MJSAT

Malaysian Journal of Science
and
Advanced Technology

journal homepage: https://mjsat.com.my/

Effect of Charge Existence on Electric Field Distribution in String Insulator

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KEYWORDS

Charge distribution
Glass insulator string
Electric field
Stainless steel mesh
Finite element software

ARTICLE HISTORY

Received 16 February 2026
Received in revised form
18 March 2026
Accepted 25 March 2026
Available online 27 March 2026

ABSTRACT

The charge existence at any region of insulator sting will distort the original electric field distribution and may result in the enhancement of local electric fields to the highest level over a long period of time. This situation would then lead to the occurrence of partial discharge and further cause premature failure of insulating material due to degradation process which can lead to electrical breakdowns and electrostatic discharges. Therefore, this paper investigates the effect of charge existence on the electric field distribution along glass insulator string. The measurement of charge distribution was experimentally collected using charge sensors to be applied in the simulation modelling. Finite element software was also adopted in this paper to assess the effect of charge existence on electric field distribution. It is found that the charge distribution is successfully collected with negative charge distribution pattern is obtained. It is proven that the value of charge collected in the experimental works indeed affects the distribution of electric field when the insulator is injected with that value. Also, it was found that the negative charge has more impact toward the electric field distribution compared with positive charge. The findings suggest that the existence of charge on the surface of insulator is certainly affect the local distribution which after a long period of time may affect the high voltage insulation performance and finally may threaten the reliability of power system network.

1. INTRODUCTION

The discovery of electricity in the early 19th century has led to the development of electric power transmission systems which consists of stages of generation, transmission, and distribution systems. However, both transmission and distribution stages together are typically exposed to the electrical, mechanical, and environmental stress that will affect the condition of overhead insulators [1]. Overhead insulators need to provide insulation and mechanical support between the transmission line and the poles/tower that are often exposed to the atmosphere. Therefore, the performance of these insulators is strongly affected by environmental conditions in which it is exposed, shape, and the intrinsic properties of the insulator. This condition has led to the accumulation of contamination sources that may attract space charge and hence modify the local field distribution [2],[3].

Solid insulators whether made from glass, porcelain or even polymer have the tendency to accumulate space charge. Space charge is generally known as the excess of an electron or free electron that form a charge density in space due to the dominance of either negative or positive ions within any region of space. The presence of space charge over a long period of time may result in the enhancement of local electric fields and ultimately lead to premature failure of insulators. Literature often tends to show that space charge exists within polymeric insulation [4],[5],[6] despite the apparent possibility of space charge accumulating on the surface of the material [7]. This situation has provided a substantial area for researchers to

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https://doi.org/10.56532/mjsat.v6i1.720

investigate the distribution of space charge on the insulator surfaces particularly the glass insulator string.

The accumulation of charge on the insulator surface conceived may result in changes to pre-breakdown conditions. This is because the existence of charge accumulation in any region of space can cause field distortion which may eventually initiate flashover. Much effort has been concentrated to develop the measurement methods of space charge distribution on the surface of insulation materials in the past few decades and has been summarized as in Figure 1. The techniques used for surface charge measurement are basically based on macroscopic and microscopic probes. However, with such rapid development, a new technique has been introduced lately by [8] with the use of charge sensors.

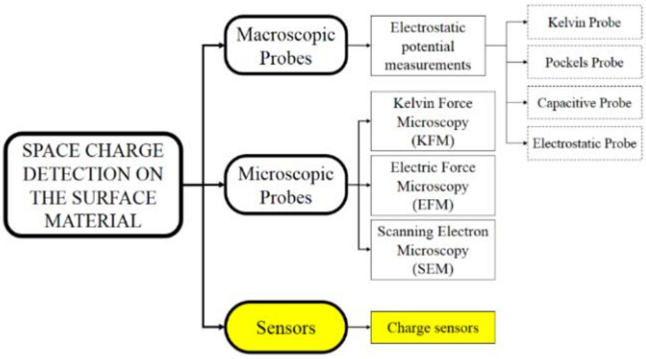


Fig. 1. Summary for space charge measurement methods on the insulation material surface

The usage of Kelvin probe was first introduced in 1898 [9] to measure the surface potential distribution has encouraged many researchers to improve the performance of the probe up to now. The scanning Kelvin probe microscope was applied in [10] to study the deposition of surface charges on polyimide sample and found the positive charge accumulated on the insulator surface. A similar result was found by using the very old method of Lichtenberg figures.

The space charge distribution was evaluated by [11] on the surface of polyethylene oxide (PEO) under DC stress. Their findings revealed that the negative charges possess a mobile nature which contributes to the space charge build up at the electrodes, in both experimental and simulation analyses.

A new surface potential probe based on Pockels sensing technique that can be placed closely to the measured sample was developed in [12]. A study on a polymethyl methacrylate sample showed this new technique has minimum sensitivity that reaches 10 V after applying the modulation techniques.

The problem faced by conventional capacitive probe in the measuring system due to charge leakage was improved in [13]. A ground metal shutter was installed as probe head in their new design by increasing the distance between probe needles to the shielding along the insulator surface to increase the charge leakage time constant. An improvement in the probe sensitivity and lower charge leakage was found on the surface of Teflon insulator under DC voltage.

Recent studies showed that surface discharge practically occurs due to the presence of electrostatic charge on the insulator surface. Therefore, different approaches to measure the electrostatic potential caused by the distributed charge on the insulator surface with different roughness were conducted by [14] using a scanning electrostatic voltmeter. It is obtained that the increase in the local electric field occurs at the surface of a flat insulator was due to the electron collision process from the triple junction and the cathode making the insulator surface positively charged. While for the rough surface of the insulator, the electric field distribution was uniform due to the neutralization process by trapped electrons on the positive charge on the surface of insulator.

The development of high-resolution scanning electrostatic probe was carried out in [15] to overcome the limitation of traditional electrostatic probes. The new system can monitor the insulator surface in three dimensions without any limitation of sample thickness. By owing to the nature of easy handling, the distribution of surface charge can be obtained accurately, and the scanning mechanism can be used for the practical geometry of the insulator.

The scanning electric potential microscopy (SEPM) is also known as Kelvin force microscopy (KFM) since the technique is based on the Kelvin method. Results presented on topography and electric potential images of thermoplastic insulators using SEPM that was modified with a standard non-contact atomic force microscope (AFM) instrument [16]. Their SEPM results showed that different types of insulators give different information on the electrical potential distribution across the polymer surfaces.

Another topographic imaging system based on electric force microscopy (EFM) was used by [17] to characterize the charge distribution between the tip and sample for charge packet scales. Although EFM has advantages to perform localized charge deposits, their findings showed that the distance between tip and insulator surface and working process of EFM, are the main factors affecting the charge distribution.

The advantages of high spatial resolution and non-destructive technique in the microscopic methods especially scanning electron microscopy mirror (SEMM) was investigated by [18] to study the insulator properties based on charge trapping nature under high electric field stress application. The outcome indicates that the measurement of ground current and SEMM image gave information on the rate of charge trapping and condition of surface distribution.

It is an accepted fact that inconsistency of space charge distribution on the insulator surface may affect and degrade the insulation performance. Apart from that, the existence of space charge subjected to applied voltage over a long period of time may also modify the original electric field which finally lead to the accelerated aging and premature electrical breakdown of the dielectric surface, resulting in line transmission failure. Therefore, this paper investigates the effect of charge existence on the electric field distribution along glass insulator string using finite element software.

2. METHODOLOGY

The flowchart of methodology is presented in Figure 2. Before the simulation works were conducted using finite element software, experimental works were carried out first to measure the value of charge distribution across each insulator surface. The charge distribution measurement on the surface of glass insulator was conducted in stage I using charge sensors.

Meanwhile, the simulation work was done in stage II by modelling the insulators using Finite Element Method Magnetics (FEMM) software. It is important to highlight that the measured charge distribution data will be used in the simulation works to monitor the charge existence effect on the distribution of electric field.

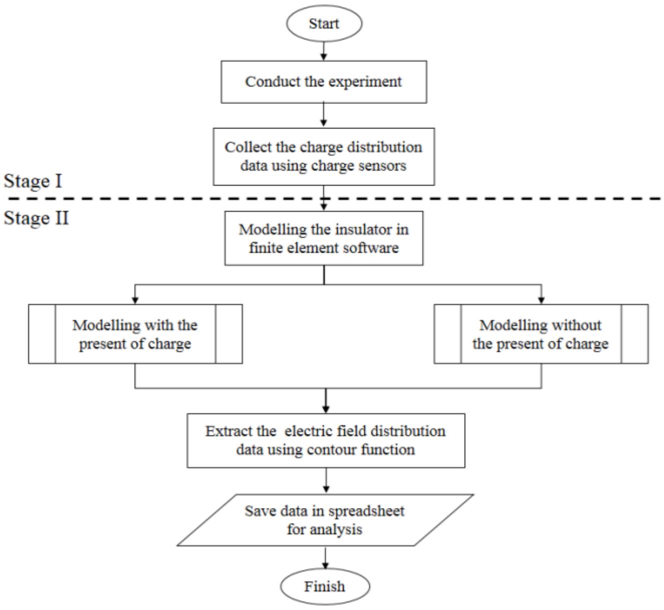


Fig. 2. Flowchart of methodology

2.1 *Experimental Works*

Four-unit glass insulators available in the laboratory were selected to be assembled in the chamber as a string insulator. The measurement of charge distribution on the glass insulator's surface was carried out with the attachment of meshes surrounding each insulator following the method explained in [19]. The charge distribution data was measured after the string insulator was injected with applied voltage of 33 kV AC stress in the duration of 20 minutes. A radially stainless-steel shaped mesh is placed axially at a radial distance of 2 cm from the insulator's circumference. The stainless-steel mesh was used in this work as proven in [20] can be successfully captured charges on the insulator surface. The connection of charge sensors is depicted in Figure 3 where the red probe was connected to the mesh while the black probe was grounded. The charge sensors were also connected to the data acquisition namely Labquest2 for data collection process. The data collection was repeated at least 3 times and lastly the data is saved to the computer. The position of tested string insulator with the mesh attachment and the whole view of experimental works is shown in Figure 4.

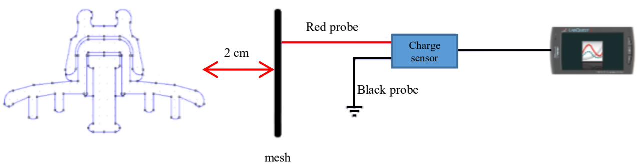
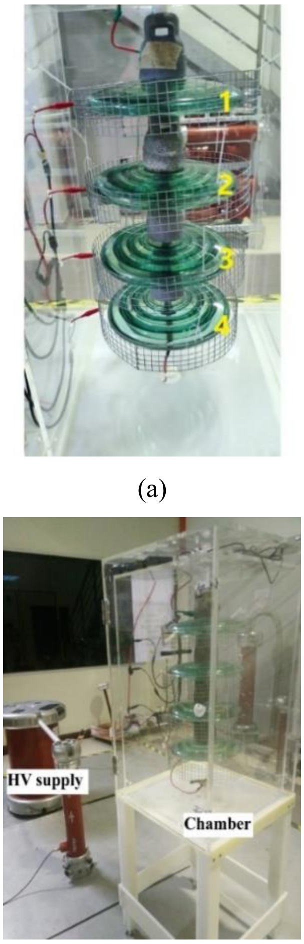


Fig. 3. The charge sensor connection



(a)

(b)

Fig. 4. (a) The insulator position in the chamber; (b) Pictorial view of experimental setup in laboratory

2.2 *Simulation Modelling*

Many sophisticated finite element software has been utilized to provide information on the condition of the insulator. The electric field distribution for three types of ceramic disc insulators using ANSYS software was investigated in [21]. Meanwhile, the electric field distribution inside and around composite insulators was studied by [22] using Opera-2d software. Electric field distributions of long-rod porcelain and silicone rubber insulators under clean, uniform, and non-uniform pollution was examined by [23] using COMSOL Multiphysics software while electric field distributions along the surface of porcelain, polymeric and glass insulators was analyzed using ANSOFTMAXWELL software by [24].

All software mentioned before has proven that the distribution of electric field across high voltage insulators can be observed using finite element software. Therefore, in this paper, finite element software, particularly FEMM software was used to estimate the electric field distribution along the glass insulator string with the presence of charge. The glass insulators were drawn in free space using Electrostatic problems and the material properties listed in Table 1 were transferred manually to the computer for simulation purpose. By adopting a cylindrical reference system with the z-axis coincident with the axis of the insulator, the simulation was modelled in an axisymmetric 2D problem to represent the 3D modelling. The glass insulator string was modelled with voltage of 33 kV was applied to the fourth insulator pin while the first insulator cap is grounded. The supporting structures, conductors, and other accessories are to be neglected in this study.

Table 1. Material properties for modelled insulator [25]

Material	Permittivity value (F/m)
Air	1
Cement	15
Iron	1000
Glass	4.2

3. RESULTS AND DISCUSSION

3.1 Experimental Results

Figure 5 illustrates the surface charge density distribution on each glass insulator along the string. The magnitude of surface charge density is noticeably higher at the insulators located near the electrodes compared to those in the middle of the string. This trend can be attributed to the flow of leakage current from the high-voltage (HV) electrode towards the ground (GND) electrode, which leads to greater accumulation of negative charges on the insulator surfaces near the electrodes [20],[26].

Moreover, the non-uniform electric field along the insulator string results in stronger electric stress at the end units, promoting increased charge deposition, while the middle insulators experience lower stress and thus reduced charge accumulation. The experimentally measured surface charge values were subsequently applied in the simulation to examine their effect on the electric field distribution.

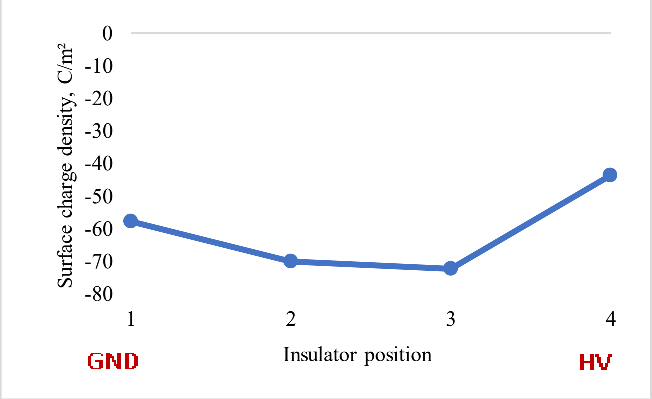


Fig. 5. The value of surface charge density on each glass insulator

3.2 Simulation Results

Figure 6 presents the electric field distribution of glass insulator string without charge existence. It can be observed that high electric field strength was focused more inside the glass insulator that was flanked by cement which is also known as triple junction region [27]. The electric field distribution for each of the insulators can be considered as like each other since no charge was injected to the insulator surface.

In addition, the electric field intensity gradually decreases along the shed surfaces away from the high-voltage end, indicating a relatively uniform field distribution when no charge accumulation is present. Since no charge was injected onto the insulator surface, the electric field profiles of each insulator unit are similar, reflecting a symmetrical and stable electric field distribution along the entire string. This uniformity suggests that, under clean and uncharged conditions, the electric field behavior is primarily governed by the insulator geometry and material properties rather than surface effects.

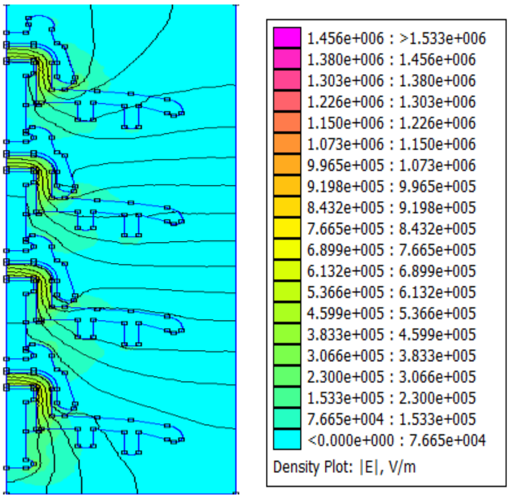
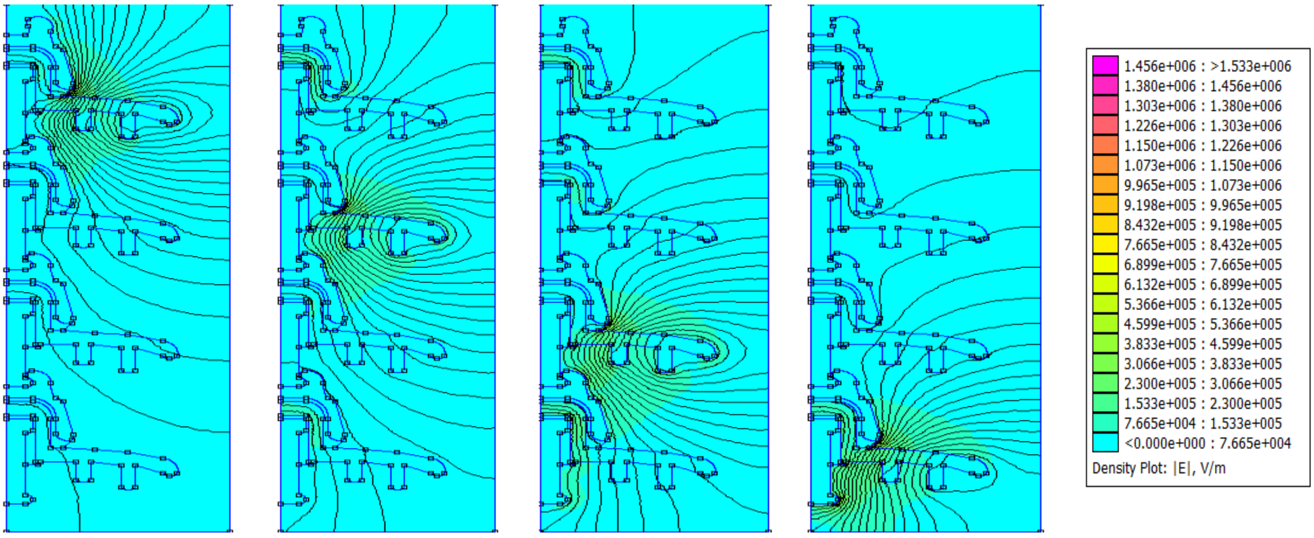


Fig. 6. The electric field distribution of glass insulator without charge existence

3.3 Comparison of Electric Field Distribution with and without Charge Existence

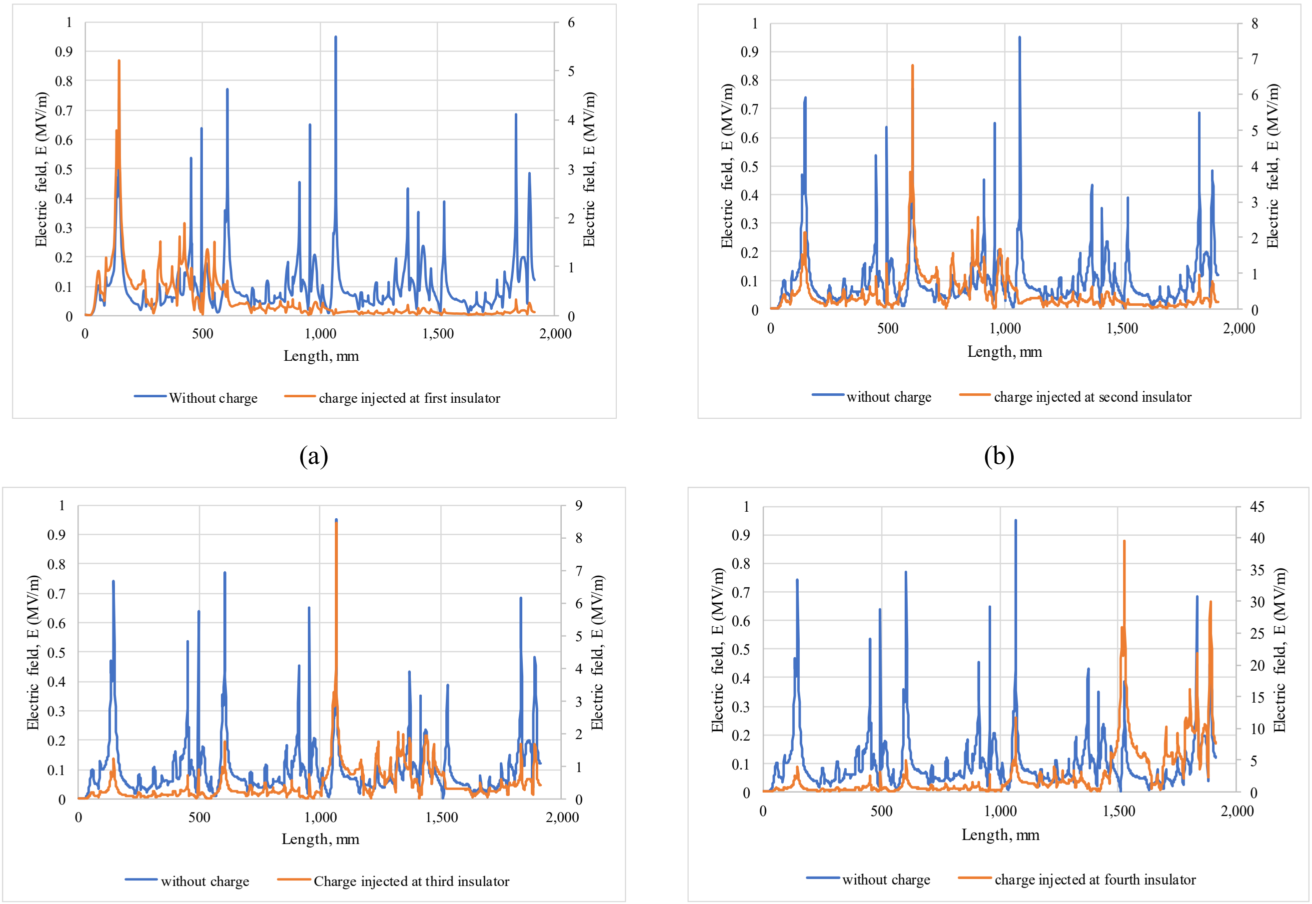
It is important to highlight that only one insulator was injected with the surface charge value measured from experimental works while the rest of the insulator is not injected with charge for each simulation in this section. The electric field distribution of glass insulator string when the surface charge was injected is illustrated in Figure 7. It is observed that the electric field is mostly distributed at insulator that was injected with surface charge. It can be concluded based on the presented findings that each time the charge is injected at the certain insulator, the distribution for electric field concentrated more at those. This finding is supported by [28] who found that the electric field is partly enhanced by the accumulated charge in the insulation material. Thus, the obtained results show that the presence of charge affects the distribution of local electric field along the insulator string. The distribution of electric field along creepage distance shown in Figure 8 also clarifies that the electric field distribution is distorted when charge is injected at insulator.

Overall, the electric field distribution pattern for all the insulators when injected with charge can be said to be quite like the insulator without charge. Only one interesting fact to note is that the electric field strength achieved the highest value at the location that injected with charge. It is noticed that the value of electric field when no charge is injected is still the highest at the certain length compared to insulator that is injected with charge. This shows that the charge plays a significant role in the electric field distribution.



(a) (b) (c) (d)

Fig. 7. The electric field distribution of charge injected at (a) first, (b) second, (c) third and (d) fourth insulator



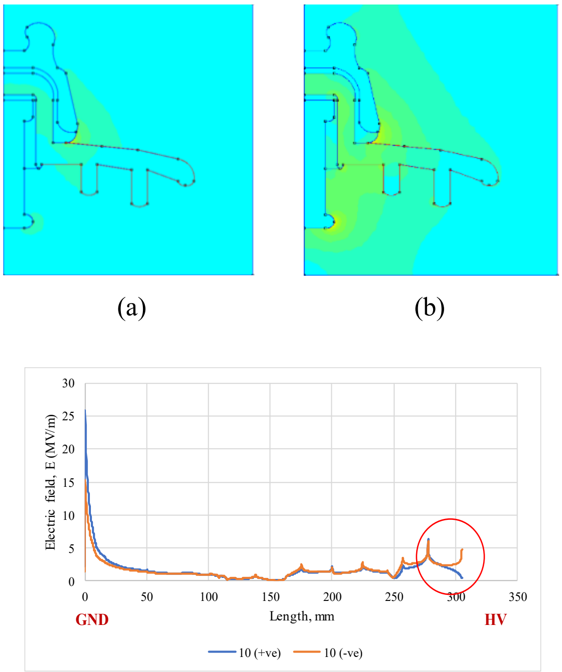
(a) (b)

(c) (d)

Fig. 8. Electric field distribution without charge and when charge injected at (a) first, (b) second, (c) third and (d) fourth insulator surface along creepage distance

3.4 Effect of Charge Polarity on Electric Field Distribution with Different Magnitude

This section is now focusing on the effect of charge polarity toward the electric field distribution. Therefore, only one insulator is considered with three different values of charge is injected to the insulator. The distribution of electric field with the charge injection value of ±10µC is shown in Figure 9. It is noticed that the electric field distribution for negative value of charge is much higher than the positive value of charge as represented in circle in Figure 9(c). It is believed due to the characteristic of charge that attract and repel may influence the charge distribution on the insulator as well as the electric field distribution for the insulator [29].



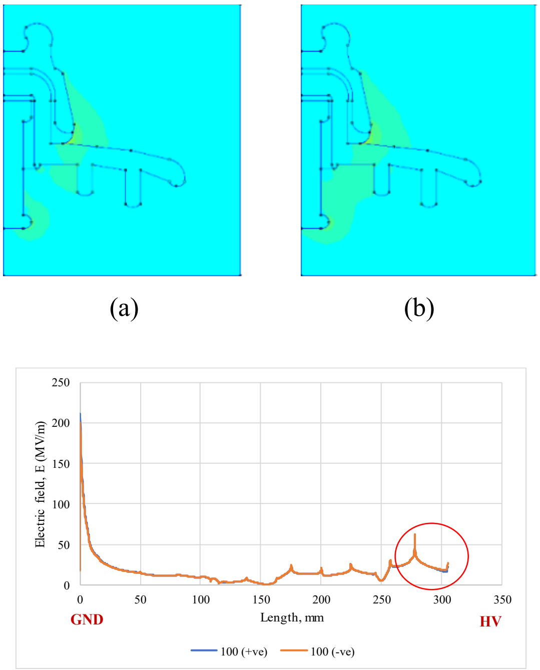
(a) (b)

(c)

Fig. 9. The distribution of electric field with (a) positive charge, (b) negative charge and (c) comparison between different charge polarity for charge 10µC

Figure 10 displays the electric field distribution when the insulator is injected with ±100 µC of charge. It is observed that the electric field distribution for the negative charge case is higher than for the positive charge case. This behavior is consistent with recent studies showing that under polarity reversal or sustained DC stress, accumulated surface charge alters the local field profile and can increase electric field peaks due to lag in charge adjustment relative to the applied voltage change [30].

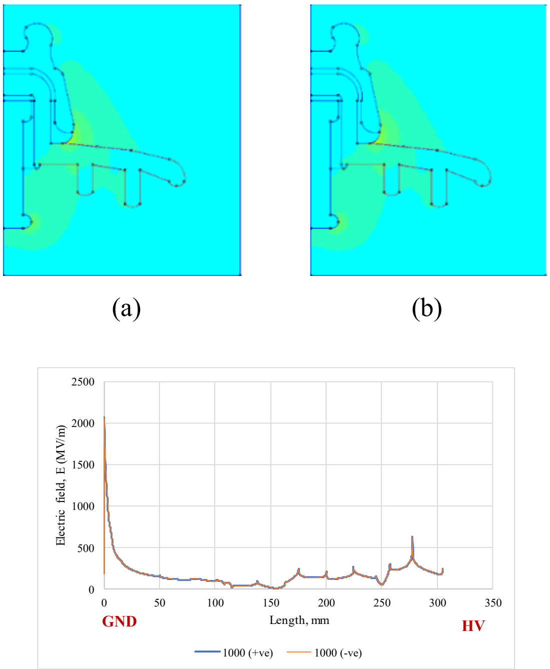
The electric field distribution when injected with positive and negative charge of ±1000µC is illustrated in Figure 11. It is noticed that the electric field distribution for both polarity of charge seems similar. From the electric field distribution along creepage distance is overlap between positive and negative charge as shown in Figure 11(c). From the presented results, it can be concluded that the smaller the value of charge contributes to the higher value of electric field distribution. In terms of polarity, the negative charge has more impact toward the electric field distribution compared with positive charge.



(a) (b)

(c)

Fig. 10. The distribution of electric field with (a) positive charge, (b) negative charge and (c) comparison between different charge polarity for charge 100µC



(a) (b)

(c)

Fig. 11. The distribution of electric field with (a) positive charge, (b) negative charge and (c) comparison between different charge polarity for charge 1000µC

4. CONCLUSION

The usage of finite element software in modelling the insulator string gives a contribution in assessing the effect of charge existence on electric field distribution profile. From the electric field distribution profile, it can be concluded that the presence of charge gives a significant effect on the local electric field distribution along the insulator string. In conclusion, the main findings of this study are as follow:

1. The measurement of charge distribution on the glass insulator surface has been successfully conducted with the negative charge distribution pattern was found in the experimental results.
2. The glass insulator string modelled using finite element software shows that the value of charge collected in the experimental works indeed affects the distribution of electric field when the insulator is injected with that value.
3. Based on the presented result, it is evident that the negative charge has more impact toward the electric field distribution compared with positive charge. It also shows that the smaller value of charge contributes to higher value of electric field distribution.

ACKNOWLEDGEMENT

The authors sincerely thank Universiti Tun Hussein Onn Malaysia (UTHM) for providing financial support and access to its facilities. This research was funded through the Tier 1 Grant (Vote No. Q362). The facilities and financial support provided by UTHM have significantly contributed to the successful execution and progress of this research project.

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