Journal of Electrostatics 72 (2014) 315–321

Contents lists available at ScienceDirect

Journal of Electrostatics

journal homepage: www.elsevier.com/locate/elstat

Characterization of charge distribution on the high voltage glass insulator string

N.A. Othman*, M.A.M. Piah, Z. Adzis, H. Ahmad, N.A. Ahmad, H. Kamarden, A.A. Suleiman

Institute of High Voltage & High Current, Faculty of Electrical Engineering, Universiti Teknologi Malaysia, 81310 Johor Bahru, Malaysia

ARTICLE INFO

Article history:
Received 7 April 2014
Accepted 29 May 2014
Available online 12 June 2014

Keywords:
Charge distribution
Electric-field distribution
Voltage distribution
Glass insulator
Finite element software
Transmission line

ABSTRACT

Irregularity in charge distribution of an insulator may lead to accelerated aging and electrical breakdown. However, knowledge of charge distribution on the insulation surface is still insufficient albeit has gained worldwide attention. The insufficiency is particularly on the charge profile along the string insulator under AC excitation. Therefore, charges distributions on the surfaces of glass insulators without installed grading ring are investigated in this paper. Simulation and experimental results were found in good agreement when studying the charge distribution pattern along glass insulator string where the polarity of charge swinging occurs at the center of suspension string insulator of I-type.

1. Introduction

The reliability of a transmission network is partly dependent on the performance of insulators available in the electric power transmission system. These insulator strings provide insulation (and mechanical support) between the transmission line and the poles/tower that are often exposed to the atmosphere. Therefore, the performance of insulators strings is strongly affected by environment conditions in which it is exposed, shape and the material properties of the insulator [1].

Materials used in high voltage insulation are usually made of organic and inorganic [2]. Inorganic materials are widely used particularly in glass and porcelain insulators, while the organic materials used in insulating polymers. Glass and porcelain insulators are the earliest insulators used in power system transmission lines. Glass and porcelain insulators offer many advantages such as very high mechanical strength under pressure and hardness, thus capable to operate under adverse conditions also suitable for environments with dust, salt and high moisture, or for combination of all aforementioned. Due to these advantages, inorganic insulators especially glass are still used even today around the world, including Malaysia, as shown in Fig. 1. Meanwhile, organic insulators use polymers instead of porcelain as weather sheds and built with mechanical load-bearing fiberglass rods.

The insulator strings are designed to minimize the buildup of electrical charges around the insulator surfaces because charge buildup causes current leakages, arcs and flashovers that can accelerate insulation breakdown. Studies have shown that the leakage current (LC) around string insulators can provide information about the insulators surface condition and indeed a promising technique to study the performance of the insulator [3,4]. Thus charge distribution on the insulator surfaces has received considerable attention for decades. It is now accepted fact that breakdown of the insulator is correlated with the presence of space charges [5,6]. Where significant positive charge propagation was observed in [5] immediately before breakdown while in [6] breakdown process was initiated by space charge nature at the interfaces of LDPE.

It is established that the flow of LC is definitely due to the flow of charges [7]. All insulators that are made of the same shape and materials that operates in same normal conditions are expected to contain equal number of positive and negative charges; no net charge. However, these charges become imbalanced in the presence of space charge and leads to the formation of static electricity effects. When these electrical effects move from one surface onto another, electrostatic discharges (ESD) occurs. The formation of electrostatic field on the surface of insulators will create electrical pathways that may allow relatively under-rated

* Corresponding author.
E-mail address: nazlin7@live.utm.my (N.A. Othman).

http://dx.doi.org/10.1016/j.elstat.2014.05.003
0304-3886/

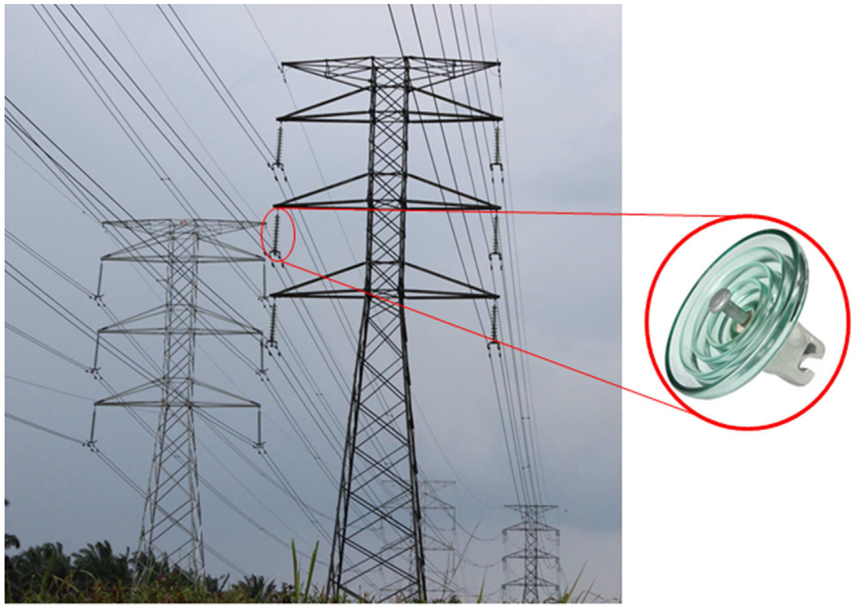

Fig. 1. Glass Insulator used in transmission line at Skudai, Malaysia (April 2014).

voltages to flow across the insulator surface and eventually lead to breakdown [8].

To the best of authors' knowledge, space charge measurement has become a common tool to investigate the internal behavior of solid insulating material under high electric field. Many methods, either direct or indirect, have been developed for investigating space charge distribution in solid dielectrics and are explained deeply in Ref. [9]. However, the most popular methods that have been used widely are pressure wave propagation and pulsed electro-acoustic methods that are described thoroughly in Ref. [10]. Though a lot of studies have been done on the accumulation of space charge inside the polymeric insulation material [11] as well as in insulator surfaces [12,13], the exploration of space charge in glass as insulating material is still limited despite the apparent possibility space charge accumulation on the surface of the material [14]. Therefore, in this paper, the charge distribution on the glass insulator surfaces was investigated both for simulation and experimental-based studies. A string of four cap-and-pin glass insulator without installed grading ring, is taken as main research object. In the simulation study, the voltage and electric field distributions that are indeed closely linked to charge distribution were simulated using available commercial software namely QuickField™ Professional. Meanwhile, an attempt to capture charge distribution on glass insulators surface by using stainless steel mesh is also introduced in this paper. This study is expected to present and compare both the simulation and experimental study of the effect of charge distribution on glass insulator surface.

2. Simulation parameters

A string of four cap-and-pin suspension glass insulator particularly U100BL [15] type is selected in this study. Technical parameters of the modeled insulator is shown in Fig. 2 where five different regions are depicted as cap (G_1), cement between cap and glass (G_2), glass (G_3), cement between glass and pin (G_4), and insulator pin (G_5). The shed diameter, D is 255 mm; while the insulator height, H is 146 mm. The nominal creepage distance of each insulator is 320 mm.

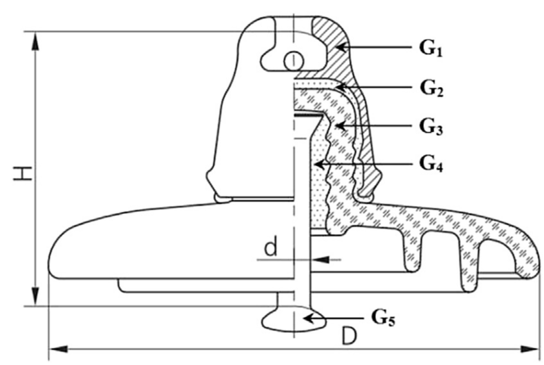

Fig. 2. Schematic of the U100BL insulator model adopted for study [15].

The simulation is modeled in free space, indeed according to the size of chamber (50 cm × 50 cm × 75 cm) used in the experiment. AC stress of 33 kV is applied to the pin at the bottom of string insulator while top insulator cap is grounded. The actual profile data of the insulator in Table 1 is transferred manually to the computer for simulation purpose. Considering that the insulator has a symmetrical shape, this simulation works was performed in an axisymmetric 2D model class. In this class, cross-section of the insulator that shown in Fig. 2 is adequate to represent the 3D modeling model in QuickField™ professional software [16]. It is worth noting that the supporting structures, conductors and other accessories are to be neglected in this study.

Table 1
Material properties [17,18].

Types of material	Relative electric permittivity, ε_r
Glass (G_3)	4.2
Cement grout (G_2 and G_4)	15
Cast iron (G_1 and G_5)	1000
Air	1

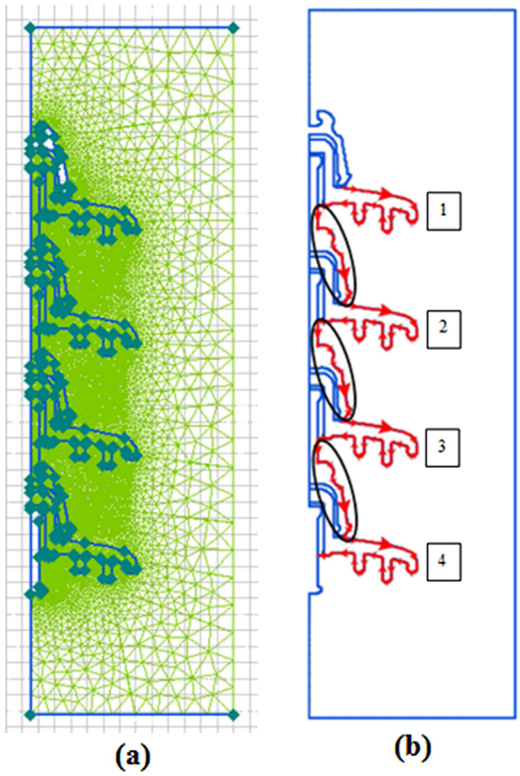

Fig. 3. (a) Mesh model, and (b) creepage distance (red in colour). (For interpretation of references to colour in this figure legend, the reader is referred to the web version of the article.)

The problem type chosen for this simulation was 'electrostatic'. Represented in Eqs. (1) and (2) is the equation for electric field and Laplace's equation for axisymmetric case:

$$E = -\nabla U \quad (1)$$

$$\frac{1}{r}\frac{\delta}{\delta r}\left(\varepsilon_r r\frac{\delta U}{\delta r}\right) + \frac{\delta}{\delta z}\left(\varepsilon_z \frac{\delta U}{\delta z}\right) = -\rho \quad (2)$$

where E is the electric field intensity vector while components of electric permittivity tensor ε_r, ε_z and electric charge density, ρ are constants within each block of the model.

3. Simulation results

The simulation is modeled as depicted in Fig. 3a and the discussed analysis is based on the creepage distance that shown in Fig. 3b. While, the voltage and electric field distribution of the string insulators are shown respectively in Fig. 4a and b. The distribution of voltage gradually increases from the first insulator cap to the fourth insulator pin. The voltage distribution along the creepage distance is non-uniform where high voltage gradient focused more on the metals parts (among dotted line) as shown in Fig. 5. Non-uniform voltage distribution is believed due to the capacitance formed in the air between metal parts. The distribution of electric field along the creepage distance is presented in Fig. 6 where highest electric field strength is obtained near the first insulator cap. An anomalous peak is found between positions 700 mm and 900 mm creepage distance. This anomalous peak is believed due to the occurrence of swinging charges from positive to negative charge and higher amplitudes

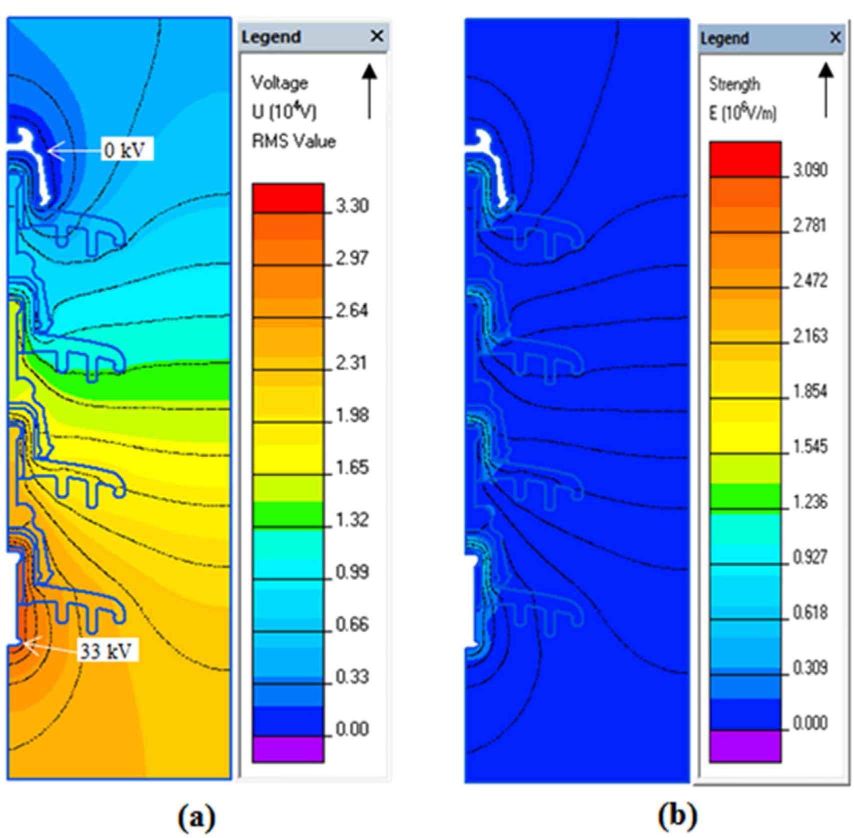

Fig. 4. (a) Voltage distribution, and (b) electric field distribution.

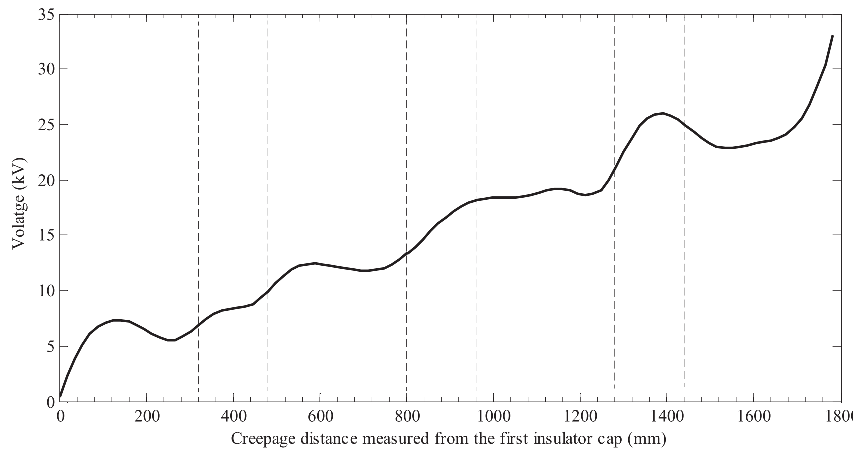

Fig. 5. Voltage distribution along creepage distance.

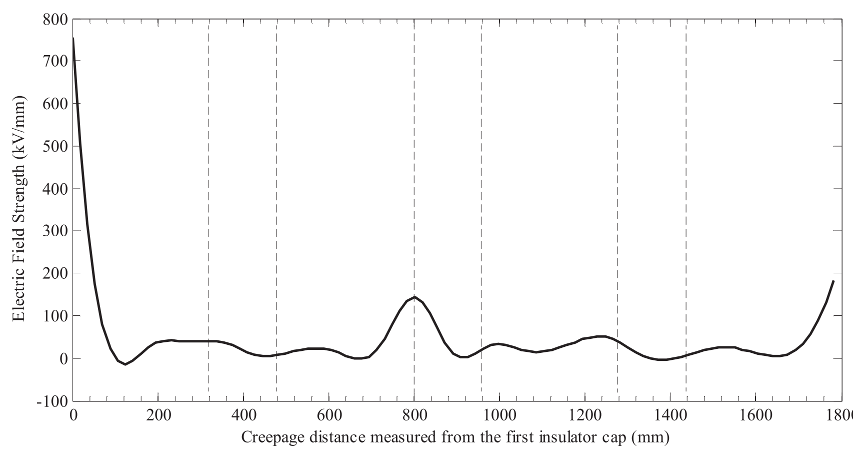

Fig. 6. Electric field distribution along creepage distance.

for this peak occur between the insulation and conductor interface.

Analysis of voltage and electric field distribution is essential in charge study since it articulates the distribution of charges in the material and this statement is in conformity with Gauss's Law. This phenomenon is reflected by the distribution of charge density along creepage distance of four insulators that presented in Fig. 7. The distribution of charge density seems concentrated more on the metal parts which represented by black circles in Fig. 3b. The distribution of positive charge density on these metal parts shows an increasing trend from the high voltage electrode to ground electrode.

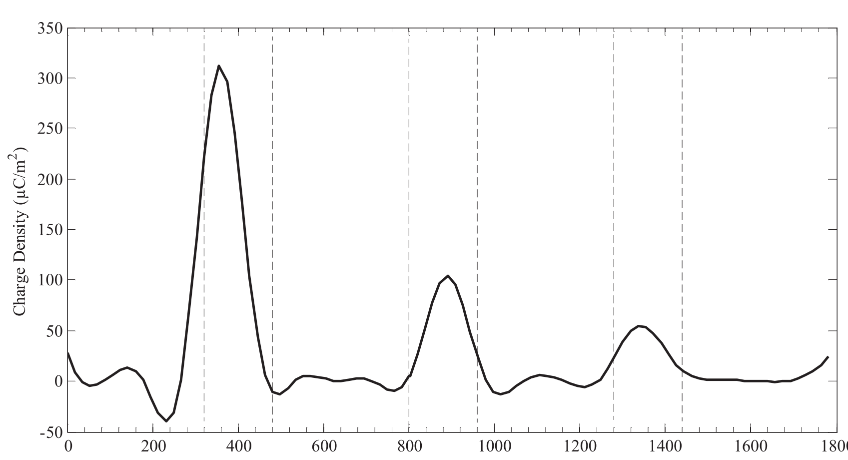

Fig. 7. Charge density distribution along creepage distance.

4. Experimental works

4.1. Sample preparation

A string of four cap-and-pin glass insulators were selected from the laboratory for the experiment purposes. The picture of sample insulators is depicted in Fig. 8 while the insulator parameters are tabulated in Table 2.

4.2. Charge measurement setup

A stainless steel mesh is introduced as a medium to capture the accumulated charge in the experimental study. This is a new idea for charge measurement that inspired by an electrostatic kit available from Vernier Software and Technology. The charge measurement setup is depicted in Fig. 9 and this modification is made by considering the behavior of charge itself. A stainless steel mesh is placed at a distance of 2 cm, which is the nearest gap that can be applied for voltage of 33 kV to capture the charge that will be accumulated on the surface of glass insulator. It is worth mention that the maximum applied voltage that can be applied at this distance is 43.7 kV.

5. Experimental setup

All samples were tested in a test chamber, made of a polycarbonate sheeted walls with measuring size of 50 cm × 50 cm × 75 cm. A 0.25/250 kV, 375 kVA, 50 Hz, single-phase transformer was used as the test source. A 33 kV of AC stress is applied to the pin at the bottom of string insulator while top insulator cap is grounded. A stainless steel mesh is placed at a distance of 2 cm from the tested insulator as a medium to capture the accumulated charge. The tested insulators were tagged as insulator I_1, I_2, I_3 and I_4 consecutively from the top as shown in Fig. 8. The accumulated charges on the surface of glass insulator 1–4 were measured by four units of charges sensor, i.e. CS1–CS4, respectively. These sensors are connected to the data logger namely Labquest2 via Wi-Fi for observation purposes. A pictorial view of the laboratory test setup for this experiment is shown in Fig. 10 and charge measurement experimental setup in Fig. 11.

6. Charge measurement results

The distribution of charge for both simulation and experimental becomes more negative from insulator 1 to insulator 4 as depicted in Fig. 12. This observation is true since the leakage current (LC) flowed from high voltage electrode to the ground. The direction of LC flow would results the charge distribution on insulator located near to the high voltage terminal is more negative in its value. It is believed that the charge distribution is due to the characteristics of charge and the material. Attributes of charges that attract and repel affect the charge distribution on each insulator in the string. Moreover, the nature of the glass material that tends to lose electrons according to triboelectric series [19] causes the electrons attracted to the positive charge. Due to this phenomenon, positive charge distribution pattern is found on insulator 1 and 2. It is believed that the electron migrate slowly through the atmosphere from the glass insulator surface to the high voltage source and this repelling process causes the surfaces of glass have more positive charge. The moving electron is believed to be homocharge type.

The negative charge distribution patterns that found on the insulators 3 and 4 are believed due to the charge injection from high voltage source. Electron injected from the high voltage source attracted to the metal parts of the insulators and the moving electrons is believed to be heterocharge type. It seems very probable more electrons accumulate at the surface of insulator 4 since the high voltage source is injected at this insulator pin. It is believed that the charge on the insulator 4 sense an ionization impact between the electrical charge flow on the surface of the insulator and air molecule [20]. Slow electron mobility from ground electrode as well as loss of electron from insulators 1 and 2

Table 2
Parameters of the sample insulators.

Parameter	Unit (mm)
Creepage distance, Cd	320
No. of ribs	4
Rib diameter	
Rd_1	50
Rd_2	120
Rd_3	190
Rd_4	255
Insulator pin diameter, D_p	30
Insulator cap diameter, D_c	80
Weight	3.9 kg

Fig. 8. Sample insulators.

Fig. 9. Charge measurement setup.

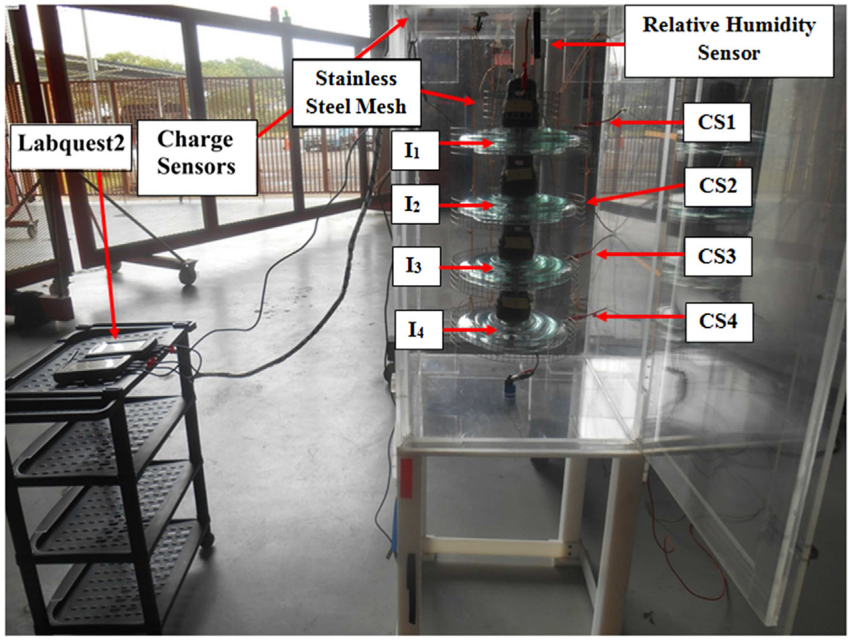

Fig. 10. Pictorial view of the laboratory test setup.

contributes to the negative charge distribution pattern on the insulators 3 and 4.

It can be seen that the value of charge for insulator 4 from the simulation part is higher than experiment part compared to other insulators. This phenomenon occurred due to the insulator used for the simulation part is an ideal condition of insulator without any defects. While for the experimental part, the selected insulators are the insulator that removed from the transmission line service for the past years. Thus, the differences value of charge found in the insulator 4 is believed due to the ionization and aging effects that occurred during service.

7. Conclusion

The simulation and experimental-based studies for distribution of charge on the glass insulator string surfaces have been investigated. It is shown in the simulation study that the distribution of charge is indeed closely link to voltage and electric field distributions. A stainless steel mesh that introduced in this work seems capable to act as a medium to capture the accumulated charge on the glass insulator surface. Good agreements that indicating the charge distribution pattern were found in both simulation analysis and experimental results where the polarity of charge swinging

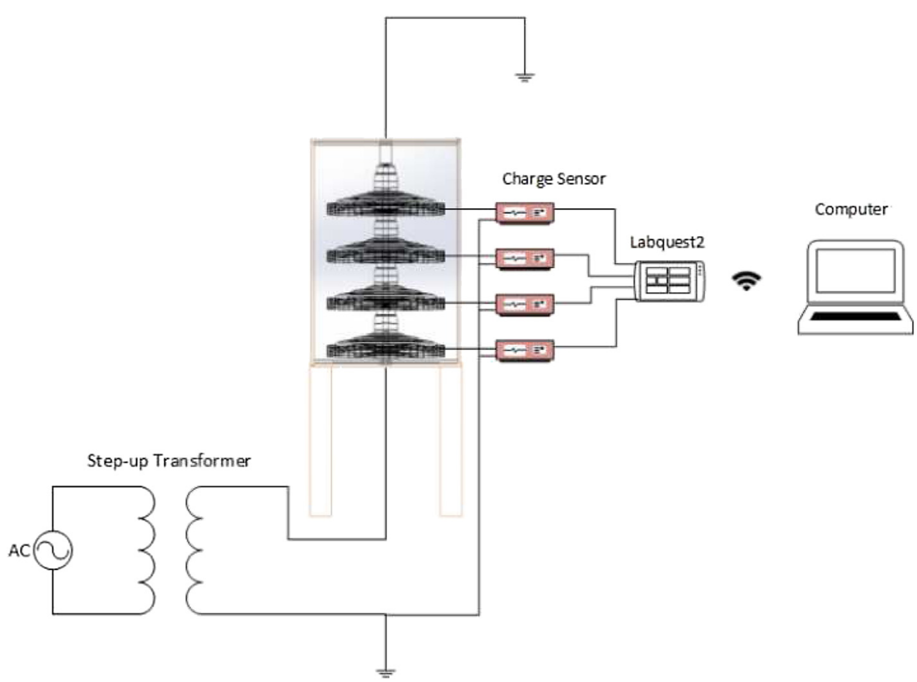

Fig. 11. Charge measurement experimental setup.

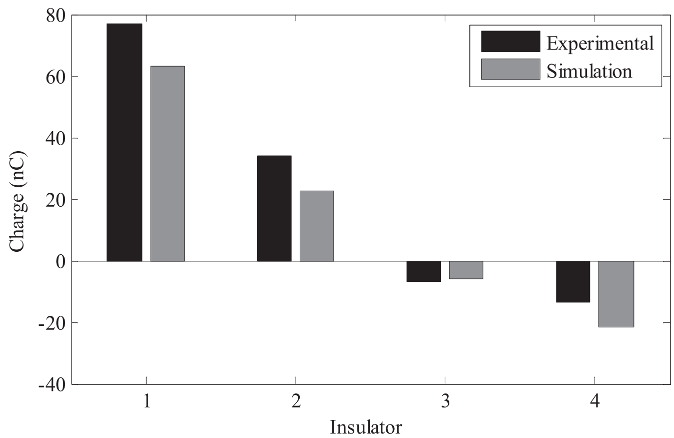

Fig. 12. Charge distribution on each insulator.

occurs at the center of the suspension string insulator of I-type. It is evident that when string insulator without installed grading ring is subjected to an AC excitation, the profile of charge polarity along the string is not uniform. From this charge distribution pattern also, it can be concluded that in the case when the insulator is closed to the high voltage source, the distribution pattern can be considered as negative charge distribution and vice versa. Therefore, further research in this area should be done thoroughly to prevent charge accumulation occurs in a certain space, which can bring to the insulation damage, thus reducing the reliability of the electricity network.

Acknowledgements

The authors would like to thank Universiti Teknologi Malaysia (UTM), for the use of facilities and by awarding a research university grants under vote number 01H69 and 03H86 from the Research Management Centre UTM and Malaysia Ministry of Higher Education (MOHE).

References

[1] Z. Zhijin, J. Xinliang, C. Yafeng, S. Caixin, H. Jianlin, Influence of low atmospheric pressure on ac pollution flashover performance of various types of insulators, IEEE Transactions on Dielectrics and Electrical Insulation 17 (2010) 425–433.
[2] M.S. Naidu, V. Kamaraju, High Voltage Engineering, McGraw Hill Education (India) Private Limited, 2013.
[3] S.C. Oliveira, E. Fontana, F.J. do Monte de Melo Cavalcanti, Leakage current activity on glass-type insulators of overhead transmission lines in the northeast region of brazil, IEEE Transactions on Power Delivery 24 (2009) 822–827.
[4] H. Ahmad, M.A. Salam, L.Y. Ying, N. Bashir, Harmonic components of leakage current as a diagnostic tool to study the aging of insulators, Journal of Electrostatics 66 (2008) 156–164.
[5] M. Fukuma, K. Fukunaga, T. Maeno, Space charge dynamics in LDPE films immediately before breakdown, IEEE Transactions on Dielectrics and Electrical Insulation 8 (2001) 304–306.
[6] M.M. Se-Ondoua, N. Zebouchi, G. Hoang The, Study of space charge effect on dielectric dc breakdown of synthetic insulators with the pressure wave propagation method, Journal of Electrostatics, 40–41 (1997) 355–361.
[7] A. Waygood, An Introduction to Electrical Science, Taylor & Francis, 2013.
[8] J.L. Davidson, T.J. Williams, A.G. Bailey, Electrostatic discharges between charged insulators and grounded spheres, Journal of Electrostatics 56 (2002) 29–42.
[9] N.H. Ahmed, N.N. Srinivas, Review of space charge measurements in dielectrics, IEEE Transactions on Dielectrics and Electrical Insulation 4 (1997) 644–656.
[10] N.A. Othman, M.A.M. Piah, Z. Adzis, N.A. Ahmad, Comparative study on space charge distribution measurements using PEA and PWP methods on high voltage insulation, Jurnal Teknologi 64 (4) (2013).
[11] R.J. Fleming, Space charge in polymers, particularly polyethylene, Brazilian Journal of Physics 29 (1999) 280–294.
[12] C.A. Rezende, R.F. Gouveia, M.A.d. Silva, F. Galembeck, Detection ofcharge distributions in insulator surfaces, Journal of Physics: Condensed Matter 21 (2009) 263002.
[13] A.G. Bailey, The charging of insulator surfaces, Journal of Electrostatics 51, 52 (2001) 82–90.
[14] H. Miyake, Y. Tanaka, T. Takada, M. Hanai, Characteristic of space charge distribution under dc stress in glass materials, In: 2000 Annual Report Conference on Electrical Insulation and Dielectric Phenomena, Vol. 121 (2000) pp. 128–131.
[15] Insulators for power transmission lines and substations with voltage from 0.4 kv to 1150 kv, G.I. Group, 2012.
[16] J.R. Claycomb, Applied electromagnetics using QuickField™ and MATLAB®, Infinity Science Press LLC, New Delhi, India, 2008.
[17] S. Ilhan, A. Ozdemir, S.H. Jayaram, E.A. Cherney, Simulations of pollution and their effects on the electrical performance of glass suspension insulators, In: 2012 Annual Report Conference on Electrical Insulation and Dielectric Phenomena (CEIDP) (2012) pp. 803–806.
[18] S. Ilhan, A. Ozdemir, S.H. Jayaram, E.A. Cherney, AC and transient electric field distributions along a 380 kv v-string insulator, In: Conference Record of the 2012 IEEE International Symposium on Electrical Insulation (ISEI) (2012) pp. 399–403.
[19] A.F. Diaz, R.M. Felix-Navarro, A semi-quantitative tribo-electric series for polymeric materials: the influence of chemical structure and properties,, Journal of Electrostatics 62 (2004) 277–290.
[20] A.X. Moronis, P.D. Bourkas, Impact ionization effects at interfaces between solid dielectrics and insulating oil or air, during high voltage pulse applications, Interface Science 2 (1995) 281–287.