The Effectiveness of Mitigation Schemes on Electric Field Intensity (Stress Control) for Overhead Line Glass Insulator

Mohamad Amirul F. Rosli[1], Noor Mazliza B. Sham[2], Muhammad S. Kamarudin[2], Mohd Fairouz M. Yousof[2], Nor Akmal M. Jamail[2], and Rahisham A. Rahman[2]
[1] TNB Labs Sdn. Bhd, Selangor, Malaysia
[2] Faculty of Electrical and Electronic Engineering, Universiti Tun Hussein Onn Malaysia, Johor, Malaysia
Email: fahmi.rosli@tnb.com.my; noormazliza@gmail.com; {saufi; fairouz; norakmal; rahisham}@uthm.edu.my

***Abstract*—This paper presents the simulation results of electric field distribution within suspension insulators on different stress control techniques under dry-clean and polluted conditions. Finite element method (FEM) is adopted to estimate the electric field behaviour along the insulator profile. For this study, COMSOL Multiphysics version 5.3a is used to perform the modelling and executing the field analysis. The effectiveness of zinc-oxide (ZnO) micro-varistor and grading ring as mitigation tools for the electric field intensity enhancement was examined in this study. The reference data from the dry-clean condition was used as the benchmark to examine the effect of pollution on electric field distribution on the insulator surface. It was found that the application of the combined techniques of ZnO micro-varistor and grading ring is the best scheme for stress control as it reduced the electric field intensity up to almost 84% for both dry-clean and polluted conditions. This study also found that the positioning the grading and corona ring is crucial as it will affect the electric field intensity distribution.**

***Index Terms*—Electric field, stress control, glass insulator, grading ring, zinc oxide micro-varistor, ceramic insulator**

I. Introduction

An insulator is a material that prevents the flow of an electric current. In an electrical system, the function of an insulator is to provide the necessary clearance between line conductors, conductors to ground, and between conductors to tower [1]. Overhead line insulators are made of porcelain, glass, and fibreglass treated with epoxy resins [2]. However, porcelain is still the most common material used for insulators. The overhead line insulators can be categorised into three types, which are suspension insulator, pin insulator, and strain insulator.

A composite-based material insulator is vulnerable to intense electrical stress due to pollution. Both glass and porcelain insulators share a common issue with the contamination affecting the dielectric performance of the insulators [3], [4]. The contamination that might caused by the saline water typically found in the sea-water combined with ultraviolet (UV) radiation will speed up the erosion on the insulator surface and subsequently resulting in ageing of the insulators [5], [6]. Other than that, the chemical waste from industries might also contribute to the pollution on the insulator surfaces.

The following section of this paper shows some of the stress control methods used for the field enhancement techniques inside and over the insulator. The stress control methods include usage of field grading material (FGM), zinc-oxide (ZnO) micro-varistor, grading rings and corona rings. The effects of ZnO micro-varistor and other mitigation schemes of stress control, such as grading rings, were examined in this study. A two-dimensional (2D) axis-symmetric simulation model of line glass insulator was established at a voltage level of 33 kV using COMSOL Multiphysics 5.3a, and the electric field distributions were computed. The analysis of the effect of pollution on the overhead line glass insulator was also presented. The effect of pollution and the grading scheme applied were tested in two conditions: dry-cleaned and polluted conditions. The post analysis result shows the effectiveness of the mitigation schemes used on the insulators.

II. Characteristics of Mitigation Schemes

A. Field Grading Material (FGM)

A composite field grading material (FGM) enhances both the electrical and mechanical performances of the insulator [7]. FGM is an inorganic filler added into the insulator host and proved to be superior in controlling the electrical stress on various insulators and voltage levels. In general, there are two types of FGM. They are listed as resistive and capacitive grading materials [1], [8]. These grading types are graded based on their nature displacement of the insulation materials [9], which are different from geometrical control methods. The reason is that FGM adoption could be seen within the insulation bulk. Examples of application of FGM are in high voltage motors and cable terminations.

Manuscript received June 1, 2021; revised September 15, 2021; accepted October 10, 2021.

Corresponding author: Mohamad Amirul F. Rosli (email: fahmi.rosli @tnb.com.my).

B. Zinc-Oxide (ZnO) Micro-Varistor

Zinc-oxide (ZnO) is an inorganic compound produced synthetically, insoluble in water and widely used as an additive material [10] for field stress control. In electrical and electronic applications, ZnO is used due to its wide-gap semiconductor characteristic with good transparency, high electron mobility and wide band gap voltage-current characteristic. This characteristic has advantages in terms of higher breakdown voltage, able to sustain intense electric field and high temperature operation that suits perfectly on high voltage application.

Its non-linear voltage-current characteristic and its ability to absorb energy are the key factors for ZnO to be used in surge suppression systems. Mixing ZnO with silicon-based material was proven in controlling the electric field intensity and alleviate the stress on the insulator surface [11], [12]. Even with a limited amount of study on stress control which utilizes ZnO, the significant effect of ZnO on the improvement of the electric field distribution along the insulator surface is noticeable.

C. Grading Rings

Grading rings and related mitigation schemes are applied to suppress the electrical stress on the overhead line insulators [13]–[15]. Grading rings redistribute the electrical stress along the insulator, and hence minimizing the occurrence of corona discharges. The positioning of the grading rings shall be determined correctly, as electric field intensity level may increase due to the mispositioning of the grading rings.

D. Corona Rings

Corona effects occur on the insulator mainly due to intense electrical stress in a localized region. This phenomena will accelerate the degradation of dielectric properties, which will lead to tracking, treeing, partial discharge, and premature breakdown. Corona ring, which basically is a metal ring, is fitted at both ends of an insulator, where high electric fields are normally produced [16]. This method is also very powerful as it helps to reduce disturbances on telecommunication signals and reduces hissing noise that eventually increases the overall efficiency [13], [16].

III. Modelling Technique of Overhead Line Glass Insulator

A. Insulator Geometry and Computation Modelling

The glass insulator was modelled with a voltage rating of 33 kV. Its dimension is listed in Table I [17]. The glass insulator consists of two main components; the metal end fittings and the dielectric material. One end of the insulator string is connected to the transmission line (high voltage), and the other end is grounded. Dielectric material (glass) is used to isolate between line and ground terminals.

TABLE I: COMPONENT DESCRIPTION FOR GLASS INSULATOR

Component description	**Length (cm)**
Height	44
Disc radius	12
Creepage length	190

TABLE II: MATERIALS PROPERTIES

Material	Relative permittivity (ε_r)	Electric conductivity (σ)
Glass	4.2	0
Concrete	15	1.0×10^{-4}
Pollution layer (NaCl)	60	Σ
Grading layer (zinc oxide)	12	Σ
Air	1	0
Grading ring (Aluminum)	N/A (conductor)	35.5×10^{-6}

Table II shows the material properties used in this study. As for the polluted condition analysis, sodium chloride (NaCl) was chosen with relative permittivity of 60. NaCl is the main material in sea-water substance, which is also known as saline water. Sea-water accumulation along with UV radiation is the most common contamination found on the insulator surface. In this study, ZnO has a relative permittivity of 12. Meanwhile, aluminium was used for the core material of the grading ring with electric conductivity of $35.5e^{-6}$.

B. Boundary Conditions

33 kV was applied at the bottom of the insulator profile, which is the rated voltage for his insulator at its high voltage (HV) terminal. The top of the insulator (LV terminal) was connected to the ground, as shown in Fig. 1.

C. Pollution Layer Modelling

The pollution model as in Fig. 2 is laid on top of each insulator disc surface to simulate the worst-case scenario of pollution accumulation. The material chosen for the pollution analysis was NaCl with relative permittivity, ε_r = 60. The study of this condition was simulated using COMSOL Multiphysics 5.3a.

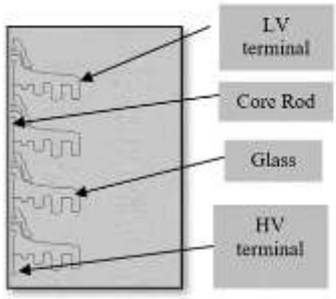


Fig. 1. Insulator profile.

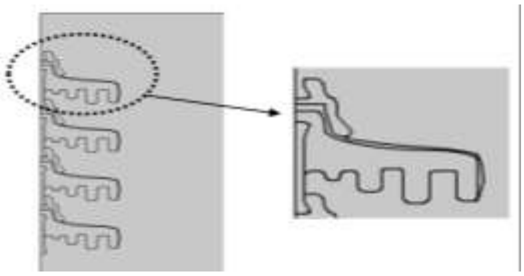


Fig. 2. Pollution condition model.

D. ZnO Micro-Varistor Layer Modelling

The ZnO micro-varistor is one of the most effective solutions to reduce electrical stress in order to improve the electric field distribution. As reported in some literatures, its non-linear characteristic is found to be very suitable for stress control [18]–[20].

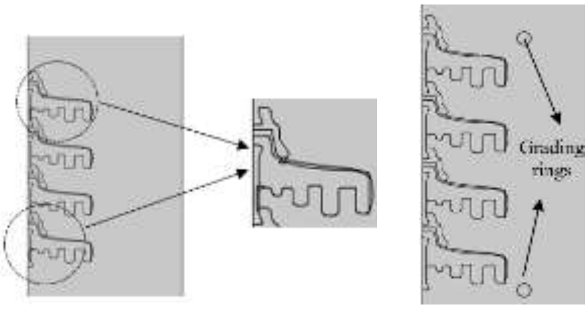


Fig. 3. Zinc oxide model.

Fig. 4. Grading rings model.

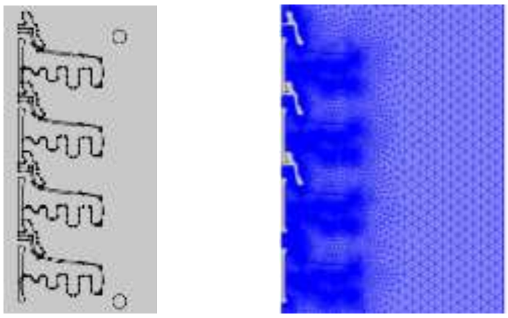


Fig. 5 Combined technique model.

Fig. 6. Finite element mesh

In this study, ZnO was applied at both ends only. The coating was thicker at the electrode ends to sustain the high electric field [15], [21] as depicted in Fig. 3. This technique will redistribute the electric field along the insulator and hence reduce the electrical stress. This technique will help to alleviate the probability of premature breakdown.

E. Grading Rings Modelling

Fig. 4 shows the modelled grading rings positioned at the high voltage (bottom) and low voltage (top) ends. The grading ring was made of aluminium with 1 cm radius.

The positioning of both grading rings is chosen based on the high electric field regions.

F. Combined Technique Modelling

The illustration of the combination of ZnO micro-varistor and grading rings is depicted in Fig. 5. This technique utilised the ZnO layer and additional installation of grading rings to provide better electric field stress management.

G. Computational Modelling

The finite element method was performed to analyse the electric field distribution along the insulator surface, which was carried out using COMSOL Multiphysics 5.3a. The simulation was carried out in an axis-symmetry setting. The modelled insulator was then assigned with the materials listed in Table II and boundary conditions as in Fig. 1. The mesh element around the area of interest, which is along the insulator leakage path, is manually assigned to increase the accuracy, as shown Fig. 6. The model was assumed to be surrounded by air.

IV. Effect of Pollution and Stress Control Techniques on Overhead Line Glass Insulator

This section presents the computational results of dry-cleaned and polluted conditions with and without stress control techniques. The first analysis is to analyse the dry-clean condition without stress control as reference data. The reference data gained will be used to determine the effectiveness of the stress control techniques applied to the insulators.

A. Analysis of Dry-Clean Condition as Reference Data

The analysis of dry-clean condition on 33 kV rated insulator is discussed in this section. The computation of electric field intensity was divided into six (6) different sections; near HV, Shank 1, Shank 2, Shank 3, Shank 4, and near LV, as shown in Fig. 7. The separation was made to identify the maximum electric field intensity and observe the electric field distribution along the insulator surface. This finding was crucial as it will act as reference data for the subsequent analysis.

Table III summarises the analysis of dry-clean insulator, and the electric field distribution on each section was plotted. The maximum electric field, E_{max} for each section were obtained as 194 kV/cm in HV terminal, 399.3 kV/cm in Shank 1, 4.4 kV/cm in Shank 2, 2 kV/cm in Shank 3, and 1.8 kV/cm in Shank. Meanwhile, in LV terminal, the value of E_{max} was recorded as 12 kV/cm.

This analysis shows that the most critical part is at Shank 1 as it produced the highest electric field intensity (399.3 kV/cm, as expected. The electric field intensity is normally high in the vicinity of an electrode, which in this case, the Shank 1 is the nearest to the high voltage electrode. The illustration of electric field intensity distribution and the maximum electric field can be shown in Fig. 8.

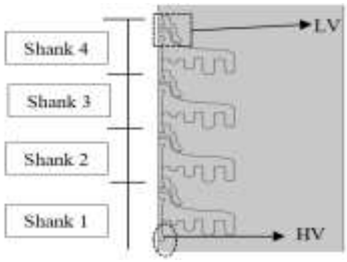
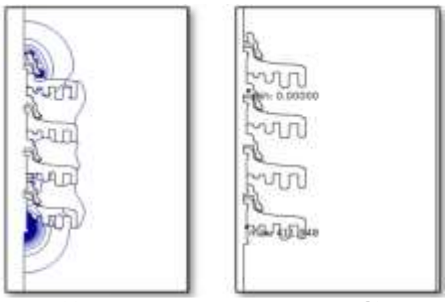


Fig. 7. Modelling profile for dry-clean condition.

TABLE III: COMPUTED MAXIMUM ELECTRIC FIELD INTENSITY DISTRIBUTION ON DRY-CLEAN CONDITION

Surface region	Electric field intensity (kV/cm)
Near HV	194.0
Shank 1	399.3
Shank 2	4.4
Shank 3	2.0
Shank 4	1.8
Near LV	12.0



(a) (b)

Fig. 8. Computation of (a) electric field intensity distribution and (b) maximum electric field intensity on dry-clean conditions.

B. *Effect of Pollution on Electric Field Distribution*

This section discusses the effect of pollution on the electric field distribution of suspension disc glass insulators with and without stress control techniques being applied.

The performance of outdoor insulators such as an overhead line insulator is severely affected by the pollution on its surface. The wet-polluted surface caused by environmental and weather conditions will affect the electric field distribution as well. When the pollution dry out, the dry bands distort the electric field distribution significantly and may lead to partial discharge, also known as premature breakdown [1], [15]. This normally happens in the regions with high electric field intensity.

The increment of electric field intensity on the insulator surface was largely due to the effect of pollution, which is modelled with NaCl. There is not much concern on the values of electric field in Shank 2 and Shank 3, but significant increments can be seen in Shank 1, Shank 4, near HV terminal and near LV terminal, as shown in Table IV.

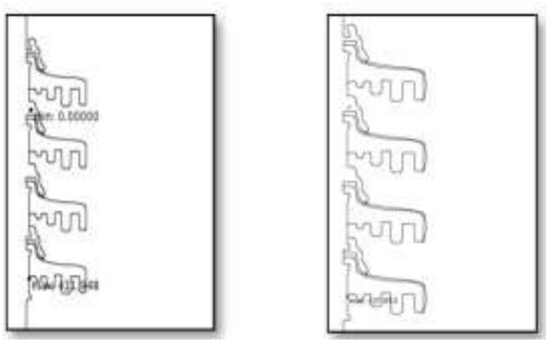
These simulation works on four strings of glass insulators model under dry-clean and polluted conditions were significant as the effect of pollution on the insulator surfaces can be seen in Fig. 9 and Table IV. This data distinctly shows the importance of stress control techniques to improve its electric field distribution.

C. *Effect of Zinc-Oxide (ZnO) on Dry-Clean and Polluted Insulator*

The computational analysis for dry-clean and polluted conditions with zinc-oxide (ZnO) material is discussed in this section. The ZnO layer was applied at the HV terminal, Shank 1 and LV terminal, as the electric field was predicted to build up at those areas [1], [10], [15].

TABLE IV: COMPUTATION OF ELECTRIC FIELD INTENSITY DISTRIBUTION ON DRY-CLEAN CONDITION AND POLLUTED CONDITION

Surface region	Dry-clean condition (kV/cm)	Polluted condition (kV/cm)
Near HV	194.0	203.6
Shank 1	399.3	423.6
Shank 2	4.4	0.95
Shank 3	2.0	1.69
Shank 4	1.8	59.0
Near LV	12.0	22.0



(a) (b)

Fig. 9. Comparison of maximum electric field intensity for (a) dry-clean condition and (b) polluted condition.

TABLE V: COMPUTATION OF ELECTRIC FIELD INTENSITY WITH AND WITHOUT ZNO

Surface region	Dry-clean condition (kV/cm)	Dry-clean with ZnO (kV/cm)	Polluted condition (kV/cm)	Polluted condition with ZnO (kV/cm)
Near HV	194.0	64.0	203.6	66.3
Shank 1	399.3	117.3	423.6	124.35
Shank 2	4.4	1.1	0.95	0.72
Shank 3	2.0	2.25	1.69	2.4
Shank 4	1.8	39.4	59.0	77.0
Near LV	12.0	16.0	22.0	27.5

TABLE VI: COMPUTATION OF ELECTRIC FIELD INTENSITY WITH AND WITHOUT GRADING RINGS

Surface region	Dry clean condition (kV/cm)	Dry-clean with grading rings (kV/cm)	Polluted condition (kV/cm)	Polluted condition with grading rings (kV/cm)
Near HV	194.0	189	203.6	203.15
Shank 1	399.3	388.4	423.6	419.32
Shank 2	4.4	3.0	0.95	0.0965
Shank 3	2.0	2.0	1.69	0.15
Shank 4	1.8	28.4	59.0	60.0
Near LV	12.0	11.8	22.0	22.0

Table V shows the values of electric field from the effect of the ZnO micro-varistor as a stress control technique on dry-clean and polluted conditions. The result shows the effectiveness of ZnO in both conditions. For the dry-clean condition, the E_{max} on Shank 1 was reduced from 399.3 kV/cm to 117.3 kV/cm. Thus, it shows that the ZnO alleviated the electrical stress by 70.6%.

For the polluted condition, with ZnO applied, the E_{max} value was recorded at 124.35 kV/cm, which was 70.6% reduction from 423.6 kV/cm when no ZnO applied. It shows the ZnO worked as grading material during stressed conditions. This analysis does clearly show the effectiveness of ZnO for stress control technique in both dry-clean and polluted conditions. Under both tested conditions, ZnO reduced and redistributed the electrical stress on the insulator profile [21].

D. *Effect of Grading Rings on Dry-Clean and Polluted Insulators*

This section discusses the approach on improving the electric field intensity distribution along an insulator profile by installing grading rings at both ends of the insulator. The analysis of the results will be based on dry-clean and polluted conditions.

The results obtained in Table VI show the effect of grading rings on both HV and LV terminals. It was noticed that the electric field distribution had improved by 2.7% in dry-clean condition and 1% in the polluted condition.

In dry-clean condition, the grading rings reduced the maximum electric field at the HV terminal, Shank 1, Shank 2 and LV terminal. On Shank 4, the electric field intensity was increased from 1.8 kV/cm to 28.4 kV/cm. It shows that the grading rings not only alleviated the electrical stress but also redistributed the stress onto other locations along the insulator surface.

TABLE VII: COMPUTATION OF ELE.0CTRIC FIELD INTENSITY WITH COMBINATION TECHNIQUE UNDER DRY-CLEAN AND POLLUTED CONDITION

Surface region	Dry-clean condition (kV/cm)	Dry-clean with both techniques (kV/cm)	Polluted condition (kV/cm)	Polluted condition with both techniques (kV/cm)
Near HV	194	64.0	203.6	67.0
Shank 1	399.3	21.8	423.6	121.3
Shank 2	4.4	3.0	0.95	0.73
Shank 3	2.0	14.77	1.69	1.9
Shank 4	1.8	36.7	59.0	77.3
Near LV	12.0	15.4	22.0	28.9

In polluted condition, stress control technique using grading rings produced almost the same pattern as in dry-clean condition. The grading rings reduced the maximum electric field, E_{max} from 423.6 kV/cm to 419.32 kV/cm in Shank 1. Electrica stresses near HV terminal, in Shank 2 and Shank 3 were also reduced.

Overall, the grading rings approach to reduce the electrical stress in insulators can be said to be working. Usage of grading rings does provide the ability to reduce and redistribute electrical stress.

E. Effect of Combined Techniques on Dry-Clean and Polluted Insulators

This section discusses the approach on improving the electric field intensity distribution along an insulator profile with a combination of grading rings and zinc-oxide (ZnO) micro-varistor at both ends of the insulator. The effectiveness of this combination was tested on both dry-clean and polluted conditions.

The analysis was modelled as in Fig. 5. The model which combines ZnO micro-varistor and grading rings was tested. Table VII shows the results of the stress control techniques for both dry-clean and polluted conditions.

The approach shows that the electric field distribution significantly improved as it reduced electrical stresses in the modelled insulators, both in dry-clean and polluted conditions. The peak magnitudes in the high field regions of the polluted condition, particularly at the HV terminals, were reduced by nearly 67%. The reduction for this condition is higher than that obtained from the previous study in [7] and [15]. Significant reduction in electric field intensity can also be observed in Shank 1 region for both conditions. On average, the electric field distribution had been improved by 58% with this combined techniques. Meanwhile, the maximum field strength at both ends of the insulator string is decreased by about 50%, as obtained in [7].

In the end, the analysis does show that the combination techniques of ZnO micro-varistor and grading rings are working extremely well under dry-clean and polluted conditions. The threat of salt layer accumulation by the dried-out sea-water can be alleviated with these techniques, thus improving the insulators' lifetime.

V. CONCLUSION

The effectiveness of the techniques applied for electric field intensity stress control along an insulator surface has been presented. Two techniques had been simulated and had shown the improvement expected in terms of electric field distribution. This study is also able to provide information on the location of the highest electric field stress, which will be the most likely location for breakdown to be initiated. The concern on pollution as in salt formation on insulators had been simulated to show its affect towards the electric field distribution. With this study, it is recommended to utilise the combination techniques of using zinc-oxide varistor and grading rings in order to provide better electrical stress control in string insulators. These techniques proved to be effective as it can reduce the electrical stress along the insulator surface by 84%, and they work under both dry-clean and polluted conditions.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

AUTHOR CONTRIBUTIONS

Muhammad S. Kamarudin supervised the conducted the research, and Noor Mazliza B. Sham edited the paper. Mohamad Amirul F. Rosli developed the model in COMSOL Multiphysics 5.3a, obtained the results, and wrote the paper. Mohd Fairouz M. Yousof was the co-supervisor in this study. Nor Akmal M. Jamail re-analysed the results and verified by Rahisham A. Rahman. All authors had approved the final version of the paper.

ACKNOWLEDGMENT

The authors gratefully acknowledge the financial supports by Ministry of Higher Education Malaysia (MOHE) and Universiti Tun Hussein Onn Malaysia (UTHM) under the research grant, FRGS (Vot. K057).

REFERENCES

[1] A. Al-Gheilani, W. Rowe, Y. Li, and K. L. Wong, "Stress control methods on a high voltage insulator: A review," *Energy Procedia*, vol. 110, pp. 95–100, Mar. 2017.

[2] T. Kim, Y. J. Lee, S. Sanyal, J. W. Woo, I. H. Choi, and J. Yi, "Mechanism of corrosion in porcelain insulators and its effect on the lifetime," *Applied Sciences,* vol. 10, no. 1, pp. 1–8, 2020.

[3] N. A. Othman, M. A. M. Piah, and Z. Adzis, "Charge distribution measurement of solid insulator materials : A review and new approach," *Renewable and Sustainable Energy Reviews*, vol. 70, pp. 413–426, April 2017.

[4] N. A. Othman, M. A. M. Piah, and Z. Adzis, "Contamination effects on charge distribution measurement of high voltage glass insulator string," *Measurement*, vol. 105, pp. 34–40, July 2017.

[5] I. Kitta, S. Manjang, W. Tjaronge, and R. Irmawaty, "Effect of fly ash filler to dielectric properties of the insulator material of silicone rubber and epoxy resin," *International Journal of Scientific & Technology Research*, vol. 5, no. 3, pp. 120–124, 2016.

[6] M. M. Hussain, S. Farokhi, S. G. McMeekin, and M. Farzaneh, "Mechanism of saline deposition and surface flashover on outdoor insulators near coastal areas part II: Impact of various environment stresses," *IEEE Trans. on Dielectrics and Electrical Insulation*, vol. 24, no. 2, pp. 1068-1076, 2017.

[7] X. Zhao, *et al.*, "Grading of electric field distribution of AC polymeric outdoor insulators using field grading material," *IEEE Trans. on Dielectrics and Electrical Insulation*, vol. 26, no. 4, pp. 1253–1260, 2019.

[8] M. M. Firozjaee and A. Vahedi, "Performance of insulation materials to enhance grading method effect in high voltage cable," in *Proc. 24th Iranian Conf. on Electrical Engineering,*

2016, pp. 1624–1628.

[9] L. F. Wang and X. P. Zhou, "Fracture analysis of functionally graded materials by the field-enriched finite element method," *Engineering Fracture Mechanics*, vol. 253, Aug. 2021.

[10] H. Ahmad, A. Haddad, H. Griffiths, S. Robson, T. Nishimura, and N. Tsukamoto, "Electrical characterisation of ZnO microvaristor materials and compounds," in *Proc. Annual Report - Conf. on Electrical Insulation and Dielectric Phenomena*, 2015, pp. 688–692.

[11] H. Ahmad, S. Robson, M. Albano, and A. Haddad, "Characterics of ZnO microvaristors-loaded grading polymeric materials," in *Proc. 13th Int. Electrical Insulation Conf.*, 2017, pp. 1–6.

[12] X. Yang, X. Zhao, J. Hu, and J. He, "Grading electric field in high voltage insulation using composite materials," *IEEE Electrical Insulation Magazine*, vol. 34, no. 1, pp. 15–25, 2018.

[13] C. Zachariades, S. Rowland, I. Cotton, V. Peesapati, and D. Chambers, "Development of electric field stress control devices for a 132kV insulating cross-arm using finite element analysis," *IEEE Trans. on Power Delivery*, vol. 31, no. 5, pp. 2105–2113, 2016.

[14] N. A. Othman, M. A. M. Piah, and Z. Adzis, "Effect of broken skirts on voltage distribution along insulator strings," *International Journal of Simulation: Systems, Science and Technology*, vol. 17, no. 41, pp. 16.1-16.4, 2017.

[15] R. Abd-Rahman, A. Haddad, N. Harid, and H. Griffiths, "Stress control on polymeric outdoor insulators using zinc oxide microvaristor composites," *IEEE Trans. on Dielectrics and Electrical Insulation*, vol. 19, no. 2, pp. 705–713, 2012.

[16] B. M'Hamdi, M. Teguar, and A. Mekhaldi, "Optimal design of corona ring on HV composite insulator using PSO approach with dynamic population size," *IEEE Trans. on Dielectrics and Electrical Insulation*, vol. 23, no. 2, pp. 1048–1057, 2016.

[17] M. P. Lalitha, K. V. P. Kumar, and V. Samala, "Design and simulation of voltage and electric field distribution on disc insulators using finite element method in Opera software," in *Proc. Int. Conf. on Smart Electric Grid*, 2014.

[18] Q. Shao, W. Sima, P. Sun, M. Yang, H. Xu, and Z. Yin, "A novel non-linear conductive ZnO micro-varistor/epoxy resin composite film for metallic particle deactivation in DC GIL," *IEEE Trans. on Dielectrics and Electrical Insulation*, vol. 27, no. 2, pp. 675–683, 2020.

[19] P. Meng, C. Yuan, H. Xu, *et al*., "Improving the protective effect of surge arresters by optimising the electrical property of ZnO varistors," *Electric Power Systems Research*, vol. 178, Jan. 2020.

[20] Z. Li, X Ren, X. Wang, *et al.*, "Effectively enhanced comprehensive electrical performance of ZnO varistors by a fast combinatorial refinement method," *Materials Science in Semiconductor Processing*, vol. 133, Oct. 2021.

[21] M. Pradhan, H. Greijer, G. Eriksson, and M. Unge, "Functional behaviors of electric field grading composite materials," *IEEE Trans. on Dielectrics and Electrical Insulation*, vol. 23, no. 2, pp. 768–778, 2016.

[22] Z. Yang, X. Jiang, Z. Zhang, D. Zhang, and Y. Liu, "Study on the influence rules of soluble contaminants on flashover voltage of disc suspension insulators," *IEEE Trans. on Dielectrics and Electrical Insulation*, vol. 23, no. 6, pp. 3523–3530, 2016.

Mohamad Amirul F. Rosli received his Bachelor's Degree in Electrical Engineering from Universiti Tun Hussein Onn Malaysia (UTHM). Currently, he is working as Technical Evaluator in Quality Assurance Unit TNB Labs Sdn. Bhd. He is being certified as a Graduate Engineer by the Board of Engineers Malaysia (BEM) and pursuing a Professional Engineer (P.Eng) soon. His main interest is in primary and substation equipment such as circuit breakers, distribution transformers and surges arrestors.

Noor Mazliza B. Sham received her Bachelor's Degree and Master's Degree in Electrical Engineering from Universiti Tun Hussein Onn Malaysia (UTHM) in 2017 and 2019, respectively. She is currently pursuing her PhD degree in Electrical Engineering at Universiti Tun Hussein Onn Malaysia. Her current research includes high-voltage gas insulation and high-voltage measurement.

Muhammad S. Kamarudin received his PhD degree in High Voltage Engineering from Cardiff University, UK in 2014. He received his M.Sc. degree in Electrical Power Engineering and Bachelor's degree in electrical engineering (electrical power engineering) from Universiti Teknologi Malaysia in 2005 and 2003. Currently, he is an associate professor in the Faculty of Electrical and Electronic Engineering at Universiti Tun Hussien Onn (UTHM). He is a Professional Engineer (Ir.) registered with the Board of Engineers Malaysia (BEM) and a corporate member of the Institution of Engineers Malaysia (IEM). His research interests include gas discharge, high-voltage surge arresters, dielectric and electrical insulation systems.

Mohd Fairouz M. Yousof received the B.Eng. and M.Eng. degrees from Universiti Teknologi Malaysia and the PhD degree from The University of Queensland, Australia, in 2015. He was appointed as a Visiting Researcher at the TNB Research from 2018 to 2019. He has been a Principal Consultant at Xair Energy Sdn Bhd since 2019. He is currently a Lecturer in the Department of Electrical Power Engineering, Universiti Tun Hussein Onn Malaysia (UTHM). His main research interests include condition-based monitoring and assessment of high-voltage equipment, specifically power transformer and rotating machine. He is also a Registered Member of the Board of Engineers Malaysia (BEM) and the Malaysian Society for Engineering and Technology (MySET).

Nor Akmal M. Jamail is a lecturer of Universiti Tun Hussein Onn Malaysia since 2008. She received a Bachelor's Degree in Electrical Engineering from Universiti Teknologi Malaysia in 2005, M.Eng. degree in Power System from Universiti Tun Hussein Onn Malaysia in 2007 and a PhD degree in High Voltage Engineering from Universiti Teknologi Malaysia in 2015. Her research interests include condition monitoring of polymer nanocomposite insulation for HV purposes, dielectrics and electrical insulation. She is registered with the Board of Engineers Malaysia (BEM).

Rahisham A. Rahman received his M.Eng. degree (Electrical & Electronic) and PhD degree (High Voltage) from Cardiff University, UK, in 2008 and 2012, respectively. He is currently a lecturer in the Faculty of Electrical & Electronic Engineering at Universiti Tun Hussein Onn Malaysia (UTHM). His research interests include dielectric materials, outdoor insulators and discharge phenomena. He is a Chartered Engineer UK (CEng) and a member of an engineering institution, such as IET (MIET), IEEE (MIEEE), and Board of Engineers Malaysia (BEM). He is also a Professional Engineer (Ir.) registered with the BEM.