times .Conventionally ,oil filled power equipment are used and with the increase in rating of power equipment ,it has become necessary to design and develop a compact ,cost effective and reliable insulation system. High temperature superconductors (HTSC) has motivated the world wide researchers on the development of superconducting power devices ,operating at low magnetic AC fields including power cables ,current limiting reactors and transformers ,where liquid nitrogen ($LN_2$) is used as coolant besides it acts as an insulant (Gerhold,2002;Garlic,1997;Dai *et al.*,2007).

Advantages of using liquid nitrogen as insulant in cryogenic power apparatus are as follows.

1. Liquid nitrogen has a higher heat flux of 16W/cm compared to.8W/cm for liquid helium.

2. Evaporation heat of liquid nitrogen is 160 kJ/L compared to 2.6 kJ/L for liquid helium. Therefore, the liquid nitrogen cooling capacity is much better than liquid helium.

3. Liquid nitrogen could be handled easily simpler and cheaper insulation, and low cooling power needed for refrigeration equipment.

4. The liquid nitrogen is chemically inert and non-irreversible compound hazardous by product forms with the insulation system due to any ageing and discharges.

The major issues in liquid nitrogen filled cryogenic insulation during operation includes

- Surface discharge in liquid nitrogen
- Surface flash over in liquid nitrogen
- Aging of dielectric materials
- Cracks formed in solid insulation due to cool down and warm up situations
- Bubbling effects due to the quench of superconductors

Surface discharge is an incipient discharge that occurs on the surface of the solid insulation one of the main causes for failure of cryogenic power equipment .The reliability of liquid nitrogen filled cryogenic power equipment’s are adversely affected due to one of the following aspects which can initiate surface discharge formation leading to catastrophic failure of insulation system(Gerhold,1998;Hara and Okubo,1998)

Surface discharge is an incipient discharge that occurs at any point in the bulk volume of insulation which does not bridge the high voltage and ground electrode. These incipient discharges can lead to catastrophic failure of the insulation system. Hence, it is essential to monitor the condition of cryogenic power apparatus for surface discharge activity.

The existing surface discharges diagnostic methods in cryogenic power equipment's include conventional surface discharge measurement process adopting IEC(b) electrode, acoustic emission technique, High Frequency Current Transformer (HFCT) and by optical emission technique.(judd *et al*., 2006)

In recent times, epoxy nano composites are gaining high importance to use as insulant in power apparatus. One of the popular techniques to reduce the impact of high non uniform electric field in insulating material is to use nonlinear dielectrics as insolent. This important property can be achieved by the use of inorganic material which has a nonlinear conductivity or nonlinear dielectric constant as filler material in insulant. By addition of in organic filler material such as silica with epoxy reinforced glass fiber resin. It can be used as a stress relieving agent in cables, insulators, generator insulation, etc. This property can be achieved by fine tuning the permittivity of the material by optimizing quantity and size of nano filler. Thus, it is essential to understand the characteristics of permittivity and tan delta (at different frequencies) of epoxy reinforced glass fiber at low and normal temperatures.

In present study an attempt has been made to understand the surface discharge activity of epoxy reinforced glass fiber silica nano The obtained break down signal is from amplifier connected to the load end capacitor it's for positive and negative impulse voltages in nano composites .The surface damage caused by surface discharge process needs to be analyzed through surface charge measurement or by the measurement of surface roughness factor calculation near damage generated region .The amount of damage generated due to surface discharge activity can be done through charge accumulation studies near damage generated zone.

With the improving grade for high temperature super conducting (HTS) Power devices the surface flash over phenomenon in liquid nitrogen has become an important factor that makes a HTS device break down so quickly .Thus studying the surface flash over in $LN_2$ is very important.

Studied the polarity effect of standard lightening impulse and oscillating impulse surface flash over and extremely non uniform conditions. Insulation coordination is usually based on impulse characteristics determined for standard impulse voltage wave (1.2/50µs),and it is essential to know the performance of insulation when stressed with non-standard wave shapes. Hiroshima koyama et.al studied voltage distribution in 8 disc transformer winding (with liquid nitrogen as medium of insulation) stressed with lightening and oscillating impulse voltages.(Xing Yang *et al***.,**2019)

Dielectric relaxation spectroscopy is studied for silica epoxy reinforced glass fiber is described as the measurement of relaxation phenomenon that are related the presence of dipoles in molecules from the spectrum information about the dynamics of molecules can be deduced. The basic quantity is the complex dielectric permittivity .the quantity depends on parameters like frequency, Temperature and pressure .The Real part describes the dispersion, whereas the imaginary parts describes absorption.

## 1.2 PROBLEM FORMULATION

As discussed earlier surface discharge in cryogenic power apparatus can cause catastrophic failure of insulation system. One of the major causes for surface discharge non uniform field distribution in liquid nitrogen .It is essential to understand the inception of surface discharge that occurs due to corona .Cryogenic power equipments requires sophisticated diagnostic measuring techniques in order to detect any abnormality and to protect the systems from critical hazards ,because some kind of internal failures cannot be immediately inspected or observed due to enclosed and complicated structures .Therefore , a more analysis should be done for surface discharge by different modes of supply AC,DC, lightening impulse with different techniques.

The different techniques for identification of surface discharge in cryogenic power apparatus include PD measurement technique, acoustic emission, HFCT and optical techniques .In recent times UHF technique has gained importance to identify partial discharge activity in GIS and oil filled transformers .The author have taken initiative to understand incipient discharges due to corona and surface discharge adopting UHF (ZHU Chaojie, YIN Yi *et al.*,2012) technique .The present work developed in this direction.

## 1.3 ORGANISATION OF THE THESIS

The first chapter introduces surface discharge activity in liquid nitrogen .The need for surface discharges adopting UHF technique is explained in detail. Upon clearly formulating the problem, the possible method for identification of surface discharge in liquid nitrogen has been proposed .A panoramic view of literature dealing the topic is reportedly as completely possible.

The second chapter deals with experimental studies .The Surface discharge analysis used in cryogenic power apparatus were explained in detail. details of the experimental setup used for the study were explained .The characteristics of UHF sensor used for surface discharge diagnostics were explained.

In the third chapter ,results of experimental studies of surface discharge in liquid nitrogen including the analysis are presented .The important findings of the author were compared with results reported in literature and critical analysis have been made

In the fourth chapter summary of author's contribution for identification and classification of surface discharges in liquid nitrogen adopting UHF technique based on experimental and theoretical study are presented .the last topic future work on the topic as an extension of present study.

## 1.4 LITERATURE SURVEY

In recent times, power transmission at high AC/DC voltages have acquired considerable importance .Surface discharge analysis have been made in conventional power equipment's ,which operates at higher voltages .In the case HTS power equipment ,there were no evident testing technique that have been reported and related works are in early stages of research development around the world.

Liquid Nitrogen has high dielectric strength but its performance is affected easily with bubble formation, foreign conducting /non conducting particles and electrode surface conditions. Surface discharge due to voids and surface irregularities is one of the major problems in cryogenic insulation also no surface discharge is allowed in HTS apparatus Since organic materials are used in its insulation system as they easily degraded by surface discharges.

Epoxy Nano composites reinforced with fiber glass, also known as hybrid composites are becoming increasingly popular due to their multi-fold advantageous features. They possess excellent mechanical, thermal and electrical properties . Epoxy nano composites provide higher specific strength, higher stiffness, higher thermal resistance, high breakdown strength and increased resistance to partial discharge than pure epoxy .Fiber glass reinforced polymer (FRP) composites provide a high strength to weight ratio, high stiffness to weight ratio, increased hydrophobicity, high impact resistance and hardness .Therefore, taking advantage of both fiber and nano particle reinforcement, we arrive at the production of hybrid composites . Unidirectional fiberglass seems to perform better than bi-directional due to the load distribution along the direction of the fibers. Arun et.al. observed higher tensile strength with good impact resistance in hybrid composites.

In the simple case appropriately adding nano particles to polymer matrix can enhance the performance often dramatically by simple capitalizing on nature and properties of Nano fillers.(these materials are better described by the term Nano filled polymer composites) the strategy is particularly effective in yielding high performance of composites when the uniform dispersion of then filler is achieved and the properties of the Nano fillers are substantially different better than those of matrix. The uniformity of the dispersion is in all Nano composites is counteracted by the thermodynamically driven phase separation clustering of Nano fillers produces aggregates that serve as structured defect as a result in failure . In layer by layer (LBL) assembly when nanometer scale layer of nano particles and a polymers are added one by one. The LBL composites display performance parameters 10-100 times better than the traditional nano composites made by extrusion of batch fixing.

The literature on the mechanical and electrical properties of hybrid nano-silica composites is scanty. Hence a complete database needs to be generated to understand the electrical and mechanical properties of epoxy nano-silica composite reinforced with unidirectional fiberglass oriented at 45°.

Lakshya Mittal & K. Sethupathi *et al***.(2013)** has studied Liquid Nitrogen (LN2) is used as an insulant as well as coolant in high temperature superconducting power equipments. Recently it is identified in HTSC transformers; the voltage distribution in the winding is oscillatory in nature. An attempt has been made to generate such unidirectional oscillatory impulse voltage (UOIV) of various frequencies to understand the breakdown characteristics of liquid nitrogen

Toshikatsu Tanaka *et al***.(2017)** have studied Surface discharge inception voltage (SDIV) with epoxy silicon carbide nano composite material in LN2 medium is about three times higher than that in air. Under AC voltage that SDIV increases with increase in wt% of silicon carbide (SIC) material in epoxy nano composites. Dielectric measurements indicates an increase in temperature of the specimen and the weight percentage of SIC filler in epoxy resin increases the permittivity of the material. Also, irrespective of percentage of SIC in epoxy resin, the tan(delta) reduces with increase in frequency and the converse at room temperature.

XinYang*et al.***(2018)** have studied the surface flashover phenomenon in liquid nitrogen has become an important factor that makes the HTS devices break down. So, the study on surface flashover characteristics in liquid nitrogen has become more important. This paper studied the polarity effect of standard lightning impulse surface flashover under the extremely non uniform electric field in liquid nitrogen by experiment. It is found that flashover voltages under positive impulses are generally higher than that under negative polarity, which is opposite to the results in gas gaps breakdown and on solid-$SF_6$ gas and solid-transformer oil interface. By the analysis of flashover traces and electric field distribution between the triangle–plan electrodes, combining the related surface flashover theory in liquid nitrogen, it is assumed that surface flashover in liquid nitrogen is started from the electron emission from cathode triple junction.

Kazuhisa Adachi *et al*.,**(2018)** have developed Super conducting cable Superconducting cable have been expected to be a game changing products for energy saving technology. Although demonstrations have been carried out in many areas, many issues to be solved still remains, and expensive system cost is one of them. Triaxial type cable configuration gives us one solution to reduce the cable cost because of less quantity of superconducting tape and less number of cryogenic tube. However, because of the compactness, subjects still remain in terms of insulation and cable technologies.

Enis Tuncer *et al***.(2009)**Non-metallic structural materials that act as an electrical insulation are needed for cryogenic power applications. One of the extensively utilized materials is glass fibre reinforced resins (GFRR) and may also be known as GFRP and FRP. They are created from glass fibre cloth that is impregnated with an epoxy resin under pressure and heat. Although the materials based on GFRR have been employed extensively, reports about their dielectric properties at cryogenic temperatures and larger thicknesses are generally lacking in the literature. Therefore to guide electrical apparatus designers for cryogenic applications, GFRR samples with different thicknesses are tested in a liquid nitrogen bath. Scaling relation between the dielectric break down strength and the GFFR thickness is established. Their loss tangents are also reported at various frequencies.

Guoqing yang *et al***.,(2016)**Based on low temperature plasma treatment of E-glass fibre, the performance of E-glass fibre reinforced epoxy resin composites are studied. Placed E-glass fibre in the device of low temperature plasma treatment for a certain time. The chemical groups on the surface of glass fibre are observed by infrared spectrometer (FTIR), and the change of the surface element content is tested by X-ray photoelectron spectroscopy (XPS). In this paper, the influence of different treatment time on the surface energy of the material is studied, and the relationship between the surface energy and the plasma condition is established. The results showed that at different time after plasma treatment, the chemical composition of the surface of glass fibre was changed greatly and a large number of oxygen-containing groups were introduced, it improved the surface polarity of the glass fibre. It is useful to improve the wet ability between glass fibre and epoxy resin. And it provides a new technology for improving the application of glass fibre reinforced epoxy resin composites.

Haoxiang Zhao *et al*.**,(2018)** have explored the influence of curing process on production practice, the wide frequency dielectric spectroscopy measurement of epoxy resin and epoxy glass fibre was made. Combined with dielectric spectroscopy, dielectric parameters with frequency and temperature were discussed. Meanwhile, frequency domain characteristics of dielectric parameters were investigated under different curing temperature. Acetone extraction method was designed to test unsolvable component concentration of epoxy resin and epoxy glass fibre , thus the curing degree was obtained. The relationship of relative dielectric constant and curing degree was discussed. It is shown that the relative dielectric constant of epoxy glass fibre is higher than that of epoxy resin under the same curing process. At 150°C, the longer the curing time, the higher the curing degree. There is a certain relationship expression between relative dielectric constant and curing degree at lower frequencies.. The dielectric dissipation factor of epoxy glass fibre is higher than that of epoxy resin.

Xinzhe Ma *et al*.**(2018)** have made analysis on Dielectric barrier discharge (DBD) with a broad range of technological applications is a hot topic in the field of gas discharge. In recent years, the dynamic distribution of surface charges on the dielectric barrier has been known as an important influence factor on the discharge characteristics of DBD.

# CHAPTER 2

# EXPERIMENTAL STUDIES

## 2.1 GENERAL:

In the basic chapter circuits for generating the Ac and Dc voltages as explained the difference is the way of connection as in the case of Ac circuit a resistor is connected as a protection as any sudden changes our test circuit can with stand .In positive Dc and Negative Dc the way diodes D1, D2 shows if the Dc is positive or negative as its also called as cock Roft Walton circuit.

## 2.2 SURFACE DISCHARGE ANALYSIS

### 2.2.1 AC SURFACE DISCHARGE ANALYSIS

In AC inception high voltage AC source 100kvA transformer is used along with 100pF capacitor which will in series with 14kΩ resistor which is used as voltage divider circuit or protection circuit as capacitor and resistor acts as snubber circuit which doesn't allow sudden variations. By Applying Ac voltage to the test specimen by maintain very low temperatures epoxy reinforced inception voltage is tested as we can se the strength of material at low temperatures as UHF sensor catches the signal at the inception as the corona as we can measure the strength of signal which can be explained next chapter.

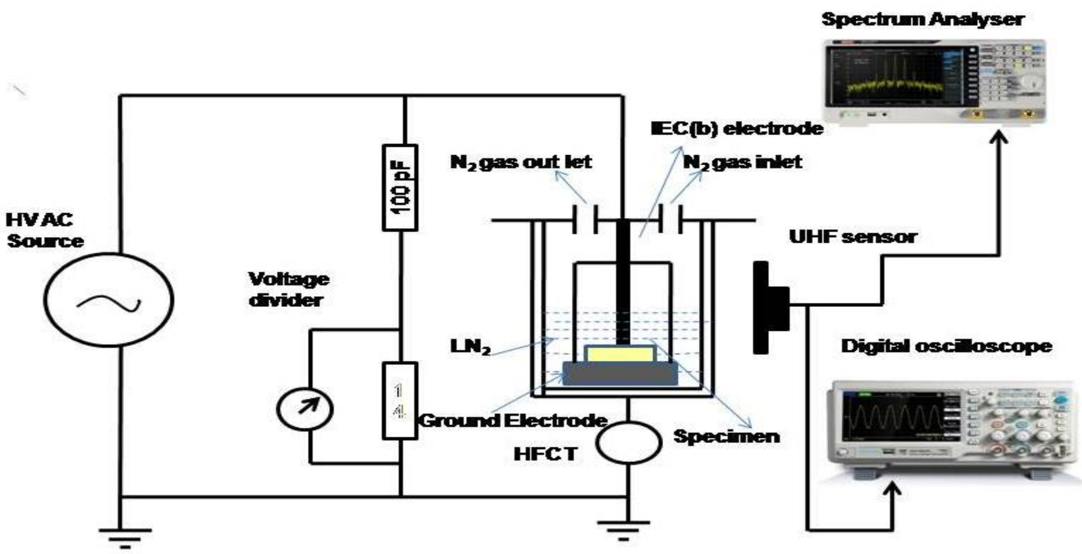



**Fig 2.1: Surface discharge phenomenon with AC circuit**

### 2.2.2 POSITIVE DC SURFACE DISCHARGE ANALYSIS

In the positive DC circuit two diodes connected in same forward direction as we can generate positive DC voltage applied to the specimen using rod IEC(b) electrode which is having diameter of 6mm.As see from above experimental set up the signals generated by the application can be sensed by the UHF sensor. Frequency analyzer called as spectrum analyzer where energy of the system can be measured mainly our analysis is carried out by the UHF sensor.

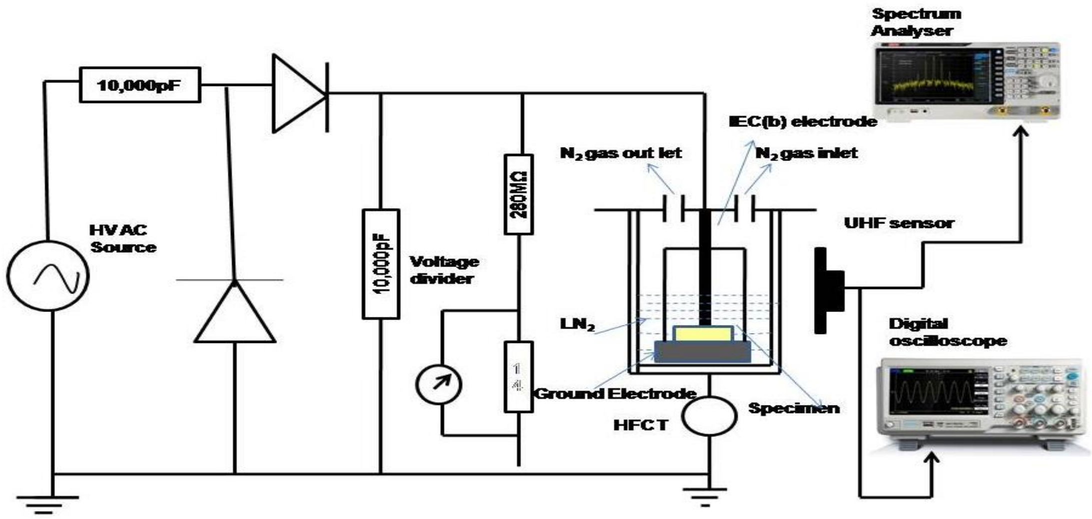



**Fig 2.2: Surface discharge phenomenon with the positive DC circuit**

### 2.2.3 NEGATIVE DC SURFACE DISCHARGE ANALYSIS

In Negative DC circuit the diode are connected the reverse direction as Negative will be generated which is applied to the rod where test for the specimen epoxy reinforced glass fiber will be tested .All this process will be performed in a cryostat where required temperature is maintained as our specimen can be tested at required temperatures.

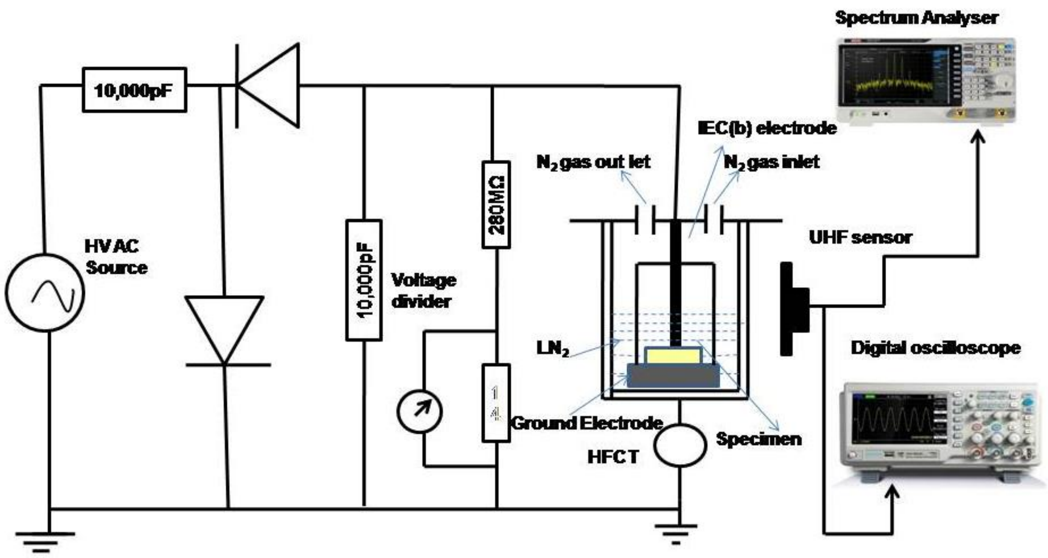



**Fig 2.3: Surface discharge phenomenon with the negative DC circuit**

### 2.3 IMPULSE BREAK DOWN ANALYSIS:

In the connection diagram positive or Negative impulse circuits Trigatron switch plays a major role in generating of impulses $R_f$ and $R_t$ are front and tail resistances by which front time and tail time is calculated which is discussed briefly in due further explanations.

The transformer used is 100Kva rating as the arrangement of test apparatus consists of needle plane arrangement is used for testing of breakdown strength.

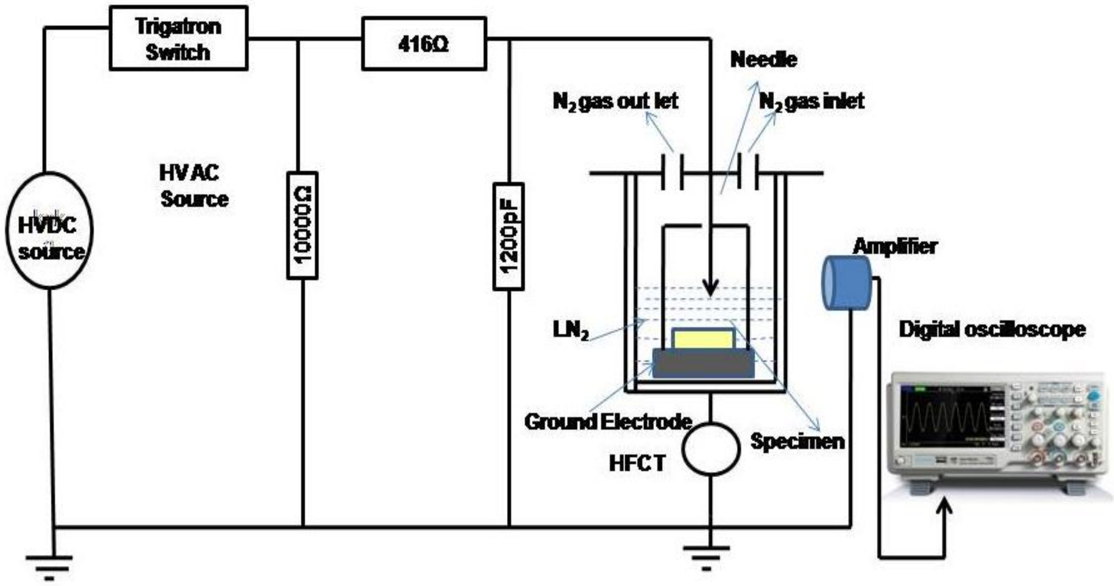



**Fig 2.4: Breakdown phenomenon with positive impulse circuit**

As in the case of Negative impulse the direction of diodes D1,D2 are changed rest of all is same as positive impulse the whole impulse circuit consisting resistances $R_f$ and $R_t$ is called as Marx circuit.

TEST APPARATUS:

1) Rod plane
2) Needle plane
3) Cryostat
4) Uhf sensor

MEDIUM OF TESTING:

1) Air
2) Liquid Nitrogen

## 2.4 SAMPLE PREPARATION:

In the present work, the nano-silica (15 nm; Nanostructure and Amorphous material Inc.) was used as the filler material. Unidirectional (UD) fiberglass mat (angular orientation 45°, fiber density 450 GSM; 1200 Texglass, Hindustan Mills Pvt. Ltd.) was used as the fiber reinforcement. Epoxy resin (Araldite CY205) and the hardener (Aradur HY951; Huntsman Advanced Materials Pvt. Ltd.) were used. The fiberglass reinforced hybrid composite was prepared by means of the hand layup method well described in previous works. The composition of the samples is given in the Table 2.1.

**Table 2.1: Composition of the Fabricated Composites**

| Fiberglass (wt.%) | Epoxy Resin (wt.%) | $SiO_2$ (wt.%) | Sample code |
|---|---|---|---|
| 50 | 50 | 0 | EP+FG |
| 50 | 49 | 1 | EP+FG+1 |
| 50 | 48 | 2 | EP+FG+2 |
| 50 | 47 | 3 | EP+FG+3 |
| 50 | 46 | 4 | EP+FG+4 |

Three layers of fiberglass (150 x 150 mm) were used for the study. The weight ratio of the epoxy resin to the fiberglass was 1:1. The nano-silica filler was heated in an oven at 100 °C for 24 hrs to remove the moisture. The dried nano-silica was dispersed in 10 ml ethanol using an ultrasonic bath for 1 hr, and then it was added to the epoxy resin and mixed by the process of shear mixing for 4 mins. The resin mixed filler was sonicated for 30 mins to ensure the removal of any agglomerations. It was mixed thoroughly once again by the shear mixing for 6 hrs to ensure the proper mixing of the filler with the resin. To ensure the de-agglomeration of the nano particles, it was sonicated again for 30 mins. The resin filler mixture is then kept in vacuum desiccators for 30 mins to remove the air bubbles. Epoxy resin was mixed with the hardener in the ratio of 10:1.Then, hardener was added to the epoxy resin mixture by the process of shear mixing, for a period of 4 mins. Finally, the as-prepared epoxy Nano mixture was added to the fiberglass by hand layup process. Then, the hybrid composite was subjected to compression molding at a pressure of 10 $kg/cm^2$ for 12 hrs at room temperature to ensure the proper curing of the epoxy resin.

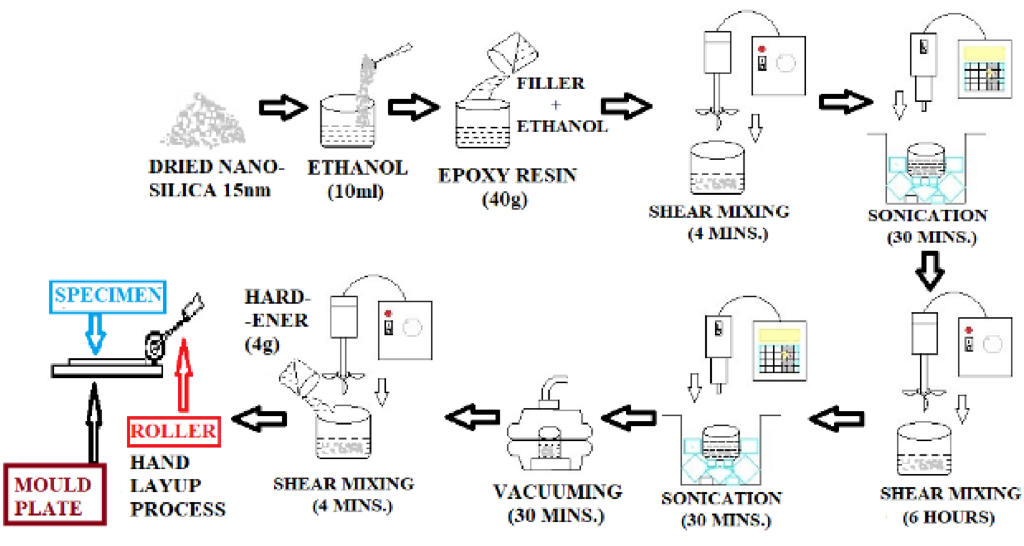



**Fig 2.5 : Preparation of the Fiber composites.**

## 2.5 ELECTRODE CONFIGURATION FOR SURFACE DISCHARGE STUDIES

The surface discharge studies were carried out using IEC (b) electrode configuration the test cell for generating surface discharges consists of two electrodes. The upper high voltage rod electrode [IEC (b) electrode] is with radius of 6 mm allowed to touch the Nano composite material (of 2 mm thick and diameter of 5 cm) which is placed above the bottom plane ground electrode. For carrying out surface discharge analyses at liquid nitrogen temperature, the test cell placed in liquid nitrogen filled cryostat. The cryostat consists of two concentric containers. The inner container filled with liquid nitrogen which acts as a coolant for the test specimen to carryout test at low temperature and the gap between the inner and the outer container was kept under vacuum with pressure level maintained at much lower than $10^{-5}$mbar, for thermal stability. The electrodes with the specimen placed into the liquid nitrogen filled cryostat and the dry nitrogen gas is circulated gently in the gap between the liquid nitrogen and the top cover plate of the cryostat to avoid any moisture formation. On immersion of cryogenic test cell in to the liquid nitrogen, thermal bubbles of large and smaller diameters were observed. The voltages were applied to the test specimen after 20 min, in order to obtain thermal stabilization of the material. The inner vessel of the cryostat was filled with liquid nitrogen and the vacuum pressure less than $10^{-5}$mbar was maintained in the gap between the outer and inner vessels, for thermal stability.

### 2.6 UHF SIGNAL MEASUREMENTS

The UHF sensor used in the present work is non-directional type and is placed at a distance of 20 cm for all measurements. Any incipient discharge generated in insulation structures generates Electromagnetic wave and it propagates at the speed of velocity of light. In the present study, the generated signal propagates in the air medium. The sensor is placed at a distance of 20 cm was fixed based on the fact that, on application of voltage to the test cell, the nearby sensor should not have any impact on corona generation or to initiate the flashover from test cell and the sensor. The sensor output fed to the oscilloscope through the RF cable with its impedance of 50 Ohms. The DSO input impedance is also matched to 50 Ohms to avoid any reflections. To identify the number of discharges occurred in a specific time period, the sensor output is connected to the spectrum analyzer was used by operating it in Zero span mode. The incipient current pulses generated by a surface discharge process were measured using a high frequency current transformer (HFCT).

### 2.7 LIGHTENING IMPULSE STUDIES

Studied the polarity effect of standard lightening impulse and oscillating impulse surface flash over and extremely non uniform conditions .Insulation coordination is usually based on impulse characteristics determined for standard impulse voltage wave (1.2/50µsec),and it is essential to know the performance of insulation when stressed with nonstandard wave shapes.

One of the researcher studied voltage distribution in 8 disc transformer winding (with liquid nitrogen as medium of insulation) stressed with lightening and oscillating impulse voltages.

For lightening impulse 1.2/50µs

$$\text{Front Time } (t_f) = 3 * R_f * \frac{C_g * C_l}{C_g + C_l} \quad (1)$$

Tail Time $(t_t)$ $= 0.7 * \left(R_f + R_t\right) * (C_g + C_l)$ (2)

We have to choose the values of $R_f$&$R_t$,$C_g$&$C_l$ According to above given specification.

### 2.7.1 EXPERIMENTAL VALUES

$$R_f = 416\Omega$$

$$R_t = 10k\Omega$$

$$C_g = 10kpicoFarads$$

$$C_l = 1200picoFarads$$

We get $t_f = 1.33\mu s$

$t_t = 50\mu s$

For lightening impulse front time is 1.2µsec and the tail time is 50µsas these are the values of capacitors and resistors which are taken for the generation of impulses can be decided. For Switching impulse front time 200µsec and the tail time is 2000µsec.The impulse ratio is frequently defined as the ratio of the breakdown voltage of a system for an impulse of a specified shape of rms breakdown voltage .The impulse break down voltage (some time 50% of impulse flash over) is defined as peak value of impulse of a specified shape for which number of breakdowns is 50% of the number of impulses applied. Obviously 50% impulse flash over voltage has very little meaning unless large number of specimens is tested.

## 2.8 HIGH FREQUENCY CURRENT TRANSFORMER (HFCT)

HFCTs have similar structure with Rogowski coil (Partial discharge signal is small current signals. Thus, ultra crystallite material having a high magnetic permeability is selected as HFCT core (inner diameter D1, an outer diameter D2, the height h), in order to improve sensitivity. In one direction by the winding core N turn coils and integrally connected to a resistor, usually close to the sampling circuit through a long coaxial cable. When the measurement happens, the current is measured by placing HFCT**.**

**Fig 2.6: Basic HFCT Apparatus used in current Signal measurement**

## 2.9 DIELECTRIC RELAXATION SPECTROSCOPY

Our lab utilizes dielectric relaxation spectroscopy to probe the molecular dynamics of small volume polymer samples and self-assembled Mono layers (SAMS). Measurable motions include segmental re orientation , these associated with glass transitions as inter molecular rotations those typically seen in side chain polymers .Samples are measured using inter digested electrodes (IDES) with an ultra-sensitive capacitance bridge as capacitance and dissipation factor (tan delta)are measured as a function of sample temperature over a broad range(4K to 400K).Relaxation peaks are created in the measurement spectrum when a dipole Active motion with in a sample occurs at approximately the same frequency of applied alternating electric field utilizing a narrow band of frequencies enables extreme sensitive measurements and the sample dynamics can be done by changing temperature .The IDE configuration allows measurement of very small volume of samples.

It measures the dielectric properties of medium as function of frequencies. It is based on interaction of an external field with the electric dipole moment of the sample, often expressed by permittivity

It is also an experimental method of characterization of electro chemical properties. The Technique measures the impedance of system over a wide range of frequencies the frequency response of system including the energy storage and dissipation properties is revealed .Electrochemical impedance spectroscopy is expressed graphically expressed in a bode plot or Nyquist plot.

Impedance is the opposition in the flow of AC in complex system. A Passive complex electrical system comprises of both energy dissipaters (resistor) and energy storage (capacitor element).

$$Z_{dl}(\omega) = \frac{1}{i\omega C_{dl}} \quad (3)$$

$$Z(\omega) = \frac{R_t}{1 + R_t C_{dl} i\omega} \quad (4)$$

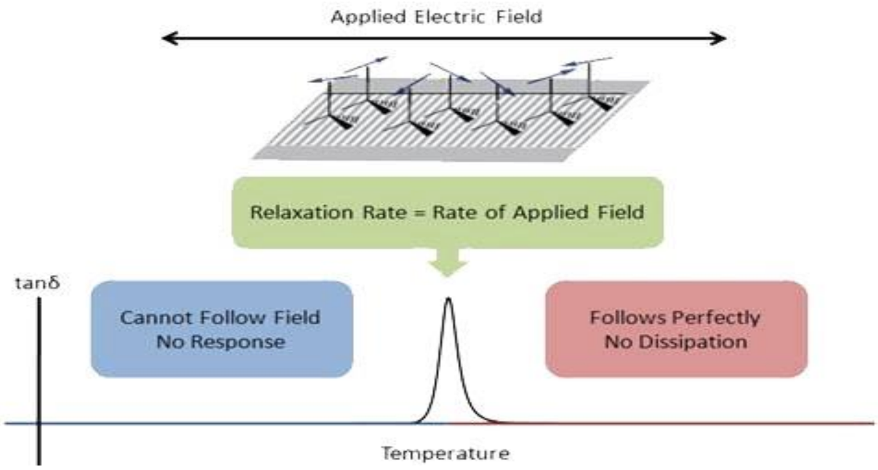



**Fig 2.7: showing dielectric spectroscopy for epoxy glass fiber reinforced silica nano composite**

Drs Measures the dielectric and dielectric properties of medium as a function of frequency are based on the interaction of an external electric field with electric dipole moment and the charges of medium.

Temperature dependence of relaxation rate (time) described by VTF equation as given below.

$$f_\alpha = f_{\infty\alpha} \exp\left\{-\frac{B}{T-T_0}\right\} \qquad (5)$$

Dielectric strength, Δε decreases with increasing temperature more strongly than predicted

$$\Delta\varepsilon \propto F * g * \frac{\mu^2}{KT}\frac{N}{V} \qquad (6)$$

## CHAPTER 3

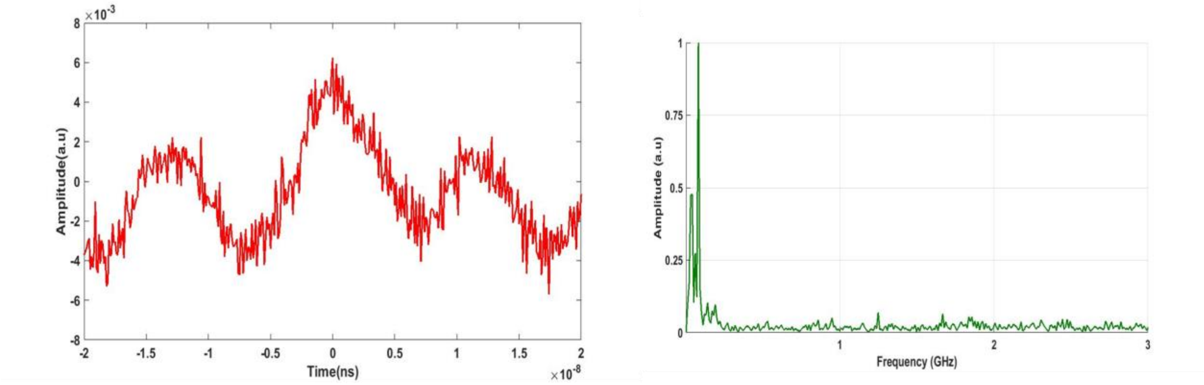
## RESULTS AND DISCUSSIONS

### 3.1 GENERAL

This chapter presents the results obtained based on the methodical experimental study and the theoretical analysis carried out to understand the surface discharge/ incipient discharge activity in liquid nitrogen medium. Critical assessment of the obtained results has been made and compared with the available literature in order to accrue important conclusions based on the study.

### 3.2 ANALYSIS OFINJECTED CURRENT PULSE DUE TO SURFACE DISCHARGE IN LN2 UNDER AC VOLTAGES

Figure 3.1 Shows typical current pulse generated due to surface discharges caused by surface discharge under AC voltages under liquid nitrogen.




**(a)** **(b)**

**Fig 3.1 Typical current pulse injected during incipient discharge a)Current signal b) FFT analysis**

From Fig 3.1 it is observed that the rise time of the injected current signal due to incipient discharges in about few nano seconds. It is also observed that increase in applied voltages has not altered the shape and duration of the current pulse formed due to incipient discharges.

### 3.3 AC ANALYSIS OF DISCHARGE INCEPTION VOLTAGE IN LIQUID NITROGEN

It is well known that the incipient discharges in cryogenic power equipment's can occur by surface and corona discharges. It is essential to mitigate the formation of surface discharge by identifying the cause of formation. The information about the instant of occurrence and magnitude of discharges with various applied voltage due to different defects in liquid nitrogen medium is scanty. Hence in the present work, an attempt made to understand voltage magnitude at which the incipient discharge formed due to different defect conditions in liquid nitrogen by adopting uhf technique. Corona discharge activity and surface discharge activity obtained based on the first uhf pulse that is captured by the oscilloscope though uhf sensor output.

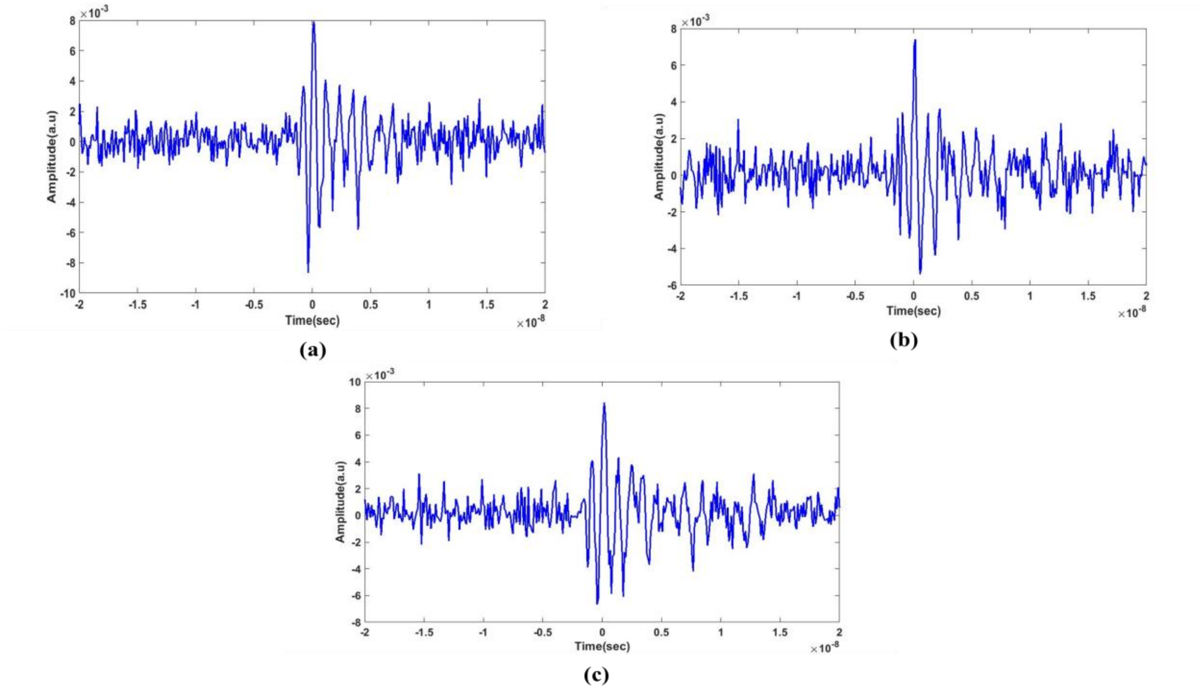



**Fig 3.2 Typical UHF Signal Generated Due To Surface Discharge in Liquid Nitrogen with a) 0% b) 3% c) 4% of silica in Time Domain for AC**

Fig 3.2 is typical UHF signal generated due to surface discharge activity in different wt% silica reinforced epoxy fiber nano composite .No characteristic change is observed in different wt% of silica added epoxy nano composite.0% epoxy reinforced glass fiber is the virgin sample by which other nano composite material can be compared. The 3% silica glass fiber reinforced epoxy nano composite is showing better performance compared to remaining silica percentage samples. The signal strength can be determined by analyzing amplitude of signal. 4% silica in epoxy glass fiber nano composite shows a reduced performance compared to 3% silica nano composite.

### 3.3.1 FFT ANALYSIS OF AC SUPPLY

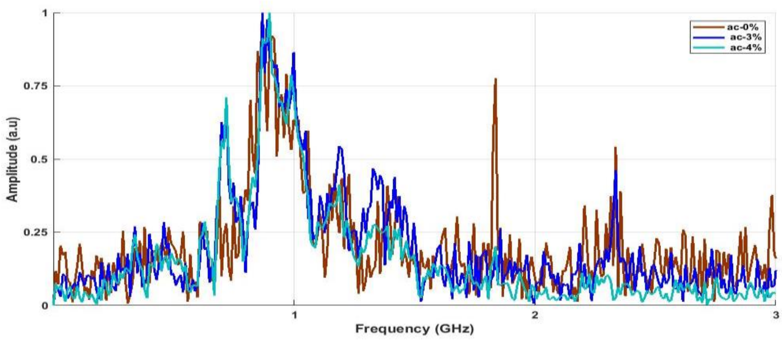



**Fig 3.3 Typical UHF Signal Generated Due To Surface Discharge In Liquid Nitrogen in Frequency Domain**

Fig 3.3 shows typical FFT analysis of UHF signal generated due to epoxy nano composite with different wt% of silica it is observed that the band width lies between 0.5-1.5 GHz .This clearly indicates that Surface discharge mechanism is almost same in epoxy nano composites..

### 3.3.2 AC SURFACE DISCHARGE VOLTAGE WITH SUPPLY

**Table3.2: SDIV for AC in air and Liquid Nitrogen**

| Percentage of silica in epoxy reinforced glass fiber | Surface discharge inception voltage in air | Surface discharge inception voltage in Liquid Nitrogen |
|---|---|---|
| 0% | 3.324 | 11.61 |
| 1% | 4.464 | 15.71 |
| 2% | 4.495 | 17.89 |
| 3% | 5.53 | 19.26 |
| 4% | 5.704 | 15.29 |

Table 3.2 shows variation in SDIV in epoxy nano composite in air and liquid nitrogen. It is observed that SDIV is about three times higher in liquid nitrogen compared air medium. There is increase in inception voltage from 0% epoxy nano composite and there is sudden decrease in inception voltage as it is seen in liquid nitrogen medium as its less seen in air medium.3% silica epoxy nano composite is showing greater inception voltages as it is observed by doing FFT analysis as above.

### 3.4 POSITIVE DC ANALYSIS OF DISCHARGE INCEPTION VOLTAGE IN LIQUID NITROGEN

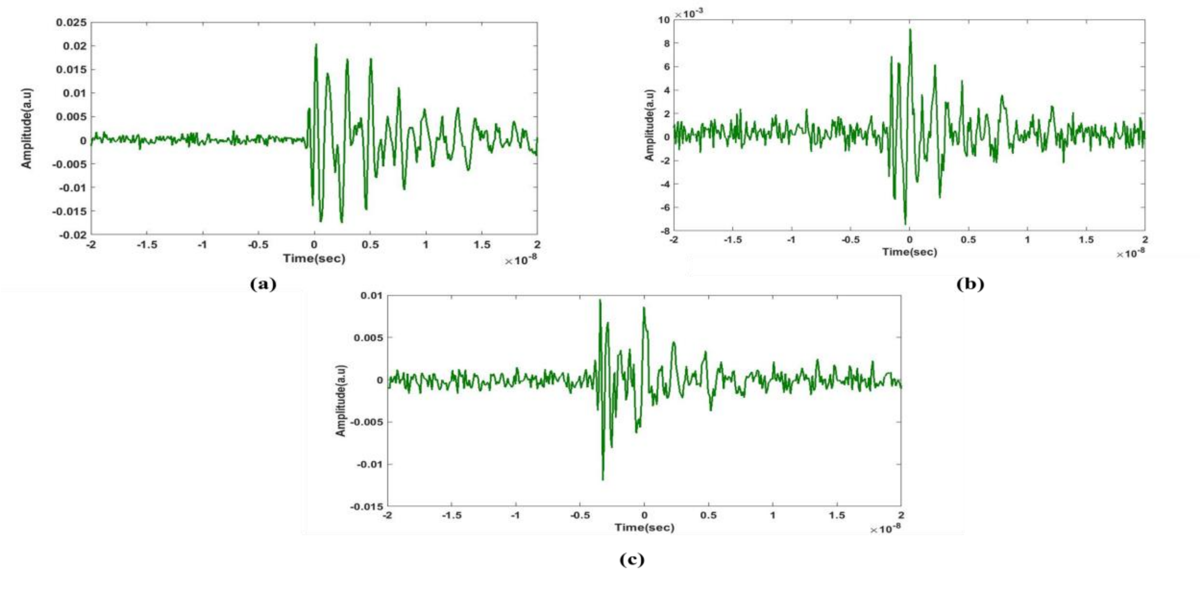



**Fig 3.4 Typical UHF Signal Generated Due To Surface Discharge in Liquid Nitrogen with a) 0% b) 3% c) 4% of silica in Time Domain for positive DC**

Fig 3.4 is typical UHF signal generated due to surface discharge activity in different wt% silica reinforced epoxy fiber nano composite are the same as observed under AC voltages. The UHF signal formed 0% epoxy reinforced glass fiber is the virgin sample by which other nano composite material can be compared. The 3% silica glass fiber reinforced epoxy nano composite is showing better the performance compared to remaining silica percentage samples. The signal strength can be determined by analyzing amplitude of signal. 4% silica in epoxy glass fiber Nano composite shows a reduced performance compared to 3% silica nano composite.

### 3.4.1 FFT ANALYSIS OF POSITIVE DC:

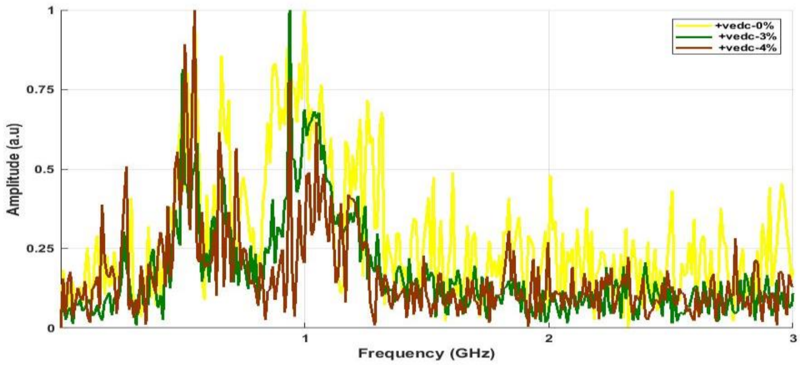



**Fig 3.5: FFT analysis of a signal of liquid nitrogen with positive DC**

Fig 3.5 shows typical FFT analysis of UHF signal generated due to epoxy nano composite with different wt% of silica it is observed that the band width lies between 0.5-1.5 GHz .This clearly indicates that Surface discharge mechanism is almost same in epoxy nano composites..Its Similar as we seen doing AC analysis FFT gives the clear picture of strength of signal .It can observed from above signal at 1 GHz frequency 3% silica epoxy reinforced nano composite is showing better performance compared other percentages with positive DC.

### 3.4.2 POSITIVE DC SURFACE DISCHARGE VOLTAGE WITH SUPPLY

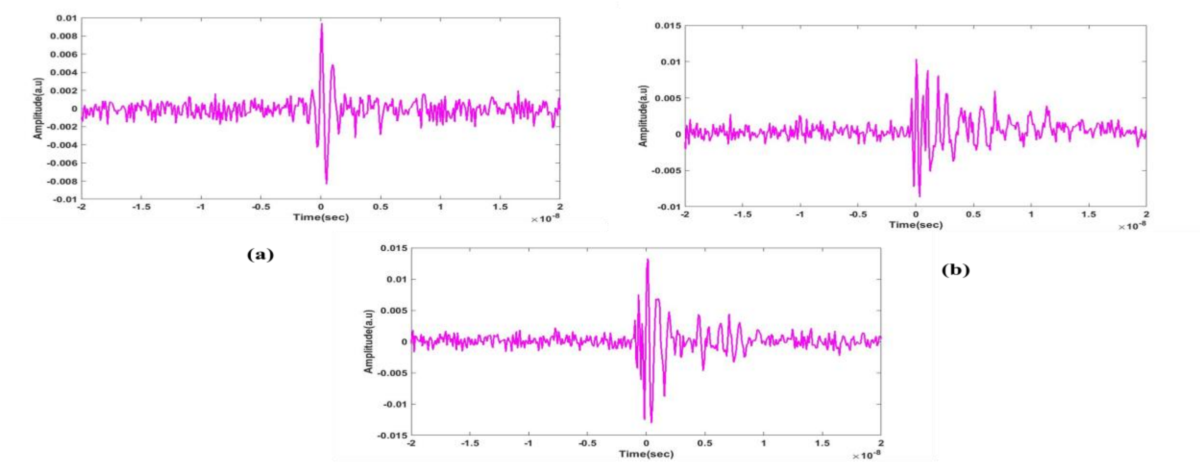
**Table3.3: SDIV Positive DC in Air and Liquid Nitrogen**

| Percentage of silica in epoxy reinforced glass fiber | Surface discharge inception voltage in Air | Surface discharge inception voltage in Liquid Nitrogen |
|---|---|---|
| 0% | 5.433 | 23.1 |
| 1% | 7.265 | 24.09 |
| 2% | 9.651 | 26.71 |
| 3% | 3.968 | 32.16 |
| 4% | 11.88 | 28.54 |

Table 3.3 has surface discharge inception voltage with epoxy nano composites under DC voltages is about 3 times higher in liquid nitrogen compared the air medium. The UHF signal generated due to surface discharge activity under positive DC is shown in fig (3.3) and

corresponding FFT is shown in fig (3.4).The Amplitude of UHF signal is same as under AC voltage. The UHF signal generated in epoxy nano composites are same as observed under AC voltages.

## 3.5 NEGATIVE DC ANALYSIS OF DISCHARGE INCEPTION VOLTAGE IN LIQUID NITROGEN




(c)

**Fig 3.6 Typical UHF Signal Generated Due To Surface Discharge in Liquid Nitrogen with a) 0% b) 3% c) 4% of silica in Time Domain for negative DC**

The typical UHF signal generated using negative DC voltage due to surface discharge activity is shown in fig 3.6 .The of UHF signal is to signal same as it formed under AC voltage and positive DC voltage . fig 3.6(a) shows 0% epoxy reinforced glass fiber is the virgin sample by which other Nano composite material can be compared.fig 3.6(b) shows 3% silica glass fiber reinforced epoxy Nano composite is showing better performance compared to remaining silica percentage samples. The signal strength can be determined by analyzing amplitude of signal.fig 3.6(c) shows 4% silica in epoxy glass fiber Nano composite gives a reduced performance compared to 3% silica nano composite.

### 3.5.1 FFT ANALYSIS OF NEGATIVE DC SUPPLY

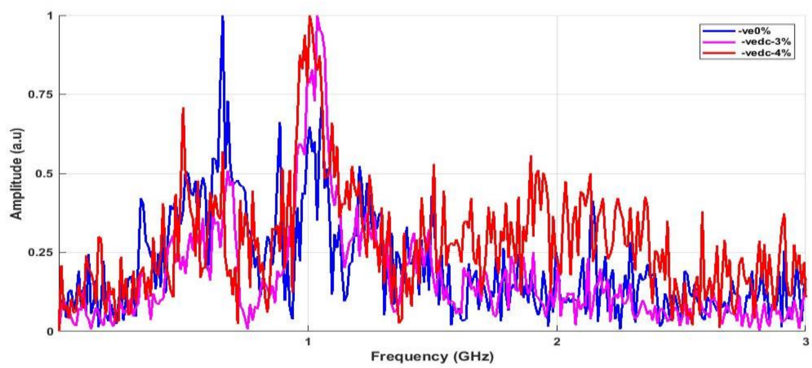



**Fig 3.7: FFT analysis of a signal in liquid nitrogen with rod plane**

The FFT analysis of UHF signal formed with different wt% of epoxy glass fiber is shown in fig 3.7 . The of frequency content nearly same as under positive DC voltage. In Negative Dc analysis and discussions its showing inverse characteristics in nitrogen rather than compared in air Normally voltages are very high than positive Dc and Ac. As shown from above FFT analysis 3% negative DC showing greater strength compared to other percentage silica in samples. At 1 GHz frequency the observed signal with highest positive peak and the lowest negative peak is decided as strengthens signal as by FFT analysis it can be easily analyzed

### 3.5.2 NEGATIVE DC SURFACE DISCHARGE VOLTAGE WITH SUPPLY

**Table3.4: SDIV Negative DC in Air and Liquid Nitrogen**

| Percentage of silica in epoxy reinforced glass fiber | Surface discharge inception voltage in Air | Surface discharge inception voltage in Liquid Nitrogen |
|---|---|---|
| 0% | 8.22 | 19.07 |
| 1% | 9.06 | 20.31 |
| 2% | 10.26 | 25.66 |
| 3% | 12.86 | 27.93 |
| 4% | 10.37 | 26.52 |

The SDIV formed due with epoxy nano composites in air ambience and liquid nitrogen is shown in table 3.4.It is observed that the SDIV in liquid nitrogen medium is about 2-2.5 times higher than air ambience.

## 3.6 IMPULSE BREAKDOWN ANALYSIS

**Table3.5: Breakdown in air and Liquid Nitrogen with Positive and Negative impulse**

| Gap distance (mm) | Positive impulse break down | | Negative impulse break down | |
|---|---|---|---|---|
| | Air | Nitrogen | air | nitrogen |
| 2 | 8.65 | 45.96 | 13.58 | 47.07 |
| 4 | 9.24 | 47.57 | 14.45 | 47.39 |
| 6 | 13.69 | 49.36 | 19.71 | 48.65 |
| 8 | 17.56 | 50.24 | 20.99 | 56.08 |
| 10 | 20.03 | 50.77 | 26.31 | 57.63 |

Table 3.5 shows breakdown voltage in air and liquid nitrogen under standard lightening impulse voltage .It is observed that break down voltage is less under positive lightening impulse compared to negative lightening impulse both in air and liquid nitrogen ambience .

It is observed that the break down voltage of liquid nitrogen is about 5 times in short gap and get reduced to about 2.5 times in large gap Similarly under negative lightening impulse voltage is 3 times higher in liquid nitrogen compared to air ambience. Positive impulse and Negative impulse break down was tested in liquid nitrogen for the needle plane is performed its showing better breakdown compared to Ac the breakdown time is varying constantly As we have to test the sample with constant time positive impulse analysis is good analysis. The impulse voltages are applied to long gaps in which the electrode field is not uniform the break down process in air consists of three main stages corona development at the electrode, at the electrode of higher electric stress ,the formation of leader channels proceeding across the gap ,and the main stroke formed by the discharge availability of energy through one of the leader channel. The criterion of breakdown is the formation of stable leader channel. As this channel is more stable in case of negative impulse compared to positive impulse in air or liquid nitrogen.

### 3.6.1 POSITIVE IMPULSE

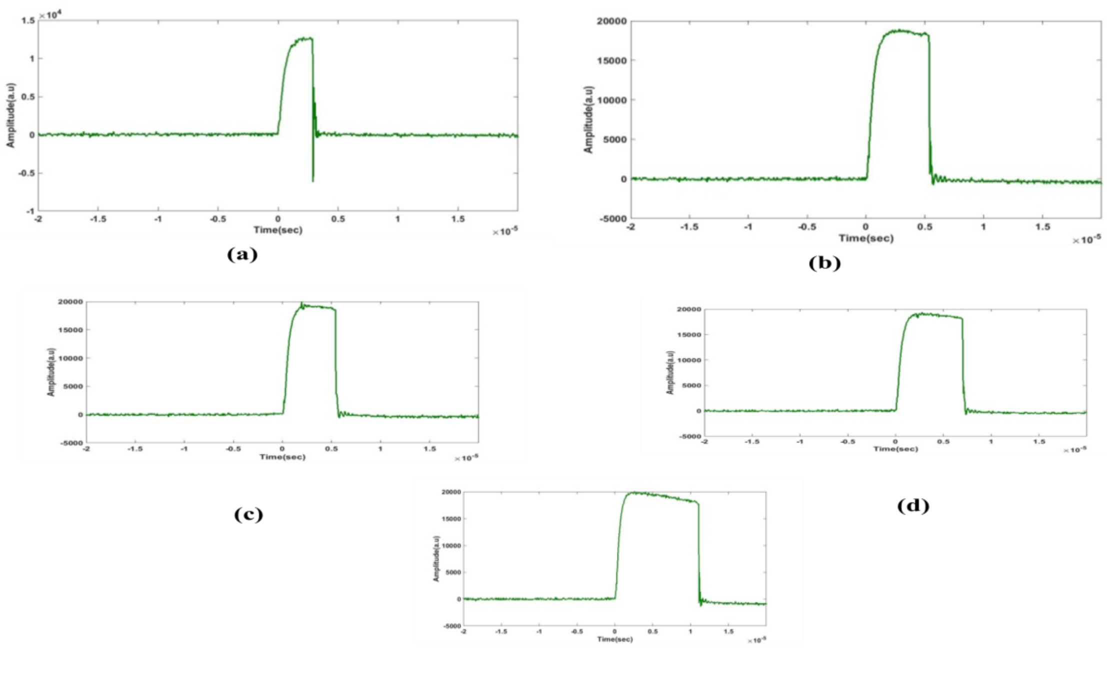



**Fig 3.8: Positive impulse breakdown signal in liquid nitrogen for different gap and fail time**

**(a) 2mm (b) 4mm(c) 6mm (d) 8mm (e) 10mm**

Fig 3.8 shows positive impulse breakdown for different gaps and there fail time is being analyzed. To obtain break down signal an amplifier connected to the load end capacitor its for impulse voltages. Positive impulse breakdown signal in liquid nitrogen fig 3.8(a) shows for 2mm gap the fail time is 4μsec and fig 3.8(b) shows 4mm gap fail time is 5.6μsec .Fig 3.8(c) shows 6mm gap fail time is 6μsec.Fig 3.8(d) shows 8mm gap fail time is 7.2μsec. Fig 3.9(e) shows 10mm gap fail time is 10.8μsec.

Breakdown without barrier in liquid nitrogen at a distance of 2mm is showing smaller break down voltages the failure time is very less. Breakdown without barrier in liquid nitrogen at a distance of 4mm is showing medium break down voltages the failure time is less. Break down without barrier in liquid nitrogen at a distance of 6mm is showing medium break down voltages the failure time is medium. Breakdown without barrier in liquid nitrogen at a distance of 8mm is showing medium break down voltages the failure time is medium. Break down without barrier in liquid nitrogen at a distance of 10mm is showing higher breakdown voltages the failure time is more.

### 3.6.2 NEGATIVE IMPULSE

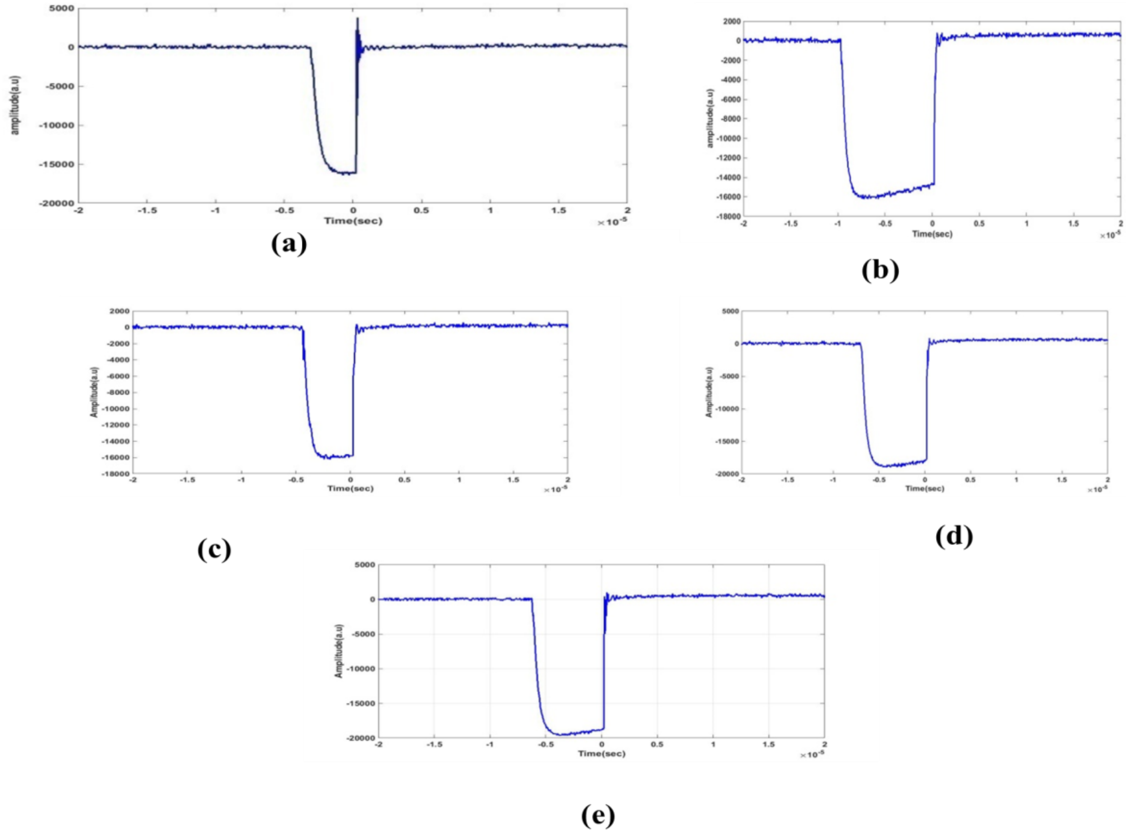



**Fig 3.9: Negative impulse breakdown signal in liquid nitrogen for different gap and fail time**

**(a)2mm (b) 4mm (c) 6mm (d) 8mm (e) 10mm**

Fig 3.9 shows the negative impulse breakdown signal in liquid nitrogen. Fig 3.9(a) shows 2mm gap fail time 3.2μsec. Fig 3.9(b) shows 4mm gap fail time 6.4μsec.Fig 3.9(c) shows 6mm gap fail time 4.8μsec. Fig 3.9(d) shows 8mm gap fail time 6.8μsec.Fig 3.9(e) shows 10mm gap fail time 7μsec

Breakdown without barrier in liquid nitrogen at a distance of 2mm is showing smaller break down voltages the failure time is very less. Break down without barrier in liquid nitrogen at a distance of 4mm is showing medium break down voltages the failure time is less. Break down without barrier in liquid nitrogen at a distance of 6mm is showing medium break down voltages the failure time is medium Break down without barrier in liquid nitrogen at a distance of 8mm is showing medium break down voltages the failure time is medium. Break down without barrier in liquid nitrogen at a distance of 10mm is showing higher break down voltages the failure time is more.

### 3.10 BREAKDOWN STUDIES WITH BARRIER:

**Table3.6: Breakdown with barrier in air and Liquid Nitrogen with +LI and –LI**

| Gap distance (mm) | Positive impulse break down (with barrier) | | Negative impulse break down (with barrier) | |
|---|---|---|---|---|
| | Air | Nitrogen | Air | nitrogen |
| 2 | 19.49 | 61.27 | 27.54 | 65.29 |
| 4 | 20.69 | 62.28 | 27.96 | 66.55 |
| 6 | 20.85 | 62.81 | 29.58 | 68.33 |
| 8 | 23.19 | 63.12 | 31.8 | 69.49 |
| 10 | 24.44 | 64.67 | 33.03 | 73.03 |

.

Table 3.6shows lightening impulse voltage and the break down voltage of electrode gap with barrier at different positions .it is seen that presence of barrier didn't show input positive polarity. The variation of barrier is high in air medium than liquid nitrogen

### 3.7.1 POSITVE IMPULSE SIGNALS WITH BARRIER:

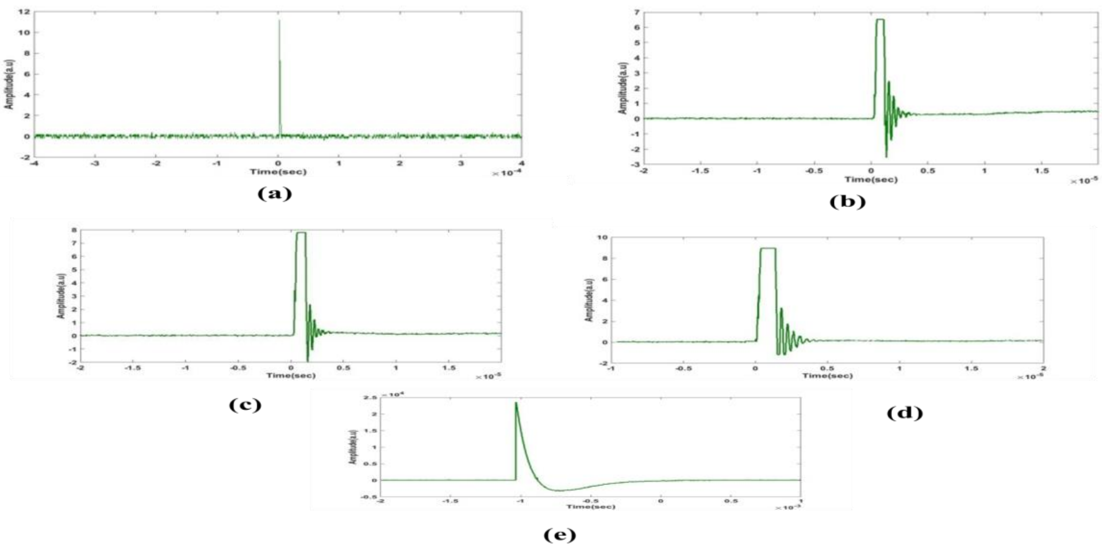


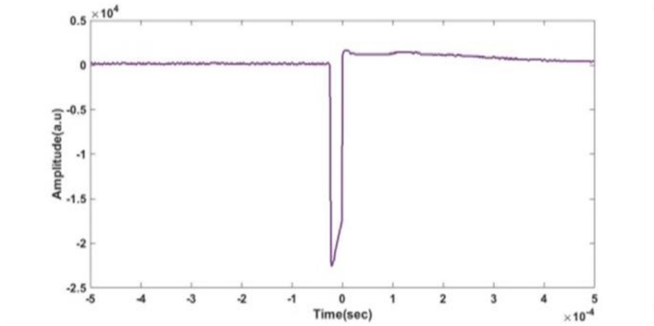

**Fig 3.10: positive impulse breakdown in liquid nitrogen with barrier for different gap and fail time**

**(a) 2mm (b) 4mm(c) 6mm(d) 8mm (e) 10mm**

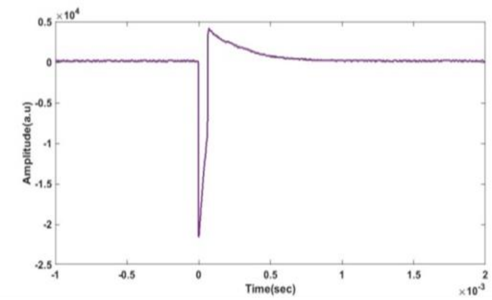
Fig 3.10 The obtained break down signal is from amplifier connected to the load end capacitor its for positive and negative impulse voltages. Positive impulse break down signal in liquid nitrogen .Fig 3.10(a) shows 2mm gap fail time of 1µsec .Fig 3.10(b) shows 4mm gap fail time of 1.2µsec. Fig 3.10(c) shows 6mm gap fail time of 1.2µsec .Fig 3.10(d) shows 8mm gap fail time of 1.4µsec.Fig 3.10(e) shows 10mm gap fail time of 2.4µsec.

3% silica epoxy glass fiber reinforced sample at a distance of 2mm is showing smaller break down voltages the failure time is very less.3% silica epoxy glass fiber reinforced sample at a distance of 4mm is showing medium break down voltages the failure time is less.3% silica epoxy glass fiber reinforced sample at a distance of 6mm is showing medium break down voltages the failure time is medium.3% silica epoxy glass fiber reinforced sample at a distance of 8mm is showing medium break down voltages the failure time is medium.3% silica epoxy glass fiber reinforced sample at a distance of 10mm is showing higher break down voltages the failure time is more

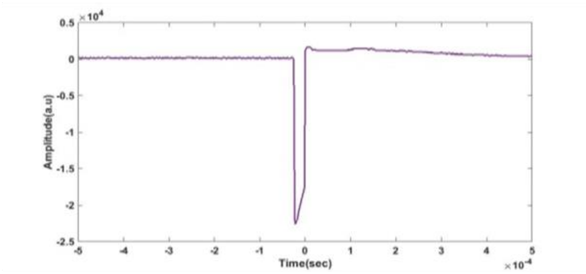
### 3.7.2 NEGETIVE IMPULSEBREAK DOWN WITH BARRIER



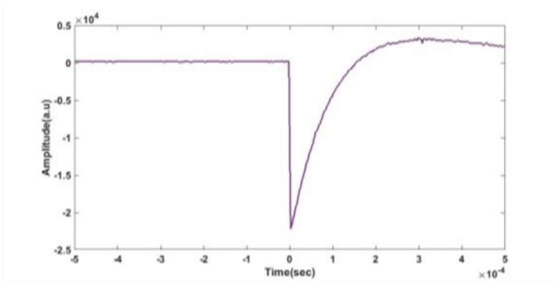

**(a)**



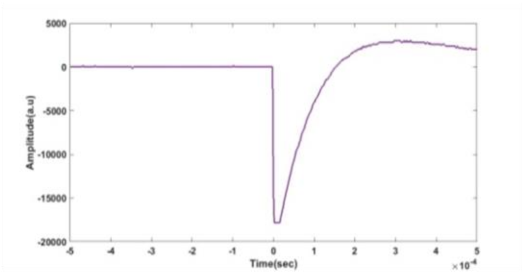

**(b)**




**(c)**




**(d)**




**(e)**

**Fig 3.11: Negative impulse breakdown in liquid nitrogen with barrier for different gap and fail time**

**(a)2mm (b) 4mm (c) 6mm (d) 8mm (e) 10mm**

Fig 3.11 shows the negative impulse break down signal in liquid nitrogen .Fig 3.11(a) shows  2mm gap fail time of 30μsec.Fig 3.11(b) shows  4mm gap fail time of 60μsec. Fig 3.11(c) shows  6mm gap fail time of 120μsec. Fig 3.11(d) shows 8mm gap fail time of 180μsec .Fig 3.11(e) shows 10mm gap fail time of 160μsec. As the distance of electrode gap increases the time of failure increases .The 8mm and 10mm gaps always has same fail time with not much  more distance of needle plane to the ground electrode the obtained failure time is of lightening impulse break down in liquid nitrogen.

### 3.8  DIELECTRIC RELAXATION SPECTROSCOPY ANALYSIS

### 3.8.1 PERMITTIVITY ANALYSIS

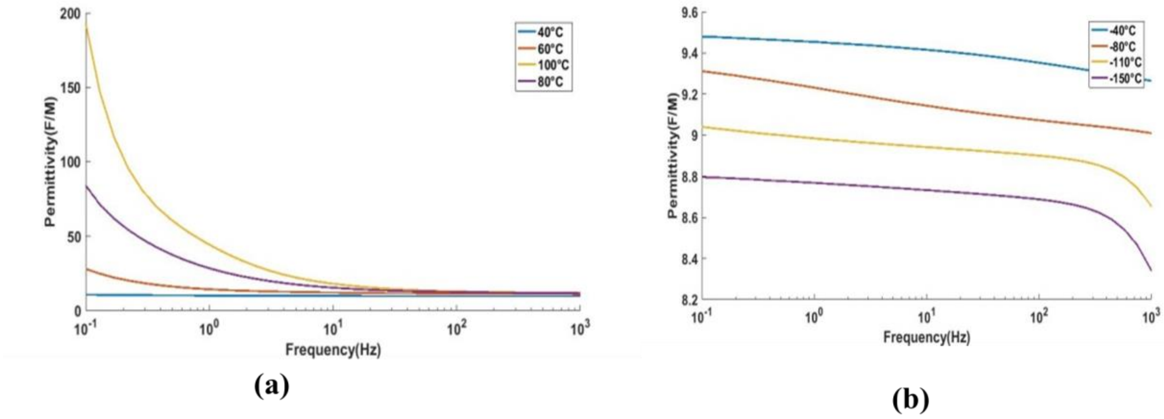



**Fig 3.12:permittivity of epoxy reinforced glass fiber wrt to frequency at a)higher temperatures and b)lower temperature.**

Fig 3.12 shows variation in permittivity with different frequencies. if increased in nano filler content should increase  in permittivity But air certainty Irrespective of percentage of nano filler the permittivity same.

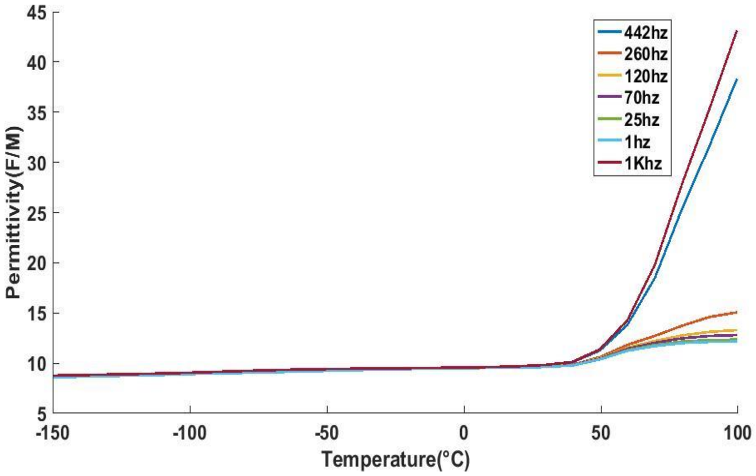
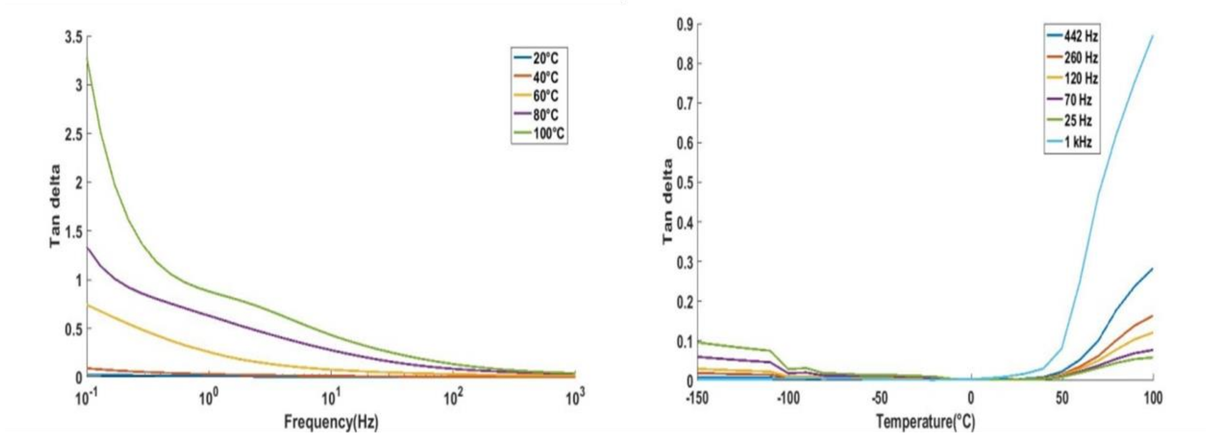



**Fig 3.13: showing permittivity of epoxy reinforced glass fiber wrt to temperature at all frequencies**

Fig 3.13 shows variation in permittivity at different temperatures increase in temperature should increase in permittivity of the material. As temperature increases permittivity increases as it can be observed that the permittivity remains constant as frequency at lower temperature when the temperature increased more than 50°C there is wide change permittivity as well as frequency and there is a quick raise.

### 3.8.2 DISSIPATION FACTOR ANALYSIS




(a) (b)

**Fig 3.14: showing tan delta of epoxy reinforced glass fiber wrt to frequency at a)higher temperature b)with different frequencies**

Fig 3.14(a) shows variation in tan delta at different frequencies, a reduction in tan delta is observed with increase in frequency. Fig 3.14(b) shows variation in tan delta at different temperatures .At higher temperature the tan delta has increased. In Tan delta test as the frequency increases tan delta decreases and reaches almost zero at higher frequencies as the rate of discharging increases with the increase of temperature as it can be explained by above graph. There is small change in tan delta at lower temperatures -150°Cand and when the temperature increase there is no change in tan delta and it becomes zero and it beyond 50°c it shows larger variations at different frequencies.

# CHAPTER 4

# CONCLUSIONS

## 4.1 SUMMARY

Surface discharge in liquid nitrogen generated due to high voltage stress ,corona and by partial discharge under AC,DC and lightening impulse voltages are analyzed by adopting UHF technique .The Surface discharges generated due to high voltage stress on the dielectric system ,under AC voltages were studied by placing epoxy glass fiber reinforced silica nano composite on the ground electrode .Use of UHF couplers for the identification in liquid nitrogen under AC,DC, lightening impulse voltages are indicated

Based on the analysis of the data acquired during experimental study ,the following important conclusions are arrived.

1. SDIV is high in liquid nitrogen ambience compared in air medium ,under AC and DC voltages .
2. SDIV in liquid nitrogen is almost three times than to occur in air
3. The Breakdown voltage of liquid nitrogen is high compared to ambience under lightening impulse voltages.
4. Break down voltage of lightening impulse voltages under positive impulse is less than negative lightening impulse voltage.
5. presence of barrier in electrode gap is high than when the barrier is present in air ambience.
6. Influence of barrier is not much observed in liquid nitrogen
7. Fail time is not much observed in air or liquid
8. The UHF signal formed due to surface discharge activity the rise time of the pulse is few nano seconds . The characteristics of UHF signal due to surface discharge under AC/DC voltages are nearly the same .Also the reduction of UHF signal formed due to surface discharge activity lies in the range of 0.5-2Ghz.
9. The Dielectric Relaxation Spectroscopy of the virgin sample taken shows the satisfactory performance as temperature increases permittivity of the material increases as this performance parameter along Tan delta and conductivity showing similar and satisfactory performances as the further analysis can be made with different percentages of silica at different frequencies at different temperatures .As my analysis my sample epoxy reinforced glass fiber nano composite showing satisfactory performance as it can be observed by seeing all the parameters like permittivity , tan delta, conductivity and impedance with different temperature ranges -150°C to100°C and Frequency ranges $.1Hz$to $1kHz$ as the performance parameters are analyzed.

10. As it can be observed the permittivity at lower temperature is constant as there is no frequency variation also there will be variation in permittivity for different frequencies after 50°C Temperature and as there will be permittivity and frequency change is predominant.

11. In DRS Analysis there will be some variation in the conductivity at very low temperatures up to150°C as the variation reaches constant at 0°C Temperature as the variation predominantly comes into the site after 50°Ctemperature.

12. Its has been seen from DRS Analysis the variation of tan delta is predominant at higher temperatures and at lower frequencies as there is no variation at lower temperatures as its effect is very negligible. As it can be seen at very lower temperatures tan delta frequency variations can be observed as it approaches 0°C it will constant as the variations comes into picture above 50°C same can be seen in permittivity and conductivity.

**4.2 SCOPE OF THE FUTURE WORK**

Identification of surface discharges is one of the major challenge in liquid nitrogen .Most of the researchers have restricted with surface discharge identification under AC voltages .An attempt has been made to understand the surface discharge activity with non standard transient voltages ,which appears in power system network ,for the completeness . Also, an attempt has been made to identify the discharges in liquid nitrogen filled cryogenic power apparatus adopting UHF technique.

To enhance the reliability of liquid nitrogen filled power apparatus ,it is essential to formulate the simplified conditions monitoring architecture that supports the pooling of diagnostic data by adopting multi sensor fusion technique which include conventional surface discharge process .Acoustic emission technique and UHF technique ,to provide engineers with meaningful diagnostic intelligent system technologies for monitoring the condition of cryogenic power apparatus during operation.

All the discharge studies were carried out with IEC(b)electrode .It is essential to understand the discharge activity with HTS material as the electrodes and any variation in the discharge process has to be analyzed.

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