

## Effect of repeated electrical breakdowns on mineral and natural ester insulating oils

Sharin Ab Ghani<sup>1</sup>, Mohd Shahril Ahmad Khair<sup>2</sup>, Imran Sutan Chairul<sup>3</sup>, Muhammad Imran Zamir<sup>4</sup>

<sup>1,2,3</sup>High Voltage Engineering Research Laboratory, Faculty of Electrical Engineering, Universiti Teknikal Malaysia Melaka, Malaysia

<sup>4</sup>SBS Letrik Sdn. Bhd., Kedah, Malaysia

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### ABSTRACT

Transformer insulating oils are exposed to repeated electrical discharge or breakdowns inside power transformers. Durability tests are conducted to analyze the ability of oil to resist decomposition due to such high electrical stresses. With the increasing demand for alternative insulating oils for oil-immersed transformers, it is worthy to compare the performance of different types of insulating oils (conventional mineral-based insulating oil and natural ester-based insulating oil) under repeated electrical breakdown. In this paper, the AC breakdown voltage of different mineral-based and natural ester-based insulating oils is reported. Durability tests were conducted based on the AC breakdown voltage behavior of insulating oils after 50 electrical breakdown shots. The AC breakdown voltage of each insulating oil sample was assessed according to the ASTM D1816 standard test method. Based on the results, it can be concluded that the dissimilarity in chemical composition of the insulating oils has a significant effect on the AC breakdown voltage behavior of these oils under repeated electrical breakdowns.

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### Corresponding Author:

Sharin Ab Ghani

High Voltage Engineering Research Laboratory

Faculty of Electrical Engineering

Universiti Teknikal Malaysia Melaka

Hang Tuah Jaya, 76100 Durian Tunggal, Melaka, Malaysia

Email: sharinag@utem.edu.my

## 1. INTRODUCTION

Mineral-based insulating oils are widely used as an insulating medium in oil-immersed transformers, enabling safe and reliable electrical energy transmission. Mineral-based insulating oils derived from petroleum were the first insulating oils used in oil-immersed power transformers. Mineral-based insulating oils have been widely used since the 1940s in power equipment such as transformers, capacitors, cables, and bushings [1]-[3]. However, mineral-based insulating oils do not provide the necessary protection against fire hazards. Qualifying transformer insulating oils must meet a minimum open-cup fire point of 300°C. A systematic research and development program began in the early 1990s due to environmental regulations and liability concerns by introducing natural ester-based insulating oils. Recently, studies have been carried out to develop natural ester-based insulating oils due to environmental concerns associated with mineral-based insulating oils [2], [3]. The quest to develop environmentally friendly insulating oils stems from the following reasons [4]. First, in the event of a severe spill, mineral-based insulating oils can contaminate soil and water resources. Second, mineral-based insulating oils are derived from petroleum, which will deplete in the future because petroleum is a non-renewable energy source. Researchers concluded

that natural ester-based insulating oils can be chemically enhanced to improve their physicochemical and electrical properties such as oxidation stability, dissipation factor, lightning impulse resistance, and viscosity [5], [6]. Table 1 shows the specifications for mineral-based and natural ester-based insulating oils according to the ASTM D3487 and ASTM D6871 standards [7], [8].

Table 1. Specifications for the physicochemical and electrical properties of mineral-based and natural ester-based insulating oils

Properties		ASTM standard test method	Mineral oil (ASTM D3487)	Natural ester (ASTM D6871)
Electrical properties	AC breakdown voltage (kV)	D1816 (1-mm gap)	$\geq 20$	$\geq 20$
		D1816 (2-mm gap)	$\geq 35$	$\geq 35$
Chemical properties	Water content (ppm)	D1533	$\leq 35$	$\leq 200$
	Acid value (mg KOH/g)	D974	$\leq 0.03$	$\leq 0.6$
Physical properties	Color	D1500	$\leq 0.5$	$\leq 1.0$
	Visual examination	D1524	Clear and bright	Clear and bright

Electrical breakdown occurs when the insulating oil becomes a conductor under the influence of a high voltage stress [9], [10]. In power transformers, the insulating oil is continuously exposed to repeated electrical discharge, resulting in breakdown of electrical insulation. Since the electrical discharge is unavoidable, it is important to understand the behavior of insulating oil properties under repeated electrical discharge to avoid insulation failure and breakdown of the transformer. The ability of the insulating oil to resist decomposition under repeated electrical discharge is one of the important factors for the safety of the transformer. Repeated electrical discharge in the presence of heat, moisture, and oxygen will oxidize the insulating oil and produce free radicals, acids, and sludge that are harmful to the transformer [11], [12]. Hence, it is crucial to study the durability of the mineral-based and natural ester-based insulating oils in terms of the AC breakdown voltage in order to prevent catastrophic failure of power transformers.

## 2. RESEARCH METHOD

In this study, Hyrax Hypertrans™ uninhibited mineral insulating oil was chosen as the mineral-based insulating oil, hereinafter MI oil. Envirottemp FR3™ (formulated with soybean oil) was chosen as the natural ester-based insulating oil, hereinafter NEI oil. Pre-processing was first carried out to remove foreign particles and moisture from the NEI oil. The insulating oil samples were filtered through quantitative filter paper with a pore size of 2  $\mu\text{m}$ . The insulating oil samples were then heated in a vacuum oven for 48 h at a temperature of 70 °C and vacuum pressure of less than 1 kPa [13], [14]. A portable oil AC breakdown voltage tester (Model: OTS60PB, Megger Ltd., UK) equipped with semi-spherical electrodes was used to conduct the AC breakdown voltage tests. This instrument can be used to test an insulating oil sample with a volume of 500 ml. The oils were left at an ambient temperature of ~20-30°C. The ambient relative humidity and oil temperature were measured using a calibrated hygrometer and thermometer, respectively. Next, the containers of the oil samples were gently inverted and swirled several times to ensure homogeneity of the oils. Within 1 min after agitation, the test cell was rinsed with a small amount of the insulating oil sample. Following this, the test cell was drained.

Next, the remaining portion of the oil sample was slowly poured into the test cell and the test cell was closed to prevent air from contacting the insulating oil. The insulating oil sample was left for 3-5 min before application of the first breakdown voltage. However, for insulating oils with a high fire point such as natural ester and synthetic ester, the hold time before the initial application of breakdown voltage is at least 30 min. The breakdown voltage was automatically applied at an increment of 0.5 kV/s until breakdown occurred. Nine additional tests were conducted, where the time between breakdowns was 1.0-1.5 min. In this study, three samples from each insulating oil (MI and NEI) were taken from the same sources for the AC breakdown voltage test. Each oil sample was tested for 10 consecutive electrical breakdowns five times, resulting in 50 data points. The data for the MI and NEI oils were analyzed statistically in order to determine the mean and standard deviation of the AC breakdown voltage. The details of the AC breakdown voltage test according to the ASTM D1816 standard test method are summarized in Table 2 and Figure 1 shows the steps involved before the AC breakdown voltage test.

Table 2. Details of the AC breakdown voltage test according to the ASTM D1816 standard test method

ASTM D1816 standard test method		
Electrode	Shape	Spherical
	Gap distance	1 mm or 2 mm
Laboratory test temperature	Liquid	Must be recorded at ambient temperature
	Ambient	20-30°C
Test voltage	Rate of applied voltage increment	0.5 kV/s
	Frequency	45-65 Hz
Breakdown	Number of breakdowns in sequence	5
	Time between breakdowns	1.0-1.5 min

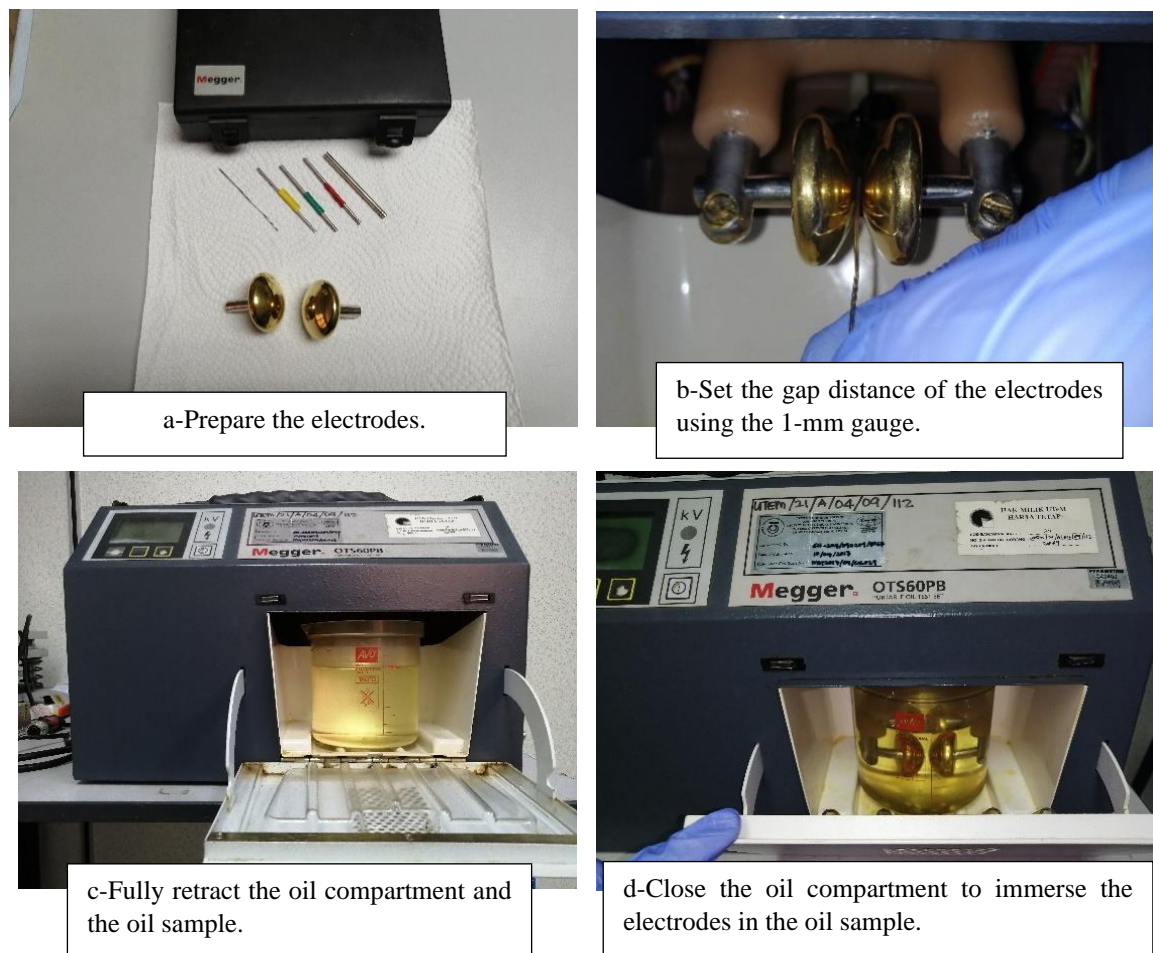


Figure 1. Steps involved before the AC breakdown voltage test

### 3. RESULTS AND DISCUSSION

The AC breakdown voltage is the voltage where discharge occurs between the electrodes immersed in the insulating oil. Table 3 shows the results of AC breakdown voltage test for the MI and NEI oils, where three samples were prepared for each oil, and each sample was subjected to 10 consecutive electrical breakdown shots five times. The average AC breakdown voltage and standard deviation were determined for each sample. Based on the results, the average AC breakdown voltage of the three MI oil samples is within a range of 21-24 kV. The minimum AC breakdown voltage is 15 kV while the maximum AC breakdown voltage is 40 kV. Figure 2 (a) shows the dielectric strength of the MI oil versus the electrical breakdown shot number. In general, the dielectric strength of the MI oil decreases with an increase in the number of electrical breakdown shots. Figure 2 (b) shows the corresponding histogram of the MI oil, which was plotted based on 150 AC breakdown voltage readings for the three MI oil samples. It can be seen from Figure 2 (b) that the data are skewed to the left, where most of the data fall on the left side of the histogram. This is known as a negatively skewed distribution. The mean and median are likely to the left of the mode. The tail is longer at the left-hand side. The results indicate that the breakdown of the MI oil frequently occurs at a lower voltage

( $\leq 25$  kV). Meantime, Figure 3 shows the regression line fitted to the AC breakdown voltage values for MI oil, which was plotted based on 150 AC breakdown voltage readings for the three MI oil samples. The regression equation obtained for the MI oil is also stated in Figure 3. Based on the regression line, it indicates a linear slope with electrical breakdown shot number coefficient is  $-0.1749$ . This coefficient represents the mean decrease of AC breakdown voltage in kilovolts for every additional 1 shot of electrical breakdown.

Table 3. AC breakdown voltage in kilovolts (kV) for the MI and NEI oil samples

Type of oil	Sample no.	Test sequence	Electrical breakdown shot no.										Average (kV)	Standard deviation
			1	2	3	4	5	6	7	8	9	10		
MI	1	1	27	19	32	22	28	22	18	25	25	18	24	4.76
		2	27	29	35	24	17	21	21	19	19	15		
		3	40	28	28	21	28	24	19	20	20	21		
		4	29	29	29	28	27	25	21	22	22	19		
		5	23	26	26	23	23	24	18	22	22	21		
	2	1	29	31	20	24	20	22	17	20	22	24	21	3.64
		2	26	16	19	23	19	19	18	20	20	20		
		3	25	20	23	19	20	16	16	15	22	18		
		4	25	17	28	20	21	16	16	21	23	18		
		5	27	24	21	24	21	15	17	18	20	19		
	3	1	31	33	30	24	24	18	25	16	22	17	24	4.81
		2	21	22	24	30	26	24	17	21	26	16		
		3	31	34	26	23	21	23	26	20	16	20		
		4	30	31	21	23	21	27	19	21	20	25		
		5	31	28	21	22	16	27	18	22	17	21		
NEI	1	1	26	32	35	32	38	39	38	33	39	35	32	5.66
		2	35	27	29	30	35	34	31	33	34	26		
		3	30	31	37	32	38	19	39	34	40	37		
		4	35	27	18	29	26	27	27	33	28	42		
		5	32	27	19	32	36	35	25	42	25	38		
	2	1	27	27	30	30	28	28	28	28	28	29	27	3.40
		2	23	22	23	18	25	31	22	29	29	27		
		3	22	25	30	25	24	25	29	29	24	27		
		4	29	29	28	25	29	28	30	16	26	30		
		5	26	26	33	30	27	27	30	20	32	28		
	3	1	31	26	27	39	36	33	28	36	36	45	32	5.18
		2	28	31	34	28	33	34	35	30	36	40		
		3	31	31	34	26	36	37	20	35	36	29		
		4	28	36	35	30	25	37	31	34	43	35		
		5	20	20	30	34	30	26	34	30	31	33		

By contrast, based on Table 3 the average AC breakdown voltage for the NEI oil is higher than that for the MI oil, with a range of 27-32 kV. The minimum and maximum AC breakdown voltage values for the NEI oil are 16 and 45 kV, respectively. Likewise, the dielectric strength and histogram were plotted for the NEI oil, and the results are shown in Figure 4 (a) and 4 (b), respectively. It can be observed that the dielectric strength increases gradually with respect to the number of electrical breakdown shots. It can be seen from Figure 4 (b) that the data are skewed to the right, where most of the AC breakdown voltage data fall on the right side of the histogram. This is also known as a positively skewed distribution. The mean and median are likely to the right of the mode. The tail is longer at the right-hand side. The results indicate that the breakdown of the NEI oil frequently occurs at a higher voltage ( $\geq 25$  kV). On the other hand, Figure 5 shows the regression line fitted to the average AC breakdown voltage values for NEI oil, which was plotted based on 150 AC breakdown voltage readings for the three MI oil samples. The regression equation obtained for the MI oil is also stated in Figure 5. Based on the regression line, it indicates a linear slope with electrical breakdown shot number coefficient is  $+0.0996$ . This coefficient represents the mean increase of AC breakdown voltage in kilovolts for every additional 1 shot of electrical breakdown.

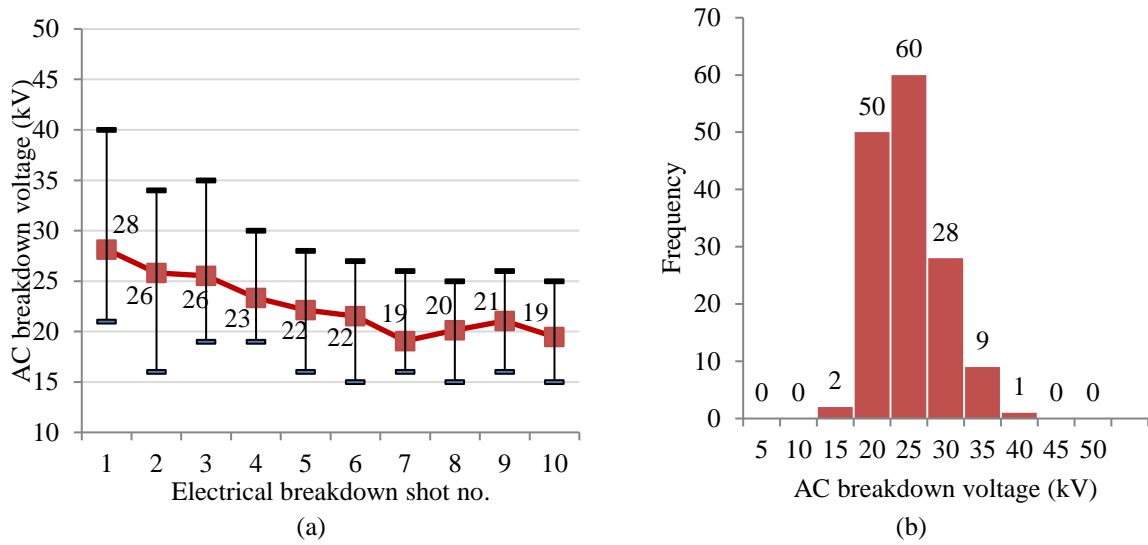


Figure 2. Distribution data of MI oil, (a) AC breakdown voltage data of the MI oil with respect to the electrical breakdown shot number, (b) histogram of the AC breakdown voltage

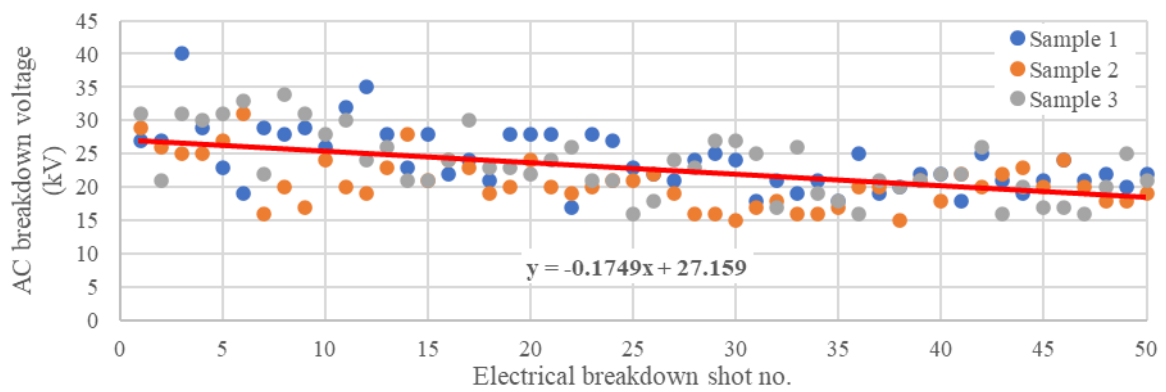


Figure 3. Regression line fitted to the AC breakdown voltage values for the overall MI oil samples

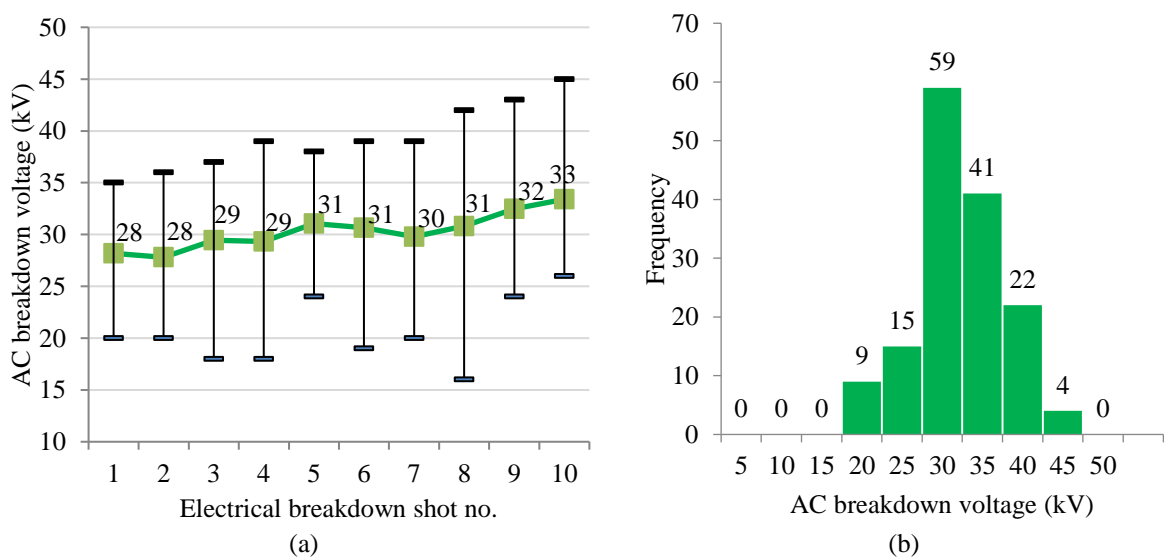


Figure 4. Distribution data of NEI oil: (a) AC breakdown voltage data of the MI oil with respect to the electrical breakdown shot number and (b) histogram of the AC breakdown voltage

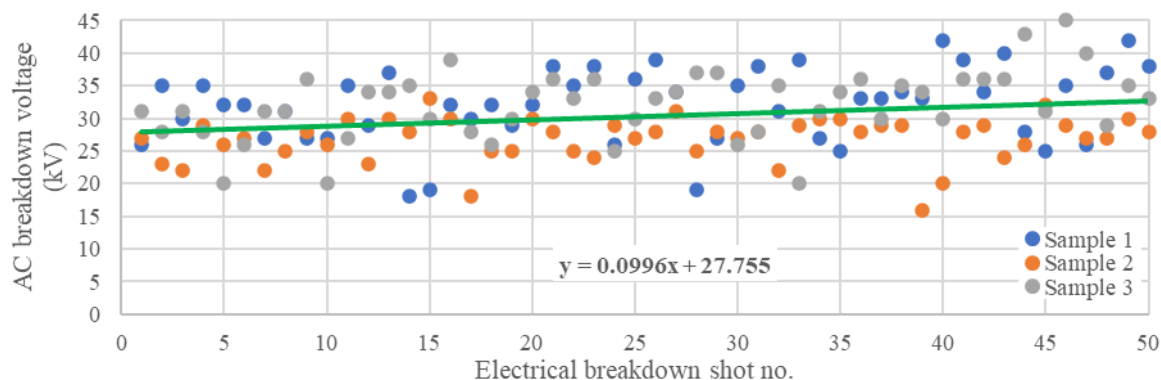


Figure 5. Regression line fitted to the AC breakdown voltage values for the overall NEI oil samples

Based on Figure 2 and Figure 4, it is apparent that the dielectric strength of the MI oil tends to decrease with an increase in the number of electrical breakdown shots. By contrast, the dielectric strength of the NEI oil tends to increase gradually as the number of electrical breakdown shots increases. Based on the histograms (Figure 2 (b) and Figure 4 (b)), the MI oil shows a left-skewed distribution, where most of the AC breakdown voltage data occur at a lower voltage ( $\leq 25$  kV). By contrast, the NEI oil shows a right-skewed distribution, where most of the breakdown voltage data occur at a higher voltage ( $\geq 25$  kV). It can be deduced that the NEI oil has higher dielectric strength than the MI oil, where 94% of 150 breakdowns occur at a voltage of more than 20 kV for the NEI oil. By contrast, only 65.3% of 150 breakdowns occur at a voltage of more than 20 kV for the MI oil. According to the ASTM D1816 standard, the AC breakdown voltage is considered as the minimum threshold for the insulating oil for a 1-mm electrode gap distance setup.

In general, the NEI oil has a higher percentage of minimum “pass” AC breakdown voltage compared with the MI oil. The NEI oil has better durability than the MI oil in terms of the dielectric strength, where most of the AC breakdown voltage data occur at a voltage of more than 20 kV. This is possibly due to the fact that NEI oil is hydrophilic (i.e., a substance that attracts water) and thus, the oil is capable of mixing well with water and dissolve water. In addition, the water saturation limit of the NEI oil is 5-8 times greater than that of the MI oil [4], [15]-[18]. The electrical stress may influence the molecular bonds (breakdown of C-H bond) of the MI oil, which reduces its breakdown voltage [18]-[24]. The chemical composition of the NEI oil is different compared to that of the MI oil, which is a petroleum hydrocarbon. This leads to differences in the AC breakdown voltage behavior between the MI and NEI oils. Other factors may also influence the AC breakdown voltage of an insulating oil, such as the relative concentration of moisture (relative to its solubility) and water content [25].

#### 4. CONCLUSION

In this study, the durability of MI and NEI oils in terms of the dielectric strength under repeated electrical breakdown was assessed. Based on the results, it can be concluded that the NEI oil has better dielectric strength where the average breakdown voltage for every 10 consecutive electrical breakdowns is higher compared with that for MI oil. Furthermore, the dielectric strength of the NEI oil shows a gradual increasing trend with respect to the number of electrical breakdown shots. The histograms also reveal that most of the AC breakdown voltage data are on the higher end ( $\geq 25$  kV) for the NEI oil compared with those for the MI oil. Hence, it is concluded that the NEI oil tested in this study is more durable compared with the MI oil.

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## BIOGRAPHIES OF AUTHORS



**Sharin Ab Ghani** received his BEng. (Hons.) degree in Electrical Engineering from Universiti Teknikal Malaysia Melaka (UTeM) in 2008, MEng. Degree in Electrical Engineering from Universiti Tenaga Nasional in 2012, and PhD degree in Electrical Engineering from Universiti Teknologi Malaysia in 2019. Currently, he is serving as Senior Lecturer at Faculty of Electrical Engineering, UTeM and Head of Energy and Power Systems (EPS) Research Group. His research interests are centered on high voltage engineering, condition monitoring of power equipment, eco-friendly electrical insulation, design of experiments, and optimization. He also has experience in consultation work with industries related to electrical installation design, transformer condition assessment, and partial discharge analysis.



**Mohd Shahril Ahmad Khair** was born in Selangor, Malaysia in 1984. He received his BSc. In Electrical & Electronics Engineering from Korea University in 2008, Master's degree in Electrical Engineering from Universiti Tenaga Nasional in 2012, and PhD degree from University of Southampton, UK in 2019. He is currently serving as Senior Lecturer at Faculty of Electrical Engineering, UTeM and Head of High Voltage Engineering Research Laboratory in UTeM, where he is also the Deputy Head of Energy and Power Systems (EPS) Research Group. His research interests include high voltage engineering and insulation materials, sensors, condition monitoring for power equipment, and asset management. Since 2013, he has published over 20 refereed conference and journal papers associated with the transformer condition monitoring and asset management.



**Imran Sutan Chairul** was born in Kuala Lumpur, Malaysia, in 1984. He received his BEng. (Hons.) degree in Electrical Engineering from Universiti Teknikal Malaysia Melaka (UTeM) in 2008 and MEng. degree in Electrical Engineering from Universiti Tenaga Nasional in 2012. He is currently pursuing his PhD degree at UTeM, where his research is focused on vegetable-based transformer dielectric liquids.



**Muhammad Imran Zamir** was born in Pulau Pinang, Malaysia in 1997. He received his BEng (Hons.) degree in Electrical Engineering from Universiti Teknikal Malaysia Melaka in 2018.