Investigation of Electrical Properties of TiO$_2$ Nanocomposite Based Polymer

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Abstract. Past research has reported the challenges regarding on degradation and aging due to high localization of electric field at triple point areas of polymeric insulator. The different materials and designs of polymeric insulator have initiated the partial discharge and arcing activities which eventually lead to the insulation failures. The compounding of nanomaterials in the polymer shows a promising result to overcome this problem by redistributing the uniformity of electrical field lines on the insulator. In the present work, ethylene-propylene-diene rubber (EPDM) and titanium dioxide (TiO$_2$) is introduced as nano composites that been embedded into insulator’s housing made of 1) silicone rubber (SiR) and 2) Ethylene Propylene Diene Monomer (EPDM) Rubber. Titanium dioxide (TiO$_2$) is a semiconductor material that can be formed in different sizes either micron or nano-sized filler and has high relative permittivity that be able to reduce the high electrical stresses on high voltage equipment. Meanwhile EPDM shows good mechanical profile, excellent resistance properties and low cost. Therefore, it brings to the new opportunity to fabricate the nanocomposite based on both materials which exhibits an improved electrical properties and good distribution of electric field on polymeric outdoor insulators. In depth investigation was carried out to analyze the effect of different nano-filler loading in the compound and behavior of nanocomposites at different polymer base. An 11kV polymeric insulator is modelled to be simulated by using COMSOL Multiphysics software under dry-clean surface conditions to investigate the electric field distribution at terminal ends and along the insulator creepage path. The Electrostatics interface from the AC/DC Module is used in the evaluation of electric field distribution of insulator model correspondingly with the variations in filler percentage in the host matrix.

Keywords: Nano-filler, Electric field, Finite element method (FEM), High voltage insulator

1. INTRODUCTION

In power system, insulators are vital components to isolate the transmission tower from high voltage cables and be able to support overhead conductors at certain height above ground level. The traditional insulation materials are made of ceramic [1-2] and glass. Ceramic insulators have been used over 100 years show great insulation performance in terms of lifespan and ageing [1,3] and acquiring high resistance and mechanical strength. However, this insulator
has numerous problems when it placed under polluted environment and distinct humidity measurement which greatly effects its electrical performance. This is due to its hydrophilic properties allowing formation of conductive film on creepage path which causing partial discharges and eventually leading to flashover phenomenon.

Since the 1970s, two common polymer materials are being used in outdoor insulation, silicone rubber (SiR) and ethylene propylene diene (EPDM) rubber [4][5]. SiR had been widely used due to its great electrical performance and equipped with good hydrophobic properties and strong mechanical strength [1]. Meanwhile EPDM has phenomenal mechanical strength, wide-ranging of stress resistance, able to withstand at high temperature and has low material cost [6-8]. Even both materials show enormous advantages, EPDM and silicone rubber still experience high electrical field stresses at both end fittings of insulator, high voltage and ground terminals. Because of such situation, a number of research have been conducted to modify their original properties by compounding this material with fillers or additives in order to improve their electrical and mechanical properties [4-9]. Fillers or additives have been used for a few decades particularly in biomedical, marine industry etc. Some examples of fillers include aluminum oxide (Al₂O₃), barium titanate (BaTiO₃), silicon carbide (SiC), zinc oxide (ZnO) and etc. [12-13]. The nanocomposite based polymer is getting great attention due to its potential in improving electrical and mechanical properties compared to micro composite materials [2], [12-13]. This is due to the large surface area that exhibit the strong interaction between the host matrix and filler [8-10] which allow vast accessibility of nanoparticles in the compound [14-15].

Titanium dioxide (TiO₂) is a semiconducting material are able to reduce electrical stress by forming the uniform distribution of electric fields on the insulator thus mitigate the surface flashover activities to occur [9,10,11 14]. Since this filler has shown in improving the electrical properties of compound, the investigation is continued by conducting the research on TiO₂-filled EPDM in high voltage insulation by using numerical studies such as Finite Element Analysis (FEA) software. Numerical studies can be utilized to estimate the electric field and potential distribution along the high voltage insulator model. COMSOL Multiphysics is performed through FEM software to analyze complex simulation of electric field and potential distribution in high voltage insulator by using Electrostatics platform. Finite element analysis is adaptive to complex geometry, flexibility of designs with simpler steps at short time of computations [12-13].

It is noticeable that the regions near ground and high voltage terminals of insulator are experiencing high accumulation of electrical stresses that would trigger the electrical discharge and corona activities. If these activities prolong to occur, it will lead to erosion and degradation on the insulation as shown in Figure 1. The current discharge that actively occur on the insulation surface will also generate the electromagnetic interference and audible waves that will influence to power network.

![Figure 1](image1.png)

**Figure 1.** The effect of electric field stress on 115 kV suspension insulator [15].

The computation studies were conducted on polymeric insulators that made from different materials, silicone rubber and EPDM. The voltage applied was 11 kV, that subjected to high voltage end fitting. The numerical analysis on electrical field distribution allows the researcher to forecast the electrical stresses profile on high voltage insulator. The preliminary study was conducted, Figure 2 shows the high concentration of electrical fields at both terminals which demand further improvement at these areas. Therefore, this research aims to evaluate the effect of different
filler loading (%wt.) in the composite materials and investigating the performance of insulator is affected by different polymer base.

![Image of electric field stress at the terminal ends of an 11kV polymeric high voltage insulator model of this research.](image)

Figure 2. Electric field stress at the terminal ends of an 11kV polymeric high voltage insulator model of this research.

2. METHODOLOGY

2.2 Mathematical Model

In this study the primary objective is to investigate the electrical properties of the field grading nanocomposite material at different concentration of nano-filler for polymeric outdoor high voltage insulator. Hence, to investigate, the finite element analysis software, COMSOL Multiphysics 5.3 is used for modelling purposes of 11 kV high voltage insulator model.

The Electrostatics interface from the AC/DC Module is used in the evaluation of electric field distribution of model correspondingly with the variations in filler percentage. In electrostatic platform, the Gauss Law, Maxwell Equation and Coulomb’s Law are applied into the present physics studies [19]–[21]. There are two things to consider in an Electrostatics interface, electric field intensity \(E\) and electric displacement or electric flux density \(D\). The Gauss Law states that the flux out of any closed volume is equal to the charge contained within the volume. The \(E\) and \(D\) must obey the differential form of Gauss Law. As for computation of electric field, Maxwell’s equations are used.

There are three steps of modelling the insulator through this software: Preprocessing, Solving and Post-processing. In the preprocessing step, the boundary conditions and geometry loading (model properties) is created before attend to the meshing procedures. In the Solving, the related equations are used according to the selection of Physics platform. The FEA solves all the model’s node potentials with respect to the boundary conditions. Meanwhile, under Post-processing step, the results are displayed through graphical and data presentation. For this study, the AC/DC Module is used for electric field analysis and voltage distribution analysis and was run under Electrostatics platform. The study is selected to be Stationary where the results that will be computed depend on the inputs such as boundary...
conditions and, element size and shape etc. The flow diagram of the finite element method (FEM) simulation which shows the procedure to the simulation works in this study is as shown in **Figure 3**.

**Figure 3.** Steps in FEM simulations of study [13].

The model of the 11kV polymeric high voltage insulator used in this investigation is shown in **Figure 4**. The polymeric high voltage insulator consists of the aluminum end fittings, fiber-reinforced plastic (FRP) core and polymeric housing. In this research, two different materials will be used: silicone rubber and EPDM. The aluminum end fittings are light weight in the meantime it provides good mechanical strength to support conductors over the transmission towers. The fiber-reinforced plastic core provides insulation between high voltage and ground terminal whilst the polymeric housing plays the role of protecting the FRP core from environmental conditions. In this research, the high voltage insulator is modeled as shown in Figure 4 following the design parameters (TABLE 1) and electrical properties (TABLE 2) respectively.

**Figure 4.** (a) An 11 kV insulator model [12], and (b) & (c) Model of 11 kV insulator with field grading material for simulation for this research.
TABLE 1. Design parameters of 11 kV polymeric high voltage insulator [14].

| Parameter (mm)     | Value |
|-------------------|-------|
| Shed diameter     | 90    |
| Shank length      | 26    |
| Trunk diameter    | 28    |
| End fitting radius| 16    |
| Axial length      | 160   |
| Creepage length   | 350   |

TABLE 2. Electrical properties of components [9], [10], [13].

| Components          | Relative permittivity $\varepsilon_r$ | Conductivity $\sigma$ (Ω$^{-1}$·m$^{-1}$) |
|---------------------|---------------------------------------|-------------------------------------------|
| Aluminium end fittings | 1.00                                  | 3.774 × 10$^7$                            |
| Silicone rubber housing | 2.50                                  | 1.210 × 10$^5$                            |
| EPDM rubber housing | 4.15                                  | 3.980 × 10$^{-17}$                        |
| Fibre Reinforced Plastic (FRP) core | 7.10                                  | 1.000 × 10$^{-17}$                        |
| Air                | 1.00                                  | 1.000 × 10$^{-14}$                        |

The boundary conditions for model were set as:

i. Nominal voltage of 18 kV applied on the high-voltage (HV) end fitting
ii. Nominal ground voltage of 0 V applied on the ground end fitting

3. RESULTS AND DISCUSSION

The list of nanocomposites corresponding to their properties that is investigated on this research is as follows in TABLE 3 below. The percentages analysed are based on the significance of the relative permittivity and conductivity. The percentage of 0 vol.% nanocomposite is chosen as a basis reference for comparison purposes. The percentage of 4 vol.% TiO$_2$-EPDM is evaluated in this the research due to the high conductivity, moreover as an exact comparison analysis with 4 vol.% of TiO$_2$ filled with SiR.

TABLE 3. Electrical properties of components [9], [10].

| Label | Nanocomposite (vol %) | Relative permittivity $\varepsilon$ | Conductivity $\sigma$ (Ω$^{-1}$·m$^{-1}$) |
|-------|-----------------------|-------------------------------------|-------------------------------------------|
|       | nano TiO$_2$-EPDM     |                                     |                                           |
| $A$   | 0                     | 4.15                                | 3.98 × 10$^{-17}$                         |
| $B$   | 4                     | 4.70                                | 7.94 × 10$^{-17}$                         |

| Label | Nanocomposite (vol %) | Relative permittivity $\varepsilon$ | Conductivity $\sigma$ (Ω$^{-1}$·m$^{-1}$) |
|-------|-----------------------|-------------------------------------|-------------------------------------------|
|       | nano TiO$_2$-SiR      |                                     |                                           |
| $D$   | 0                     | 2.50                                | 1.21 × 10$^{-5}$                          |
| $E$   | 4                     | 4.90                                | 1.33 × 10$^{-5}$                          |

The nano compounds are investigated on different types of base polymer or polymeric housing by having the two set of composite $B$ and $E$ samples that referring to silicone rubber and EPDM respectively. Meanwhile, $A$ and $D$ on its own without filler are also investigated.

3.1 Equipotential and Voltage Distribution

The equipotential lines at the high voltage terminal in numerical electrostatics can be observed to study the undulations at those regions. The electrical performance of two insulators made from SiR and EPDM are investigated.
As seen in Figure 5(a), it has experienced non-uniform of field lines that intersect on the insulator surface exceeding than one point. The equipotential lines that represent 9.54 kV and 10.9 kV respectively, each touches the insulator surface three times at three different locations namely point 1, point 2 and point 3. From this scenario, it is observed that the same voltage level acts on these points along creepage distance. However, as illustrated in Figure 5(b), undulation on voltage profile is not seen as there is only one single intersection for the equipotential lines that represents 9.54 kV and 10.9 kV respectively.

![Figure 5](image.png)

(a) SiR polymer without field grading material  
(b) EPDM polymer without field grading material

**Figure 5.** Equipotential distribution on sheds near high voltage

Therefore, the improvement of controlling electrical fields has been done through inserting the nanocomposites filled with SiR into both insulators’ structure. The design of nanocomposites is proposed along the FRP core with thickness of 1.4 mm. From this integration, the pattern of electrical fields will be changed and re-distributed uniformly along the insulator surface.

Figure 6(a) and Figure 6(b) shows the electrical field lines are shifted compared to previous electrical profile. The comparison of field distribution of both insulators can be seen through the intersection lines at certain voltage levels on the insulator surface. The equipotential lines that represent 9.55 kV and 10.62 kV in Figure 6(a) touches the insulator surface two times at two different locations namely point 1 and point 2. From this scenario, it is observed that the same voltage level acts on these points along leakage distance. Figure 6(b), shows undulation on voltage profile is not seen as there is only one single intersection for the equipotential lines that represents 9.55 kV and 10.62 kV respectively.

The similar simulation concept has been used for next insulator model; however, the new usage of nanocomposites is based EPDM. As seen in Figure 7(a), it has experienced a curve undulation which can be clearly understood by the intersections on the insulator surface exceeding than one point. The equipotential lines that represent 9.54 kV and 10.9 kV respectively, each touches the insulator surface two times at two different locations namely point 1 and point 2. From this scenario, it is observed that the same voltage level acts on these points along leakage distance. Therefore, generating a non-smooth voltage profile. However, as illustrated in Figure 7(b), undulation on voltage profile is not seen as there is only one single intersection for the equipotential lines that represents 9.54 kV and 10.9 kV respectively.
3.2 Electric Field Distribution

The electric field distribution along the creepage path is studied in the numerical electrostatic to investigate the electrical properties of the insulator. In this research, the concern is on the field at the terminals (triple point) which have high peaks due to accumulation of charges. The triple point consisting of end-fitting-air-polymeric housing which has high emission of electrons in the presence of strong electrical field. As a base for comparison the polymeric insulators (without field grading nanocomposite), SiR and EPDM rubber are simulated for the tangential electric field norm along the insulator creepage distance.
As illustrated in **Figure 8**, the field at the terminals are higher in SiR when compared with EPDM. This is due to the combination of dielectric and conductive values under high voltage condition of the materials. However, the SiR has strong hydrophobicity property and great mechanical strength when compared to EPDM.

![Figure 8. The tangential electric fields along insulator surface](image)

The nanocomposites as field grading materials, 4 vol.% TiO$_2$-SiR and 4 vol.% TiO$_2$-EPDM are respectively simulated on both polymer bases as illustrated in **Figure 9**. It is seen that 4 vol.% TiO$_2$-EPDM on SiR base polymer has successfully reduced the high electrical fields at both end fittings compared to another nano compounds. This is because the nanocomposites have a higher conductivity and dielectric constant, hence will provide better electric field distribution along the insulator surface.

![Figure 9. The tangential electric fields along insulator surface](image)
The electric field magnitude for SiR with and without 4 vol.% TiO$_2$-SiR as well as 4 vol.% TiO$_2$-EPDM field grading nanocomposite are summarized and tabulated for comparison as shown TABLE 4 below. From this electric field profile, it is clearly seen that the nano composite for both polymers’ housing shows the reduction of high electrical field at the susceptible areas such as HV/ground end fittings. Meanwhile at middle regions such as shank A, B and C shows similar reduction trend of electrical field after embedded with TiO$_2$ nanocomposites.

**TABLE 4.** Tangential electric field magnitudes at different regions

| Regions                  | SiR (pure) Electrical field (kV/cm) | 4 vol.% TiO$_2$-SiR Electrical field (kV/cm) | 4 vol.% TiO$_2$-EPDM Electrical field (kV/cm) |
|--------------------------|-------------------------------------|--------------------------------------------|---------------------------------------------|
| High Voltage end terminal | 5.28                                | 4.2                                        | 4.00                                        |
| Shank A                  | 0.92                                | 0.79                                       | 0.84                                        |
| Shank B                  | 0.65                                | 0.62                                       | 0.61                                        |
| Shank C                  | 0.82                                | 0.78                                       | 0.79                                        |
| Ground end terminal      | 5.14                                | 4.06                                       | 4.06                                        |

4. **CONCLUSION**

In conclusion, the objective of this research is achieved by successful simulations and analysis using finite element software, COMSOL Multiphysics. The effect of different filler loading such as 0 vol.%, and 4 vol.% for TiO$_2$-EPDM and TiO$_2$-SiR nanocomposites are investigated correspondingly. Moreover, the effect of different base polymer to composite’s performance as field grading material is also achieved by investigating with two base polymers, SiR and EPDM.

A 2D symmetry model of the 11kV high voltage insulator was modelled by considered to the design, parameters and electrical properties. It was simulated with a nominal voltage of 18 kV at high voltage end and 0 V at ground end. The focus was given to the triple point regions near ground and high voltage terminals that are experiencing electrical stresses. Therefore, a unique nanocomposite material is investigated to act as the field controller. Whereby, the filler, TiO$_2$ is nano-sized for great surface area and a semiconducting material for better distribution of electric field as well as voltage profile. The insulators made from SiR and EPDM were tested with nanofiller starting at 0 vol.% and 4 vol.% of TiO$_2$ compounded with EPDM. From the simulation results, 4 vol.% of TiO$_2$-EPDM nanocomposites on insulator with SiR base polymer show good performance in both voltage profile and electric field characteristics compared with another combinations.

5. **REFERENCES**

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