AN ANALYTICAL APPROACH TOWARDS THE DEVELOPMENT OF SILICONE RUBBER NANO COMPOSITE AS HIGH VOLTAGE INSULATOR

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by

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Contents

Chapter 1 Introduction **Page No**

Chapter 2 Background of Outdoor Insulators

Chapter 3 Condition Assessment Technique

Chapter 4 Sample Preparation and Experimental Procedure

Chapter 5 Results and Discussions

Chapter 6 Conclusions and Future Work

CHAPTER-1

INTRODUCTION

Chapter-1

1.1. Background

High voltage distribution and transmission, as well as the usage of high voltage insulators, particularly in high voltage transmission lines, have become unavoidable due to the rise in power consumption in all industries. These insulators are exposed to electrical and mechanical stressors in addition to the whims of nature like rain, fog, humidity, snow, and pollution depending on their location, whether it be coastal or semi-arid locations. The point being made is that we need to ensure the reliable operation of the insulators and subsequently of the entire transmission system because they are thought to be the weakest link in the high voltage insulation system, failure of which results in the failure of the entire transmission system.

Porcelain and glass, which are conventional ceramic insulators, are inert, stable0020materials that didn't experience any surface deterioration, but because of their high surface energy, these materials have a high degree of wettability when exposed to moist environments like rain, fog, and dew. Leakage current rises when insulators are dirty and moist, which may cause flashover and system failure. Due to their ability to sustain high tensile strengths and overcome the traditional issues with porcelain and glass insulators, polymeric insulators have begun to gain popularity. On a surface level, they also benefit from being significantly lighter in weight, more affordable to install and maintain, and less vulnerable to vandalism. Technically speaking, compared to ceramic insulators, it has a very high resistance to flashover, puncture, tracking, and erosion. Due to its great hydrophobic feature, or excellent water repellency, polymeric insulators perform far better than ceramic insulators when exposed to contamination and pollution.

Due to these factors, either high temperature vulcanised (HTV) or room temperature vulcanised (RTV) silicone rubber may be utilised as the bulk material for composite insulators in new installations. (SiR). However, when replacement is not a possibility due to technical issues or financial restrictions, the ceramic insulators are covered with a 0.5mm layer of RTV silicone rubber. This is when room-temperature vulcanised silicone rubber is used.

1.2. Motivation

With the recent advancement in polymeric insulator, both high temperature vulcanised silicone rubber and room temperature vulcanised silicone rubber are being widely used in power transmissions systems because of their excellent hydrophobic properties. There have been an ample number of investigations carried out to determine variation in the hydrophobic properties of high temperature vulcanised in the case of contamination and the hydrophobicity recovery. In addition to this, it is very necessary to do research on the hydrophobicity of vulcanised silicone rubber at room temperature. The majority of the studies and analyses that have been carried out are through fast Fourier transform, which essentially converts the leakage current signal from time domain to frequency domain, and the analyses have been carried out in respect to variation in harmonic content with respect to contamination, but a study of harmonic content with different concentration is also essential. There have been a large number of studies on the leakage current analysis of polymeric insulator, and the majority of the studies and analyses that have been carried out are through fast Fourier transform.

1.3. Contribution

A Comparative Research was conducted on the fluctuation of leakage current (LC) magnitude with varying alumina nanofiller concentration in room temperature vulcanised (RTV) silicone rubber (SiR). Additionally, the result was validated with the root mean square value of the LC pattern that was produced. After that, a Fast Fourier Transform (FFT) was carried out on the LC pattern, and subsequent discussion focused on the fluctuation in harmonic content as well as the ratio of third harmonic content to fundamental.

A research project on the determination of hydrophobicity was carried out on two-part RTV SiR with various concentrations of Alumina nanofiller, and the resulting difference in contact angle was observed and explained. In order to get a better idea of the dynamic hydrophobicity of the RTV samples, they were contaminated in a separate experiment, and then the researchers measured the hydrophobicity that was transferred to the surface of the contaminated insulator, as well as the percentage of hydrophobicity that was recovered after the contaminant was removed. This was done by measuring the contact angle of a water droplet using a goniometer and the sessile drop technique. Following that, the process of hydrophobicity transfer to the surface of contaminated RTV samples with various concentrations of Alumina filler was discussed, as well as the hydrophobicity recovery.

1.4. Literature Review

1.4.1 Introduction

Insulator plays a highly significant function in power systems by separating live components from each other and from ground, as well as by providing mechanical protection. Insulators have seen widespread use across a variety of networks, including substations, transmissions, and distributions [1].

Ceramic insulators have had a significant presence in the power system for a very long time and continue to have a significant amount of importance in both the transmission and distribution systems. Ceramic insulators have favourable mechanical and electrical properties, and they are also relatively inexpensive. However, because they are intended to be used outdoors, they are susceptible to a number of flaws, particularly when subjected to particular environmental conditions, such as when the air is humid, when it is raining, or when there is pollution, all of which cause a decrease in their surface resistance. Because of the decrease in surface resistance, the amplitude of the leakage current that flows on the surface is increased [2]. Degradation of the insulator surface may be attributed to the presence of a substantial leakage current (LC) that flows on the surface for an extended length of time [3]. Furthermore, since ceramic insulators are hydrophilic in nature, they promote the production of continuous water films in the event of humid conditions or during the rainy season. This leads to greater tracking, which might ultimately result in flashover. Coating ceramic insulators with room temperature vulcanised silicone rubber is one of the solutions to the issue that ceramic insulators present, regardless of whether the insulator in question is made of porcelain or glass. Suwarno and Pratomosiwi [4] carried out research that examined the leakage current, hydrophobicity, and surface smoothness of RTV silicone rubber coated porcelain insulator with uncoated porcelain insulator.

1.4.2. Sample preparation

In the recent past, there has been a significant amount of focus placed on silicone rubber (SiR) composites for use in electrical insulation applications as a consequence of the good findings achieved for the dielectric and surface characteristics of these composites [5]. However, in order to increase these features of the underlying polymer even further, it is often compounded with a variety of fillers, the specific nature of which is determined by the property that has to be improved [6]. In terms of tracking and erosion resistance, for example, it has been shown in [7,8] that a highly loaded SiR performs better than SiR composites that have a lower filler content. In addition to this, it has been noted that increased loadings of the hydroxide filler might result in poor mechanical qualities such as a low tensile strength [9].

Although micro and nanodielectrics open a new arena of opportunities in the electrical insulation industry, a major challenge for the researchers is to accurately distinguish their dielectric properties. One of the factors that has directly affected these properties is the method of processing adopted for the preparation of these SiR composites, so this is one of the factors that is a major concern. The processing technique, on the other hand, ought to be one that can be used profitably in business and should include a production procedure that is not too complicated. Direct mixing, mechanical stirring, ultrasonication, and in-situ polymerization are only some of the typical processing methods that may be used to disperse micro and nanoparticles in a polymeric foundation [10]. In addition, a technique has been given in [10,11] in order to have a good dispersion of filler and to have superior features for the polymer composites. When discussing the composite's mechanical and dielectric characteristics, the datasheet for the RTV SiR material is referred to [12].

According to the findings of a comprehensive research on various organic, inorganic, and metallic filler that was carried out by A Khattak and M Amin [13], Alumina filler is great for imparting mechanical strength to the polymer composite, whilst alumina trihydrate was fairly effective in boosting the electrical characteristics of the material. An exhaustive investigation on the use of Alumina filler as a reinforcing filler in silicone rubber compounds including Alumina, precipitated Alumina, and modified precipitated Alumina was carried out by FANG Su and colleagues. According to the results of his research, Alumina performed extraordinarily well in tests measuring its hardness, elongation, and tear strength. In addition to this, its tensile strength was superior than that of its competitors. The study of the morphological characteristics of the compound with these various Alumina fillers using transmission electron microscopy revealed that the compound had long chain aggregates, which resulted in excellent mechanical properties. The study also revealed that the Alumina compound had less moisture content in comparison to the precipitated Alumina compound and also in its datasheet [14,18].

1.4.3. Leakage current

Insulators that can withstand high voltage are extensively used in transmission and distribution lines. Their primary function is to physically separate two electrical conductors as well as electrical conductors from towers. Insulators that are situated in places that are prone to industrial activity or that are near the shore are more likely to be contaminated by salt deposits and industrial dust, respectively. In conditions of high humidity and rain, the layers will get wet and conductive, which will cause leakage current (LC) to flow over the surface of the insulator. This will occur because the layers will become conductive after being wet. This progression of LC causes a flash over which short circuits occur between two lines or between line and towers. Because of this, leakage currents are monitored and studied in a lab or out in the field, depending on the circumstances, so that a comparative assessment of the state of the insulator surfaces can be made [15]. Leakage currents may give us with valuable information on the state of the insulator surfaces if we investigate their amplitude and pattern [16,17]. In the beginning, the magnitude of the leakage currents is relatively low, and they have a capacitive character. However, as time passes, the magnitude of the leakage currents grows, and it also becomes more resistive; afterwards, the leakage currents' harmonic content also grows [16,19,20]. The appearance of a dry band on the surface of the insulator is caused by an increase in the LC. A further boost in the harmonic richness may be achieved by dry band arcing [19]. Therefore, analysis of leakage currents is often performed in both the time and frequency domains [15]. As shown by D. Pylarinas *et al.* [20,21], there are quite a few features in both the time domain and the frequency domain that may be employed alone or collectively to analyse LC values. These features can be found in both the time domain and the frequency domain.

A study that was carried out by *M. Amin et al.* [22] demonstrates that the use of composite insulators in decreases the leakage current significantly even in the presence of pollution, as well as various LC measuring techniques. An extensive survey on the micro and nano-filler to improve the performance of outdoor silicone rubber insulator was done by G. Momen and M. Farzaneh [23]. The results of this survey showed that aluminium trihydrate (ATH) and Alumina were the most commonly used filler, with Alumina being the reinforcing filler because it increases the tensile strength and ATH being the extending filler because it imparts tracking resistance and also acts as a flame retardant. Additionally, the impacts of different inorganic, metallic, carbonaceous, and organic fillers have been investigated by them as well.

1.4.4. Hydrophobicity

Since the early 1960s, composite insulators have been used for the outdoor electric power insulations. In the last 25 years, the present style of composite insulators has been created [24,25]. Composite insulators have been used since the early 1960s. In the beginning, ethylene-propylene-diene monomer (EPDM) and epoxy resin were the most common insulator materials utilised; however, silicone rubber (SiR) composites began garnering greater attention for outdoor insulation in the 1990s, mostly due to its superior hydrophobicity [26]. Since then, EPDM and epoxy resin have been used less often as insulator materials. Which Room temperature vulcanised (RTV) silicone rubber is becoming popular largely because it offers outstanding hydrophobicity and the unique capacity of hydrophobicity to migrate, which leads in a considerable rise in the pollution flashover voltage for glass and porcelain insulators [27,28]. This is the fundamental reason why RTV silicone rubber is becoming so popular.

Degradation of the hydrophobicity of RTV SiR has been demonstrated to take place during corona discharge and is mostly attributable to the length of time that the material was subjected to severe environmental conditions, according to a significant number of studies [29]. Hydrophobicity indices are impacted by numerous characteristics, such as measurement temperature, surface charge, surface roughness, and volume of the water droplet, amongst many others. These indexes are used to assess the degree to which the state of the materials has deteriorated. As a result, making a note of the influence that these measurement parameters have on the assessment of hydrophobicity is of the utmost importance. [30–34] are some of the articles that conducted an analysis of these impacts.

RTV silicone rubber contact angle measurement, study on discharge, and Fourier transform infrared spectroscopy (FTIR) analysis are the main techniques for determining the hydrophobicity of RTV silicone rubber [35-39]. The contact angle is essentially a direct assessment of the hydrophobicity of the surface, while FTIR demonstrates the change in the function groups present on the surface.

The researchers looked at the change in hydrophobicity that is the mechanism of transfer associated with the diffusion of low molecular weight (LMW) in [40-42].

1.5 Thesis Organisation

The next chapter that is chapter 2 will be deals with the different outdoor insulators that have been in use, their comparative study and the different insulator coatings that are used, with emphasis on silicone rubber.

Chapter 3 presents different condition assessment techniques of high voltage insulators Chapter 4 deals with different raw material and equipment used with a brief description about them, the sample preparation method adopted, and the experimental setup and procedure for leakage current measurement and hydrophobicity measurement.

Chapter 5 presents the experimental results of the leakage current measurement, the leakage current analysis, the static and dynamic hydrophobicity measurement of two-part room temperature vulcanised silicone rubber and discusses the findings.

Chapter 6 provides conclusion from the present study and the future scope of the work.

CHAPTER-2

BACKGROUND OF OUTDOOR INSULATORS

Chapter-2

2.1. Introduction

Since the invention of electricity, there has been a pressing need for adequate electrical insulation. As for the insulators used outside, the vast majority were made of porcelain or glass and were referred to as ceramic insulators. Porcelain is still one of the most extensively used outdoor insulators, although polymeric composite insulators are quickly replacing it as the most common kind of outdoor insulator. Porcelain was once the most common type of outdoor insulator. In the following sections, we will go through a full review of the drawbacks of ceramic insulators, the benefits of polymeric insulators, as well as the ways that can be used to enhance the performance of ceramic insulators so that they are on par with polymeric insulators.

2.2. Ceramic Insulators

Since the 1850s, ceramic insulators have been utilised as outdoor insulators. Prior to that time, porcelain insulators were employed for their ability to serve as telegraph insulators. However, ceramic insulators continued to be used in the electrical industry for outdoor insulators because porcelain and glass are both very stable materials that can withstand significant amounts of arcing without causing significant surface degradation. Ceramic insulators also have a high withstand capacity for heat and dry-band discharges [1.2]. The primary issue with ceramic insulators, however, is that they have extremely wettable surfaces, which is particularly problematic when they are subjected to humid climatic conditions such as dew, rain, or fog. This is due to the fact that ceramics are very high surface energy materials.

It is well knowledge that when insulators are damp and polluted, a significant amount of leakage current occurs. This, in turn, finally results in flashover and disruptions to the electrical system. Insulator contamination is one of the most significant issues that affect electrical power systems. This is because contaminated insulators are the main source of flashovers, which occur when the surface leakage current is increased. The presence of impurities causes huge amounts of leakage current to develop on the surface of the insulator. This uncontrolled rise in leakage current eventually results in flashover [3]. Wet atmospheric conditions often cause water films to form on the surface of the insulator.

Ceramic insulators are susceptible to contamination, which is one of the most significant problems associated with these materials. Contaminants often cause surface deterioration, the nature of which varies depending on the climate and topography of the area in question. Depending on the kind of contaminated deposit being studied, a contamination study may be roughly categorised as taking place in either an urban or industrial region, a rural area, or a coastal location. The categories are analysed in the next section [42].

1. In urban or industrial area: The discharge of pollutants from factories and vehicle manufacturing are the primary contributors to the accumulation of contaminants in these regions. There are many distinct types of industrial pollution, the majority of which are

determined by the kind of industry, such as chemical, metallurgical, petrochemical, textile, etc. industries.

2. In rural regions: Due to the fact that these areas are relatively undeveloped or are in the process of being developed, the primary cause of pollution in these areas is the particle of dust. The widespread use of pesticides, herbicides, and fertilisers is another factor that may contribute, at least in part, to the pollutant deposit that was found.

3. The coastal region is one of the locations that are severely impacted by the deposition of contaminants, the majority of which take the form of salt deposits and salty moisture. This makes the coastal area one of the areas that suffers the most. These kinds of pollutants may be detected on insulators not only on those that are placed close to the sea, but also on those that are positioned up to a substantial distance away from it. Coastal winds that blow towards the wind bring salty moisture and deposit it on the surface of the insulator, which makes the issue of contamination worse and causes an increase in the amount of current that leaks through. This causes increased contaminant deposits on the insulator.

The primary strategies that are used in order to eliminate the issues of surface deterioration and contamination, particularly in regard to pollution causing an increase in surface wetness, are as follows:

1. The use of polymeric insulators, which have enhanced resistance to the effects of weathering and erosion or corrosion, has become increasingly popular in the electrical industry. These insulators are made from synthetic materials that offer superior durability and longevity compared to traditional ceramic or glass insulators. Polymeric insulators are also lighter in weight, making them easier to install and transport. In addition, they are less prone to cracking or breaking under stress, which can result in costly downtime for power systems.

2. To deposit a protective coating on the insulator surface of a ceramic insulator in order to slow down the process of deterioration;

These are the two most feasible solutions that are now accessible from an economic standpoint, and an investigation into each of them has led us to the next section. The first choice is dissected in great depth in the next section (2.3). In contrast, the second choice is dissected in great depth in the next section (2.4).

2.3. Polymeric Insulators

Polymeric insulators have been in use as an outdoor high voltage electrical insulator for a considerable amount of time, roughly for more than 40 years at this point. In contrast to ceramic insulators, however, they have only been around for a very short time and are not yet fully understood. The cores of the polymeric insulators are exceedingly robust, and the insulators themselves have a very high tensile strength. They are considered to be insulators of the contemporary day due to the fact that they have shown to be highly effective in combating the issue that plagued the traditional insulators made of glass and porcelain in terms of contamination performance as well as resistance to weathering and erosion. They are able to handle very large mechanical loads, which is particularly useful for the transmission of very high voltages. In addition, they are capable of being constructed for atypical insulating structures as well. In compared to ceramic insulators, polymer insulators are much lighter, have better resistance to vandalism, and, as was previously said, much better contamination performance. When a polymeric insulator is subjected to severe climatic conditions or electrical stress for extended periods of time, the same degradation process takes occur in the insulator.

Ethylene propylene diene monomer (EPDM) and silicone rubber (SiR) make up the majority of polymeric insulators. EPDM has strong hydrophobicity qualities, but it lacks weathering resistance and hydrophobicity resistance [23]. Silicone rubber (SiR) is the other primary kind of polymeric insulator. In addition to that, these insulators offer good resistance to the effects of weathering and the capacity to reduce leakage current. In most cases, the composite polymeric insulator will feature a fiber-glass rod for mechanical strength as well as a weather shed made of EPDM or SiR, and it will also have metal end fitting at both ends for connection. Figure 2.1 shows the composite insulator.

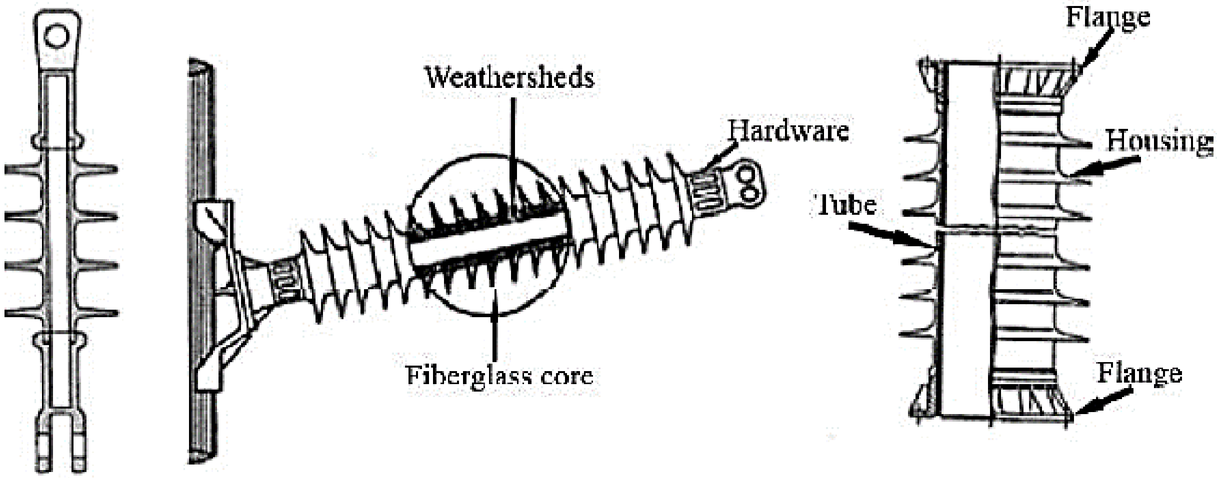

Figure 2.1: A composite polymeric insulator [23]

2.4. Coatings of Line Insulators

Weathering and degradations have been a challenge for ceramic insulator from the beginning. As early as in 1920's oil bath method was applied to avoid wetness of the insulator surface [42]. Around 1950's the hydrocarbon coating technology in the form of petroleum jelly was utilised widely, but it had its negative therefore an improved coating in the form of silicone grease were employed. Around 1980's the silicone grease coatings were replaced with silicone rubber coatings, which are effective till now.

2.4.1. Hydrocarbon Coatings

Jellies derived from petroleum were composed of a variety of various petroleum fractions, the majority of which were microcrystalline and slack waxes, in addition to hydrocarbon oils. It has been shown that they become more malleable as the temperature rises and that they often melt at the areas of electrical discharges caused by heat. This causes them to swallow the contaminant, but when they cool down, they regain their original qualities. According to the findings of several studies [42], a maximum thickness of about 7.6 millimetres and a minimum thickness of 3.2 millimetres were shown to significantly reduce flashover. It was projected that they had a working life of three years. Therefore, it was discovered to be a cost-effective choice in that respect.

The results were excellent in terms of the number of flashovers that occurred, but the main problem was that application couldn't take place in places with moderate or high temperatures due to the propensity of petroleum jelly to melt. It was discovered that removing the contaminated petroleum jelly after it had served its purpose was a highly expensive and tedious operation since the contaminants had to be physically scraped, which is a time-consuming activity [42]. In addition, as a result of technological breakthroughs, materials made of silicone, which are recognised for their water-repellent properties, became accessible.

2.4.2. Silicone Grease Coatings

Because removing hydrocarbon coatings from ceramic insulators required a laborious procedure, a substance similar to silicone grease was employed instead as a protective coating for the insulator. Because of the developments made in silicone compounds, which are well-known for their superior hydrophobicity and resilience to the effects of weathering, these compounds have also been used for coatings on ceramic insulators. Silicone greases were made out of silicone oil and silicone filler, both of which do not melt but instead break down when exposed to temperatures higher than 200 degrees Celsius. In contrast to hydrocarbon coatings, they may be used nearly everywhere, regardless of the weather [42].

Another significant advancement made in comparison to the hydrocarbon grease was the fact that the material retains its greasy state even after being subjected to an electrical discharge. Even when salt, dust, and other impurities were accumulated on the surface of the insulator, the grease-like components ensured that the surface did not get wet and, as a result, maintained a high surface resistance. Even in wet conditions, a coating made of silicone rubber was able to prevent leakage current and keep flashover voltage at a high level until the coating became completely saturated with contaminant. It has been said that the thickness of the coating as well as its uniformity have a significant role in determining how effective the coating is. It was discovered that a silicone grease packed with aluminium trihydrate had a significantly improved antitracking resistance but a diminished water repellent property.

In spite of the fact that it was able to maintain its hydrophobicity for an extended period of time, the silicone grease coating was still susceptible to water erosion. Additionally, the infusion and adsorption of particle matter led to a loss of hydrophobicity after a predetermined amount of time, and the coating required more frequent reapplication in comparison to hydrocarbon coatings. Getting rid of silicone grease in preparation for reapplication was a procedure that required a lot of time and led to an increase in expense.

2.4.3. RTV Silicone Rubber Coatings

Coatings made of silicone rubber (SiR) that have been room temperature vulcanised (RTV) have found usage in a variety of electrical applications. They give great resistance to thermal degradations as well as corona discharges, in addition to maintaining outstanding dielectric characteristics and flexibility throughout a broad temperature range. Due to the low surface energy of the silicone rubber compounds, they, like all other silicone rubber compounds, have a good water repellency property. The hydrophobic surface of RTV SiR helps to decrease the creation of dry bands as well as developments in leakage current, which contributes to an improvement in contamination performance.

It is possible to produce a great deal of variety in the characteristics of silicone rubber by incorporating filler into it. The amount of filler, the size of the filler, and even the kind of filler used has a significant impact on the properties of the coatings. It is well knowledge that Alumina and aluminum trihydrate (ATH), in particular, are among the most efficient fillers for imparting anti-tracking resistance and improving mechanical properties [4,8].

Spray coating the clean ceramic insulators with a thin layer of RTV SiR, with an approximate thickness of 0.5 millimeters, results in the formation of a flexible elastomer that has good dielectric characteristics after curing. Even after prolonged exposure to electrical stress, the coated surface of ceramic insulators has been shown to retain their hydrophobic properties in most cases. This is something that has been observed. Furthermore, SiR coatings have the property of hydrophobicity recovery, which can be attributed to low molecular weight (LMW) compounds present in the bulk of coatings [42]. Advantages of SiR coating to silicone grease coatings include that the thickness of the coating applied is greatly reduced, thereby reducing the material consumption, labour saving, and longer life of the coatings also prove to be cost effective. SiR coatings also have a longer life. The application procedures for RTV coating are straightforward and not too expensive. In addition to this, it is incredibly simple to clean and maintain its water repellency. As a result of all of these variables, it has been shown that RTV SiR coatings significantly cut down on the amount of money spent on maintaining insulators.

2.4.3.1. Silicone Rubber Compounds

When exposed to humid circumstances and coastal environments, the surface resistance of ceramic insulators rapidly drops. This results in the increased leakage current that finally leads to flashover, which causes the insulator to become damaged permanently. In order to solve this issue, ceramic insulators are being switched out for polymeric insulators. In most cases, the new insulators being installed are high temperature vulcanised (HTV) silicone rubber (SiR). However, in the event that in-use insulators cannot be removed from the system, room temperature vulcanised (RTV) SiR coating is applied on the surface of the insulator [4].

Silicone rubber is a synthetic, or man-made, material that is well-known for its outstanding weatherability and its ability to keep its qualities across a broad range of temperatures. Silicone rubber is also noted for its ability to retain its elasticity even when exposed to extreme temperatures. SiR is used as an electrical insulator because of its resistance to oxidation, low surface energy, and resistance to deterioration from ultraviolet (UV) light. These properties allow it to be used in this capacity. These characteristics of silicone rubber are a result of the structure of the basic polymer that it is made from. due of the strength of the connections between silicon and oxygen, silicone rubber is resistant to oxidation, heat stability, and weathering. Silicone rubber also offers low temperature flexibility and low surface energy, which contributes to superior hydrophobicity. This is mostly due of its flexible polymer chains.

Silicone rubbers are considered to be "polymers," and like other polymers, they are composed of a large number of molecules. These molecules have their atoms organised one after the other in a chain-like structure, and each link in the chain has the same fundamental structure. Polysiloxane is constructed using a chain-like structure that is comprised of repeating basic units of siloxane. The structures are exactly the same, and the variable n represents the total number of units that are repeated. If this number, n, is quite low, the molecules in question are referred to as having a low molecular weight (LMW), and they have few distinguishable physical features. When 'n' is increased, the molecular weight likewise rises, and the enhancements to the physical attributes continue. The length of a SiR polymer may be anything between 3000 and 10000 monomers in length. Attached to the silicon atoms are organic side groups, which often comprise carbon. This allows for crosslinking and specialised uses, such as improved tracking resistance, weathering resistance, beat resistance, and so on. SiR contains a methyl side-group connected to the siloxane unit, which allows for water repellency qualities. As a consequence of this, dimethyl siloxane is its basic unit, and the term for the polymer that is formed as a result of this process is poly dimethyl siloxane (PDMS) [6]. Because of the significant link that is produced between carbon (which belongs to the organic group) and silicon (which belongs to the inorganic group), SiR is categorised as an organo-silicone compound. This is because of the bond that is formed between carbon, which belongs to the organic group, and silicon, which belongs to the inorganic group. Figure 2.2 illustrates the fundamental component of SiR, which is the dimethyl siloxane molecule.

RTV silicone rubber has a poly dimethyl silicone base and a combination of reinforcing filler, extending filler, low molecular weight silicone of increasing dynamic hydrophobic characteristics, and structuring additive also to prevent crepe hardening. This rubber is often used in high voltage insulator coatings. The basic unit of SiR that is dimethyl siloxane is shown in Figure 2.2.

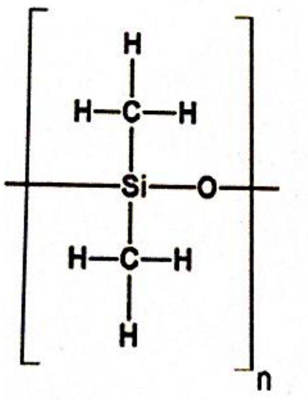

Figure 2.2: Dimethyl siloxane unit

RTV silicone rubber that is commonly used in high voltage insulator coatings have poly dimethyl silicone base and a mixture of reinforcing filler, extending filler, low molecular weight silicone of improving dynamic hydrophobic properties, and structuring additive also to reduce crepe hardening.

2.4.3.2. Fillers

Fillers are consistently combined with the silicone rubber (SiR) foundation in order to enhance the material's electrical and mechanical qualities. Fillers are another factor that contribute to the total cost reduction of composite insulators. In addition to the fact that fillers of the same kind can change in qualities owing to their varied sizes, for example, micro filler and nanofiller both have markedly different properties, there are a range of other forms of filler that may be used to enhance a variety of different features in SiR insulators. Even filler of the same kind and the same size might cater to extending distinct properties simply as a result of having different surface treatment or different surfactants [23]. The degree to which filler particle size, structure, morphology, degree of dispersion, filler concentration, filler surface treatment, and also the degree to which adhesion and orientation in the matrix all have a role in determining the amount to which properties are enhanced by the filler.

The filler may be generically categorised as either an extending filler or a reinforcing filler, depending on the property enhancements that it confers on the basic polymer chain. In general, the reinforcing filler works to strengthen the mechanical strength of the polymer in areas such as tear strength, abrasion resistance, tensile strength, and other similar areas. while extending fillers, in most cases, improve certain characteristics of the base polymer that are being sought. Alumina, carbon black, and aerogel Alumina are examples of fillers that are recognised for their ability to reinforce, whereas aluminium trihydrate, zinc oxide, and titanium dioxide are examples of fillers that are renowned for their ability to extend. In silicone rubber, the filler that is most usually used is shown in Table 2.1 together with the feature that is increased by using it [23].

Table 2.1: Fillers and the corresponding property enhanced [23]

FILLER TYPE	PROPERTY ENHANCED
Zinc oxide	mechanical properties and electrical conductivity
Titanium dioxide	thermal strength and relative permittivity
Alumina	antitracking, erosion resistance
Alumina	mechanical properties and antitracking
Barium titanate	thermal stability and relative permittivity
Calcium carbonate	Flame retardant and hydrophobicity
Carbon black	mechanical and electrical properties

CHAPTER-3

CONDITION ASSESSMENT TECHNIQUES

Chapter-3

3.1. Introduction

Monitoring of insulators is of the utmost significance for the efficient operation of the power system since the total dependability of the system is dependent on the insulators' level of dependability. Scanning electron microscopy (SEM), leakage current measurements, hydrophobicity measurements, and Fourier transform infrared spectroscopy (FTIR) are some of the most important condition assessment methods that are used at the moment for efficient system monitoring. There are now a great number of condition assessment methods that are available. In this section, the various methodologies for condition evaluation are reviewed, with a particular focus placed on leakage current and hydrophobicity measuring methodology. This is because these techniques were used in this research for the purpose of assessing the state of insulators.

3.2. ESDD Measurement

For simulation of the polluted environmental condition and pollutant on the insulator surface, researchers have suggested to have equivalent salt deposit density (ESDD) and non-soluble salt deposit density (NSDD) as measure of the contamination severity. Generally, kaolin (Al Siz05(OH)4) and sodium chloride (NaCl) are mixed in distilled water to get the desired ESDD values

ESDD calculations are based on the temperature and the conductivity of the contaminant. Based on IEC 60507 [38] the formula for conductivity at 20°C is given in equation (3.1)

$$\sigma_{20} = \sigma_{\theta}[1 - b(\theta - 20)] \tag{3.1}$$

Where
σ_{20} = is the volume conductivity at 20^{o}C (S/m)
σ_{θ} = is the volume conductivity at θ°C (S/m)
θ= is the solution temperature in ^{o}C
b= is a factor depending on θ.

The relationship between salinity (Sa) and volume conductivity at 20^{o} C is given in equation (3.2) as

$$Sa = (5.7\sigma_{20})^{1.03} \tag{3.2}$$

And ESDD is calculated from the value of salinity using the equation (3.3)

$$ESDD = Sa \times V/A. \tag{3.3}$$

3.3. Scanning Electron Microscopy

Since its introduction more than four decades ago, the scanning electron microscope (SEM) technology has been instrumental in elucidating the surface topography of insulating materials. It is similar to an electron microscope in that it provides us with a magnified view of the surface. The scanning electron microscope (SEM) approach involves accelerating an electron beam and directing it towards the surface whose topography is being examined. When electrons collide with a surface, they split into four distinct groups: the electrons that are halted, the electrons that are absorbed, the electrons that are deflected or secondary electrons, and the electrons that are reflected, or what we may also call back scattered electrons. The stopped electrons are those electrons that are stopped upon impacting the surface, which in turn results in the transfer of energy to the sample, which in turn results in stimulating the material electrons and providing a brightness. The second group of electrons that are absorbed by the sample causes an ejection of another electron from the surface, which ultimately results in the production of X-rays. The sample also absorbs the first group of electrons. The electrons that are deflected or secondary travel in their direction, whereas the electrons that are reflected go back towards the source. In order to provide a thorough examination of the surface roughness, surface degradation, and the form of the surface up to the micrometer range [26], each of these electron groups is detected and collected.

3.4. Fourier Transform Infrared (FTIR) Spectroscopy

It is likewise a method for assessing the quality of insulators, but unlike SEM, its emphasis is not on the topographical changes that have occurred but rather on the structural alterations that have occurred in the insulator [26]. It is a method for quantitative measurement and is most often used for organic compounds; however, it may also be utilised for inorganic compounds. It is predicated on the idea that when any substance is exposed to infrared radiation, the material will absorb radiation of a certain frequency, which will then line up with the frequency of vibration of the atoms that are present in the material. This idea underpins the concept of infrared heating.

So, in this approach, the samples are exposed to infrared radiation, and the samples absorb the radiation of frequencies that correspond with the vibrating frequency of the component atoms. Consequently, the method yields accurate results. As a result, a drop may be seen in that frequency band when looking at the infrared spectrum that was acquired. After that, an infrared spectrum is compared with a standard set of spectrum curves, and the component elements are found. It is especially valuable for research on sample degradation since it allows us to measure the FTIR response for virgin samples, compare it with the FTIR response of aged or deteriorated samples, and examine the changes in either of those responses. This is a very useful technique.

3.5. Leakage Current Measurements

Insulation is one of the most important factors that determines how well an electrical power system performs. Polymeric insulators are now being utilised extensively in both the transmission and distribution of high voltage, and they are slowly taking a large portion of the market due to their versatility and low cost. Polymeric insulators have several benefits over their more traditional counterparts, such as glass and porcelain, which have contributed to their meteoric rise in popularity. These benefits include, but are not limited to, a lower surface energy, a smaller weight for the same capacity, increased mechanical strength, resistance to vandalism, and significantly improved functionality when exposed to damp and polluted conditions. The capacity of polymeric composites to function over an extended period of time as an insulator for high voltage is evaluated using a design test, which consists of an accelerated ageing test and a normal ageing test. The performance of polymeric insulators is evaluated by using a variety of measuring techniques for the purpose of performing diagnostics on the insulators. The most frequent approaches for monitoring and researching the performance of polymeric insulators are referred to as equivalent salt deposit density (ESDD), surface conductance, the measurement of leakage current, and non-soluble deposit density (NSDD). Other key aspects that influence the performance of insulators under environmental and electrical stress are hydrophobicity and ageing [22]. Insulators' performance may be negatively impacted by these conditions. The surface of the polymeric insulator experiences a considerable acceleration of the deterioration process as a direct result of the growing leakage current (LC) and discharges. In both laboratory and field research, the measurement of LC is carried out often in order to evaluate the effectiveness of polymeric insulators after taking into account their age. The leakage current study is a very significant part of the process that helps us understand the surface state and degeneration of the polymeric insulators, and it plays a very vital function in this process. The mechanism for the generation of the leakage current is first addressed in depth, followed by its examination in both the time domain and the frequency domain.

3.5.1. Leakage Current Analysis

The LC is driven by a source voltage and is collected at the ground end of the insulator, which gives quite a lot of helpful information on the process of defining the present state of a contaminated polymeric insulator. The LC will often exhibit capacitive behaviour and exhibit a sinusoidal waveform when the applied voltage is low or when the contamination level is low. If the voltage that is applied goes over a specific amount or if the degree of contamination goes above a given level, then the LC will start to behave in a more resistant manner. The appearance of spikes on the LC crest is brought because by the discharge of dry bands. This causes the waveform of the LC current to become deformed, which in turn causes an increase in the amount of harmonic content. It has been said that the transformations that take place in the LC waveforms prior to the occurrence of flashover may be broken down into five distinct phases. When the magnitudes and harmonic contents reach a specific level that are more than what is considered normal, the risk of a flashover happening rises [17]. The chemical processes that take place on the surfaces of the materials eventually lead to surface discharge activity, which in turn leads to a degradation in the materials' electrical and mechanical characteristics. Both the establishment of tracking and a reduction in material weight are forms of deterioration that may be seen. In addition, tracking can be considered as a method of degradation. Both the size and the form of the LC are impacted when there is a change in the surface state of polymeric insulators. According to the findings of the mathematical study, there is a nonlinear connection between the temporal fluctuations of the leakage current, the surface discharge, and the length of the arc. The are will occur if the extension of surface discharge is greater than the electrical breakdown stress of the air. As a result, both the size and form of the LC will shift as a result of this. Therefore, RMS and the peak value of the current are insufficient metrics with which to evaluate the state of the surface. This ultimately results in the idea of doing a frequency domain analysis on the LC waveform [15]. But before using a tool for frequency domain analysis, the moving average approach is used on the LC waveform to smooth out the temporal fluctuation and provide a more accurate image of the LC pattern. This is done before using the tool for frequency domain analysis.

3.5.2. Moving Average Technique

In order to get an understanding of the typical fluctuation of LC over time, the approach of moving average technique is used. Because the characteristic variations are smoothed out as a consequence of having an average magnitude of the LC that moves with the addition of new data points, there are fewer fluctuations with time and as a result, there is a greater indication of the trend in the variation of the LC magnitude throughout the period. A simple explanation of what a moving average is and what it does may be summed up by saying that it is the magnitude of the current value on average at a given moment in time. There are a wide variety of moving average methods, such as the basic moving average method, the exponential moving average method, the time series moving average method, and many more. In this study, the approach of using a simple moving average has been used. When calculating the moving average using the expression given in equation (3.4), a window size that consists of k points is selected as the window size to use.

$$X_i = \frac{\sum_{N=i}^{N=i+k} Y_n}{k} \tag{3.4}$$

Where X_i are the calculated moving average points corresponding to each Y_N the raw data points. In this work frame 25 data points has been taken.

3.5.3. Fast Fourier Transform

The study that is carried out to determine the precise harmonic content of the leakage current signals is referred to as frequency domain analysis. The Fast Fourier Transformation (FFT) is the method that is used to extract the harmonic content that is present in the signals. The FFT analysis technique is an effective one that generates realistic results for large-scale signal processing.

Either the Fourier series or the Fourier transform may be used in order to convert the signal from the time domain to the frequency domain. One of the powerful tools for computing is known as the Discrete Fourier Transform, or DFT for short. This tool also has the ability to evaluate the Fourier Transform of a discrete signal. The DFT calls for about N2 times of performing complex multiplications, although this number may be cut down by making use of the symmetric features of the trigonometric functions. The Fast Fourier Transform (FFT) is a technique that was introduced by Tukey and Cooley in 1965. This approach reduces the number of operations required to compute DFTs by a factor that is proportional to N log N. It is for this reason that the FFT is considered to be a N log(N) algorithm. Since this is the case, the improvement in speed is on the order of (log, N)/N, where N is the length of the time series sampled.

Let x(t) be the time domain representation of the given signal x then the frequency domain representation of the signal x is given by in the equation (3.5).

$$X(f) = \int_{-\infty}^{\infty} X(t)e^{-j2\pi}\, dt \tag{3.5}$$

The amplitude spectrum of the leakage current in amperes rms is computed by the equation (3.6).

$$\text{Amplitude of LC } (I_{rms})=\sqrt{2}\,\frac{Magnitude[FFT(A)]}{N} \qquad \text{for i = 1 to (N/2-1)}$$

Where A is the leakage current in the frequency domain.

3.6. Hydrophobicity Measurements

The resistance of a substance to the passage of water over its surface is referred to as its hydrophobicity. It is claimed that a material is hydrophobic if it prevents water from flowing when it is dropped on it, and it is said that the material is least hydrophobic if the water flows leaving a trail on its surface after being dropped. A hydrophobic surface is one that is resistant to water absorption, in contrast to a hydrophilic surface, which is one that absorbs water readily. The contact angle (c) that a drop of liquid creates when it comes into contact with a solid surface may be used to define the hydrophobicity of any material; this angle is often employed as a measurement of the surface's wettability. Hydrophobicity is a measure of how easily a surface can be penetrated by liquid. The term "easily wettable" refers to a material that allows water to come into contact with a large surface area of the material and, as a result, has a contact angle that is significantly less than 90 degrees. In contrast, the term "hydrophobic" refers to a material that allows less water contact with the surface, which results in a contact angle that is greater than 90 degrees.

We are able to get information about the surface roughness, surface energy, and surface heterogeneity from the contact angle. High energy surfaces and low energy surfaces are the two primary categories that are used to describe solid surfaces. A surface with a high energy may be readily wetted, and the water will spread out across the whole surface to create a continuous film with a contact angle of zero. On the other hand, a surface with a low energy will reject water, which will result in the formation of individual droplets on the surface with a contact angle that is larger than 90 degrees. The contact angle may also be used as a tool for determining the degree to which a surface is contaminated. The contact angle that is created between a water droplet and the surface of an insulating material is used to quantitatively assess the hydrophobicity of the material. This angle is a direct reflection of the tension that exists between the atoms of the material and the water interface. Both the form of the liquid droplet and the contact angle are heavily influenced by the kind of solid material that is being tested for its hydrophobicity as well as the chemical and physical condition of the surface of the solid substance [32].

When the contact angle between a water droplet and a surface is less than 35 degrees, the surface is said to be hydrophilic. When the contact angle between the water droplet and the surface is more than 90 degrees, the surface is said to be hydrophobic. Surfaces with contact angles ranging from 35 degrees to 90 degrees are said to be somewhat wettable. It is important to note that the word "hydrophobicity" really means "resistance to water," but in common parlance, it refers to "resistance to any liquid."

Measurements of a substance's hydrophobicity performance may be divided into two categories: static hydrophobicity measurements and dynamic hydrophobicity measurements. The hydrophobicity of the raw material or the hydrophobicity of the material under normal stresses is the measurement that is considered to be static [40]. The measurements of hydrophobicity loss in the event of long exposure to electrical stress, hydrophobicity transfer in the event of contamination, and finally the hydrophobicity recovery when the electrical stress is removed or when the contamination is washed off, depending on the circumstances, are what are referred to as dynamic measurements.

3.6.1. Hydrophobicity phenomenon

It is vital to have a grasp of surface energy and surface tension before moving on to comprehend the hydrophobicity phenomena. The propensity of a fluid's surface to contract into the smallest possible surface area is what's meant to be understood by the term "surface tension." It may be described as follows for liquid air: The larger force of attraction that exists between molecules of a liquid (because to cohesion) as compared to the force of attraction that exists between molecules of air (due to adhesion) is what causes surface tension. The unbalanced forces have the effect of causing the surface to become tense, which is where the phrase "surface tension" originates from. The dimension of surface tension is either force per unit length or energy per unit area, depending on how you look at it. The two dimensions are comparable to one another; nevertheless, when discussing energy in terms of area, it is preferable to speak about surface energy since this concept is more universal and can be applied to solids as well. The excess amount of energy that exists at the surface of a material in comparison to the bulk is referred to as the surface energy. Or, to put it another way, the surface energy is the amount of effort that must be done in order to split a bulk sample in half, so producing two surfaces.

There is a correlation between the wettability of a surface and its contact angle [40-42]. The contact angle of a water droplet is reliant on the free energy of the surface, and the wettability of the surface is connected to its contact angle. The Young's equation, which is shown as equation (3.7), establishes the interconnections between the free energies. Surface tension and surface energy are synonymous terms that may be used interchangeably. A water droplet is seen in Figure 3.1, along with the contact angle that is generated and the surface tension that is present at the interface.

$$cos\theta_y = \sigma_s - \sigma_{sl}/\sigma_l \tag{3.7}$$

where θ_y= *Young's* contact angle

σ_s= surface tension of the solid

σ_{sl}= surface tension of the solid-liquid surface

σ_l=surface tension of the liquid.

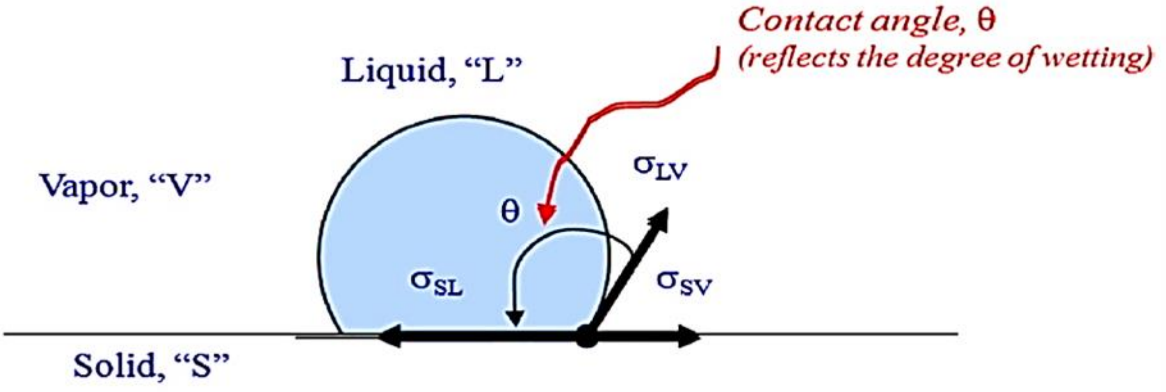

Figure 3.1: contact angle and surface tension for water droplet

When distinct phases of solid and liquid are brought together, there will be some adhesion, and the energy associated with this is represented as $w_c = 2\sigma$. The energy required to create two new surfaces is denoted by the symbol a, and the energy required to maintain cohesion is denoted by the symbol w_{sl}. The energy required for a pure phase is denoted by the symbol We = 20. The Dupre equation (3.8) describes the connection that exists between the amount of energy needed to separate the liquid from the solid and their surface energy expressed as a function of the unit area of contact.

$$\sigma_{sl} = \sigma_s + \sigma_l - w_{sl} \tag{3.8}$$

For two identical which adhere perfectly,$\sigma_s = \sigma_l$ and $W_{sl} = W_C$ therefore $\sigma_{sl} = 0$.

On combining equation (3.7) and (3.8) the resulting equation (3.9),

$$w_{sl} = \sigma_{sl}(1 + cos\theta_y) \tag{3.9}$$

All solid surfaces that have higher values of σ_s than the surface free energy of water will be wetted by it, and those that have lower values will not be wetted. The lower the value of σ_s the greater the contact and angle.

3.6.2. Hydrophobicity Measurement Methods

The preceding explanation has made it abundantly clear that hydrophobicity measurements are necessary for examining the status of outdoor insulators, particularly those that are located in situations that are both wet and near the shore. The sessile drop technique, which involves measuring the contact angle, and the STRI classification guide are the two primary approaches that are used in the process of determining a substance's hydrophobicity.

3.6.3. STRI classification Method

STRI, which stands for the Swedish transmission research institute, came up with an innovative approach for measuring hydrophobicity by categorising the various phases of hydrophobicity. Spraying a cleaned surface of about (50-100 cm3) with distilled water in order to assess its hydrophobicity is what the STRI technique entails. This procedure is relatively straightforward. One of the seven different classes of hydrophobicity, ranging from HC1 to HC7, is responsible for the drop pattern that is left behind on the surface [27]. The most hydrophobic surface is denoted by the letter HCI, whereas the surface with the least hydrophobicity is denoted by the letter HC7. Figure 3.2 is a reference guide for the STRI classification, and it covers HCI all the way up to HC6.

3.6.4. Contact Angle Measurement

The STRI categorization technique has the disadvantage of relying on human judgement, which means that the results might differ depending on who is doing the judging. In order to get over this obstacle, the sessile drop method or the contact angle measurement is used to determine the hydrophobicity [35]. Using a syringe, a drop of water is deposited onto the surface whose hydrophobicity will be tested in order to carry out this approach. A goniometer is used to get an accurate reading of the contact angle. When the volume of the drop is held constant, the contact angle measurement may be relegated to the category of the contact angle measurements. When measuring the advancing and receding contact angles of a water droplet, the volume of the droplet is increased until it just starts to flow for the advancing contact angle measurement, and the water content is decreased until the droplet begins to recede for the receding contact angle measurement. This allows for a more in-depth analysis of the advancing and receding contact angles. The advancing and receding contact angles are shown here in Figure 3.3.

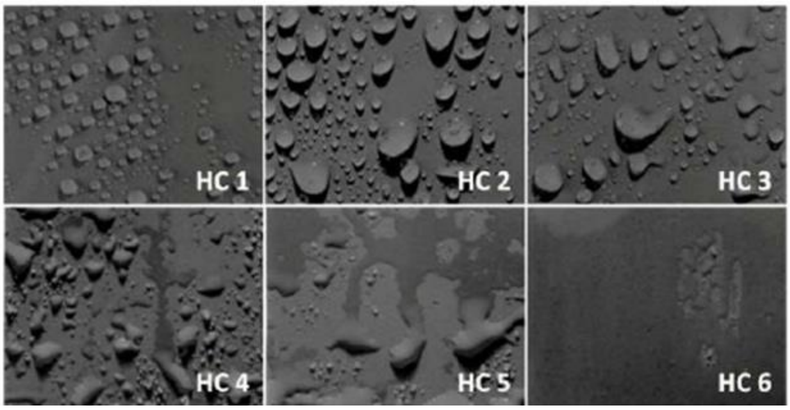

Figure 3.2: Hydrophobicity classification from HC1 to HC7[39]

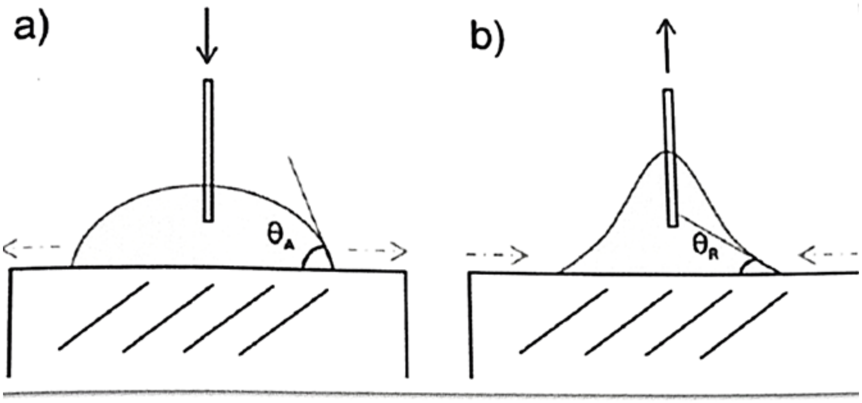

Figure 3.3: (a) Advancing contact angle; (b) Receding contact angle [43]

CHAPTER-4

SAMPLE PREPARATION AND EXPERIMENTAL PROCEDURE

Chapter-4

4.1. Introduction

Samples of vulcanized silicone rubber made at room temperature with different amounts of alumina nanofiller were mostly put through two tests: the leakage current test and the hydrophobicity test. The details of the raw materials used, the laboratory equipment employed, the experimental setup, their schematic diagram and the experimental procedures are discussed in this section.

4.2. Material Used

In the last chapter the detailed structure of the base polymer of Silicone Rubber (SIR) has been shown and the usage of different extending and reinforcing fillers has been discussed. In this study, a two-part room temperature vulcanised (RTV) SIR without any preloaded filler was used. It was bought from a distributor of Chemzest technoproducts Pvt Ltd as which comes with a catalyst for hardening LSR-2 series. The potting glue and the catalyst are shown in Figures 4.1 and 4.2. This potting gel is used to coat insulating material as well as embedding and potting electrical and electronic equipment. In its uncured state, it is a thick, sticky liquid that is clear and has a specific gravity of 0.97 at 25°C. For a detailed understanding of its usage and working time the technical data sheet has been referred to [12].

Next, to evaluate the performance of SiR with the addition of filler, we zeroed in on alumina filler, which has traditionally been used as reinforcing filler for the purpose of providing mechanical strength. Among the various fillers that are commercially used, such as aluminium trihydrate, silica, zinc oxide, and titanium oxide, among others, we found that alumina filler performed the best. silica, precipitate alumina, and a mixture of fumed and precipitate alumina are the three main forms of alumina filler that may be used as reinforcing filler.Alumina is the most common type of alumina filler. FANG Su *et al.* [14] conducted research to investigate the influence that each of these three distinct fillers has on the RTV SIR's tensile and shear strengths.. Observing the impact is the primary purpose of this investigation. Alumina filler on the dielectrics and surface qualities of SR. In this work, fumed silica gel was used as a filler, and Acrosil fibre was used as a filler. Figure 4.4 shows a picture of Alumina(alpha) nano fillers container . Casts made of 90mm alumina have been used. Figure 4.3 represents the aluminium cast which is used for mixing purpose.

Figure 4.1: RTV SiR Liquid

Figure 4.2: Hardener

Figure 4.3: 90mm diameter aluminium cast

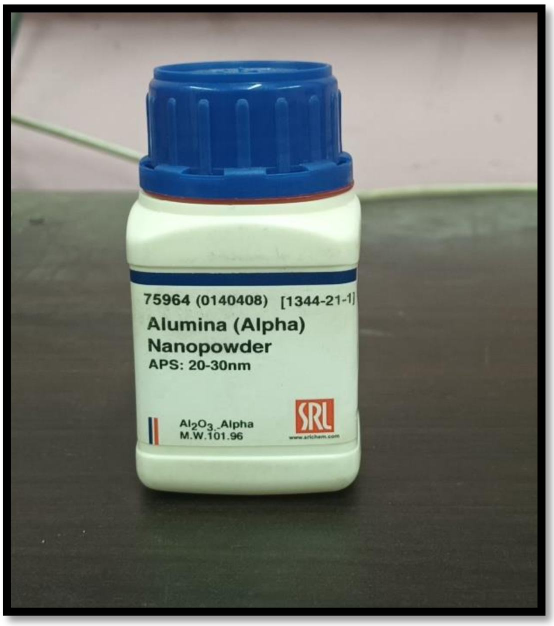

Figure 4.4: Nano fillers

4.3. Equipment

In order to carry out this experimental work, a significant amount of laboratory equipment was required. This equipment, along with others such as those for sample mixing, degassing, measuring leakage current, and determining hydrophobicity, may all be found in the high-tension Laboratory at Jadavpur University. This section includes a rundown of the many pieces of equipment that were used, an explanation of their function, as well as a graphical illustration of that function.

4.3.1. Electronic Analytical Balancing Unit

A type of balance shown in Figure 4.5. called a "analytical balance" is used to measure small amounts of mass, like sub-milligram amounts. The measure pan of an analytical balance (0.1 mg or better) is inside a clear box with doors to keep dust out and keep the balance from being affected by air currents in the room. People often call this structure a draught guard. When you use a manually vented balance safety cage with specially designed acrylic air foils, you get a smooth, turbulence-free airflow that keeps the balance from shifting and lets you measure mass down to 1 g without any shifts or product loss. Also, the sample must be at room temperature to keep air currents from building inside the container due to natural convection, which could throw off the reading. Single-pan mechanical replacement balances have a consistent reaction throughout their useful capacity. This is done by keeping a steady load on the balance beam and, by extension, the pivot, by taking mass away from the same side of the beam where the sample is added. Electronic analytical scales don't use real masses to measure. Instead, they measure the force needed to counter the mass being measured. Because of this, they need to be re-calibrated to account for changes in gravity pull. They use an electromagnet to create a force to balance out the sample being tested, and they get the answer by measuring how much force it takes to get the sample to balance out. An electromagnetic force repair monitor is a device used to measure things like this.

Figure 4.5: Analytical Balancing Unit

4.3.2. Goniometer

One of these approaches is the STRI classification, and the other is the measurement of the contact angle. Both of these methods may be used to determine the hydrophobicity of a substance. The instrument that assists us in determining the contact angle is called a goniometer. The configuration of the goniometer in the laboratory is shown in Figure 4.6. It first takes a picture of the water droplet that is on the sample, and then, using a process called pixel calibration, it determines where the triple point of contact is between the air, the water droplet, and the sample. After that, it determines the angle of contact between the water droplet and the sample surface using a variety of different techniques, including the tangent, the ellipse, and the half angle, among others. The apparatus includes a water dispensing system that may be operated manually and has a minimum volume that can be controlled of 0.20 l. The apparatus makes use of a source of controlled light for contrast and precise contact angle measurement over a range of sample colours. In addition to that, it has a tilting function for measuring contact angles of uneven and distorted samples. It has a pixel resolution of 744 by 480, which is rather high. The frame rate is set at 75 frames per second, and the magnification power is 5. The goniometer that Apex instrument offers boasts of an accuracy of up to +0.5 degrees.

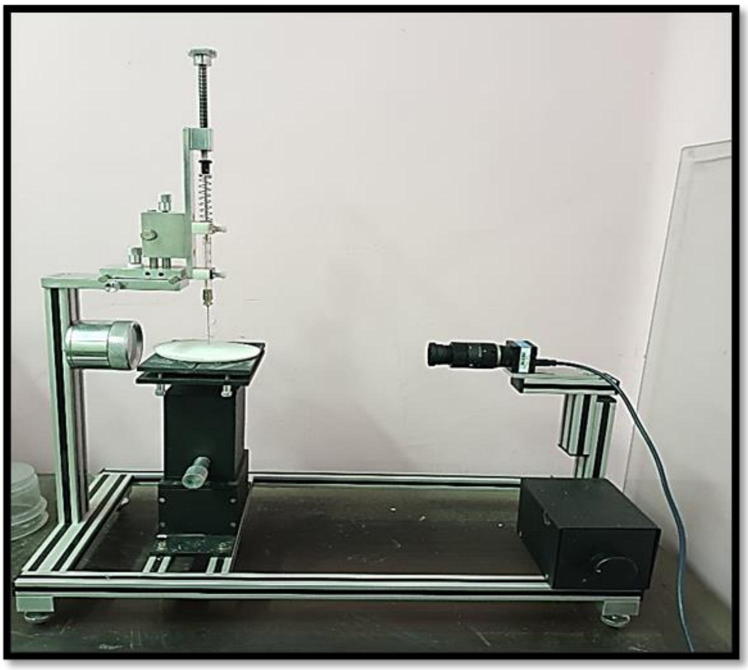

Figure 4.6: Goniometer

4.3.3 Degassing Unit

During the sample preparation process, degassing or vacuuming is an extremely critical step because gaps or the presence of gas bubbles that are trapped within a material significantly decrease its insulating characteristic. Moulds containing elastomers are introduced into the degassing unit as part of the degassing process. Because a reduction in pressure, according to Henry's Law, lowers the solubility of air bubbles and gases in elastomers, causing their evolution, the application of vacuum reduces the pressure within the chamber, resulting in the evolution of gases and air bubbles. This is because the application of vacuum reduces the pressure inside the chamber. Attaching a pump to the chamber's outlet and drawing air out of it to create a vacuum, which results in a decrease in pressure, is the standard method of vacuuming. During the process of preparing the sample, vacuuming is performed twice: the first time, immediately after pouring the uncured rubber, and the second time, after adding the filler and the catalyst. The degassing equipment is capable of reaching pressures as high as -1 atmosphere. The degassing unit that is accessible in the laboratory is seen in Figure 4.7.

Figure 4.7: The Degassing unit

4.3.4. Magnetic stirrer

In Figure 4.8, you can see the electrode magnetic stirrer that was used for the mixing of liquid with catalyst. Magnetic stirrers use a spinning magnetic field to move a stir bar around in a sample of liquid. Some magnetic stirrers also have a hot plate that stirs the liquid. This stir bar moves quickly and agitates the samples so that they are fully mixed. The user can change the speed of the magnetic field so that it fits the sample that is being mixed. To keep the magnetic field from getting messed up, these stirrers should be used with glass or other non-metal beakers.

Figure 4.8: Magnetic Stirrer

4.3.5. Digital Storage Oscilloscope

The TEKTRONIX TBS1152 digital storage oscilloscope was used in order to conduct the measurement for leakage current. Through the USB 2.0 host port located on the front panel, it is used to facilitate the rapid and uncomplicated storing of leakage current data inside a flash drive. It features a sampling rate of up to 1 GS/s, a bandwidth of 150 MHz, and a data record length of 2500 points on both channels. The maximum sampling rate is 1 GS/s. The picture of a digital storage oscilloscope is shown in Figure 4.9.

Figure 4.9: Digital Storage Oscilloscope

4.4. Sample Preparation

When samples of insulating material are created in a laboratory, the actions that are taken to prepare them always have an effect on the dielectric and surface characteristics of the material. Therefore, as was covered before in the section, the important actions that were taken are covered as follows:

1. Both the mixing container and the castings are given a thorough cleaning with ethyl alcohol to remove any form of contaminant that could be present.

2. After that, The RTV silicone rubber and hardener is placed on degassing unit at 40^{o}C for 2 hrs, after that the RTV silicone rubber is poured into the mixing container gently so that as little air as possible is entrapped within.

3. The measured amount of weight percentage of filler is placed in the heating chamber for 24 hrs at a constant temperature of 150^{0}C in order to dehumidify the nanofiller. Thereafter, the nanofiller is mixed with the RTV silicone rubber along with catalyst in a mechanical stirrer for 1 hour at a speed of 750 r.p.m. Afterwards, the mixing placed in the degassing unit once more for 15 minutes at a constant pressure of -1 atm.

4. Because degassing causes the release of previously trapped air pockets, the impact of uniform dispersion produced by Mixing through ultrasonic agitation at 24 kHz for 1 hour followed by degassing. After that, the predetermined quantity of catalyst is added (1 ml of catalyst for every 30 ml of RTV silicone rubber), and the mixture is then mechanically mixed for ten minutes. After that, it is placed in a degassing machine for fifteen minutes at a pressure of -1 atmosphere.

5. Following the degassing step, 18.5 grammes of samples were poured into each cast in order to keep the thickness of the samples at 3 millimetres throughout the whole batch. While the samples were being poured, each of the casts was placed once again in the degassing equipment for a period of five minutes to remove any air that had been trapped.

6. The castings are stored in a protected atmosphere so that any dust or other particles don't end up settling on the surface of the object. After the samples have been allowed to sit undisturbed for around six hours, the creation of the skin will begin to take place. After a period of 4 hours, the samples may be withdrawn from the cast as they have reached their final state of cure.

7. It is recommended to run tests on samples after 48 hours have passed after the samples have been completely cured in order to account for the possibility that sample settling and internal bond forms are still occurring.

The results of the laboratory's work are shown in figure 4.10 in the form of five samples of alumina with varying concentrations of filler and the flow chart of the total work has been shown in the Figure 4.11.

Table 4.1: Sample Details of Silicone rubber composite

Name	Description
S1	Pure Silicone rubber
S2	Silicone Rubber + 0.25%wt alumina
S3	Silicone Rubber + 0.5%wt alumina
S4	Silicone Rubber + 1%wt alumina
S5	Silicone Rubber + 1.5%wt alumina

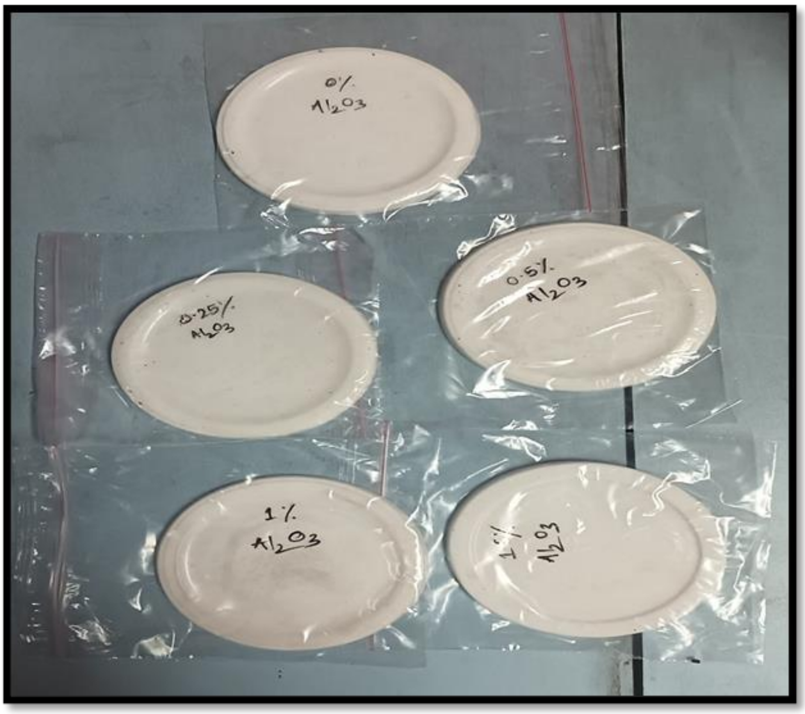

Figure 4.10: RTV SiR samples with difference filler concentration

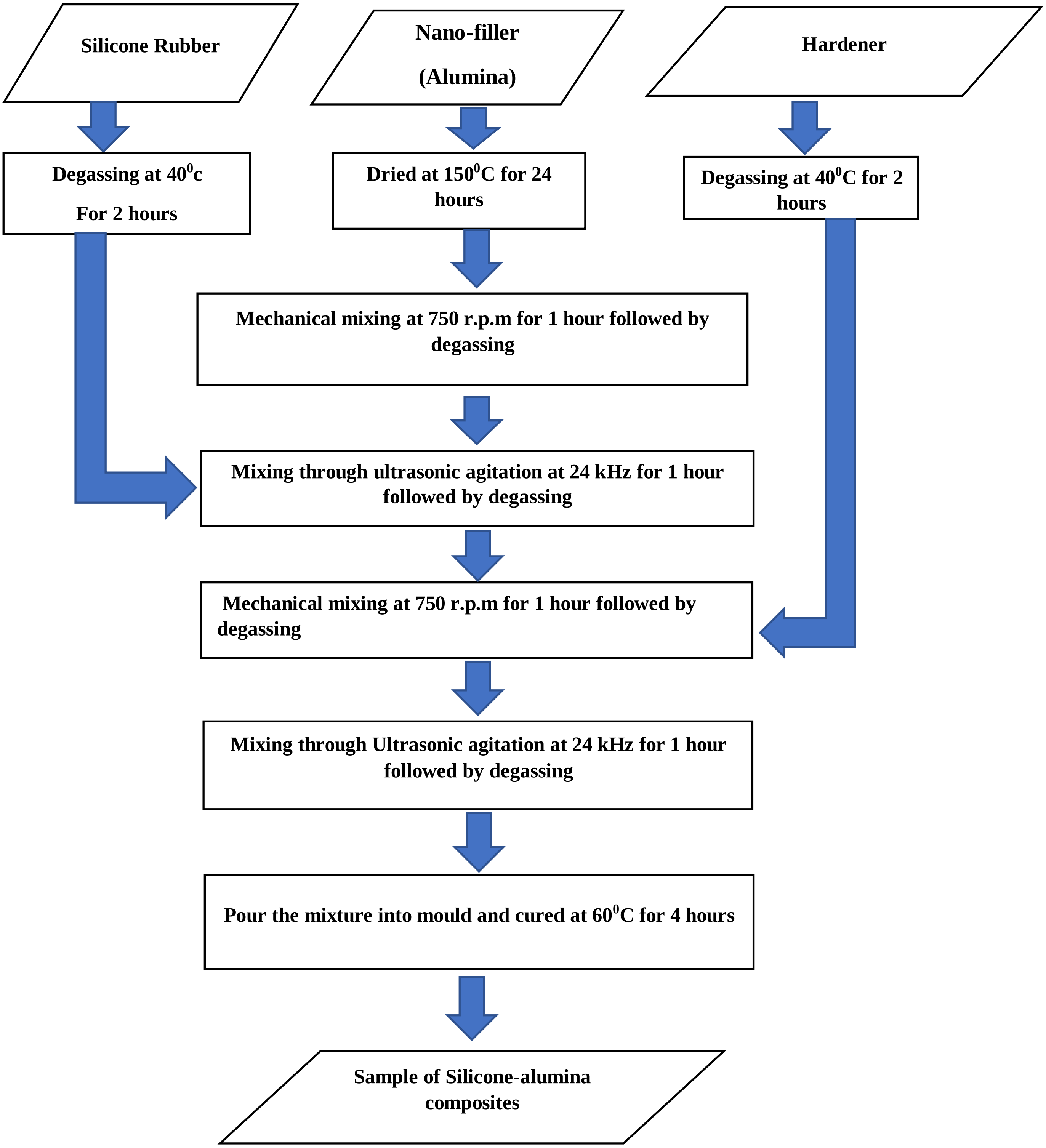

Figure 4.11: Flowchart of the preparation of silicone-alumina nanocomposites samples.

4.5. Leakage Current Measurement

Figure 4.12 depicts a diagrammatic representation of the experimental setup, and Figure 4.13 depicts the actual experimental setup in its entirety. The high voltage source, which may be anywhere from 0 to 10 kilovolts, is linked to the top electrode of the electrode arrangement. The sample is positioned in between the electrodes with the greatest accuracy in order to ensure that the centres of the electrode and the sample are properly aligned. If this is not done, it is possible that the length of the leakage current route on each side will be different. The leakage current travels from the ground electrode to the current divider circuit. From there, the voltage magnitude across the series resistor is sent to the digital storage oscilloscope (DSO), which measures the LC across the samples that are located between the electrodes. The information that was saved to the flash memory of the DSO is copied into the personal computer so that it may be analysed further using the LC waveform that was acquired. In addition, an overvoltage safety circuit is connected across the measuring instrument in order to safeguard it from any overvoltage that may occur as a result of an accident involving the experimental setup.

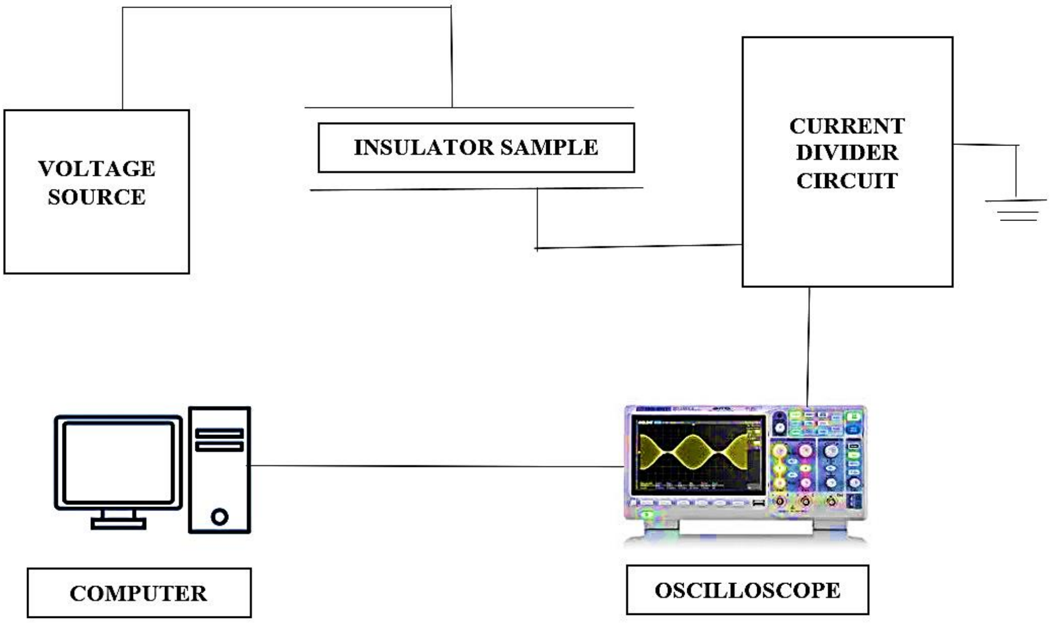

Figure.4.12: Schematic diagram of the LC measurement setup

Figure.4.13: Actual diagram of the LC measurement setup

4.6. Hydrophobicity Measurement

The goniometer was used in the laboratory for the purpose of conducting hydrophobicity tests. The experimental apparatus is shown in Figure 4.14. Before beginning the measurements, the surface on which the contact angle measurements will be performed was meticulously cleaned to remove any dust particles that might be present. After that, the surface was discharged by placing a grounded electrode on it for five minutes; this ensured that there was no charge left on the surface, which is important because the presence of charges on the surface has a significant impact on the accuracy of contact angle measurements [39]. The picture is taken by the camera, and when it has been recorded, it is examined by some software. The sample is then positioned on the surface, and the water droplet with a volume between 4.97 and 5.17 l is positioned in the ACAM that has been given by the apex instruments. The picture that was sent by the goniometer may be seen in Figure 4.15. The user decides where the base line will be, and then a fitting technique is selected; in this instance, the tangent approach was selected since it is the one that works best when the contact angle is higher than 90 degrees. The reading was then exported to an excel file and displays the final contact angle as the average of the two measurements taken from the left and right sides of the droplet. The measurement indicates the contact angle of the droplet as measured from both sides. It was always made sure that there were no other particles in the neighbourhood of the droplet since doing so makes the test more difficult and leads to an inaccurate assessment of the contact angle. Second, the value of the contact angle is highly dependent on the size of the water droplet; hence, for the purpose of this comparison research, it was maintained within the aforementioned range. An additional step was taken to eliminate any discrepancies or incorrect readings by taking the average of five measurements for each sample.

In order to perform dynamic hydrophobicity measurements, the samples were artificially contaminated in accordance with the standards set forth in IEC 60507 for a contamination level of approximately 0.1 mg/cm2 for equivalent salt deposit density (ESDD), and approximately 1 mg/cm2 for non-soluble salt deposit density (NSDD), both of which represent a medium level of pollution severity. The sample that had been contaminated was allowed to dry out, and then the hydrophobicity transfer was assessed after 96 hours had passed. The contamination was removed using water, and then the samples were washed and cleaned with acetone in preparation for the hydrophobicity recovery measurement. After removing the pollutant and waiting for forty-eight hours, another measurement of the contact angle was taken.

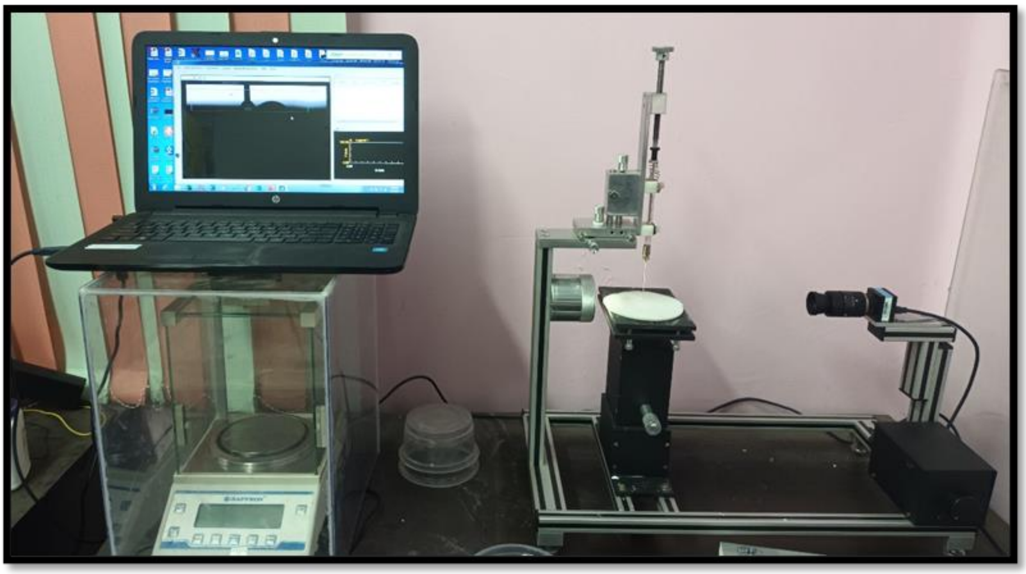

Figure 4.14: Contact Angle measurement setup

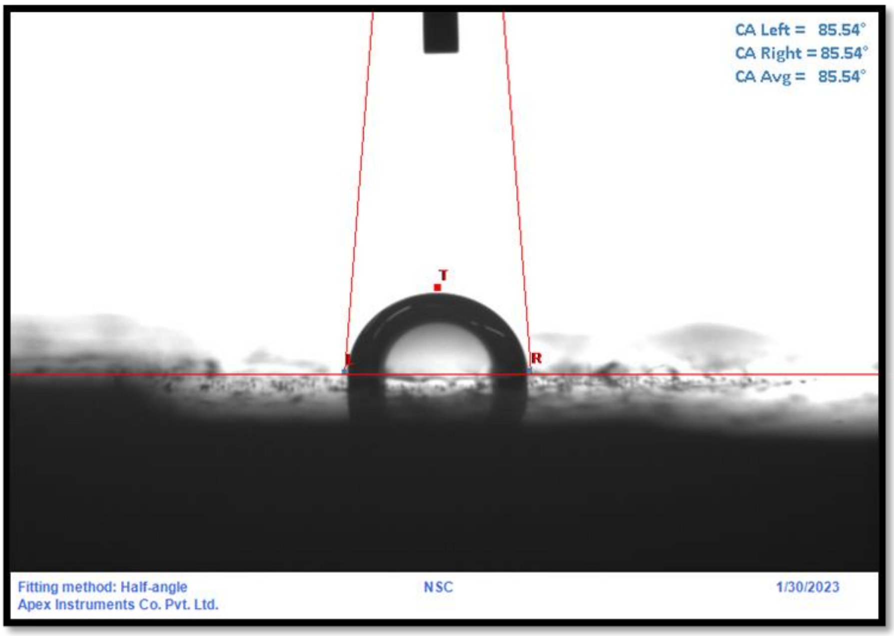

Figure 4.15: Image transmitted to ACAM software

CHAPTER-5

RESULTS AND DISCUSSIONS

5.1. Introduction

Insulators made of silicone rubber (SiR) have been employed in electrical power systems for a long time, primarily because of their capacity to suppress significant amount of Leakage Current (LC) even in extremely polluted and humid environments. This ability has been the primary reason for their widespread usage. In addition to this, it is well known that SiR insulators have outstanding hydrophobic characteristics and it is needed to find the hydrophobicity variation in SiR with the use of nano fillers. This chapter describes the effect of varying Alumina (Alpha) fillers in (SiR) The findings from the experiments, which are so acquired, may be roughly categorized as

I. Study of the effect of filler material on Leakage Current.
II. Study the effect of filler material on Harmonic present in Leakage Current (LC).
III. Study the effect of filler material on Hydrophobicity.

5.2. Study of the effect of filler material on Leakage Current

I. Variation of Maximum Leakage current waveform for different voltage level.
II. Percentage change in maximum current at different voltage level.

5.2.1. Variation of Maximum value of leakage Current & percentage change in current:

Figure 5.1 shows that how leakage current is varying along with variation of nano filler percentage at both contaminated and uncontaminated situations at 3kV

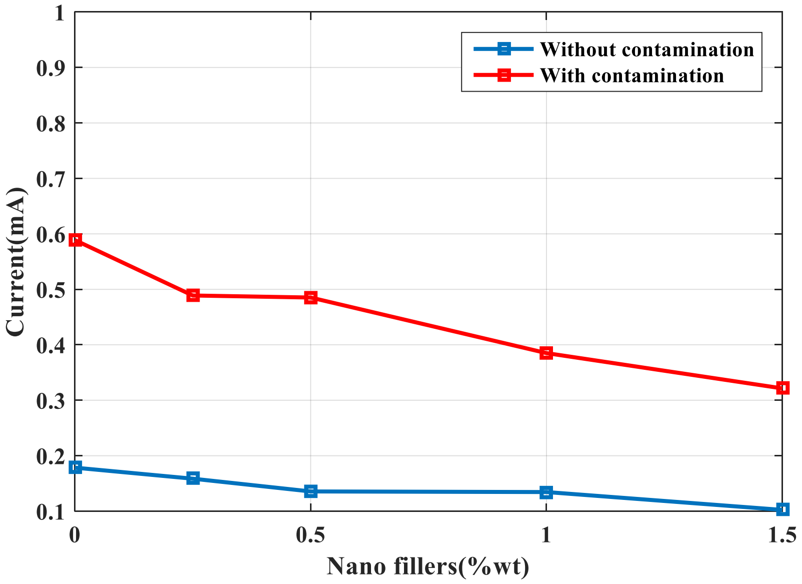

Figure 5.1: Variation of the maximum value of Leakage Current with different filler concentration of SiR at 3 kV (with Contamination and without Contamination)

Table 5.1. Variation of maximum Current Value with and without contamination at 3 kV

Leakage Current (mA)			% Change in Leakage current	
Sample	**Without Contamination**	**With Contamination**	**Without Contamination**	**With Contamination**
S1	0.0875	0.3832	_	_
S2	0.0632	0.3323	-27.77%	-13.28%
S3	0.0612	0.2877	-30.05%	-24.68%
S4	0.0557	0.2552	-36.34%	-33.40%
S5	0.0533	0.2272	-39.08%	-40.70%

The percentage change in leakage current at different voltage have been calculated as shown in the above table. Here the leakage current value of S1 has been taken as a reference. With respect to value of S1, the percentage change in other sample's current has been tabulated format. The formula that has been used to calculate the value of percentage change in current has been shown in the below equation,

$$\text{\% change in Current} = \frac{Measured\ Value - Reference\ \ Value}{Reference\ Value} \times 100$$

Here Leakage current of "S1" sample is Reference value and remaining sample's value of leakage current is Reference Value.

From the above graph it can be concluded that the value of Leakage Current decreasing as the concentration of fillers has been increasing. Based on the information in the table, it can be seen that the value Leakage Current of samples S2, S3, S4, and S5 are lower than the reference sample (S1). The percentage change in maximum current value is increasing as we go from upward to downward of the table which means that current is decreasing in a linear manner. The maximum change in current at uncontaminated condition is -39.08% and maximum change in current at contaminated situations is -40.70%. o it has been shown that an increase in the quantity of nanoparticles in the mixture leads to a decrease in the amount of current that leaks out of the silicon rubber barrier. This finding is important because it shows how nanoparticles could be used to improve the electrical qualities of materials that don't conduct electricity.

Figure 5.2 shows that how leakage current is varying along with variation of nano filler percentage at both contaminated and uncontaminated condition at 4 kV.

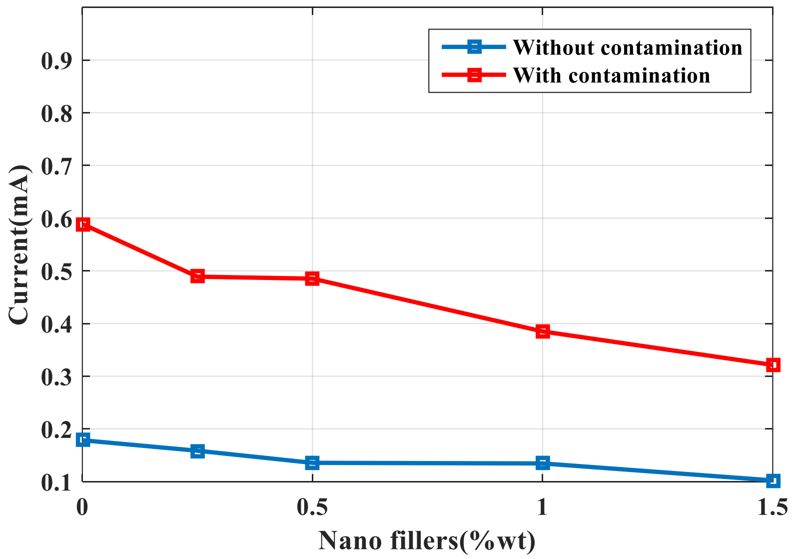

Figure 5.2: Variation of the maximum value of Leakage Current with different filler concentration of SiR at 4 kV

Table 5.2: Variation of Maximum Current Value with and without contamination at 4 kV

	Leakage Current(mA)		**% Change in Leakage current**	
Sample	**Without Contamination**	**With Contamination**	**Without Contamination**	**With Contamination**
S1	0.1785	0.5889	-	-
S2	0.1586	0.4889	-11.14%	-12.52%
S3	0.1356	0.4852	-24.03%	-13.18%
S4	0.1345	0.3850	-24.64%	-31.14%
S5	0.1023	0.3214	-42.62%	-42.49%

It is possible to draw the following conclusion after examining the graph: the value of Leakage Current has been dropping while the concentration of various fillers has been growing. According to the data in the table, it is possible to deduce that the values of the samples S2, S3, S4, and S5 for the parameter "Leakage Current" are lower than the value for the "reference sample" (S1). As it is gone from the top to the bottom of the table, the % change in maximum current value increases, which indicates that current is dropping in a linear fashion. When it comes to uncontaminated settings, the greatest change in current is -42.68%, while when it comes to contaminated situations, the maximum change in current is -42.49%.

Figure 5.3. Shows that how leakage current is varying along with variation of nano filler concentration at both contaminated and uncontaminated situations at 5 kV.

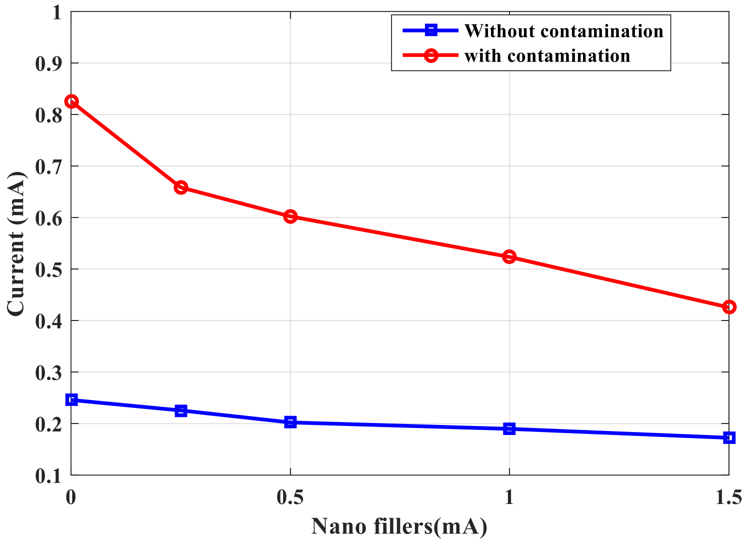

Figure 5.3: Variation of the maximum value of Leakage Current with different filler concentration of SiR at 5 kV.

Table 5.3. Variation of Maximum Current Value with and without contamination at 5 kV

Leakage Current(mA)			**% Change in Leakage Current**	
Sample	**Without Contamination**	**With Contamination**	**Without Contamination**	**With Contamination**
S1	0.2459	0.8256	_	_
S2	0.2256	0.6586	-8.25%	-17.73%
S3	0.2023	0.6023	-17.73%	-22.81%
S4	0.1898	0.5235	-22.81%	-29.84%
S5	0.1725	0.4256	-29.84%	-48.44%

The above graph shows the decrement of the Leakage Current with the variation of the nano fillers. In that graph, it can be seen that the maximum value of the Leakage Current at uncontaminated condition is “0.8256” and the minimum value is “0.4256”, therefore it can be said that the percentage decrement is almost 50% which is positive outcome for this experiment.

From looking at tables 5.1, 5.2, and 5.3, it is clear that the value of the leakage current at different voltages goes down as the amount of nanoparticles in silicon rubber goes up. This phenomenon occurs in both scenario (with and without contamination), as the tables show. It is also possible to deduce, using the table that has just been shown that the difference in current between the two scenarios without nano particles and with nano particles is enormous, although the difference in current between the two nano particles of difference % is smaller. This indicates that the value of reducing leakage current in percentage terms is fairly low, despite the fact that the proportion of nanoparticles is increased. However, this does not suggest that the percentage of nanoparticles is increasing. Nevertheless, nanoparticles contribute to a reduction in the amount of current lost via leakage. In fact, studies have shown that even a small proportion of nanoparticles can significantly reduce leakage current. This is because nanoparticles have a high surface area to volume ratio, which allows them to form a dense and uniform layer on the surface of the material. This layer acts as a barrier, preventing electrons from escaping and reducing the amount of current lost through leakage. Additionally, nanoparticles can also improve the overall performance of electronic devices by enhancing conductivity and increasing the efficiency of charge transport. As such, incorporating nanoparticles into electronic materials has become an increasingly popular strategy for reducing leakage current and improving device performance. While there may be some limitations to this approach, such as cost and scalability issues, it is clear that nanoparticles hold great promise for advancing the field of electronics and paving the way for new technologies in the future.

5.2.2. Study the effect of filler material on Harmonic present in Leakage Current (without contamination)

On the data on the leakage current that was gathered for the samples at the three distinct voltage levels, a Fourier transform is carried out. The results that were obtained from the Fast Fourier Transform (FFT) of LC at different voltages are shown in below tables. It can be seen that an increase in the Alumina filler concentration leads to a decrease in the LC harmonic components, and this is also justified by given values in tables, which displays the values of odd harmonics all the way up to the 7th harmonic.

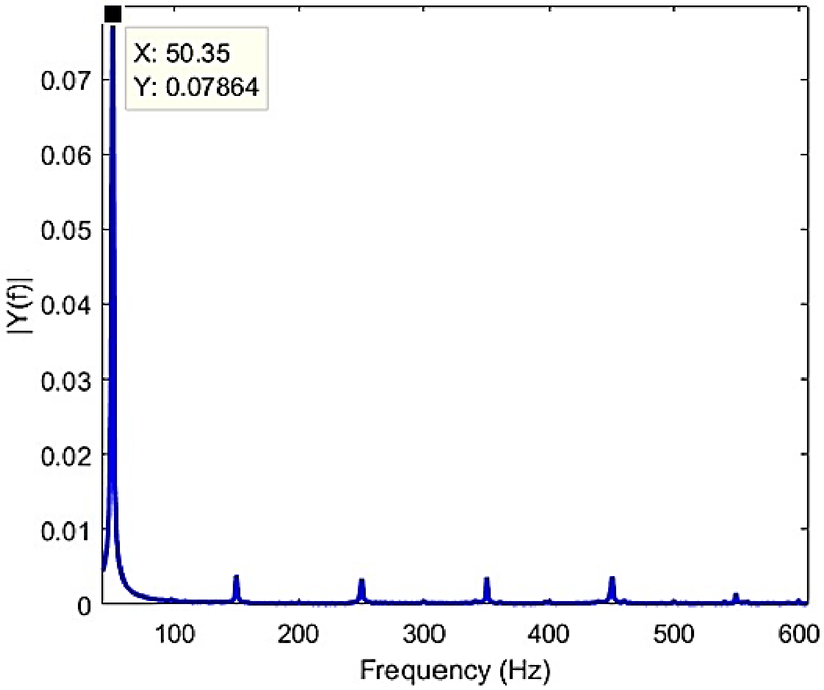

Figure 5.4. Harmonic content of SiR with 0wt% nano fillers concentration at 3kV

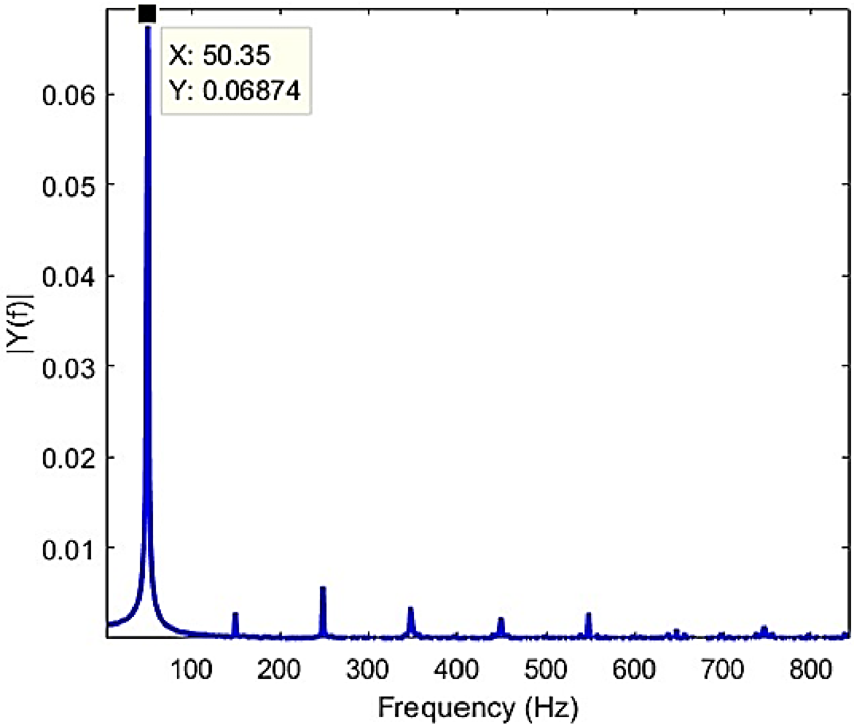

Figure 5.5. Harmonic content of SiR with 0.25wt% nano fillers Concentration at 3kV

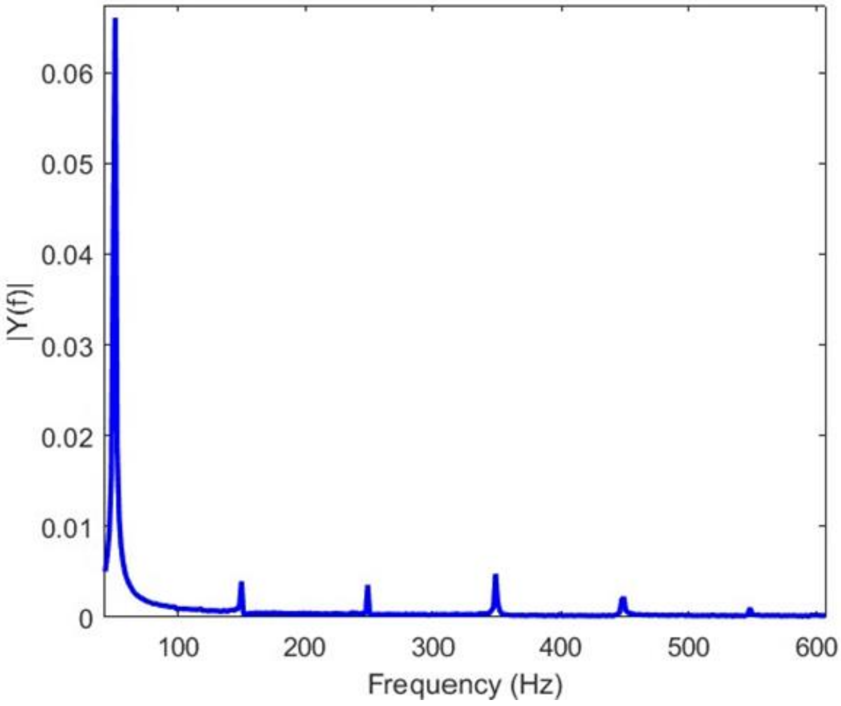

Figure 5.6. Harmonic content of SiR with 0.5wt% nano fillers Concentration at 3kV

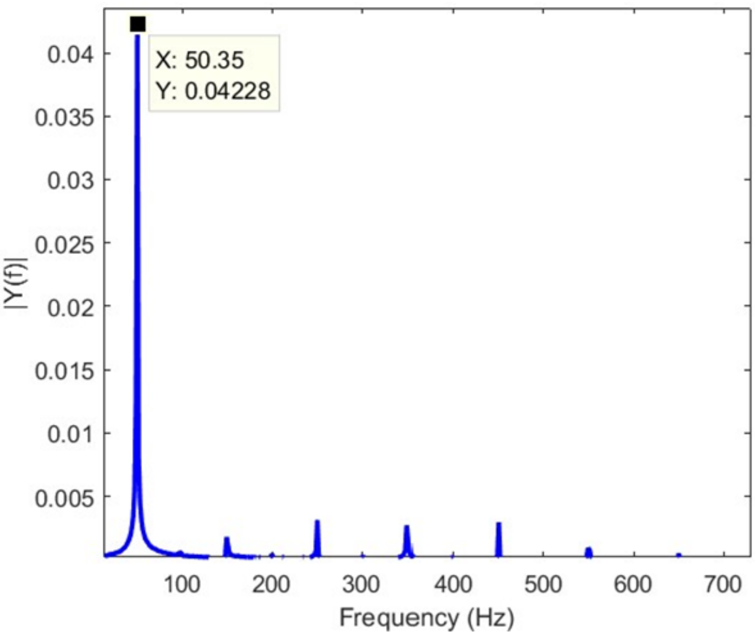

Figure 5.7. Harmonic content of SiR with 1wt% nano fillers Concentration at 3kV

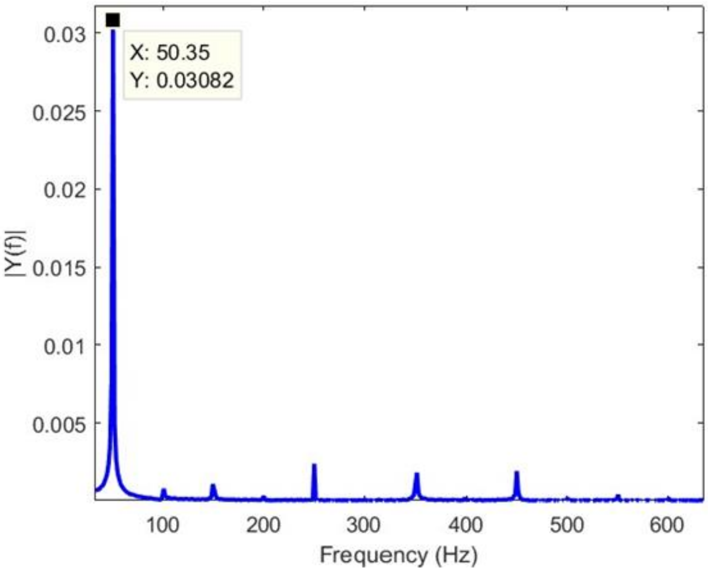

Figure 5.8. Harmonic content of SiR with 1.5wt% nano fillers Concentration at 3kV

Table 5.4: Variation in harmonic content of leakage current with increase in filler percentage at 3kV

Harmonic Order	S1	S2	S3	S4	S5
3rd harmonic	0.003925	0.00188	0.00158	0.00123	0.00075
5th harmonic	0.003511	0.00247	0.00231	0.00145	0.00123
7th harmonic	0.002965	0.00235	0.00185	0.00105	0.00895

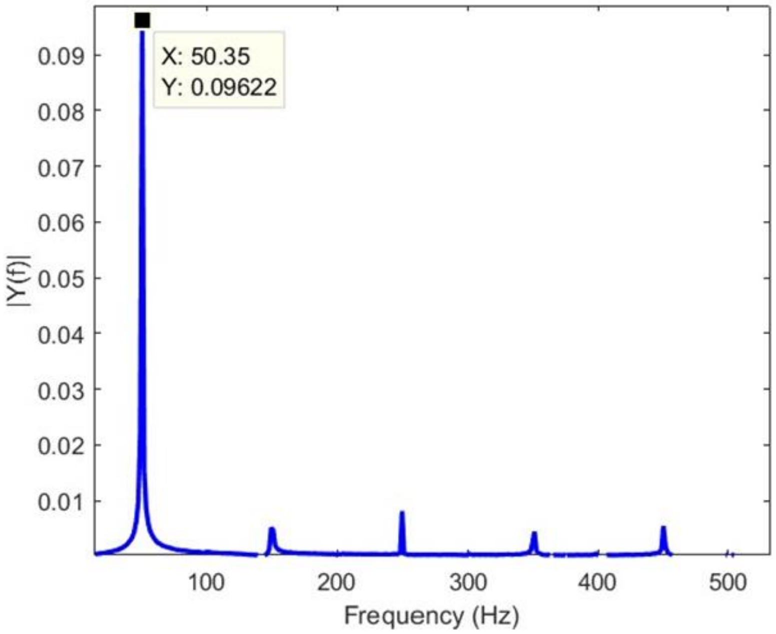

Figure 5.9. Harmonic content of SiR with 0wt% nano fillers Concentration at 4kV

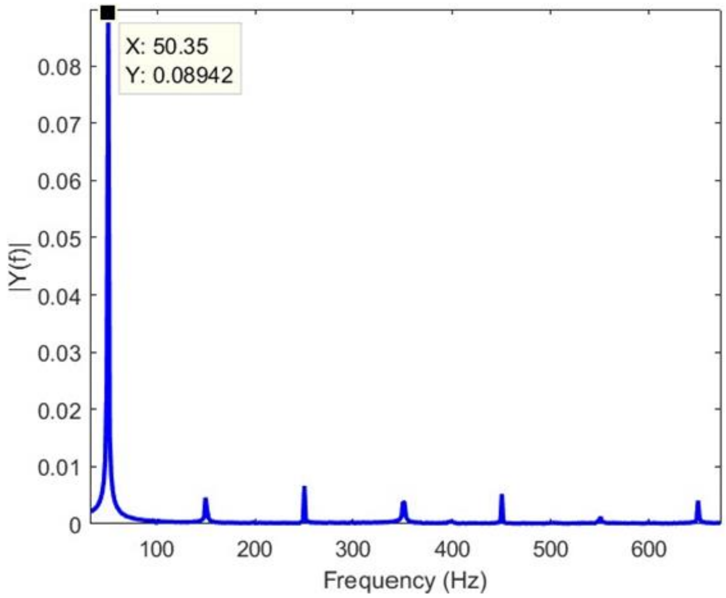

Figure 5.10. Harmonic content of SiR with 0.25wt% nano fillers Concentration at 4kV

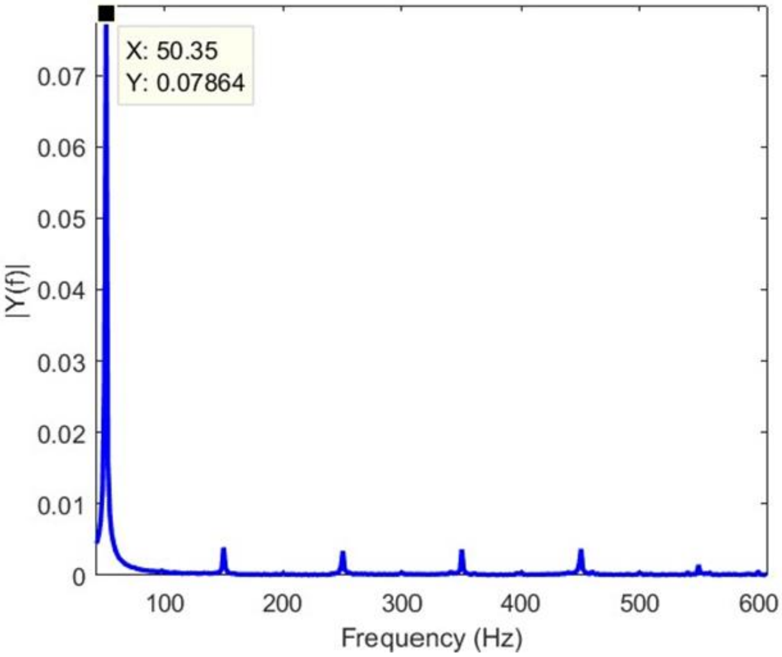

Figure 5.11. Harmonic content of SiR with 0.5wt% nano fillers Concentration at 4kV

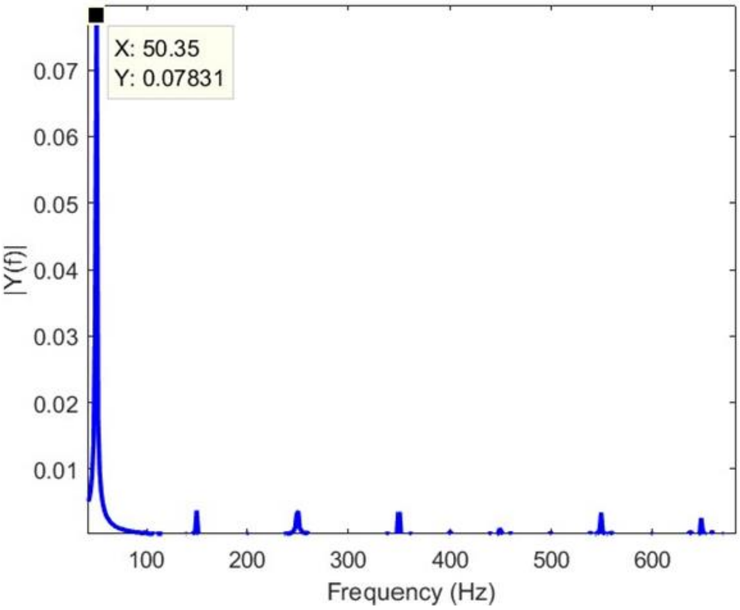

Figure 5.12. Harmonic content of SiR with 1wt% nano fillers Concentration at 4kV

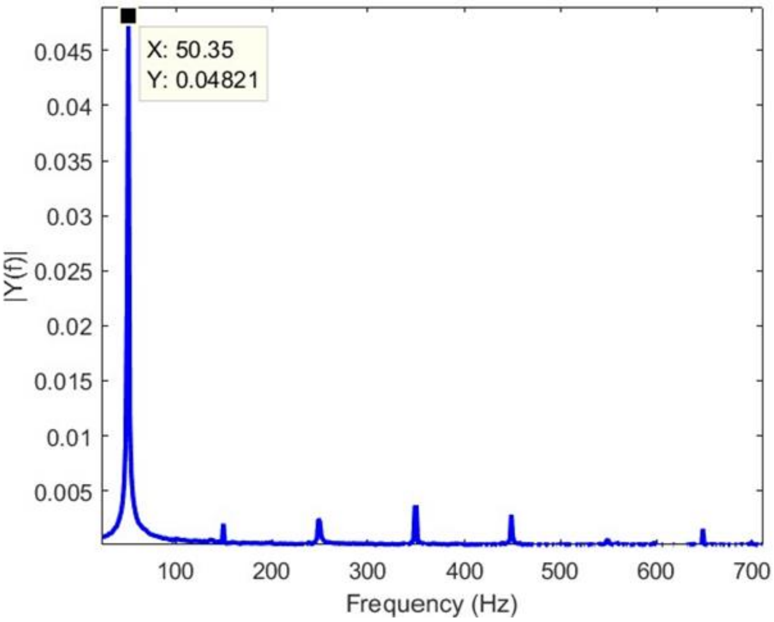

Figure 5.13. Harmonic content of SiR with 1.5wt% nano fillers Concentration at 4kV

Table 5.5: Variation in harmonic content of leakage current with increase in filler percentage at 4kV

Harmonic Order	S1	S2	S3	S4	S5
3rd harmonic	0.00422	0.00385	0.00365	0.00273	0.00177
5th harmonic	0.00400	0.00395	0.00387	0.00288	0.00188
7th harmonic	0.04231	0.00357	0.00323	0.00271	0.00158

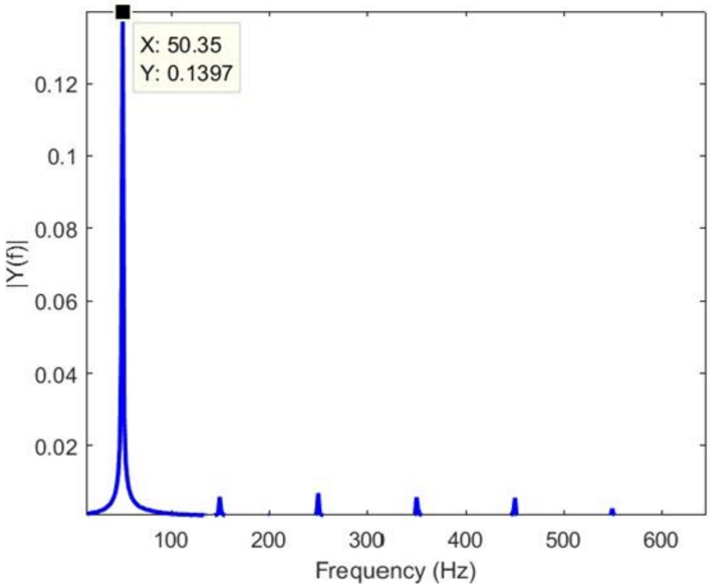

Figure 5.14. Harmonic content of SiR with 0wt% nano fillers Concentration at 5kV

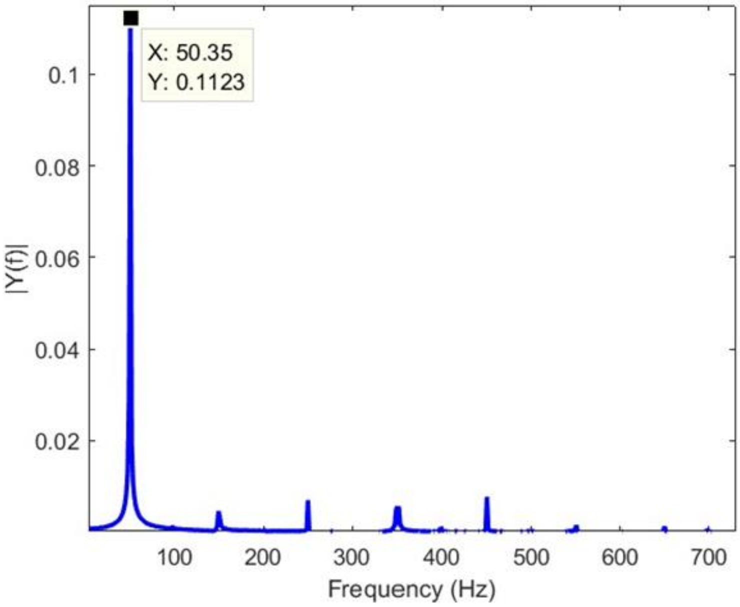

Figure 5.15. Harmonic content of SiR with 0.25wt% nano fillers Concentration at 5kV

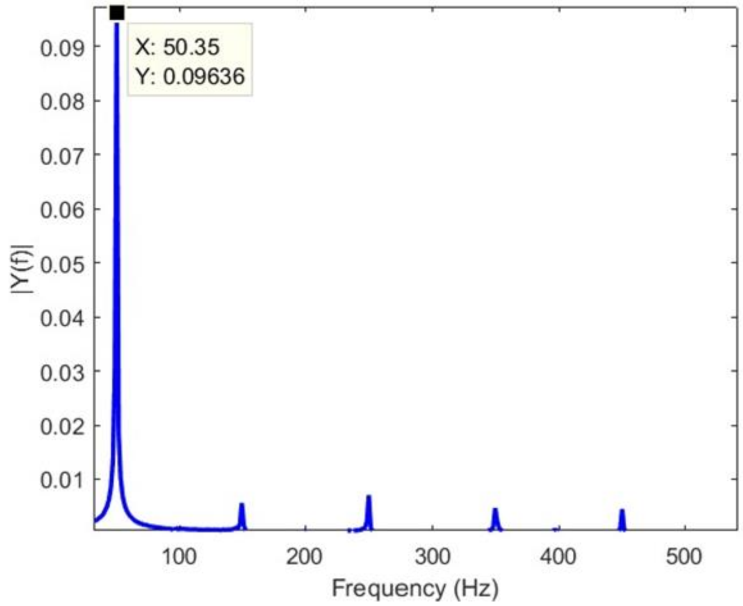

Figure 5.16. Harmonic content of SiR with 0.5wt% nano fillers Concentration at 5kV

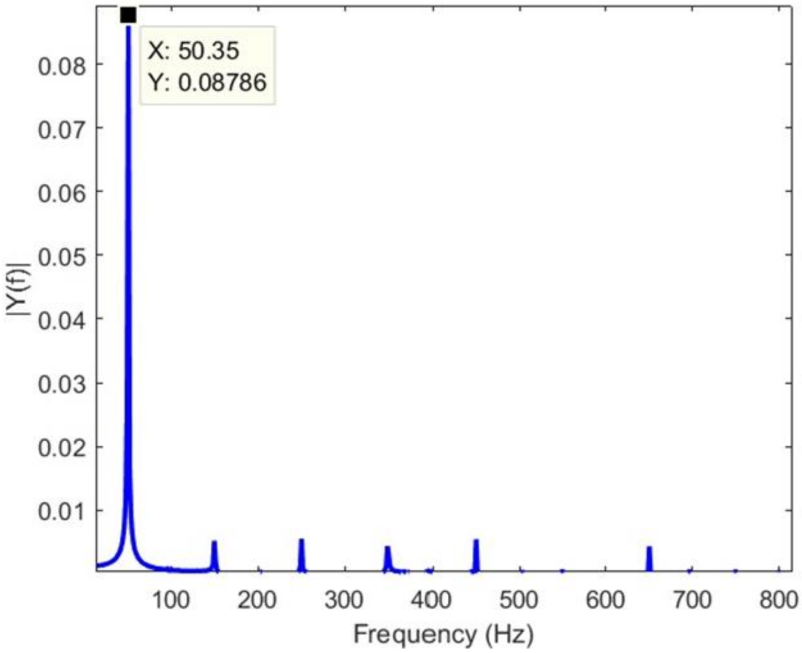

Figure 5.17. Harmonic content of SiR with 1wt% nano fillers Concentration at 5kV

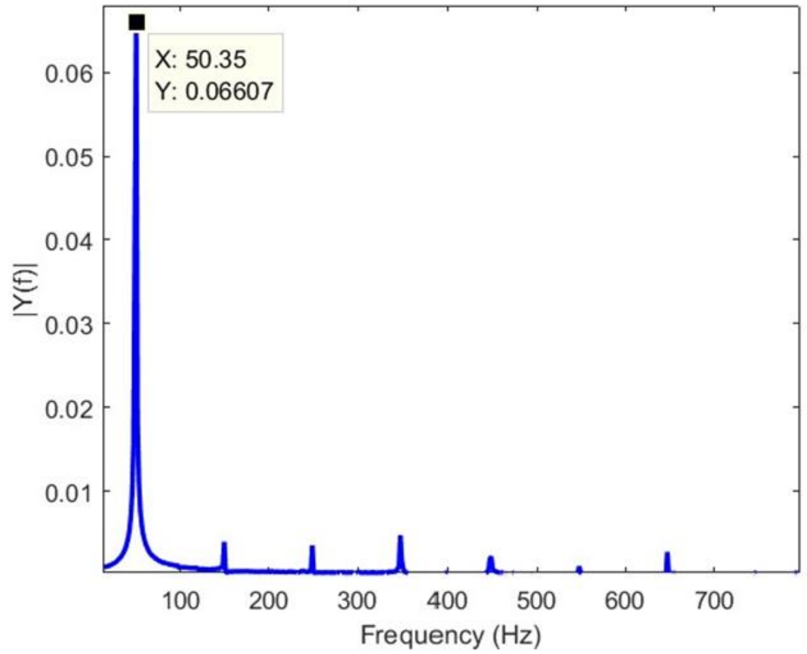

Figure 5.18. Harmonic content of SiR with 1.5wt% nano fillers Concentration at 5kV

Table 5.6: Variation in harmonic content of leakage current with increase in filler percentage at 5 kV

Harmonic Order	S1	S2	S3	S4	S5
3rd harmonic	0.00527	0.00452	0.00386	0.00365	0.00179
5th harmonic	0.00512	0.00492	0.00412	0.00385	0.00256
7th harmonic	0.00529	0.00353	0.00256	0.00312	0.00196

From Tables 5.4, 5.5 and 5.6 it can be seen that with increasing filler concentration there is a significant decrease in fundamental harmonic content. The other odd harmonics components are also decreasing. These observations are in perfect tandem with observation from theleakage current plot. The values of 3rd harmonics are less than 20% of the fundamental harmonics, so it can be safely assumed that dry band formation has not yet started taking place [17]. From the decreasing nature of the 3rd, 5th and 7th harmonic content, it can be asserted that the electrical stress is decreasing. 5th harmonic too is decreasing, increase of which is seen as a sign of the development of surface discharge. Analysis of 3rd harmonic values of the leakage current data are of utmost importance in the investigation of the insulator properties because they give a greater insight into the condition of the insulator Studies on the condition monitoring of insulator has revealed that the leakage current across the insulators are mostly resistive barring the initial low magnitude leakage current which is of capacitive in nature. It is further found that, the increase in the resistive component of the leakage current is proportionate to the 3rd harmonic. Due to these reasons, 3rd harmonic variations have special significance. Fundamental values and 3rd harmonics values of all samples has been shown in the Table 5.7. The ratio of 3rd harmonic to fundamental was calculated for all the readings of different samples and the average value obtained for the ratio at different voltage level is shown in Table

5.8. A graphical representation of the average value of 3rdto fundamental for different voltage level is shown in Figure 5.9.

Table 5.7: Fundamental and third harmonics values of the leakage current at different voltages

Sample No	Voltages					
	3 kV		4 kV		5 kV	
	fundamental	3rd harmonics	fundamental	3rd harmonics	fundamental	3rd harmonics
S1	0.07864	0.00638	0.09622	0.00587	0.1397	0.00769
S2	0.06874	0.00385	0.08942	0.008155	0.1123	0.00698
S3	0.05823	0.00461	0.07864	0.07214	0.0963	0.00724
S4	0.04574	0.00194	0.07831	0.00729	0.0878	0.00757
S5	0.0382	0.00152	0.04821	0.00329	0.0660	0.00522

Table 5.8: variation in the ratio of 3rd harmonic to the fundamental component of the leakage current.

Voltage	S1	S2	S3	S4	S5	Average
3 kV	0.0812	0.0561	0.0792	0.0425	0.0394	0.0876
4 kV	0.0611	0.0912	0.0917	0.0931	0.0683	0.0810
5 kV	0.0551	0.0622	0.0752	0.0862	0.0719	0.0712

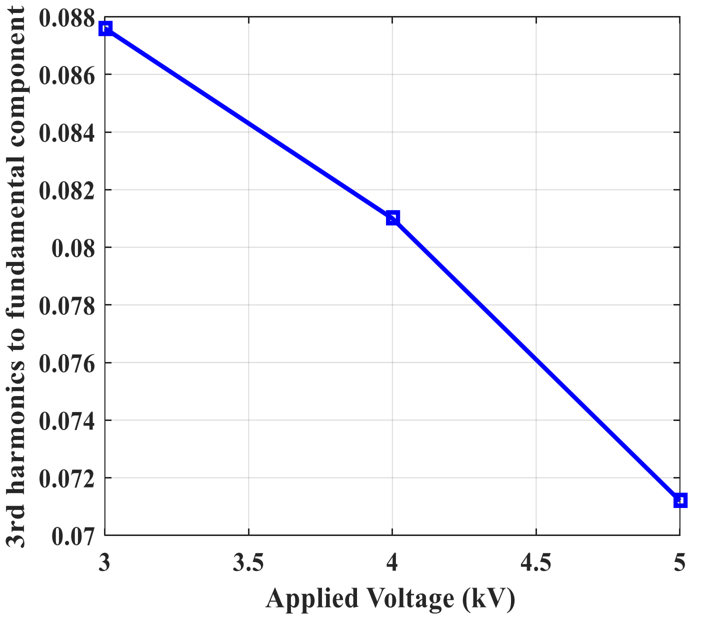

Figure 5.19: Variation of average value of 3rd harmonic to fundamental component with different voltage level.

It can be observed from Figure 5.19 that when the amplitude of the voltage level rises, the ratio of the fundamental component to the three harmonics falls in a linear fashion, which is a very encouraging indicator. This finding is based on the fact that the ratio is falling. As was described earlier, monitoring the third harmonic content of the leakage current is of the utmost significance, and the fact that it has a diminishing character (the ratio of the third harmonic to the fundamental) indicates that its resistance to the flow of leakage current is growing with the size of the rise in voltage. As can be seen from Table 5.8, the decrease in percentage component of third harmonic to fundamental is uniformly present across the table regardless of the filler concentration. Since this decrease is present across the table regardless of the filler concentration, it can be attributed to the inherent property of SiR, which remains intact even with increasing Alumina filler concentration. However, on a closer study, it can be said that this property is being further enhanced on the addition of filler.

5.2.3.Study the effect of filler material on Harmonic present in Leakage Current (without contamination)

A Fourier transform is used to the data on the leakage current that was collected for the samples at the three different voltage levels in order to analyse the data. The tables that follow provide the outcomes of running the Fast Fourier Transform (FFT) on LC at several voltages. These tables include the findings that were achieved. It is clear that increasing the amount of nano particles leads to a reduction in the number of LC harmonic components, and this is supported by the Figures shown in the tables, which show the values of odd harmonics all the way up to the seventh harmonic.

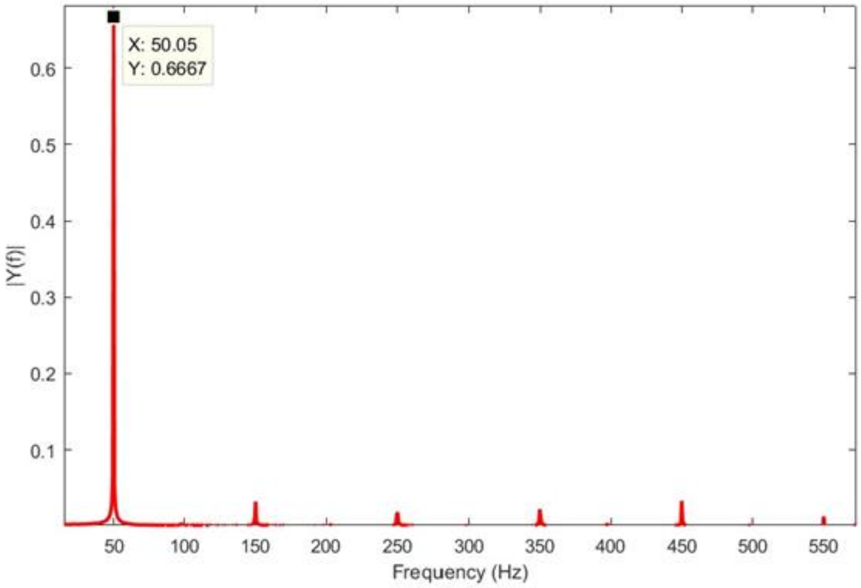

Figure 5.20: Harmonic Content of contaminated SiR of 0wt% nano fillers at 3kV

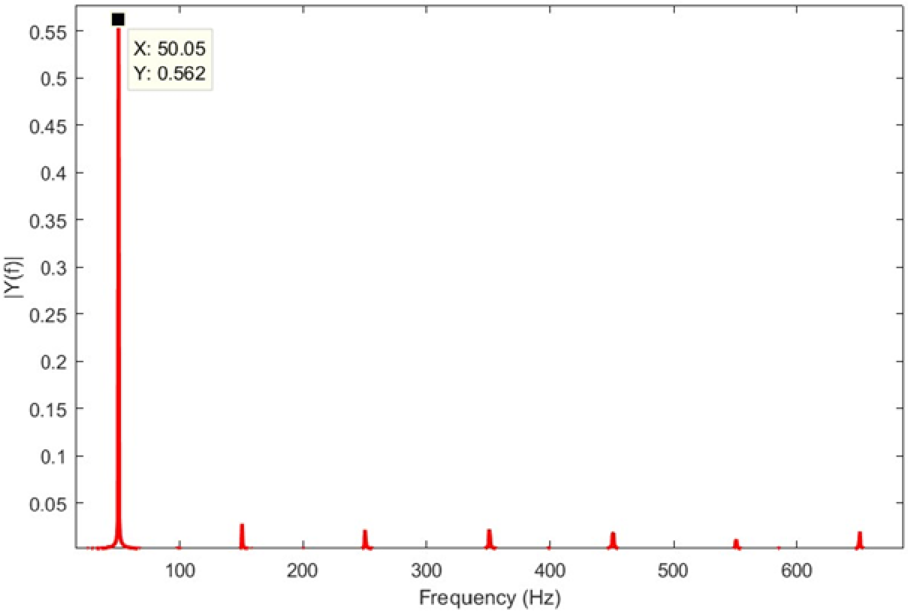

Figure 5.21: Harmonic Content of contaminated SiR of 0.25wt% nano fillers at 3kV

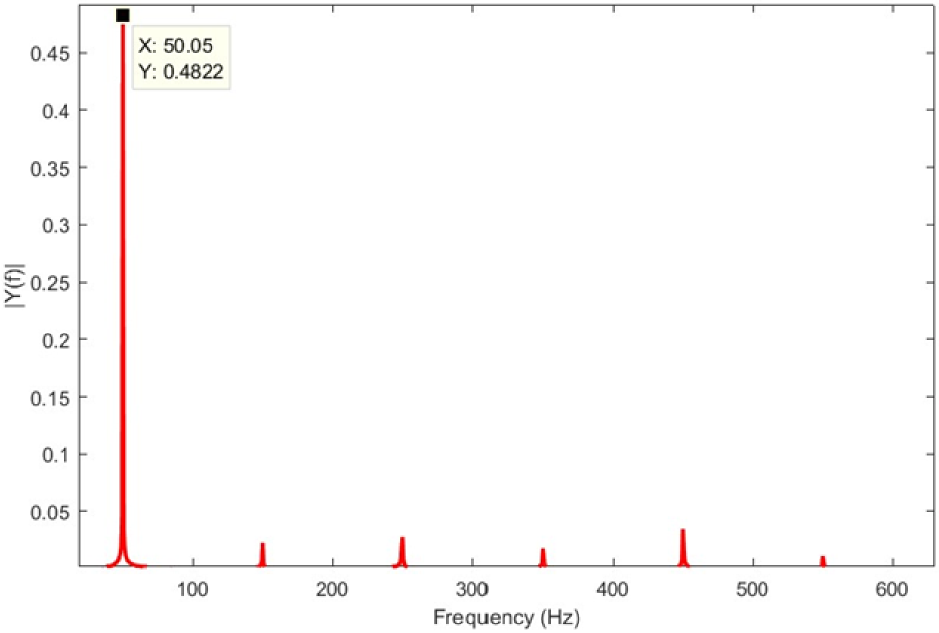

Figure.5.22: Harmonic Content of contaminated SiR of 0.5wt% nano fillers at 3kV

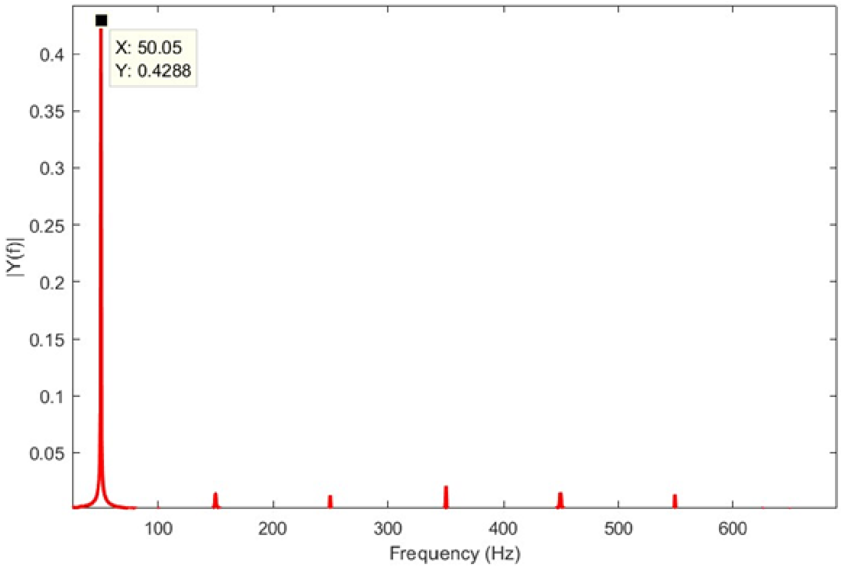

Figure.5.23: Harmonic Content of contaminated SiR of 1wt% nano fillers at 3kV

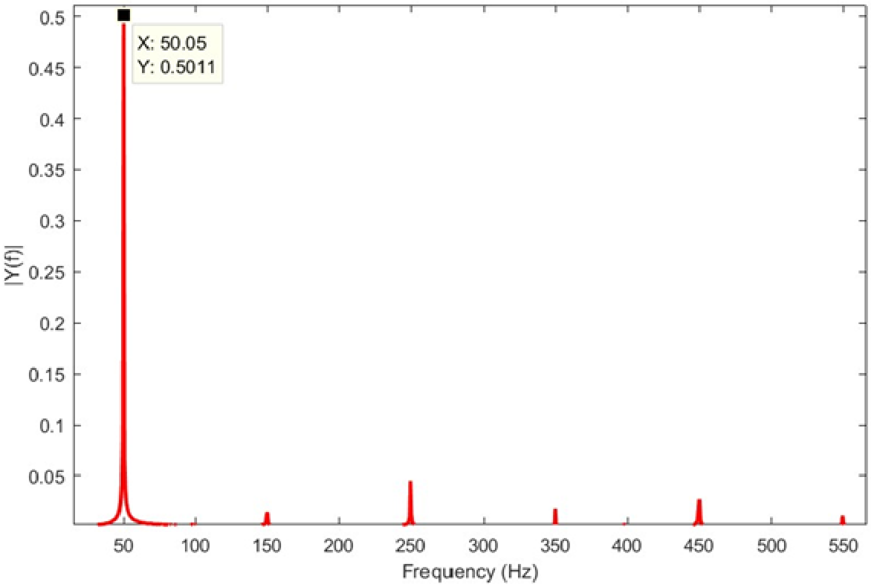

Figure.5.24: Harmonic Content of contaminated SiR of 1.5wt% nano fillers at 3kV

Table 5.9: Variation in harmonic content of leakage current with increase in filler percentage at 3kV

Harmonic Order	S1	S2	S3	S4	S5
3rd harmonic	0.03261	0.02574	0.01668	0.01487	0.01467
5th harmonic	0.01878	0.02908	0.02802	0.01234	0.04506
7th harmonic	0.03342	0.02156	0.01219	0.02101	0.01803

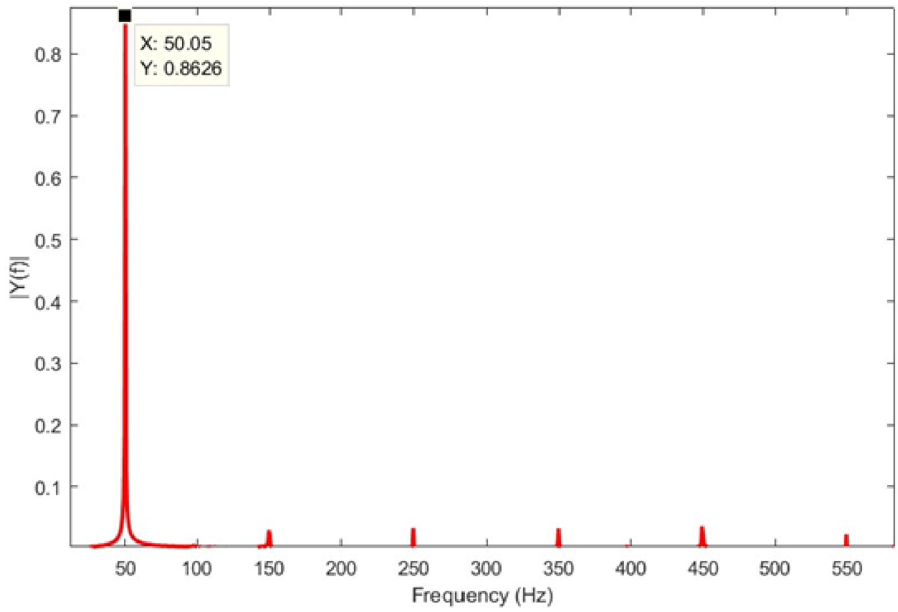

Figure 5.25: Harmonic Content of contaminated SiR of 0wt% nano fillers at 4 kV

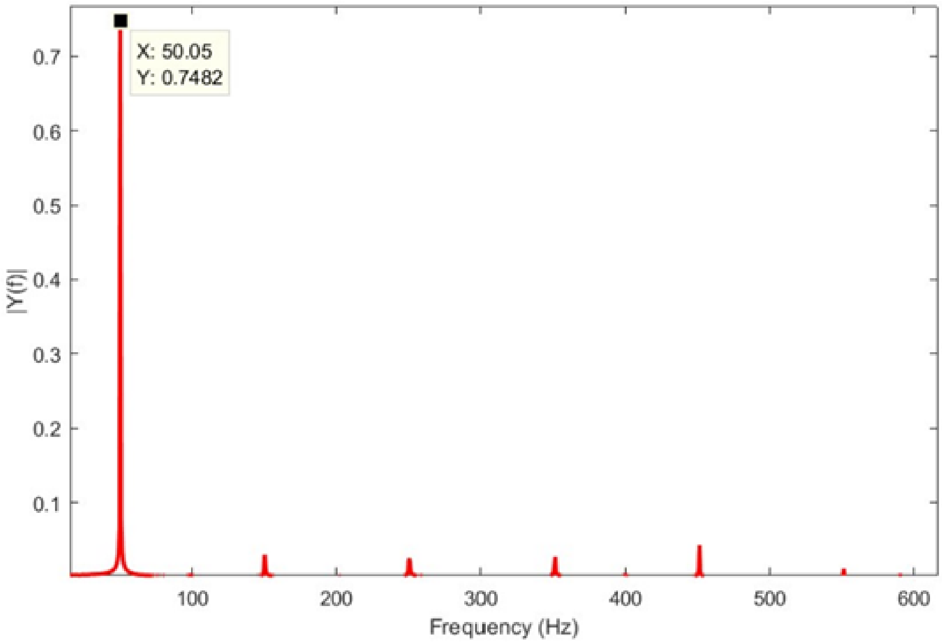

Figure 5.26: Harmonic Content of contaminated SiR of 0.25wt% nano fillers at 4 kV

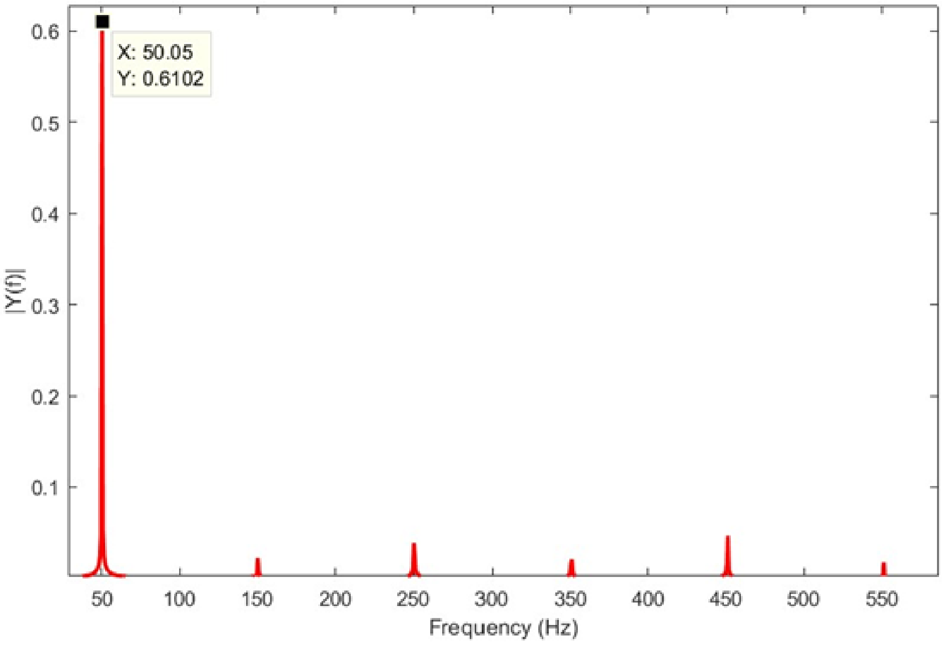

Figure 5.27: Harmonic Content of contaminated SiR of 0.5wt% nano fillers at 4kV

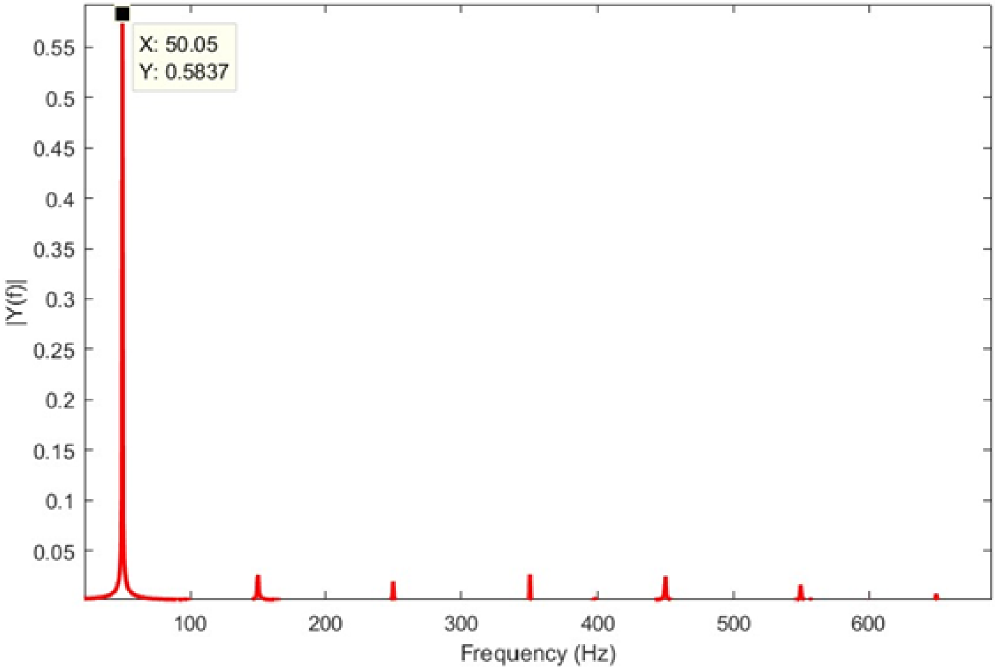

Figure 5.28: Harmonic Content of contaminated SiR of 1wt% nano fillers at 4kV

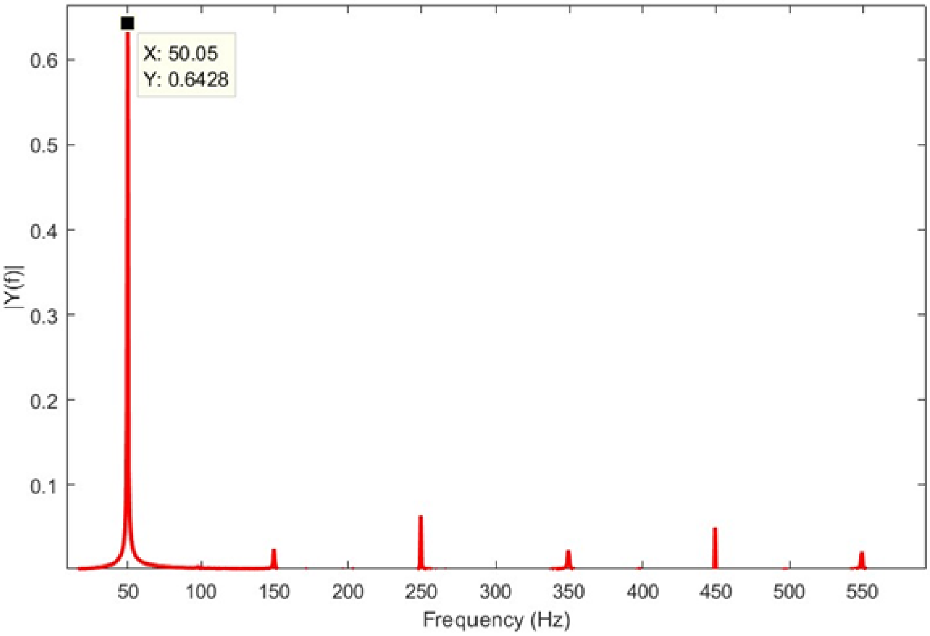

Figure 5.29: Harmonic Content of contaminated SiR of 1.5wt% nano fillers at 4kV

Table 5.10: Variation in harmonic content of leakage current with increase in filler percentage at 4 kV

Harmonic Order	S1	S2	S3	S4	S5
3rd harmonic	0.02916	0.02978	0.02219	0.02578	0.01122
5th harmonic	0.03225	0.02489	0.03859	0.01939	0.06403
7th harmonic	0.03406	0.02722	0.04647	0.02603	0.02325

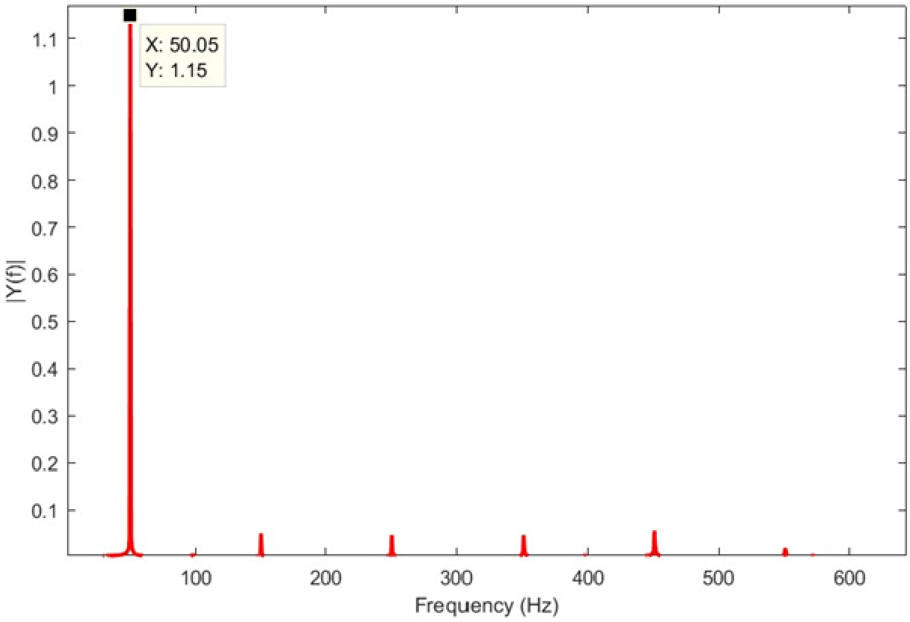

Figure 5.30: Harmonic Content of contaminated SiR of 0wt% nano fillers at 5kV

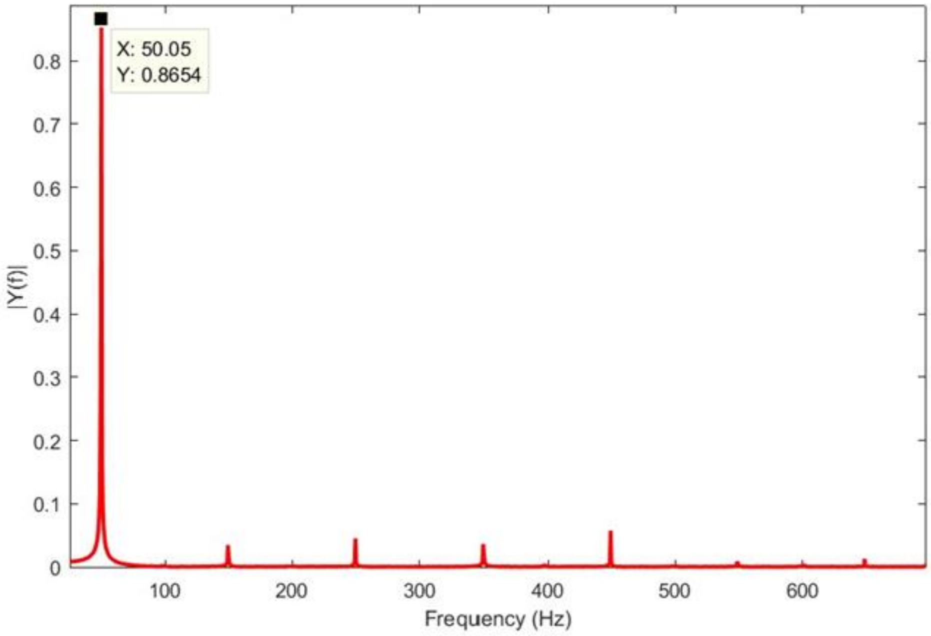

Figure 5.31: Harmonic Content of contaminated SiR of 0.25wt% nano fillers at 5kV

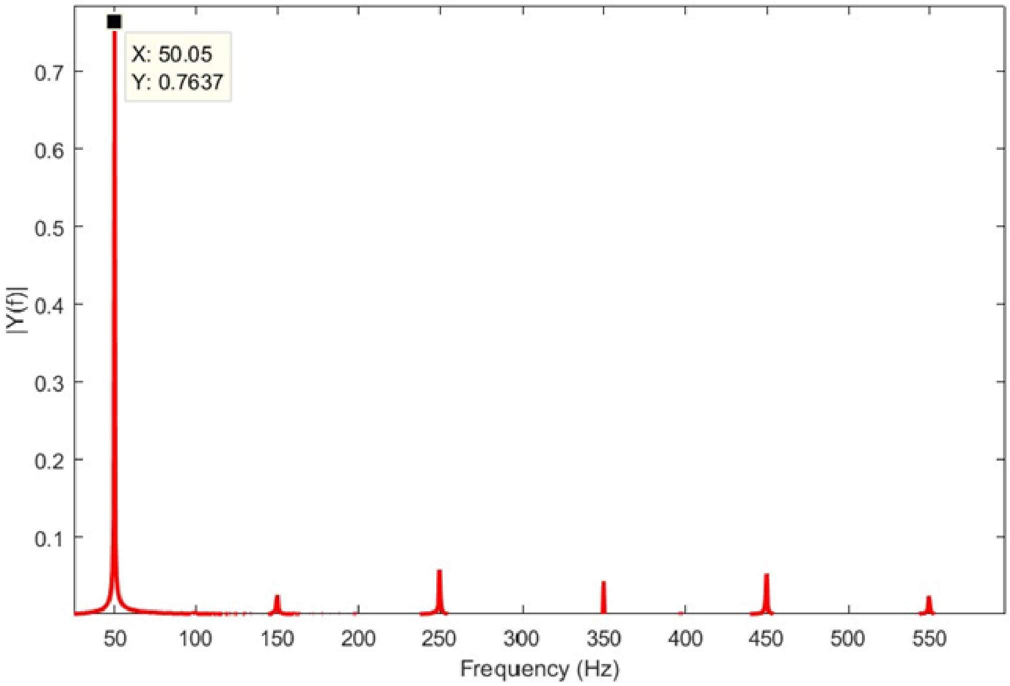

Figure 5.32: Harmonic Content of contaminated SiR of 0.5wt% nano fillers at 5kV

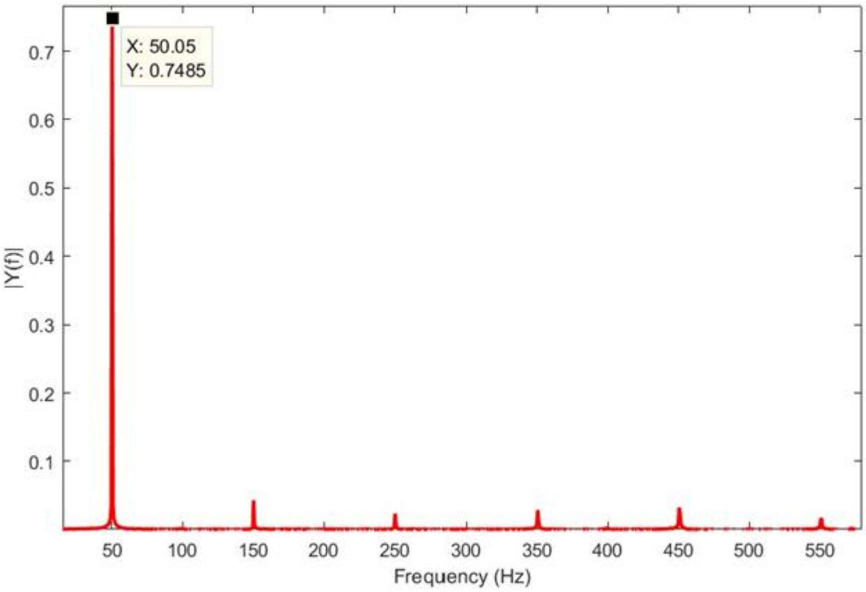

Figure 5.33: Harmonic Content of contaminated SiR of 1wt% nano fillers at 5kV

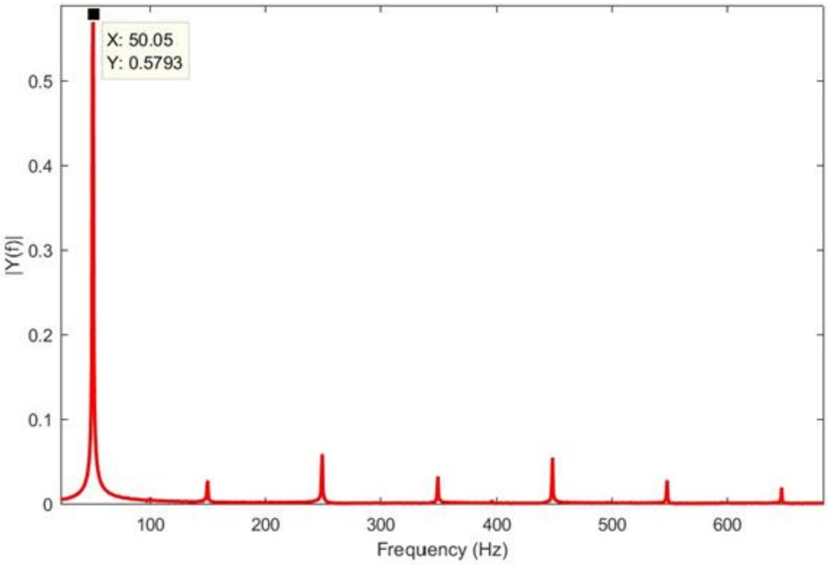

Figure 5.34: Harmonic Content of contaminated SiR of 1.5wt% nano fillers at 5kV

Table 5.11: Variation in harmonic content of leakage current with increase in filler percentage at 5kV

Harmonic Order	S1	S2	S3	S4	S5
3rd harmonic	0.05135	0.03462	0.02583	0.02583	0.02256
5th harmonic	0.04465	0.04519	0.05872	0.05872	0.05824
7th harmonic	0.04936	0.03627	0.04367	0.04367	0.03205

From the Tables 5.9, 5.10, and 5.11 makes it abundantly evident that there is a commensurate decrease in the quantity of basic harmonic content whenever there is an increase in the filler concentration. The remaining components of odd harmonics are all demonstrating a falling trend at the same time. These findings, as well as the observation that was obtained from the plot of the leakage current, are in complete accord with one another. Because the values of the third harmonics are less than 20% of the values of the fundamental harmonics, it is safe to assume that the process of creating dry bands has not yet commenced [17]. This is because the values of the third harmonics are less than 20% of the values of the fundamental harmonics. Due to the fact that the values of the third harmonics make up less than 20% of the fundamental harmonics, it is reasonable to make this assumption. As a consequence of the downward trend seen in the contents of the third, fifth, and seventh harmonics, it is reasonable to assume that the electrical stress is likewise going down as a direct result of this pattern. The increase in surface discharge may be inferred from the observation of a rise in the frequency of the fifth harmonic, which is otherwise exhibiting an overall declining trend. The investigation of the insulator's properties should begin with an examination of the values of the third harmonic of the data on the leakage current. This is the most important step in the process since it provides a clearer picture of the insulator's present condition. Research on the condition monitoring of insulators has revealed that the bulk of the leakage current across the insulators is resistive in nature. The initial low-magnitude leakage current is of a capacitive character; however, research on the condition monitoring of insulators has shown that this is not the case. Additionally, it was found that the increase in the resistive component of the leakage current is proportional to the third harmonic of the frequency of the leakage current. This was an interesting discovery. As a direct consequence of these several circumstances, variations in the third harmonic take on a very significant role. The ratio of third harmonics to fundamentals was determined for each and every reading taken from a unique sample, and Table 5.4 displays the average value that was achieved for this ratio at each of the various voltage levels. Figure 5.6 is a diagram that provides a graphical depiction of the average value of the third-to-fundamental ratio for a variety of voltage levels.

Table 5.4: Fundamental and third harmonics values of the leakage current at different voltages.

Sample No	Voltages					
	3 kV		4 kV		5 kV	
	fundamental	3rd harmonics	fundamental	3rd harmonics	fundamental	3rd harmonics
S1	0.6607	0.03823	0.8578	0.03492	1.1525	0.0402
S2	0.6658	0.03256	0.7282	0.03256	0.8250	0.0269
S3	0.4722	0.02639	0.6102	0.02257	0.7637	0.0285
S4	0.4288	0.02551	0.5837	0.01719	0.7485	0.0254
S5	0.5011	0.0267	0.6428	0.029	0.5793	0.0105

Table 5.12: variation in the ratio of 3rd harmonic to the fundamental component of the leakage current.

Voltage	S1	S2	S3	S4	S5	Average
3kV	0.0576	0.0486	0.0559	0.0595	0.0534	0.0438
4kV	0.0408	0.0416	0.0478	0.0401	0.0462	0.0433
5kV	0.0398	0.0327	0.0374	0.0340	0.01824	0.0405

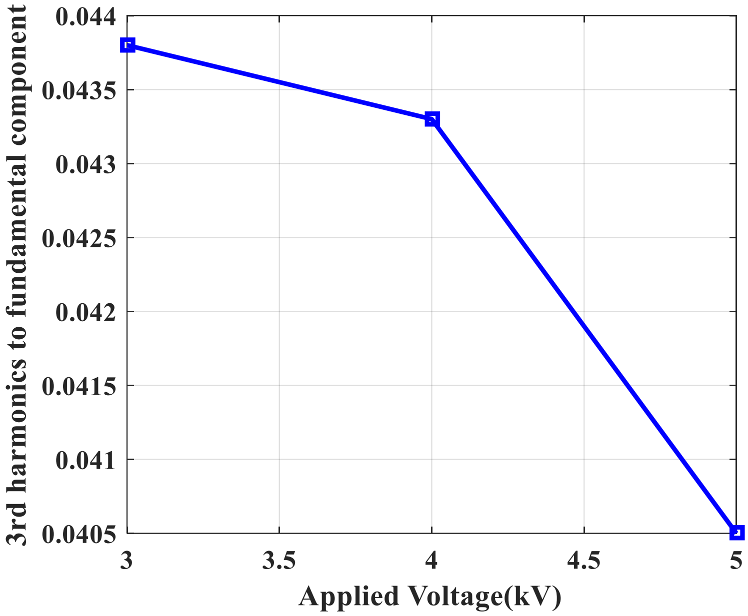

Figure 5.35: Variation of average value of 3rd harmonic to fundamental component with different voltage level.

Figure 5.35 shows that even after the contamination when the voltage level's amplitude goes up, the ratio of the fundamental component to the three harmonics goes down in a straight way, which is a very good sign. This conclusion can be made because the number is going down. As was already said, it is very important to keep an eye on the third harmonic content of the leakage current. The fact that it has a decreasing character (the ratio of the third harmonic to the fundamental) shows that its resistance to the flow of leakage current is getting stronger as the voltage rises. Table 5.4 shows that the ratio of the third harmonic to the fundamental decreases as the filler quantity goes up. This is true no matter how much filler is used. Since this drop is seen in all of the tables, no matter how much Alumina is used as filler, it can be traced to a feature of SiR that stays the same even as the amount of Alumina used as filler goes up. But if you look at it more closely, you can say that the filler is making this trait even better. Therefore it can be concluded that even after the contamination the 3rd harmonic to fundamental ratio is decreasing even at different voltage level.

5.3. Hydrophobicity Estimates

Hydrophobicity is an important property of polymeric insulators, and it is even more important for Silicone Rubber insulators. A goniometer was used to measure this property, and its change with filler concentration was described. For each percentage of filler concentration, three samples were taken, and the contact angle of each sample was measured five times in a controlled setting. The average of these measurements was then used to analyze the samples.

5.3.1. Contact Angle of SiR Samples for different nano fillers Concentration (without Contamination)

Figure 5.36 shows the variation of raw (uncontaminated) state contact angle for SiR samples with different concentration of nano fillers.

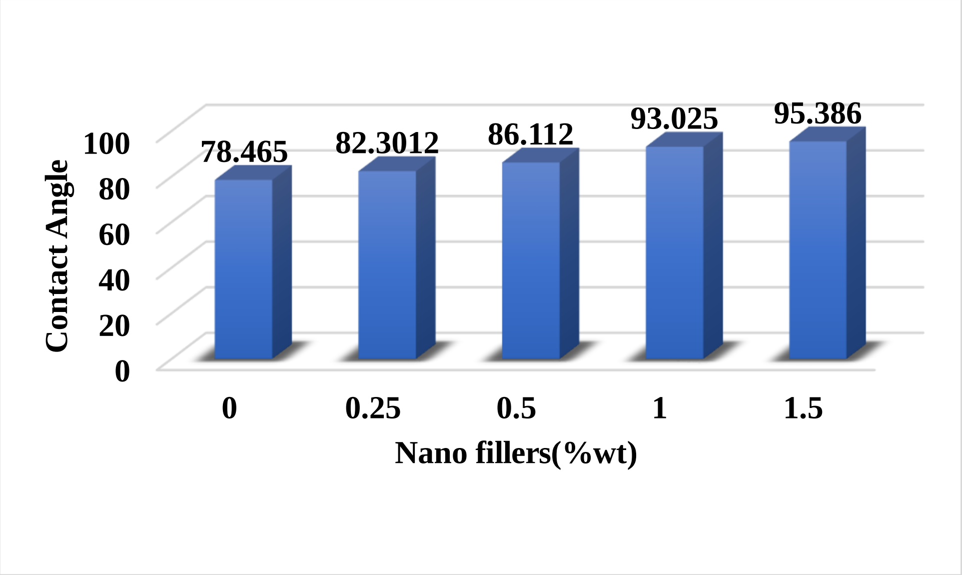

Figure 5.36: Variation in contact angle with the increase of nano fillers concentration.

Figure 5.36 makes it possible to draw the conclusion that a rise in the filler concentration contributes to an increase in the contact angle, which helps to increase the hydrophobicity nature of the samples. As it is known that material with contact angle greater than 90^0 is hydrophobic in nature, so from the graph it can be said that the silicone rubber insulator with 1% and 1.5% nano fillers gaining the hydrophobicity and this is a positive outcome of this experiment. This experiment aimed to investigate the impact of nano fillers on the hydrophobicity of silicone rubber insulators. The results indicate that the addition of 1% and 1.5% nano fillers led to an increase in hydrophobicity, which is a desirable outcome. This finding is consistent with the understanding that materials with a contact angle greater than 90^0 are typically hydrophobic in nature. These results suggest that incorporating nano fillers into silicone rubber insulators could be a promising approach for enhancing their performance in applications where hydrophobicity is important. Further research could explore the optimal concentration of nano fillers for achieving maximum hydrophobicity, as well as other potential benefits or drawbacks of this approach. Overall, this study provides valuable insights into the potential applications of nano fillers in improving the properties of silicone rubber insulators. The reason behind this is attributed to the fact that silicone rubber has base polymer of poly dimethyl siloxane (PDMS) which is a low surface energy material and as explained earlier that a low surface energy substance exhibits excellent hydrophobicity that is it has very high contact angle with water droplets [42]. Alumina nano fillers have a significantly larger surface area compared to their bulk counterparts. The increased surface area-to-volume ratio makes them highly reactive and enhances their catalytic properties. The surface of Alumina nano fillers can undergo modifications, such as functionalization with different chemical groups or coatings with other materials. These modifications can alter the surface chemistry, allowing for tailored interactions with other substances.

5.3.2. Contact Angle of SiR Samples for different nano filers Concentration (with Contamination)

Figure 5.37 shows the variation of state contact angle for SiR samples with different concentration of nano fillers (without contamination)

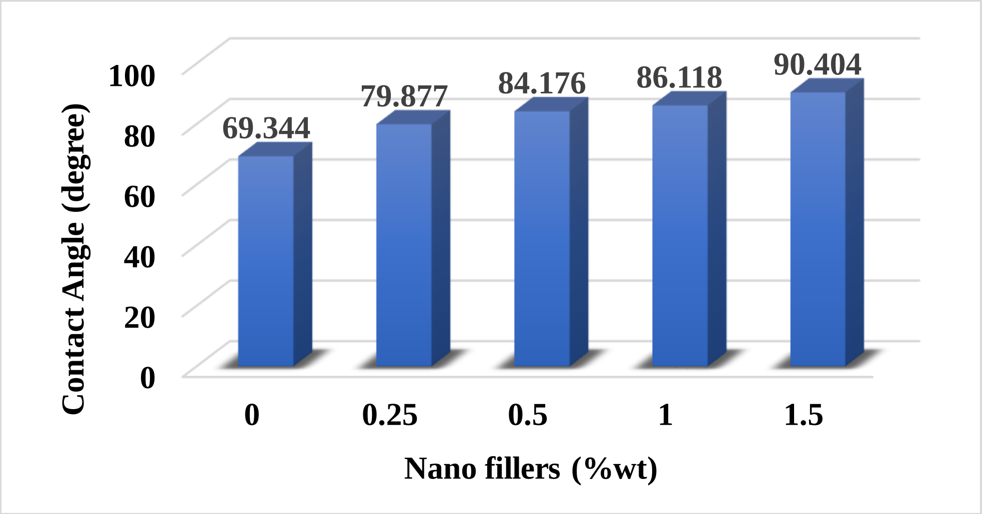

Figure 5.37: Variation in contact angle with the increase of nano fillers concentration (with contamination).

As it can be seen that from the histogram that even after contamination the reduction of contact angle is less. The silicone rubber insulator with 1.5% nano fillers concentration is not losing its hydrophobicity nature even after contamination which is positive sign to indicate that nano particles mixing SiR insulator can be used as outside insulator. The hydrophobicity of the insulator is crucial in preventing water from penetrating the surface, which can cause electrical breakdown and damage to the equipment. The addition of nano particles to the SiR insulator has shown promising results in maintaining its hydrophobicity even after contamination. This could potentially lead to the development of more durable and reliable insulators for outdoor use. Further research is needed to optimize the concentration and size of the nano particles for maximum effectiveness. Additionally, testing under different environmental conditions should be conducted to ensure its applicability in various settings. Overall, this study highlights the potential benefits of incorporating nano particles into SiR insulators for improved performance and longevity. for electrical equipment This could potentially lead to improved performance and durability of the equipment in harsh environments. Additionally, the use of nano particles in insulators could also lead to a reduction in material usage and cost, as smaller amounts of the material would be needed to achieve the same level of insulation. However, further research is needed to fully understand the long-term effects of using nano particles in insulators and to optimize their use for different applications. Overall, the findings suggest that incorporating nano particles into insulators has promising potential for improving electrical equipment performance and reducing costs.

5.3.3 Percentage change in Contact angle with respect to reference:

The Table 5.13 suggests that the surface chemistry is not significantly affected by the presence of contaminants. However, it is important to note that the absolute contact angle values were lower in the contaminated samples compared to the uncontaminated ones. This could be due to a number of factors, such as changes in surface roughness or the formation of a thin film on the surface. Further investigation is needed to fully understand these effects and their implications for practical applications. Additionally, it should be noted that the results presented in this study were obtained under controlled laboratory conditions and may not fully reflect real-world scenarios. Nevertheless, this research provides valuable insights into the behaviour of surfaces in contact with different types of contaminants and can inform the development of more effective cleaning and maintenance strategies for a wide range of materials and applications.

Table 5.13: the percentage change in contact angle in both contaminated and uncontaminated condition.

Percentage Change in Contact Angle		
Sample	**With Contamination**	**Without Contamination**
S1	_	_
S2	4.90%	15.13%
S3	9.74%	21.38%
S4	18.55%	24.27%
S5	21.56%	30.37%

CHAPTER-6

CONCLUSIONS AND FUTURE WORK

Chapter-6

6.1. Conclusion

Samples of temperature-vulcanised (TV) silicone rubber (SiR) with different filler concentrations of Alumina nanofillers were successfully made in the laboratory. [TV] stands for temperature-vulcanised. The generated samples were utilised to evaluate the variation in the waveform of the leakage current (LC) and the changes in hydrophobicity that occurred as a result of varying concentrations of the Alumina nanofiller.

During the course of the research on the waveform of the leakage current for samples of SiR with various concentrations of Alumina filler, the most important findings were that an increase in filler concentration results in a consequent decrease in leakage current magnitude. This was further supported by the measurement of the RMS value of the leakage current, which showed a linearly decreasing nature with increasing filler concentration. In order to conduct additional research, the combined LC data were subjected to a Fourier transform, which revealed that the odd harmonies (specifically the fundamentals 3, 5, and 7) showed decreasing trends. This indicates that an increase in filler concentration suppresses the formation of dry bands in addition to reducing LC magnitude. The average value of the 3" to fundamental component ratio was found to be reducing as the magnitude of the voltage level increased. This is a great positive indicator that the leakage current suppressing performance is growing with increasing voltage magnitude. Another interesting point that was seen is that the magnitude of the voltage had an effect on the leakage current suppressing capability. The findings of the LC study allow one to draw the conclusion that Alumina filler not only functions as a reinforcing filler but also suppresses the LC current, and a rise in filler concentration produces better results in terms of LC suppression. This can be inferred from the fact that the filler concentration was increased. Furthermore, it is important to note that the use of Alumina filler in various industries has become increasingly popular due to its unique properties. In addition to its reinforcing abilities and LC suppression, Alumina filler is also known for its high surface area and chemical stability. This makes it a valuable additive in the production of rubber, plastics, and coatings. attracting oxides away from the surface towards the bulk. After 48hrs of removal of the contaminant, the hydrophobicity recovery was measured which also showed an increase percentage of recovery with increasing filler concentration. Increased hydrophobicity recovery is mainly due to the reorientation of methyl groups towards the surface of the insulator and the oxidised groups away from the surface which is propelled due to the presence of Alumina fillers as they develop intermolecular forces which attract the oxidised group towards the bulk. So overall it can be said that addition of Alumina nanofillers suppresses the LC development and enhances the dynamic hydrophobicity of room temperature vulcanised silicone rubber However, it is crucial to carefully consider the concentration of Alumina filler used in these applications, as too much can lead to negative effects such as decreased flexibility and increased viscosity. Overall, the study highlights the multifaceted nature of Alumina filler and its potential benefits when used in appropriate concentrations.

The hydrophobicity estimates of SiR samples also gave positive results on the addition of Alumina nanofiller, despite the fact that the initial hydrophobicity measurements or the raw hydrophobicity measured after 96 hours of sample preparation showed that the increasing filler concentration resulted in a decrease in the contact angle measured. The reason for this is that Alumina is an inorganic filler that has high surface energy, which therefore permits surface wetting. The dynamic hydrophobic characteristics of the samples were also tested by contaminating them with a medium degree of pollution in accordance with the norms of IEC 60507 and then measuring the hydrophobicity transfer after 96 hours had passed. It was discovered that an increase in the amount of filler led to an increase in the percentage of hydrophobicity transferred to the surface of the contaminant. This was discovered because an increase in the amount of Alumina filler was used for generating new chains of low molecular weight (LMW) compounds and for increasing the amount of filler. As a result, the hydrophobicity transfer to the surface of the contaminant was significantly enhanced. This finding has important implications for the development of new strategies for contaminant removal and remediation. By using Alumina filler to generate new chains of LMW compounds, it may be possible to increase the efficiency and effectiveness of current remediation techniques. Additionally, this research highlights the importance of understanding the role that filler materials can play in enhancing hydrophobicity transfer and other key properties. Moving forward, further studies are needed to explore the full potential of Alumina filler and other materials in this context, as well as identify any potential drawbacks or limitations associated with their use. Ultimately, these efforts could lead to significant advances in our ability to address environmental contamination and protect public health.

6.2. Future Work

In this work, the attention was focused on the impact that Alumina nanofiller had on RTV Si. Although the nanofiller demonstrated a good augmentation of leakage current suppression and hydrophobic qualities, more research is required to determine whether or not it is suitable for use in a variety of environmental situations. Consideration may be given to carrying out more study on the subjects that are mentioned below.

1. The tracking and erosion test, which is an essential measurement of the performance of outdoor insulators, may be done, and the influence of Alumina filler on the resistance to tracking and erosion can be explored in more depth. 2. The influence that a change in temperature has on the dynamic hydrophobic characteristics of the sample with

It's possible that alternative filler concentrations may be the focus of future research.

3. An investigation of the interaction between the effects of aluminium trihydrate, which is a relatively typical kind of filler

for characteristics that prevent tracking) and varying quantities of Alumina filler on the LC

suppression as well as increases in the hydrophobic property. This study aimed to explore the potential benefits of alternative filler concentrations in future research. Specifically, we investigated the interaction between aluminium trihydrate and varying amounts of Alumina filler. Aluminium trihydrate is a common type of filler that is known for its ability to prevent tracking, while Alumina filler has been shown to enhance LC suppression and increase hydrophobicity. By examining how these two fillers interact, we hoped to identify new ways to improve the performance of fillers in various applications. Our findings suggest that alternative filler concentrations may offer significant advantages over traditional approaches, particularly in terms of improving hydrophobic properties and reducing tracking. Further research is needed to fully understand the potential benefits of these alternative filler concentrations, but our study provides a promising starting point for future investigations.

REFERENCES

[1] R.S. Gorur, E.A. Cherney, and J.T. Burnham. Outdoor Insulators. Arizona: Ravi Gorur Inc,1999.

[2] K. Siderakis, D. Agoris, P Eleftheria and E. Thalassinakis, "Investigation of Leakage Current on High Voltage Insulators-Field Measurments," *WSEAS Transaction on Circuits and System*, pp.1188-1191, 2004.

[3] T Suda, "Frequency characteristics of leakage current waveforms of a string of suspension insulators," *IEEE Trans. Power Delivery*, vol. 20 no. 1, pp. 481-487, 2005.

[4] Suwarno and F. Pratomosiwi, "Application of RTV Silicone Rubber Coating for Improving Performances of Ceramic Outdoor Insulator under Polluted Condition," *International Conference on Electrical Engineering and Informatics*, pp. 581-587, 2009.

[5] T. Tanaka, "Dielectric Nanocomposites with Insulating Properties," *IEEE Transactions on Dielectrics and Electrical Insulation*, vol. 12, no. 5, pp. 914-928, 2005.

[6] R.A. Bernstorf, D. Ryan, "Silicone Compounds for High-Voltage Insulators: Compounding Silicone Rubber", *Hubbell Power Systems*, Inc.

[7] H. Deng, R. Hackam, E.A. Cherney, "Role of the Size of Particle of Alumina Trihydrate Filler on the Life of RTV Silicone Rubber Coating". *IEEE Transactions on Power Delivery*, vol. 10, no. 2, pp. 1012-1023, 1995.

[8] S. Kumagai, S. Yoshimura, "Tracking and erosion of HTV Silicone Rubber of Different Thickness", *IEEE Transactions on Dielectrics and Electrical insulation*, vol. 8, no. 4, pp. 673-678, 2001.

[9] J. Wang, J.F. Tung, M.Y. Ahmad Fuad and P.R. Hornsby, "Microstructure and Mechanical Properties of Ternary Phase. Polypropylene/ Elastomer/Magnesium. Hydroxide Fire-Retardant Compositions", *Journal of Applied Polymer Science*, vol. 60, no.9, pp. 1425-1437, 1996.

[10] T. Tanaka, G.C. Montanari and R. Mulhaupt, "Polymer Nanocomposites as Dielectrics and Electrical Insulation - perspectives for Processing Technologies, Material Characterization and Future Applications," *IEEE Transactions on Dielectrics and Electrical Insulation*, vol. 11, no. 5, pp. 763-784, Oct. 2004.

[11] C. Calebrese, L. Hui, LS. Schadler and J.K. Nelson, "A Review on the Importance of Nanocomposite Processing to Enhance Electrical Insulation". *IEEE Trans. Dielectr. Electr. Insal*, vol. 18, no. 4, pp. 938-945, 2011.

[12] Wacker Chemicals, "datasheet for Silicone Potting Gel" online document URL: https://mail.google.com/mail/u/0/?tab=rm/search/wacker/FMfcgxwBVWHKICGBPIXBSFCVbelaFIC?projector-1&messagePartId-0.1.

[13] Abraiz Khattak and Muhammad Amin, "Influence of filler on the aging behaviour of polymeric insulators", Rev. Adv. Mater. Sci. 44 (2016) pp.194-205.

[14] FANG Su, JIA Zhidong, GAO Haifeng, GUAN Zhicheng. "Influence of fillers on silicone rubber for outdoor insulation", *2007 Annual Report Conference on Electrical Insulation and Dielectric Phenomena*, pp. 300-303, 2007.

[15] M.A.R.M. Fernando, and S.M. Gubanski, "Leakage current on nonceramic insulators and materials," *IEEE Trans. Dielectrics and Electrical Insulation*, vol. 6, no. 5, pp. 660-667, 1999.

[16] M.A.R.M. Fernando, and S.M. Gubanski, "Leakage current patterns on contaminated polymeric surfaces," IEEE Trans. Dielectrics and Electrical Insulation, vol. 6, no. 5, pp. 688- 694, 1999.

[17] Online Document, Leakage current wavefrom analysis https://shodhganga.inflibnet.ac.in/bitstream/10603/16454/11/11 chapter%206.pdf

[18] Evonik Industries, "Aerosil-Fumed Silica: Technical overview", Online Document URL: https://www.aerosil.com/sites/lists/RE/DocumentsSI/Technical-Overview-AEROSIL-Fumed- Silica-EN.pdf

[19] A.H. El-Hag, S.H. Jayaram, and E.A. Cherney, "Fundamental and low frequency harmonic components of leakage current as a diagnostic tool to study aging of RTV and HTV silicone rubber in salt fog", *IEEE Trans. Dielectrics and Electrical Insulation*, vol. 10, no. 1, pp. 128-136, 2003.

[20] D. Pylarinos, K. Theofilatos, K. Siderakis, E. Thalassinakis, I. Vitellas, A.T. Alexandridis and E. Pyrgioti, "Investigation and Classification of Field Leakage Current Waveforms", *IEEE Transactions on Dielectrics and Electrical Insulation*, vol. 19, no. 6, pp. 2111-2118, 2012.

[21] D. Pylarinos, K. Theofilatos, K. Siderakis and E. Thalassinakis, "Discharges Classification using Genetic Algorithms and Feature Selection Algorithms on Time and Frequency Domain Data Extracted from Leakage Current Measurements". *ETASR - Engineering, Technology & Applied Science Research*, vol. 3, no. 6, pp. 544-548, 2013.

[22] M. Amin, S. Amin, M. Ali, "Monitoring of leakage current for composite insulators and electrical devices". *Rev. Adv. Mater. Sci.*, vol. 21, pp. 75-89, 2009.

[23] G. Momen and M. Farzaneh, "Survey of micro/nano filler use to improve Silicone rubber for outdoor insulators", *Journal on Advanced Materials Science*, pp. 1-13, 2011.

[24] M. Amin, M. Akbar and M. Salman, "Composite insulators and their aging: an overview" *Science in China series E: Technological Sciences*, vol. 50, no. 6, pp. 697-713, 2007.

[25] A. Phillips. "Ceramic vs. Polymer (Non-Ceramic) Insulators". *EPRI Report*, 2002.

[26] WG CIGRE 22.03, "Worldwide Service Experience with HV Composite Insulators", *Electra*, vol. 130, pp. 68-77, 1990.

[27] R.C. de Jesus, J. Pissolato, J.L, de Franco, S.R. de Abreu, D.A. da Silva, M.A.A. Romano, E.C.M. Costa and LH.I. Mei, "Hydrophobicity classification of distribution of silicone arresters before and after solid layer contamination", *18" International Symposium on High Voltage Engineering*, pp. 1172-1177, 2013.

[28] Z. Guan, S. Yu, Z. Jia and K. Wang. "A study on the hydrophobicity transfer of silicone rubber coating." Journal of Tsinghua University, vol. 34, pp. 23-31, 1994.

[29] Q. Wang, F. Lu, Y. Liu, and Y. Liang, "Study on the influence of corona on the hydrophobicity of RTV silicone rubber," *Journal of North China Electric Power University,* vol. 37, pp. 14-17, 2010.

[30] J.T. Simpson, S.R. Hunter and T. Aytug, "Superhydrophobic materials coatings: a review", *Rep. Prog. Phys.*, pp. 1-14, 2015.

[31] T. Tokoro, A. Ohno and M. Nagao, "Effect of Temperature on the Evaluation of Hydrophobic Condition of Polymer Surface", *CEIDP*, 3- 23, pp. 316-319, 2007.

[32] T Tokoro, H. Iwase and M. Nagao, "Diagnosis of Degradation Condition of Materials Using Hydrophobic and Dielectric Analysis", *Conference Proceedings of ISEIM*, vol. 1, pp. 453-456, 2014.

[33] T Tokoro, S. Kojima and M. Nagao, "Effect of Surface Condition on the Evaluation of Hydrophobicity of Polymer Insulator", *ISEIM*, P5, pp. 451-454, 2011.

[34] H. Homma, M. Nagao, T. Matsumoto, M. Otsubo and T Tokoro, "Examination of Dynamic Drop Test Method for Evaluation of Hydrophobicity Stability of Polymeric Insulating Materials by CIGRE Round Robin Test", *IEEJ Transactions on Fundamentals and Materials*, vol. 131, no. 9, pp. 797-803, 2011.

[35] H. Bai, "Study on hydrophobicity evaluation of composite insulators and the influences of hydrophobicity on flashover characteristics," *Chongqing University (in Chinese)*, 2011

[36] Y. Liu, B. Du, B. Yang, B. Liu, and Y. Wang, "Hydrophobicity evaluation of silicone rubber insulator by using dynamic drop test method," *High Voltage Engineering*, vol.36, pp.1906-1911, 2010.

[37] C. Xie, Y. Zhang, J. Wang, L. Yang, Y. Hao, and et al., "Microstructure analysis of AC corona aging of silicone rubber", *Proceedings of the 9th International Conference on Properties and Applications of Dielectric Materials*, pp. 481-484, 2009.

[38] "IEC 60507 Artificial pollution tests on high-voltage insulators to be used on a.c. systems", *Intern. Electrotech. Comm.* Geneva, Switzerland, 1991.

[39] X. Yuan, H. Lu, L. Lan, H. Wang, X. Wen, Y. Liao, F. Zhang, "Study on the Effect of Corona on Hydrophobicity Recovery Performance of RTV Silicone Rubber and its Failure Criterion", *Electrical Insulation Conference*, pp. 215-218, 2016.

[40] H. Deng, R. Hackam, and E.A. Chemney, "Low Molecular Weight Silicone Fluid Content and Diffusion in RTV Silicone Rubber Coating". *IEEE International Symposium on Electrical Insulating Materials*, pp. 181-184, 1995.

[41] H. Deng, and R. Hackam, "Low-molecular Weight Silicone Fluid in RTV Silicone Rubber Coatings", *IEEE Transactions on Dielectrics & Electrical Insulation*, vol.6, pp. 84-94, 1999.

[42] S.H. Kim, "Electrical performance and surface analysis of RTV silicone rubber coatings for H.V outdoor insulators", *Doctoral dissertation, University of Windsor*, 1992.

[43] E. Nowak, G. Combes, E.H. Stitt and A.W. Pacek, "A comparison of contact angle measurement techniques applied to highly porous catalyst supports", *Power Technology*, pp. 2-64, 2013.