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Accelerated thermal aging of Kraft papers impregnated with dielectric liquids

Imran Sutan Chairul[1], Norazhar Abu Bakar[1], Sharin Ab Ghani[1], Mohd Shahril Ahmad Khiar[1], Nor Hidayah Rahim[1], Syahrun Nizam Md Arshad@Hashim[2]
[1]High Voltage Engineering Research Laboratory, Faculty of Electrical Engineering, Universiti Teknikal Malaysia Melaka (UTeM), Melaka, Malaysia
[2]School of Electrical Systems Engineering, Universiti Malaysia Perlis, Pauh Putra Campus, Arau, Malaysia

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ABSTRACT

Accelerated thermal aging was conducted on Kraft papers impregnated with mineral insulating oil (MO) and palm insulating oil (PO), and the effect of aging time on the oils and Kraft papers was observed. Each sample consisted of insulating oil, dried Kraft paper, and weighed metal catalysts (copper, iron, zinc, and aluminum) in a bottle. Prior to aging, the bottles were left for 24 h at room temperature for impregnation to take place. The thermal aging experiments were carried out at 130 °C for 250, 500, and 750 h. The properties of the MO and PO (moisture content, acidity, and ultraviolet-visible absorption spectra) and the properties of the Kraft papers (tensile strength and colour) were determined. Results showed that the aged PO had higher moisture content compared with the aged MO. However, the Kraft papers impregnated with PO had better tensile strength after 750 h of aging, which may be attributed to the affinity of PO to moisture. This slows down the hydrolytic degradation mechanism. In terms of colour, the Kraft papers were darker than their original colour as the tensile strength decreased. To conclude, the Kraft paper impregnated with PO had higher tensile strength compared with those impregnated with MO.

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Corresponding Author:

Imran Sutan Chairul
Faculty of Electrical Engineering, Universiti Teknikal Malaysia Melaka (UTeM)
Hang Tuah Jaya, 76100 Durian Tunggal, Melaka, Malaysia
Email: imransc@utem.edu.my

1. INTRODUCTION

Electrical power is typically generated in bulk in power plants. This generated electrical power is then transmitted to consumers via transmission lines. The transmission line voltage networks used in Peninsular Malaysia are 500, 275, and 132 kV whereas the distribution voltages vary depending on the consumer sector: i) industrial; ii) commercial; iii) residential; and iv) transportation. The corresponding voltage supply levels for these consumers are 33 kV, 11 kV, 400 V, and 230 V, respectively. The different voltage levels are achieved by using power transformers that step-up or step-down the voltage levels.

In general, there are two types of power transformers: i) dry transformers and ii) oil-immersed transformers. Like other electrical equipment, oil-immersed transformers consist of conducting materials (e.g., copper, aluminum, iron, and galvanized steel) and insulating materials (transformer oil, pressboard, and paper). Transformer oil is used as an insulating and cooling medium as well as an information carrier while paper is used to insulate the conductors between turns, windings, and phases [1]–[3]. At present, there are two types of insulating oils used in power transformers: i) petroleum-based oils and ii) vegetable-based oils. In terms of cost and environmental impact, petroleum-based oils are inexpensive and nonbiodegradable. In contrast,

vegetable-based oils are more expensive compared with mineral insulating oil (MO), but they are biodegradable [4]–[6].

The lifetime of a power transformer is dependent on its insulating media: i) liquid insulation (oil) and ii) solid insulation (paper). The oil-paper will degrade over time because of stresses (i.e., electrical, ambient, mechanical, and thermal stresses), which reduces the remnant life of the power transformer. The thermal stress acting on the oil-paper can be simulated in a laboratory via accelerated thermal aging experiments, where the type of materials (insulating oil, pressboard, paper, metal catalysts), aging parameters (temperature, period), and type of transformer (free-breathing or sealed transformer) are considered. Many thermal aging experiments have been carried out over the years, where researchers investigated different types of materials, aging parameters, and type of transformer.

Based on the authors' literature survey, the aging temperature can be between 90 to 185 °C [7]–[13], either above or below the reference hottest spot temperature of 110 °C [14]. The aging temperature affects the aging rate of the insulating paper because it is one of the factors that lead to the degradation of the insulating paper, along with the presence of oxidizing agents and moisture [15], [16]. It has been reported that the aging period varies from 504 h to the point where the degree of polymerization (DP) of the insulating paper falls below 250. The degradation of the insulating paper can be determined based on its tensile strength, DP, and furanic compounds (i.e., furfuryl alcohol, 2-acetyl furan, 2-furaldehyde, 5-hydroxymethyl-2-furaldehyde, and 5-methyl-2-furaldehyde) [15], [17], [18]. Among these measures, the tensile strength is most preferable method of assessing the degradation of the insulating paper because of its accuracy, followed by the DP, and least of all, furanic compounds.

Unlike aged oils that can be replaced with new oils, aged insulating papers cannot be easily replaced. Hence, insulating oil is used to slow down the degradation of the insulating paper, which will prolong the lifetime of the transformer. In this work, accelerated thermal aging experiments were carried out to investigate the effects of aging on the condition of different insulating oil-paper combinations.

2. RESEARCH METHOD

The preparation and characterization of samples are presented in this section. Two oil-paper combinations were prepared in this work: i) Kraft papers impregnated with MO (KP-MO) and ii) Kraft papers impregnated with PO (KP-PO). Characterization of samples are moisture content, acidity, UV-VIS absorption spectra, relative DDP, tensile strength and color.

2.1. Sample preparation

The properties of the MO and PO are tabulated in Table 1. The procedure of the thermal aging experiment is summarized in a flow chart, as shown in Figure 1. Each sample consisted of the insulating oil, Kraft paper, and metal catalysts (copper, iron, aluminum, and zinc). The MO and PO were filtered and then bubbled with nitrogen [19] to ensure that the moisture content of the oils were less than permissible limits: i) <30 ppm (MO) and ii) <200 ppm (PO). The Kraft papers were weighed to ensure that the paper strips were 1:10 of the insulating oil mass. The weights of the copper, iron, aluminum, and zinc catalysts were fixed at 0.25, 0.25, 0.05, and 0.05 g, respectively [13].

Table 1. Properties of the MO and PO

Property	MO	PO	Unit
Density	0.87	0.86	g/cm^3
Flash point	152	186	°C
Pour point	−51	−32.5	°C
Viscosity	9	5.06	mm^2/s
Breakdown voltage	60	81	kV

After weighing, the Kraft papers and metal catalysts were dried in an air-ventilated oven at 105 °C for 12 h according to the BS EN 60641 standard [20], as shown in Table 2. The drying process is essential to ensure that the weight of the Kraft papers is 0.05 wt.% less than their initial weight. Following this, the Kraft papers and metal catalysts were immersed in the insulating oils for 24 h at room temperature. Next, the accelerated thermal aging experiment was conducted using a laboratory oven set at 130 °C in the absence of air for 250, 500, and 750 h. After the aging process, the samples were taken out from the oven and left at room temperature for 24 h before measuring properties of the insulating oils (moisture content, acidity, relative content of dissolved decay products (relative DDP)) and properties of the Kraft papers (tensile strength and color).

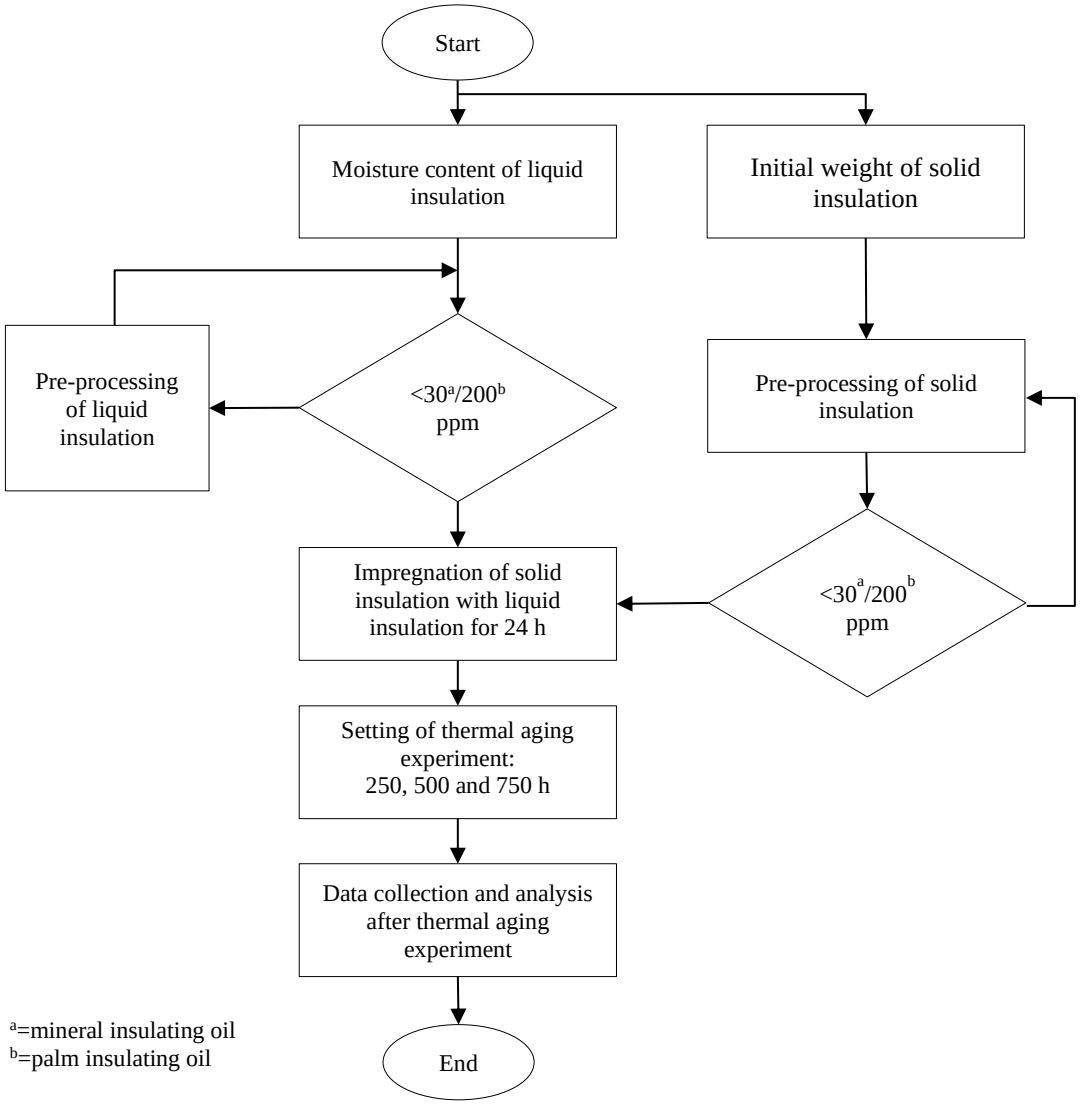


Figure 1. Flow chart of the thermal aging experiment

Table 2. Time required to dry insulating paper or pressboard according to the BS EN 60641 standard

Nominal thickness, *s* (mm)	Time, *t* (h)
$s \leq 0.5$	12
$0.5 < s < 1.5$	24
$1.5 < s < 5$	48
$s > 5$	72

2.2. Characterization

The moisture content of the insulating oil samples was determined via oxidation of sulfur dioxide by iodine in methanolic hydroxide solution using Karl Fischer coulometer (Model: 899, Metrohm AG, Switzerland) according to the ASTM D1533 standard [21]. The acidity of the insulating oil samples was measured based on the amount of potassium hydroxide (KOH) in milligrams (mg) required to neutralize hydrogen ions (H^+) in 1 g of oil sample. The acidity was measured using a compact titrator (Model: 848 Titrino plus, Metrohm AG, Switzerland) according to the ASTM D974 standard [22]. The relative DDP of the aged insulating oil samples was determined using an ultraviolet-visible (UV-Vis) spectrophotometer (Model: UV-1800, Shimadzu Corporation, Japan) [23]. The tensile strength of the Kraft papers was determined by initially placing a paper sample between two clamps: upper and lower clamps. The upper clamp was then moved upward until the paper broke and the breaking force was simultaneously measured and recorded

according to the BS 4415-1 standard [24]. Changes in the color of the aged Kraft papers were observed and compared with the original color of a new Kraft paper.

3. RESULTS AND DISCUSSION

Results on aged insulating oils and papers are presented in this section. Moisture content, acidity, UV-VIS absorption spectra, and relative DDP of the insulating oil samples are discussed. While for paper samples: tensile strength and color of the Kraft paper samples are considered.

3.1. Moisture content, acidity, and relative dissolved decay products of the insulating oil samples

Figure 2(a) shows the moisture content of the MO and PO samples thermally aged for 250, 500, and 750 h. The moisture content of the MO and PO samples increased as the aging period increased. The initial moisture content of MO was 18 ppm. After 250, 500, and 750 h of aging, the moisture content of the MO increased to 34, 42, and 105 ppm, respectively, corresponding to an increase of 89, 133, and 483%, respectively, relative to the initial value. The initial moisture content of the PO was 186 ppm. After 250, 500, and 750 h of aging, the moisture content of the PO increased to 541, 565, and 714 ppm respectively, corresponding to an increase of 191, 204, and 284%, respectively, relative to the initial value.

Figure 2(b) shows the acidity of the MO and PO samples thermally aged for 250, 500, and 750 h. In general, the acidity of both insulating oils increased after the aging process. The acidity of the MO increased to 0.0507, 0.1690, and 0.8116 mg KOH/g after 250, 500, and 750 h of aging, respectively. This indicates that the acidity increased by a factor of 1.15, 3.82, and 18.36, respectively, relative to the initial acidity of 0.0442 mg KOH/g. Likewise, the acidity of the PO increased to 0.0760, 0.2262, and 0.6652 mg KOH/g, respectively, indicating that the acidity increased by a factor of 1.52, 4.52, and 13.30, respectively, relative to the initial acidity of 0.0500 mg KOH/g.

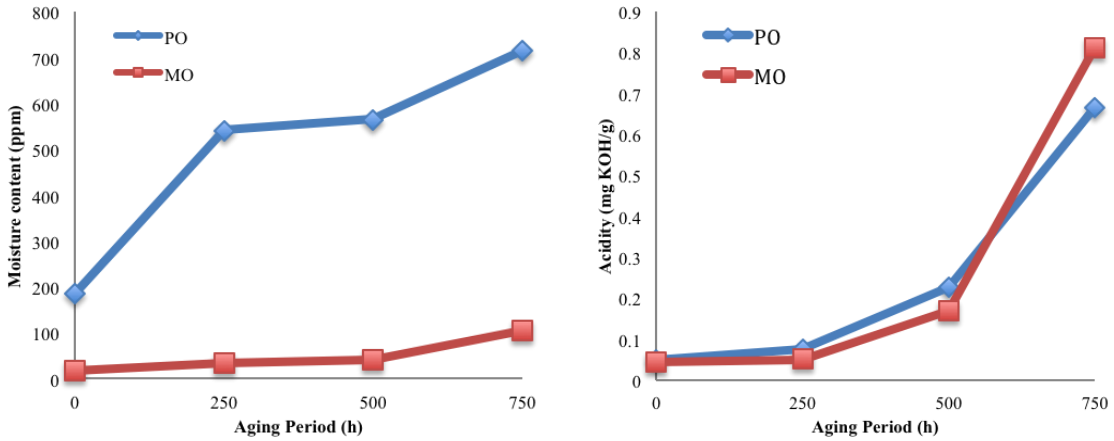


Figure 2. Variations of the (a) moisture content and (b) acidity of the MO and PO samples with respect to the aging period

The increase in the moisture content and acidity for both MO and PO samples after thermal aging is indeed expected because cellulose material (i.e., Kraft paper) subjected to heat will experience glycosidic bond scission, which opens the glucose rings. This produces free glucose molecules, carbon oxides, moisture, and organic acids [15]. Figure 3 shows the relative DDP of the aged PO and MO samples, which was determined from the area under the UV-VIS absorption spectra within the following limits: 0–4 a.u. (absorbance) and 360–600 nm (wavelength) [25]. The relative DDP of the aged PO increased from 48 a.u. to 470 a.u at 250 and 500 h respectively, indicating an increment of 879% relative to the initial value. In contrast, the relative DDP of the aged MO increased from 176 a.u. at 250 h to 710 a.u at 500 h, indicating an increment of 303% relative to the initial value. The relative DDP of the PO and MO samples at 750 h barely increased from their respective relative DDP values at 500 h. The absorbance at 450 nm and relative DDP indicate an increase in the amount of by-products produced because of the thermal aging process.

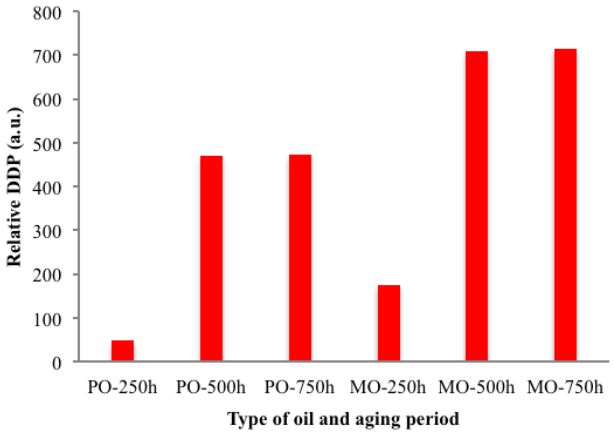
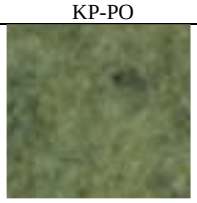
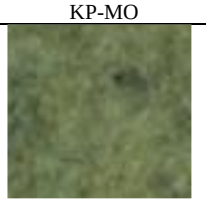


Figure 3. Relative DDP of the aged MO and PO samples

3.2. Tensile strength and color of the Kraft papers

Table 3 shows colors of kraft papers impregnated with dielectric liquids. In general, the tensile strength of the KP-MO and KP-PO samples decreased with an increase in the aging period. While Figure 4 shows the tensile strength of the Kraft papers impregnated with MO and PO and thermally aged at different aging periods.

Table 3. Color of the KP-PO and KP-MO

Aging period (h)	KP-PO	KP-MO
0		
250		
500		
750		

The tensile strength of the new Kraft paper (aging period: 0 h) was 86.485 MPa. After the Kraft papers were impregnated with different types of insulating oil and thermally aged, the tensile strength of the Kraft papers decreased. The tensile strength of KP-MO decreased to 79.984 MPa at 250 h, and the value further decreased to 55.758 and 3.546 MPa at 500 and 750 h, respectively. Likewise, the tensile strength of the KP-PO decreased to 60.148 MPa at 250 h, and the value further decreased to 40.535 and 8.779 MPa at 500 and 750 h, respectively. After 750 h of aging, the total decrease in the tensile strength was 96 and 90% for the

KP-MO and KP-PO samples, respectively, relative to the tensile strength of the new Kraft paper. Qualitatively, the Kraft papers appeared darker than their original color after aging, as shown in Table 3. The KP-MO sample was darker than the KP-MO sample at 750 h, indicating that the Kraft papers were darker than their original color with a decrease in the tensile strength. This can be explained in terms of the ability of the insulating oil to absorb moisture. In this regard, PO, which is a natural ester, has greater affinity to moisture compared with MO. Based on the results, it can be deduced that the hydrolytic degradation mechanism [15] experienced by the KP-PO samples is lesser than that of the KP-MO samples. The PO slows down the degradation of the Kraft paper, as indicated by the brighter color of the Kraft papers impregnated with PO.

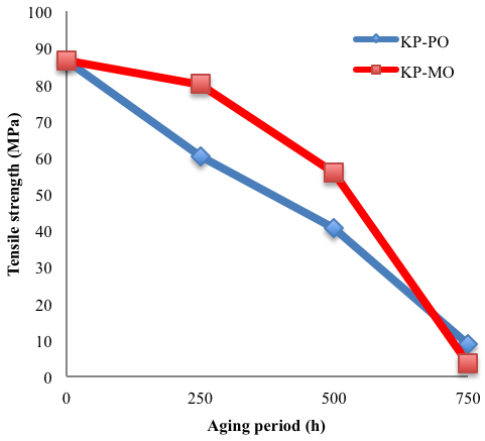


Figure 4. Variations of the tensile strength of the Kraft paper samples impregnated with PO and MO with respect to the aging period

4. CONCLUSION

In this work, the condition of two different oil-paper combinations was compared: i) KP-MO and ii) KP-PO. The Kraft papers impregnated with MO and PO were thermally aged in a laboratory oven at 130 °C for 250, 500, and 750 h. The properties of the insulating oils (moisture content, acidity, UV-VIS absorption spectra, and relative DDP) and properties of the Kraft papers (tensile strength and color) were measured after the thermal aging experiments. The results showed that the moisture content, acidity, absorbance at 450 nm of the UV-VIS absorption spectra, and relative DDP of the MO and PO samples increased with an increase in the aging period. The tensile strength of the Kraft papers impregnated with MO and Kraft papers impregnated with PO decreased with an increase in the aging period. In addition, the Kraft papers were observed to be darker than their original color as the tensile strength decreased. After 750 h of aging, the tensile strength was lower and the color was darker for the Kraft paper impregnated with MO compared with those for the Kraft paper impregnated with PO. The results indicate the condition of the Kraft paper is related to the ability of the insulating oils to absorb moisture. PO, which is a natural ester, is known to have a higher moisture absorption/saturation level compared with MO. In general, if more moisture is absorbed by the insulating oil because of its moisture saturation level, the Kraft paper impregnated in this oil will be drier. This delays the hydrolytic degradation mechanism experienced by the Kraft paper, which preserves its tensile strength and colour.

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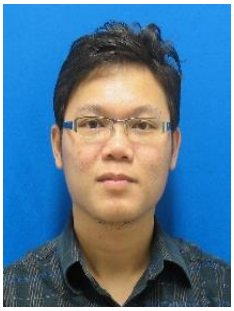
BIOGRAPHIES OF AUTHORS

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 M.Eng. degree in Electrical Engineering from Universiti Tenaga Nasional in 2012. He is currently pursuing his Ph.D. degree at UTeM, where his research is focused on vegetable-based transformer dielectric liquids. He can be contacted at email: imransc@utem.edu.my.

Norazhar Abu Bakar received his BEng. (Hons.) degree in Electronics and Electrical Engineering from Leeds University, UK, MSc. (Eng.) in Control Systems from Sheffield University, UK, and Ph.D. degree in Electrical and Computer Engineering from Curtin University, Australia. He started his career as Assembly Engineer at Toshiba Electronics, Malaysia, and then moved to TNB as SCADA/DA Project Engineer. Currently, he is the Deputy Dean (Research & Postgraduate Studies) at Faculty of Electrical Engineering, UTeM. He is a member of the High Voltage Engineering Research Laboratory in UTeM. His research interests are condition monitoring, asset management, and artificial intelligence. Since 2013, he has published several articles related to transformer condition monitoring and asset management in IEEE Transactions on Dielectrics and Electrical Insulation and IEEE Electrical Insulation Magazine. He can be contacted at email: norazhar@utem.edu.my.

Sharin Ab Ghani received his BEng. (Hons.) degree in Electrical Engineering from UTeM in 2008, M.Eng. Degree in Electrical Engineering from Universiti Tenaga Nasional in 2012, and Ph.D. degree in Electrical Engineering from Universiti Teknologi Malaysia in 2019. Currently, he is serving as Senior Lecturer at Faculty of Electrical Engineering, Universiti Teknikal Malaysia Melaka. His research interests are centered on high voltage engineering, power equipment condition monitoring, green electrical insulation, design of experiments, and optimization. To date, his outstanding research works have been published in WoS-SCI (3) and Scopus (29) indexed journals. He also has experience in consultation work with industries related to electrical installation design, transformer condition assessment, and partial discharge analysis. He can be contacted at email: sharinag@utem.edu.my.



Mohd Shahril Ahmad Khiar 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 Ph.D. 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. He can be contacted at email: mohd.shahril@utem.edu.my.

Nor Hidayah Rahim received her B.Eng. in Electrical Engineering from Universiti Teknologi Malaysia in 2008 and her M.Eng. degree in Electrical Engineering from Universiti Tenaga Nasional, Malaysia in 2012. She recently completed her Ph.D. degree at Universiti Teknologi Malaysia. She is now a Senior Lecturer at Faculty of Electrical Engineering, Universiti Teknikal Malaysia Melaka. Her research interests include high voltage engineering and dielectric materials. She can be contacted at email: hidayah.rahim@utem.edu.my.

Syahrun Nizam Md Arshad@Hashim received his B.Eng. in Electrical Engineering from Universiti Teknologi Malaysia in 2008, MEng. Degree in Electrical Engineering from Universiti Teknologi Malaysia (UTM) in 2011, and Ph.D. degree in Electrical Engineering from Universiti Putra Malaysia (UPM) in 2017. Currently, he is serving as Senior Lecturer at Faculty of Electrical Engineering Technology, UniMAP and Head of High Voltage and Transient (HVTrans) Research Group. Previously he was an Electrical Engineer at Minconsult Sdn. Bhd. and involved in many project developments. His current research interests including lightning protection system, renewable energy. He can be contacted at email: syahrun@unimap.edu.my.