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Influence of contamination distribution in characterizing the flashover phenomenon on outdoor insulator

Ali Ahmed Salem [a,*], Rahisham Abd-Rahman [b,*], Mohd Taufiq Bin Ishak [c,*], Kwan Yiew Lau [a], Zulkurnain Abdul-Malek [a], Salem Al-ameri [e], Samir A. Al-Gailani [d], Sherif S.M. Ghoneim [f]

[a] Institute of High Voltage and High Current, School of Electrical Engineering, Universiti Teknologi Ma-laysia, Johor Bahru 81310, Malaysia
[b] Faculty Electric and Electronics Engineering, Universiti Tun Hussein Onn Malaysia, Parit Raja 86400, Johor, Malaysia
[c] Department of Electrical and Electronic Engineering, Faculty of Engineering, National Defence University of Malaysia, Kuala Lumpur 57000, Malaysia
[d] Faculty of Engineering & Computer Technology, AIMST University, Bedong, Kedah, Malaysia
[e] Department of Electrical & Computer Engineering, Curtin University Malaysia, Miri 98009, Malaysia
[f] Department of ELectrical Engineering, College of Engineering, Taif University, P.O. BOX 11099, Taif 21944, Saudi Arabia

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ABSTRACT

The aim of this work is to model the influence of uneven contamination distribution under various humidity on the pollution flashover voltage of 11 kV porcelain insulator disc. Four scenarios of contamination distribution were proposed to test the sample under various severities of contamination simulated by salt deposit density (SDD). Series flashover experiments on contaminated insulators were performed under various conditions. The voltage of flashover under clean condition was appointed as a reference value for analyzing the effect of pollution. Based on the percentage value of breakdown voltage of the contaminated insulator to the clean insulator, the conditions of the tested sample are classified into three categories namely normal (55–60%), caution (45–54 %) and severe (35–44%). In the experimental tests, the uneven contamination area dimension was taken into consideration. An artificial neural network (ANN), derived from experiment results was used as a tool to predict the flashover voltage. The ANN method is built with five inputs related to the geometry of the sample and pollution factors while the flashover voltage was set as the model's output. The results showed that the distribution of pollutants according to the presented scenario has a significant impact on the performance of the flashover voltage. In addition, the error value between the experiment outcomes and the prediction system appeared to be less than 6%. This suggests that the proposed ANN model can be an effective tool in forecasting the insulators' flashover voltage under test.

1. Introduction

Contamination flashover on high voltage insulators in the transmission lines is a substantial issue that endangers the safety and reliability of electricity transmission operations. A Cap and pin porcelain insulator, which is used in electrical distribution and transmission lines, have been receiving a great of interest recently [1–3]. With the presence of wet (rain, fog, humidity), the contaminants that float through the air on the HV insulator resulted in the production of a conductive layer. Consequently, the flow of the leakage current from high voltage terminal to ground electrode across the insulator surface became easy. Contamination flashover of the insulators could easily occur in this situation [4–7]. Insulator contamination is the first step in the flashover creation, and its propagation method is influenced by a variety of factors, like insulation architecture, contamination modes, and environmental conditions so on. As a result, more research into insulator pollution is still needed. Several methods of pollutant deposition studies [4,8–16] have been performed recently. The flashover performance of several insulators was examined under uniform pollution [4]. In comparison to ceramic insulators, composite insulators' flashover voltage (FOV) under uniform pollution is observed to interact more

* Corresponding authors.
E-mail addresses: ahmedali.a@utm.my (A.A. Salem), rahisham@uthm.edu.my (R. Abd-Rahman), mtaufiq@upnm.edu.my (M.T.B. Ishak), S.ghoneim@tu.edu.sa (S.S.M. Ghoneim).

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[4]. Pollution non-uniformity on the bottom and top [8], longitudinal [11], and fan-shaped [11,12], has been studied. As per [4], the uneven contamination grade (bottom/top) has a significant effect on the magnitude values of flashover voltage, which is roughly 28–30 % more than the FOV with uniform pollution. According to [11], decreasing the flashover voltage stress is results of increases the non-uniformity degree of the fan-shaped non-uniform pollution on the insulator surface. Whereas [13] looked at how the formation, dimension, and location of the dry band affected FOVs and arc development. According to [13], the dry band raises FOVs and encourages arcs develop on insulators surfaces in present of moist. Artificial intelligence approaches such as the Artificial Neural Network (ANN) [17], fuzzy logic (FL) [18], Support Vector Machine (SVM) [19], and Adaptive Fuzzy Inference System (ANFIS) [20] are shown to be effective in forecasting the voltage of flashovers in the literature. The fuzzy logic model has been employed to predict the critical voltage of the insulators under pollution in [21]. In [22], the Particle Swarm Optimization (PSO) coupled with LS-SVM was also used to predict the FOV of contaminated insulators', insulator size, and pollution intensity. The result indicated that the error was less than 10%, demonstrating that the proposed method is useful. Authors in [17] recently estimated the flashover voltage using ANN based on arc constants A and n. According to the study, the ANN delivers satisfactory results for forecasting flashover voltage. However, the distribution of contamination over the insulators' surface was not considered in [17].

On the surface of the insulator, pollution is usually not instantly and uniformly deposited. In [12] (Table 1), the authors assert that the pollution takes several surface forms, such as rings, top/bottom shapes, and fans. Simulating the real-world pattern, where the conductivity of the contaminated layer fluctuates at various levels in particular locations with humidity variations, is difficult due to the complicated nature of the non-uniform pollution deposition on the insulator. On this basis, it is required to test and predict the effects of various configurations for non-uniform pollution with diverse dimensions and different contamination levels as well in order to establish the flashover voltage in such circumstances.

The contribution of this paper is to evaluate the influence of contamination distribution, humidity, and non-polluted-zones dimensions and position on the insulator's flashover voltage using laboratory test and ANN model. Four different scenarios have been studied. The test chamber was used to perform AC pollution flashover experiments on cap-pin porcelain insulators. The flashover voltage values of insulators under contamination were defined as proportion of the clean-state flashover voltage, which served as a point of reference. Based on the experimental test, the flashover voltage under the suggested scenarios of contaminated insulators was estimated using the artificial neural network ANN method. The ANN approach was verified in order to assess the model's performance.

2. Experimental work

2.1. Sample preparation

In this study, the 11 kV cap-pin porcelain insulators were used in this paper. The insulator technical and its geometrical parameter and contamination distribution suggested scenarios are shown in Fig. 1. Fig. 1 (b) shows that the percent of area covered by pollution was 40% in scenarios SC-A, SC-B, and SC-C, whereas the scenario SC-D represents full pollution (100 %). The insulator has been investigated in both clean and contaminated environments in four scenarios. In the event of pollution. The insulator was artificially contaminated with four varying quantities of Salt Deposit Density (*SDD*) of NaCl combined in 1 L of distilled water: 0.05, 0.15, 0.25, and 0.35 mg/cm^2. The thicknesses of the contamination layer were 0.5 cm for all pollution profiles. The contaminant layer was created over the insulator surface uniformly using the solid layer technique [23–27]. The prepared solutions were applied to the sample using spray method and hung it in the test room after being left to dry normally at lab temperature for about a day. To characterize the degree of contamination on the insulators at a specific conductivity, the *SDD* was calculated using the equation below in accordance with IEC 60507[28]:

$$SDD = (5.7 \times (\sigma_{20})^{1.03} \times V)/A \tag{1}$$

σ_{20} represents the electrical conductivity of contamination solution at 20 °C in S/cm, A is an area of insulator surface in cm, and V is the volume of pollution solution in cm^3.

A conductivity meter HI8733 [7] was used to measure the solution's electric conductivity. According to the IEC60507 standard [28], about 40 (g/l) Kaolin was utilized as a non-soluble contaminant *NSDD* (Non-Soluble Deposit Density). The degree of unevenness of pollution between the top and down sides $F_{T/B}$ in the case of non-uniform pollution is determined as:

$$F_{B/T} = SDD_B/SDD_T \tag{2}$$

where SDD_T and SDD_B represents the salt deposit density on the top and bottom insulator surface. The $F_{B/T}$ were chosen to be 3, 5, and 8. To examine the effect of uneven pollution distribution on flashover voltage, the ratio of contaminated to clean surface area can be defined as:

$$S\% = \frac{A_P}{A_C + A_P} \times 100 \tag{3}$$

where A_P and A_C denote the polluted and the clean surface area, respectively. The S values were set to 40%, 60%, and 80% to examine the impact of the difference of contaminated area surface on the flashover voltage. In this study, the contamination levels (*SDD*) are selected by 0.05 mg/cm^2, 0.15 mg/cm^2, 0.25 mg/cm^2, and 0.35 mg/cm^2, which correspond to light, medium, heavy, and very heavy pollution, respectively.

2.2. Test arrangement and procedure

The sample was suspended vertically in a test room made of 500 × 500 × 750 mm polycarbonate sheet walls after drying. To supply power to the tested insulators, an AC 0.23/100 kV transformer providing 100 kV AC voltage was employed. The flashover voltage was measured using a capacitive divider. Fig. 2 depicts the schematic diagram as well as a laboratory view of the FOV test. The FOV test was carried out under three humidity levels of 75%, 85%, and 95%, which were controlled by a fog generator. Before starting the test, the fog generator was

Table 1
Fitting results under scenario SC-B.

$F_{B/T}$	1	3	5	8	1	3	5	8	1	3	5	8
$S\%$	40				60				80			
a	7.97	9.18	10.27	11.99	7.22	8.45	9.42	11.36	6.96	8.014	8.61	10.33
b	0.332	0.32	0.311	0.304	0.346	0.33	0.334	0.293	0.322	0.314	0.332	0.215
R^2	0.999	0.998	0.997	0.995	0.987	0.990	0.999	0.989	0.995	0.993	0.997	0.999

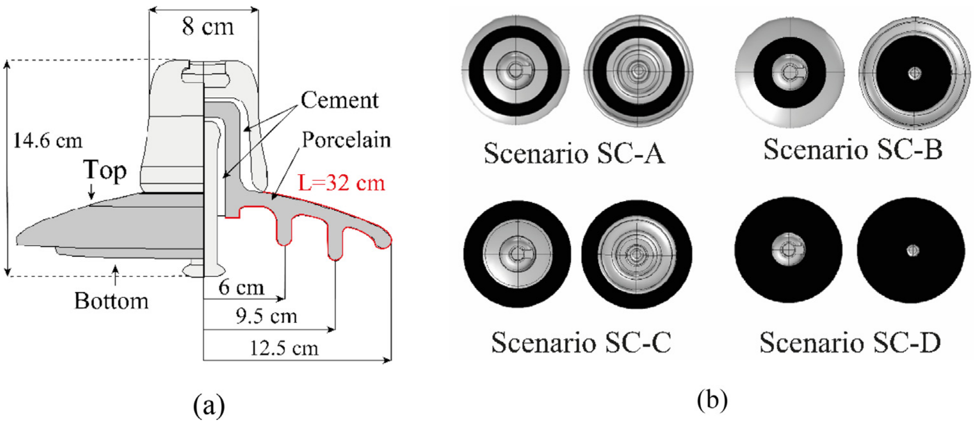


Fig. 1. Test sample: (a) Insulator dimensions; (b) Proposed scenarios of contamination distribution.

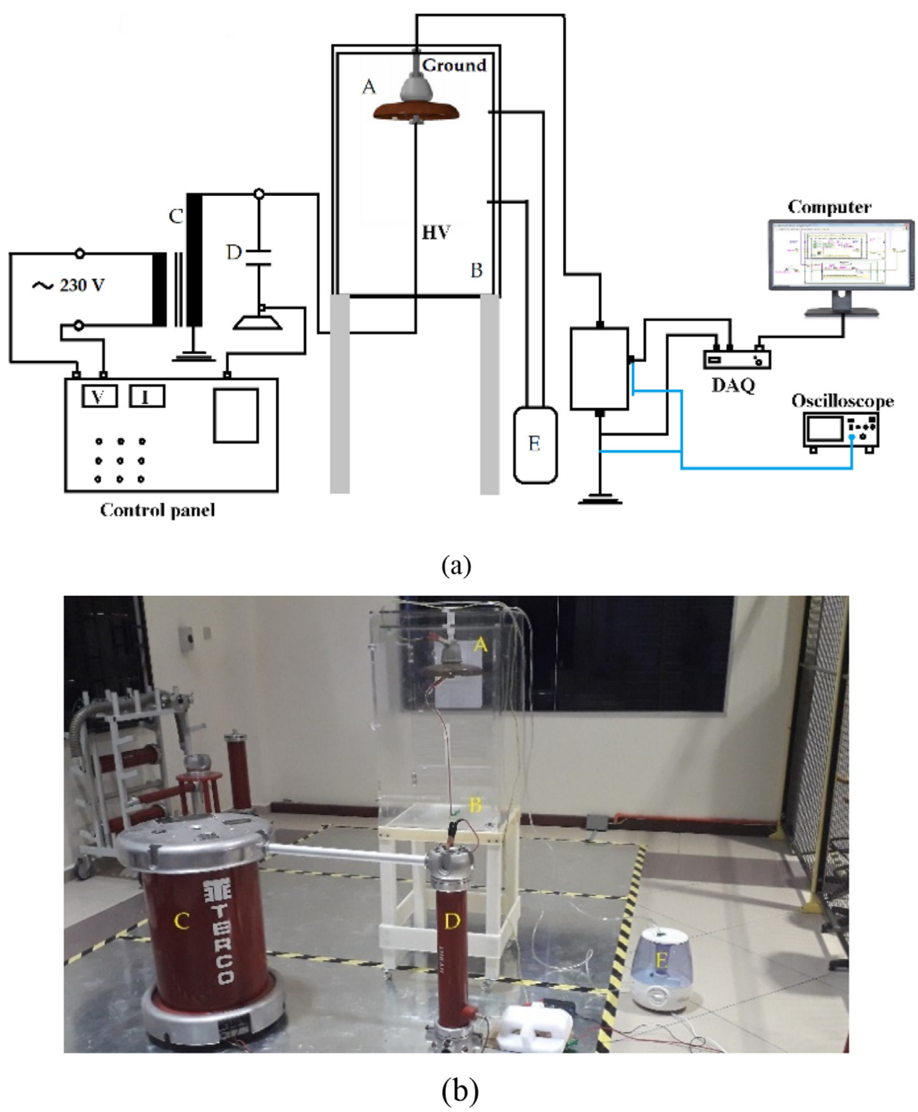


Fig. 2. Flashover test (a) schematic diagram (b) laboratory view: A: the test sample, B: test chamber, C: transformer, D: divider, and E: fog generator.

activated to wet the sample. The pollution layer over the insulator surface should be completely wet before the voltage for the flashover test can be applied.

The voltage step was set at about 5% of the expected flashover voltage. The flashover voltage U_F measurement was repeated at least four times for each humidity and pollution level. Eqs. (4) and (5) were employed to calculate the average U_F and standard deviation error σ (%), respectively [29],

$$U_F = \sum(U_i n_i)/N \tag{4}$$

$$\sigma\% = \sqrt{\frac{\left(\sum_{i=1}^{N}(U_i - U_F)^2\right)}{(N-1)}} \times \frac{100\%}{U_F} \tag{5}$$

Here U_i is supply voltage, n_i represents tests that were carried out at U_i, N is the total number of conducted tests.

3. Results

3.1. Uniform distribution

The U_F of the clean insulator was found at about 44 kV. For polluted insulators, the U_F value is decreased sharply compared to the U_F value in a clean state. According to the experimental results, the

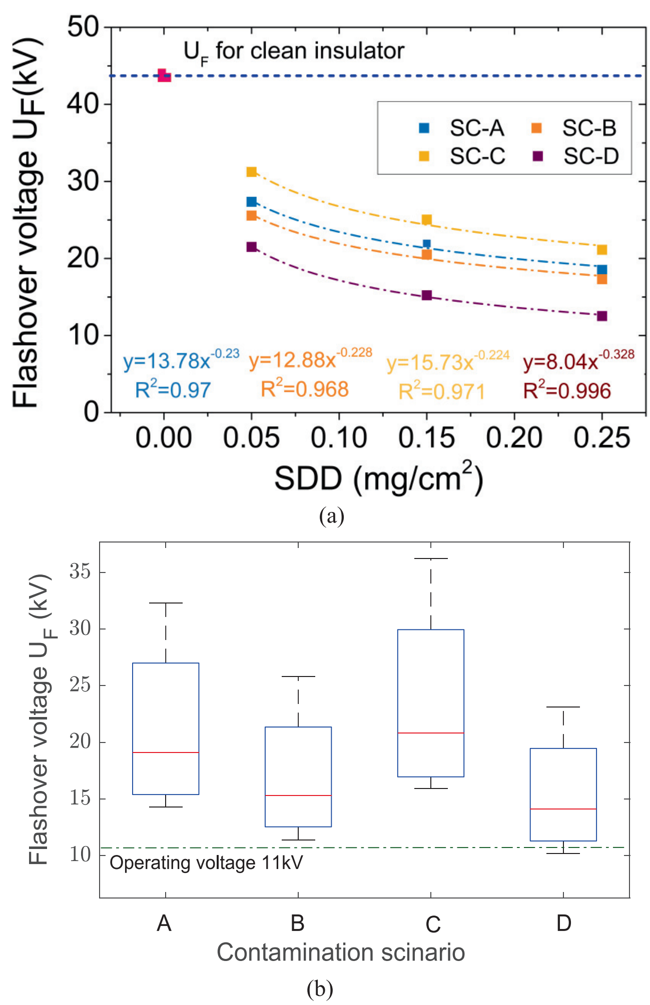


Fig. 3. Studied insulator test results of four scenarios: (a) Relationship between U_F and SDD; (b) Box plot of U_F for SDD from 0.05 to 0.25 mg/cm^2.

U_F of the insulator decreases significantly with increasing SDD in all scenarios, and a negative power function was between U_F and SDD as indicated in Eq. (6), which is the outcome of fitting the test findings.

$$U_F = a.SDD^{-b} \tag{6}$$

where a is constant which is related to the materials and structure of the insulator and air pressure and so on. And b represents the contamination's characteristic indication on the insulator. It should be noted that the higher flashover voltage, the better the insulator's condition. Fig. 3 (a) depicts the connection between the U_F and SDD for the suggested scenarios with different pollution degrees at the moisture of 75%. It should be highlighted that the offered scenarios' pollutant distribution has a major impact on FOV value. For SDD of 0.05 mg/cm^2 for instance, the ratio of U_F values of the polluted insulator to U_F values of the clean insulator is 73.91 %, 59.06%, 83.13%, and 52.84% for scenarios SC-A, SC-B, SC-C, and SC-D respectively. The U_F drops dramatically with the increase of SDD. For example, under uniform pollution of scenario SC-B, when SDD is 0.05 mg/cm^2, 0.15 mg/cm^2, and 2.5 mg/cm^2 respectively, the corresponding value of U_F is 25.5 kV, 20.51 kV, and 17.3 kV, which indicates that the U_F value reduced by 19.77% and 32.3% with SDD increasing from 0.05 mg/cm^2 to 0.15 mg/cm^2, and 2.5 mg/cm^2, respectively. At the same rise in SDD, the flashover voltage percentage to 43.73 kV decreased by 58.5 %, 46.9 %, and 39.6 %. The decrease in U_F with increased pollution is explained by the increase in electrical conductivity, which leads to a decrease in the insulator resistance then a decrease in the insulation strength. When SC-A and SC-B are compared, it can be shown that increased SDD in SC-A has a higher effect on the U_F than increased SDD in SC-B does under the same conditions. As a result, the position of pollution buildup affects the generation of flashover on the surface of the insulator.

The box plot (Fig. 3(b)) compared the effect ranges of the suggested scenarios for SDD within 0.05 mg/cm^2 and 0.25 mg/cm^2 on U_F to assess the effect of the pollutant distribution for every scenario on flashover voltage results. This can be useful knowledge for comprehending the insulator's characteristics under various contamination distribution scenarios. According to the findings of the tests in Fig. 3, the relative deviation error for all tests is obtained lower than 6%. This means that the scattering rate of U_F is acceptable, implying that the experimental technique used in this work was acceptable. The minimum value of median for U_F is 14.11 kV, which has been observed in scenario SC-D as shown in Fig. 3(b). Whereas the highest value for the moderate of U_F is 20.8 kV in scenario SC-C. This means that when the contaminated region on the insulator surface expands, the insulator enters a critical state faster, increasing the likelihood of flashover, as in scenario SC-D. It is worth noting that the working voltage of the test insulators is 11 kV. However, Fig. 3(b) reports that the minimum U_F in scenario SC-D would be below 11 kV, indicating that the breakdown happens at a voltage lower than the operational voltage, potentially resulting in an outage.

3.2. Influence of humidity

This section discusses the influence of humidity in the contamination scenarios provided. To examine this impact, three humidity values of 75%, 85%, and 95% were chosen to simulate the humidity which can be exposed to the real electrical network insulators. In fact, raising the humidity level facilitates the formation of a conductive water film on the insulator, lowering the U_F of insulators with uniform and non-uniform contamination. Fig. 4 depicts the relationship between U_F and SDD as humidity varies. Fig. 4 indicates that humidity has a substantial influence on the UF findings, with rising humidity causing a decrease in U_F. For example, when

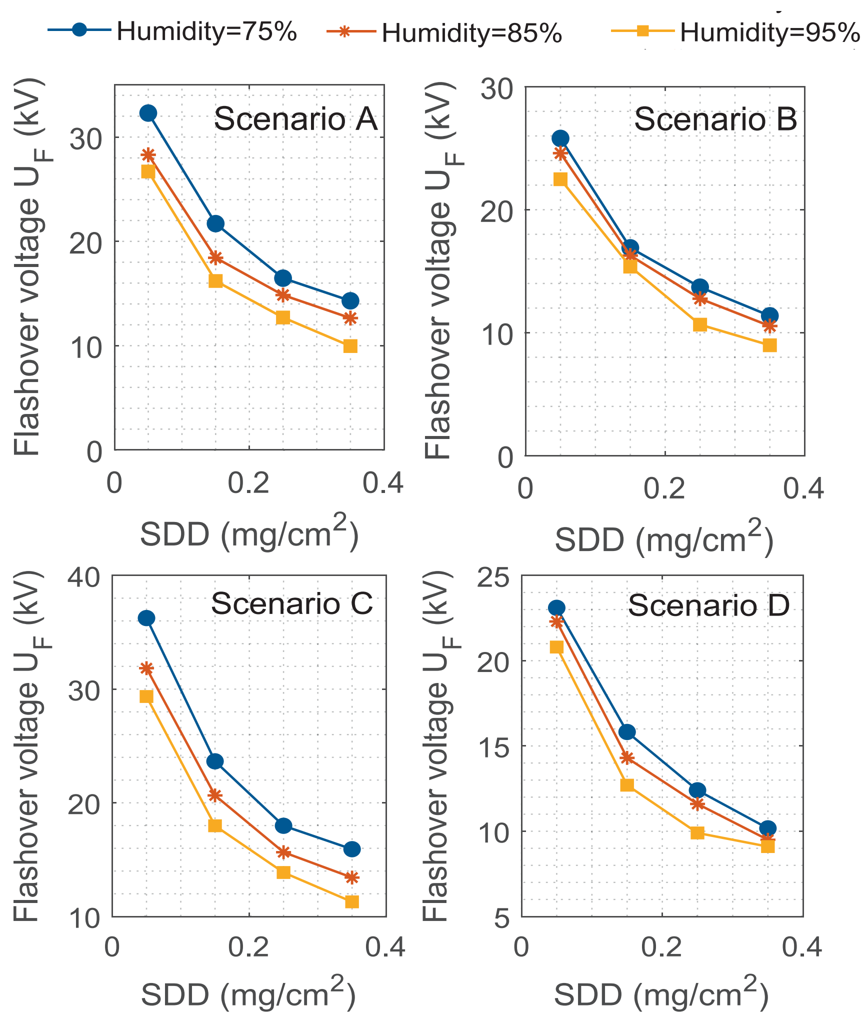


Fig. 4. Flashover voltage versus humidity under studied scenarios.

SDD = 0.15 mg/cm^2 and the humidity increases from 75% to 85% and 95% under scenario SC-A, the FOV of the insulator decreases by 3.75 kV and 5.5 kV, respectively. Under SC-B, SC-C, and SC-D scenarios, the reduction in U_F-*SDD* line slope with increasing humidity of contaminated insulators is roughly identical to the SC-A slope scenario, with minor oscillations in some cases due to varying in conductance in the pollution layer.

3.3. Non-uniform distribution

Fig. 5 illustrates the results of flashover voltage testing for insulator under uneven contaminated with scenario SC-B (for example) at different levels of *SDD*, $F_{B/T}$, and *S%*. For all experiments, the humidity was 75% in the presence of non-uniform contamination. According to Fig. 5, the greatest value of deviation was 4.4 % for all tests, demonstrating that the test results were acceptable. With the same $F_{B/T}$ and S, the U_F of the tested sample reduced extremely as the *SDD* levels are increased. When $F_{B/T}$ = 3, *S%* = 40% and *SDD* is raised from 0.05 to 0.15 and 0.25 mg/cm^2, for example, the U_F of the insulator under scenario SC-B falls by 23.613 and 18.914 %, respectively.

In addition, the flashover voltage data were fitted using Eq. (6), as shown in Fig. 5, and the correlation coefficients R^2, a, and b, as specified in Eq. (6), of the contaminated insulator under scenario SC-B were displayed, as shown in Table 1.

Under non-uniform contamination, the value of *a* also influenced by the change of $F_{B/T}$. For example, the values of *a* for scenario SC-B increases from 9.18 to 10.27, and 11.99, when $F_{B/T}$ increases from 3 to 5, and 8, respectively, under *S%* = 40%. This shows that the value of a grows by 10.4% and 30.3%. The U_F of test sample is related to the $F_{B/T}$ at the top and bottom sides. The $F_{B/T}$ and S% impacts on U_F of insulator under scenario SC-D with vary of the SDD degree are depicted in 3D graphs in Fig. 6 (a and b). Meanwhile, the $F_{B/T}$ and *S%* effects on U_F at a constant of SDD = 0.15 mg/cm^2 are demonstrated in Fig. 6 (c). According to the output tests in Fig. 6, the increase of $F_{B/T}$ causes a gradual rise in U_F. For example, in the case of scenario SC-D, when SDD is 0.05 mg/cm^2, *S%* = 40% and $F_{B/T}$ is 1, 3, 5, 8. U_F is 21.6 kV, 23.8 kV, 26.04 kV, and 29.6 kV, respectively. It can be seen that the U_F increase by 9.9, 18.86, and 33.96% when the $F_{B/T}$ rises from 1 to 3, 5, and 8, respectively. This occurs because at the high $F_{B/T}$ there are higher variations in the pollution levels on the top and bottom

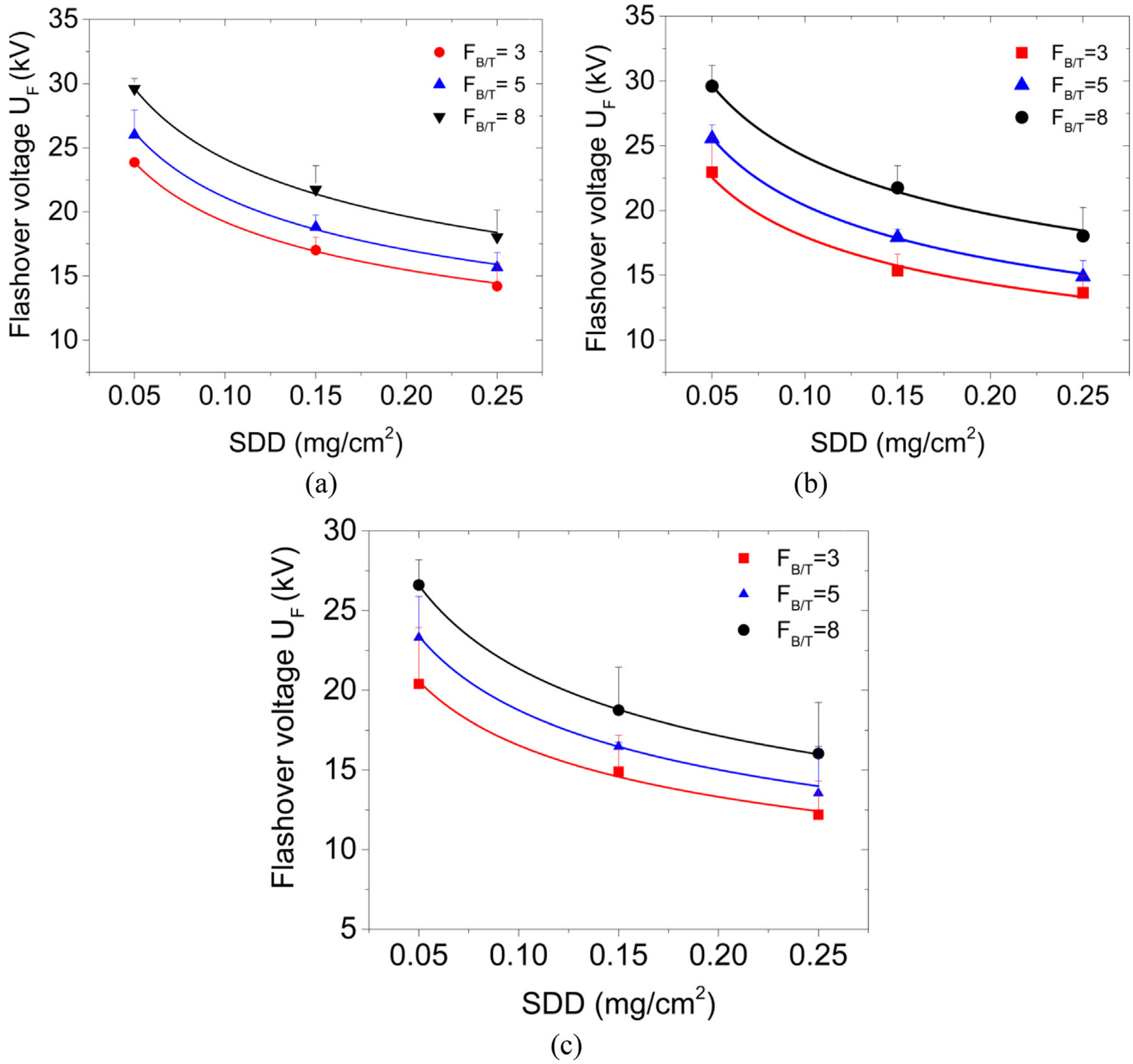


Fig. 5. Non-uniform flashover voltage under *S%* of 40, 60 and 80%.

sides than there are at low $F_{B/T}$. Due to differences in pollution levels between the top and bottom surfaces, electrical conductivity on the side with less pollution may be poor. As a result, a high value of voltage is required for discharge creation in low pollution zones.

S% has also affected the FOV results. There is a slight decrement in the U_F with *S%* increase steadily under a certain value of $F_{B/T}$ and *SDD*. Because the polluted-zone increases with increasing S%, it was noted that the voltage value that causes discharge in a large polluted-zone is lower than the voltage value when the zone is small due to increases in surface conductance and leakage current passage through the pollution layer on the insulator's surface in the case of a large polluted-zone.

Fig. 7 demonstrates the influence of S% on the insulators' flashover voltage behavior in scenario SC-D as an example. From Fig. 7, It can be observed that the U_F value of scenario SC-D is 31.6 kV, 29.41 kV and 26.82 kV when $F_{B/T}$ = 5 and S% is 40, 60, and 80%, correspondingly, at SDD is 0.15 mg/cm^2. This denotes that the U_F decreased about 7.6% if the *S%* grows by 20 To evaluate the pollution effect under uneven distribution on the flashover voltage of tested porcelain insulator, the U_F results of studied scenarios were plotted and fitted as shown in Fig. 5 above. The coefficient R^2 is more than 0.92 for all tests, indicating that the U_F results versus SDD were successfully fitted nonlinearly using the function of power.

4. Artificial neural network model (Ann)

4.1. ANN model training

The Artificial Neural Network (ANN) is one of the artificial intelligent tools that focuses on training using known data [30–33]. The ANN is made up of a large number of linked processing units called neurons that work together to solve a problem by transferring

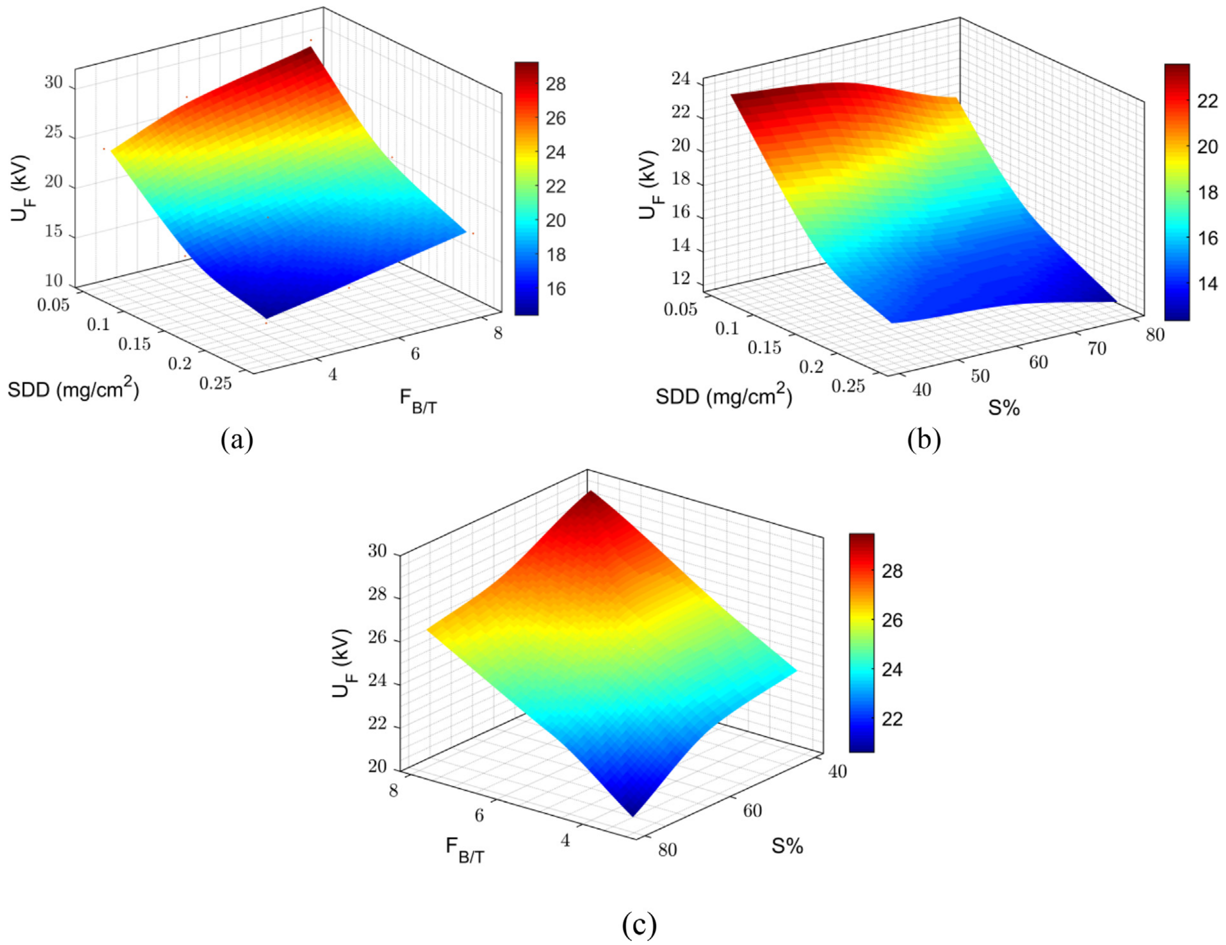


Fig. 6. U_F of scenario SC-D in term of: (a) *SDD* and *S%* at $F_{B/T}$ = 3; (b) SDD and $F_{B/T}$ at *S%*=40%; (c) *SDD* and *S%* at $F_{B/T}$ = 3.

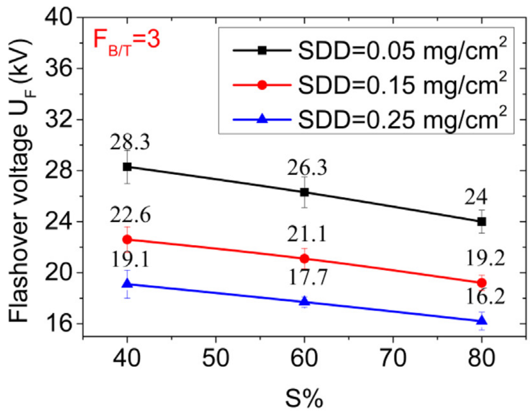
data. The ANN technique was simulated in this article using the back-propagation approach in MATLAB to obtain maximum convergence to the smallest feasible point, following which the model was learnt and assessed. The U_F was calculated using the ANN output. SDD, $F_{B/T}$, *S%*, and relative humidity were the model's inputs. As indicated in the experiment setup section, several pollution flashover experiments were performed on test sample under various contamination situations with uniform and non-uniform pollution. 432 U_F data (Fig. 8) were gathered in this simulation. 70% of data (302) are selected for training the model, 15% for verification of performance the model (65 data), and 15% for model testing (65 data).

Fig. 9(a) shows the model's Mean Squire Error (MSE) for training, validation, and testing. As illustrated in Fig. 9(b), the model's optimal response was seen at epoch 44, with MSE hovering around 0.657. Fig. 10(a) illustrates the model's (Training, Validation, and Test) regression results.

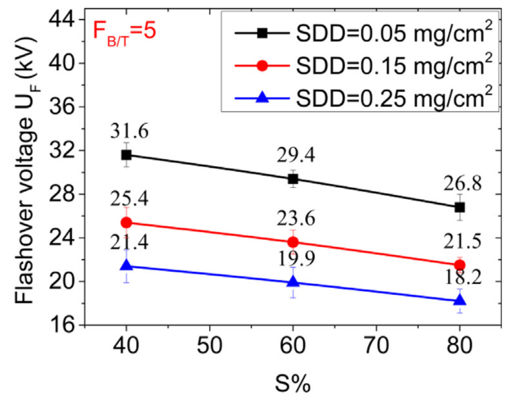
The R^2 of the whole regression was greater than 0.98, implying that the performance the ANN model is adequate. The comparison of test and model prediction findings with error is shown in Fig. 10 (b). It's worth noting that the difference between the test and simulation results is less than 1.5. Wherefore, the ANN model may be considered to introduce a successful prediction.

4.2. Verification of ANN model

The data of three different forms of uneven pollution distribution results are selected for the verification of the presented ANN model forecast. To validate the proposed model, random data from the training data of uneven pollution of the bottom, top, and whole surfaces were chosen. Table 2 shows the ANN model results compared to the experimental results as well as the error of model respect to test results. According to Table 2, the absolute values of relative errors E_r between the experimental results of flashover voltage and predicted results U_P using the ANN model are below 2.5%. Therefore, the prediction model gives accurate results of the U_F under various levels of humidity, *S%*, $F_{B/T}$, and *SDD*.



(a)



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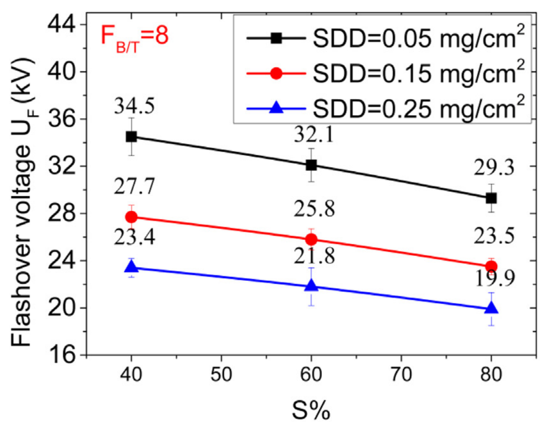

(c)

Fig. 7. U_F of scenario SC-D in term of *S%*: (a) $F_{B/T}$ = 3; (b) $F_{B/T}$ = 5; (c) $F_{B/T}$ = 8.

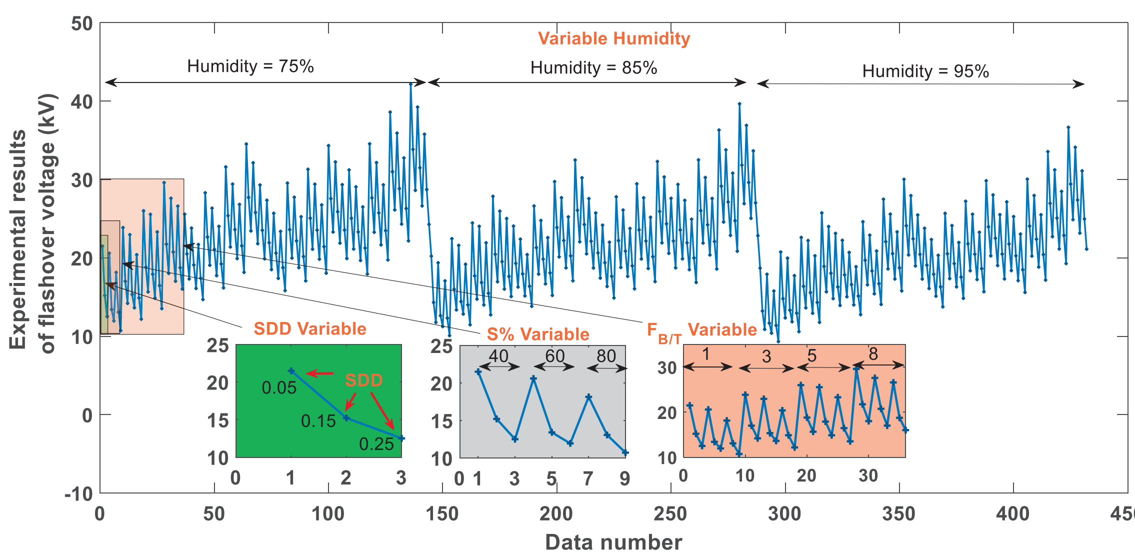

Fig. 8. Experimental results of flashover voltage data under different of *SDD*, *S%*, $F_{B/T}$ and humidity.

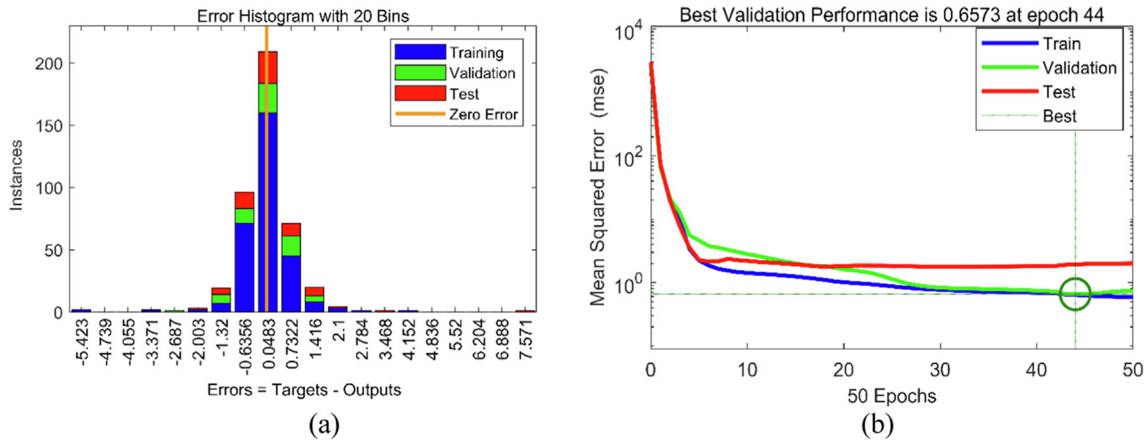

Fig. 9. (a) Artificial neural network error histogram; (b) MSE of trainings, validation and test data.

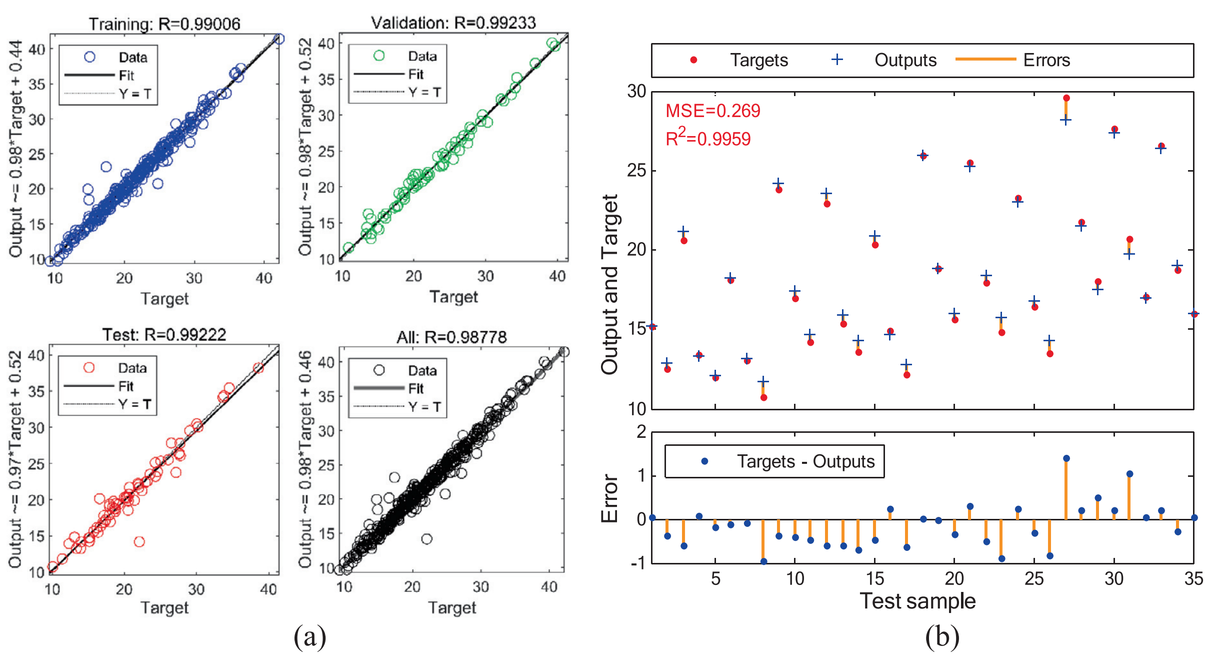

Fig. 10. (a) ANN model regression; (b) Comparison of the Tests data with the model prediction.

Table 2
Comparison between The ANN and experimental results.

Humidity	$F_{B/T}$	S%	SDD (mg/cm2)	U_F (kV)	U_P (kV)	$E_r = \lvert (U_p - U_F)/U_F \rvert \times 100$
75	3.00	40	0.05	23.86	24.22	1.50
75	3.00	40	0.15	17.02	17.42	2.35
85	1.00	60	0.25	15.15	14.87	1.90
85	1.00	80	0.05	20.42	20.46	0.20
95	3.00	40	0.05	24.61	24.96	1.43
95	3.00	40	0.15	19.70	19.35	1.81

5. Conclusion

The study carried out in this paper explores how insulators under test behave during flashovers in varied pollution and humidity conditions. This study was conducted in four scenarios regarding pollution distribution. During the experimental and testing procedure, the clean and polluted insulators' flashover voltage was investigated. In addition, the effect of flashover voltage value on the non-polluted-zone, humidity, and contamination level was measured. In fact, the SDD, humidity, location and dimension of non-polluted-zone the insulator, are the factors that mainly affect the flashover voltage. The interaction of UF as function with SSD usually has appeared as a negative power advantage when there is contamination on the insulator. It was noticed that the contaminated region on the sample and the flashover voltage has an inverse relationship between them. It means that, if there is a growth in the contaminated area on the insulator, the flashover voltage decreases. Moreover, flashover subsides when the humidity increases. Among the selected scenarios, it was concluded that, scenario SC-D resulted in the lowest value of flashover voltage. The proposed ANN model was developed as a comparison tool to predict the flashover voltage value to compare it with the test result. The results showed that the relative error value appeared to be less than 2.5%, which means that the ANN model is significantly precise, and can be employed efficiently for forecasting the samples' flashover voltage.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Ali Ahmed Salem **(A. A. Salem)** Received M.Eng. in Electrical Power Engineering from University Tun Hussein Onn Malaysia (UTHM) 2016. He received Ph.D. degree at High Voltage in Faculty of Electrical Engineering, also from UTHM 2021. Currently, he is with the Universiti Teknologi Malaysia (UTM) Grantee for a postdoctoral fellow. His research interest includes the dynamic arc modelling of pollution flashover on high voltage outdoor insulators. This author was IEEE member in 2017.

R. Abd Rahman was born in Kedah, Malaysia in 1984. He received the M.Eng. Degree in electrical and electronic engineering from Cardiff University, UK in 2008. After his graduation, he joined University Tun Hussein Onn Malaysia (UTHM) as an academic staff and research fellow. In 2008, he came back to Cardiff as a PhD candidate within the High Voltage and Energy Systems group and received his PhD in 2012. Currently, he is a lecturer at University of Tun Hussein Onn Malaysia (UTHM), Batu Pahat, Malaysia.

Mohd Taufiq Ishak received the B. Eng. degree in Electrical Engineering (2002) from Universiti Tenaga Nasional in Malaysia and M. Eng. in Electrical Engineering (2004) from UMIST, UK. He received the PhD degree in Electrical Power Engineering from University of Manchester, UK in 2010. Currently he is a Senior Lecturer in the Department of Electrical and Electronic Engineering, Universiti Pertahanan Nasional Malaysia. His research interests are high voltage, power transformer, asset management, lifetime prediction, renewable energy, conditioning monitoring and smart grid.

Kwan Yiew Lau received his B.Eng. degree in electrical engineering (First Class Honors) and M.Eng. degree in electrical power engineering from the Universiti Teknologi Malaysia in 2007 and 2010, respectively. Later in 2013, he received his Ph.D. degree in electronics and electrical engineering from the University of Southampton, UK. He is an associate professor at the Institute of High Voltage and High Current, Universiti Teknologi Malaysia. He is also a Chartered Engineer of the Engineering Council UK, a Professional Engineer of the Board of Engineers Malaysia, and the Past Chair of the IEEE DEIS Malaysia Chapter. His research interests include high voltage engineering, dielectric materials and renewable energy systems.

Zulkurnain Abdul-Malek received the B.E. degree in electrical and computer systems from Monash University, Melbourne, Australia, in 1989, the M.Sc. degree in electrical and electromagnetic engineering with industrial applications from the University of Wales Cardiff, Cardiff, U.K., in 1995, and the Ph.D. degree in high voltage engineering from Cardiff University, Cardiff, U. K., in 1999. He was with Universiti Teknologi Malaysia (UTM) for 30 years, and he is currently a Professor of High Voltage Engineering with the Faculty of Engineering. He is also the Director of the Institute of High Voltage and High Current (IVAT), UTM. He has published two books, and has authored and coauthored more than 150 articles in various technical journals and conference proceedings. His research interests include high-voltage instrumentation, lightning protection, detection and warning systems, partial discharges, nanodielectrics, and condition monitoring of power equipment. He is actively involved in many international and national committees. He is also a member of MT 03 IEC 60060-2 High voltage test techniques–2: Measuring systems, the Chairman for ICPADM 2021 Organising Committee, Malaysian High Voltage Network (MyHVNet), from 2015 to 2016 and Malaysian Working Group on High-Voltage and High-Current Test Techniques. He is also a member of Malaysian IEC Certification Body Management Committee, Malaysian Technical Committee on High Voltage Power Transmission, and the Department of Standards IEC 17025 Technical Assessors. He is a member of the IEEE Power and Energy Society, the IEEE Dielectrics and Electrical Insulation Society, IET and CIGRE.

Salem Mgammal Al-Ameri received B.Eng. in Mechatronics Engineering from Asia Pacific University (APU) in 2012. He received M.Eng. in Electrical from Universiti Tun Hussein Onn Malaysia (UTHM) in 2016. He received Ph.D. degree from The Universiti Tun Hussein Onn Malaysia in 2020. Currently, he is with the Universiti Tun Hussein Onn Malaysia Grantee for a postdoctoral position. His research interests include transformers Condition monitoring.

Samir Ahmed Al-Gailani started his career as senior lecturer at Higher Technical institute for applied B.Sc. degree Aden Yemen in 1992. He obtained his PhD in the field of optoelectronics from University Technology Malaysia (UTM) in 2014 with best student award and since then has been given various responsibilities including teaching, postdoctoral fellow, supervising laboratory sessions, supervising post-graduate students and undergraduate students, academic advisor, head of laboratory, head of research group, chairman and member of different committees, conducting short courses and training, He authored 20 ISI papers and has an H-Index of 7 and total citations of 212, presented more than 90 papers in reputed refereed conferences. He also successfully supervised 9 undergraduate students.

Sherif S.M. Ghoneim (Senior Member, IEEE) received the B.Sc. and M.Sc. degrees from the Faculty of Engineering at Shoubra, Zagazig University, Egypt, in 1994 and 2000, respectively, and the Ph.D. degree in electrical power and machines from the Faculty of Engineering, Cairo University, in 2008. Since 1996, he has been teaching with the Faculty of Industrial Education, Suez Canal University, Egypt. From 2005 to 2007, he was a Guest Researcher with the Institute of Energy Transport and Storage (ETS), University of Duisburg–Essen, Germany. He joined the Electrical Engineering Department, Faculty of Engineering, Taif University, as an Associate Professor. His research interests include grounding systems, dissolved gas analysis, breakdown in SF6 gas, and AI technique applications.