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A STUDY OF MOISTURE EFFECTS ON THE BREAKDOWN VOLTAGE AND SPECTRAL CHARACTERISTICS OF MINERAL AND PALM OIL-BASED INSULATION OILS

Sharin Ab Ghani[1,2], Nor Asiah Muhamad[2], Imran Sutan Chairul[1] and Norhashidah Jamri[1]
[1]High Voltage Engineering Research Laboratory, Center for Robotics and Industrial Automation, Universiti Teknikal Malaysia Melaka, Durian Tunggal, Melaka, Malaysia
[2]Institute of High Voltage and High Current, Universiti Teknologi Malaysia, Johor Bahru, Johor, Malaysia
E-Mail: sharinag@utem.edu.my

ABSTRACT

Based on a theoretical perspective, the primary function of insulation oils is to dissipate heat, and it serves as an insulator in between turn-to-turn windings in power transformers. To date, the majority of power transformer failures is attributed to the physicochemical reaction that takes place in the insulation oils due to the presence of heat, moisture content, oxidation and electrical stresses. Knowing that moisture content is one of the factors that leads to the degradation of transformer insulation oils, the main objective of this study is to examine the effects of moisture content on the breakdown voltage and Fourier transform infrared spectral characteristics of transformer insulation oils. Two types of insulation oils are chosen for this study: (1) conventional mineral-based insulation oil and (2) palm oil-based insulation oil which is a relatively new substitute for mineral-based insulation oils in Malaysia. The effects of moisture content is investigated by varying the amount of distilled water added into the oil samples from 1 to 5 ml, with an increment of 1 ml. Breakdown voltage test is conducted six times and the mean breakdown voltage is determined for each oil sample. The spectral characteristics of the oil samples are determined by means of Fourier transform infrared spectrometry. The breakdown voltage test and Fourier transform infrared spectrometry is carried out in accordance with the MS IEC 60156:2012 and ASTM D2144 standards, ensuring the reliability of the test procedures. Based on the findings of the study, it can be concluded that moisture content has a significant effect on the breakdown voltage and spectral characteristics of mineral and palm oil-based insulation oils – however, the effect is more pronounced for the mineral oil samples. Analysis of the Fourier transform infrared spectra reveals that the chemical composition of PFAE oil samples is not significantly influenced by moisture content and thus, this oil is a promising alternative for use as insulation oil in power transformers.

Keywords: insulating oil, mineral, palm oil, breakdown voltage, fourier transform infrared spectrometry.

INTRODUCTION

Power transformers play a crucial role in power networks since they regulate the voltage levels for safe transmission and distribution of electricity from power stations to residences and commercial buildings throughout a nation. There are various types of transformers available in the power industry which include dry-type and oil-immersed transformers. In Malaysia, oil-immersed transformers are used as distribution transformers, whereby they convert electricity having a higher voltage to a lower value of 240 V (single-phase electrical power) or 415 V (three-phase electrical power). Hence, frequent breakdowns of power transformers will not only affect the daily activities of end users and businesses, but will also incur undesirable costs to energy providers due to maintenance and repair. For these reasons, it is crucial that all components of power transformers are monitored on a regular basis in order to minimize the occurrence of breakdowns. One of the essential elements of power transformers is the insulation oil which is a medium used for heat dissipation, arc quenching as well as insulation (Fofana, 2013). There are two types of insulation oils currently used in transformers, namely mineral oils and natural ester oils. Mineral oils are used in most of the transformers in Malaysia for many years. Natural ester oils, however, are produced from plant or vegetable-based derivatives. Palm oil is a type of natural ester oil that has gained importance as an alternative insulation oil for transformers (Kano *et al*., 2008; 2012).

Previous studies have shown that the main factor which leads to the failure of oil-immersed power transformers is the physicochemical reaction that takes place in the insulation oil due to the presence of heat, oxygen and moisture when the transformer is in operation (Prosr *et al*., 2010). A variety of diagnostic techniques have been used over the years to evaluate the quality and performance of transformer insulation oils in the laboratory. One of the conventional diagnostic techniques used for this purpose involves determining the following parameters: interfacial tension (IFT), dissipation factor (tan δ), water content and acidity. However, an alternative technique that can be used to assess the quality and performance of transformer insulation oils is Fourier transform infrared (FTIR) spectrometry. FTIR is a tool capable of identifying and detecting the changes in the chemical structure of the insulation oil, based on the original fingerprint of the waveform of the oil. Based on a detailed literature review conducted by the authors (though not presented in this paper), it is found that the number of studies pertaining to the the breakdown voltage (BdV) and FTIR spectral characteristics of mineral and palm oil-based insulating oils is rather limited. Knowing that moisture content is one of the factors that leads to the

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degradation of transformer insulation oils, the objective of this study is to investigate the effects of moisture content on the BdV and FTIR spectral characteristics of mineral and palm oil-based transformer insulation oils commercially available in Malaysia.

INSULATION OIL

a) Mineral and palm oil-based insulation oils

Mineral oil, also known as petroleum-based oil, is widely used in the industry as a coolant for electrical components and mechanical parts. However, mineral oil is not an electrical conductor. Mineral oil is produced from mixtures of various organic compounds whose molecules are primarily composed of carbon and hydrogen, and it can be classified into three types of crude oil: paraffinic, napthenic and mixed crude oil. The last one is basically a combination of paraffinic and napthenic crude oils. Mineral oil is widely used as an insulation oil for transformers owing to its favourable properties: (1) good resistance to oxidation, (2) good viscosity index, and (3) relatively low fire point. However, mineral oil also has a couple of disadvantages, namely: (1) low moisture tolerance and (2) susceptibility to sulphur corrosion. Vegetable oils are one of the new insulation oils which have gained importance as substitutes for conventional mineral insulation oils. Vegetable oils are scientifically known as natural esters (Martins, 2010; Oommen, 2002).

Table-1. Properties of mineral oil and PFAE oil (Kano *et al*., 2008; 2012).

Property	Mineral oil	PFAE oil
Density at 15°C [g/cm^3]	0.88	0.86
Kinetic viscosity at 40°C [mm^2/s]	8.1	5.1
Flash point [°C]	152	186
Pour point [°C]	-45	-32.5
Total acid value [mg KOH/g]	< 0.010	0.005
Moisture [ppm]	< 10	15
Relative permittivity at 80 °C	2.20	2.95
Tan δ at 80°C [%]	0.001	0.310
Volume resistivity at 80°C [Ω.cm]	7.6×10^{15}	1.9×10^{13}
Breakdown voltage (2.5 mm) [kV]	70.75	81.00

Ester is the product of a process called esterification, which involves the reaction between an acid with alcohol by the elimination of water (Tenbohlen *et al*., 2010). For instance, the esterification of fatty acid and glycerin produces fat and oil. Fatty acid is the collective term for mono-carboxylic acids, which consist of the carboxyl group (-COOH) having a variable length, but almost exclusively unbranched hydrocarbon chains. Natural esters are attractive because they are biodegradable (and thus, they have low environmental impact) and the dielectric loss of natural esters is rather low at frequencies higher than 1 kHz. However, the disadvantage of natural esters is that they have low oxidative stability (Kano *et al*., 2008; 2012). Table-1 shows the properties of mineral and palm fatty acid ester (PFAE) insulating oils.

EXPERIMENTAL TESTING

a) Breakdown voltage test

Breakdown voltage test is one of the main tests performed in the laboratory in order to assess the quality and performance of transformer insulation oils. The purpose of this test is to determine the capability of the oil to withstand electrical stresses without failure. It has been shown in a previous study that the presence of contaminants (particulates and water) in the oil will influence its BdV value (Murad *et al*., 2013). In this study, the equipment used to measure the BdV of the insulation oil samples complies with the MS IEC 60156:2012 standard. The equipment consists of two electrodes immersed in the insulation oil, in which the gap between the electrodes is fixed at 2.5 mm. The dimensions of the breakdown voltage test cell are shown in Figure-1. The breakdown voltage test is conducted six times and the mean BdV value is determined for each oil sample. It can be expected that the BdV will decrease with an increase in moisture content. According to (Naidu *et al*., 2004), the presence of 0.01% water in the transformer oil reduces its electrical strength by approximately 20%.

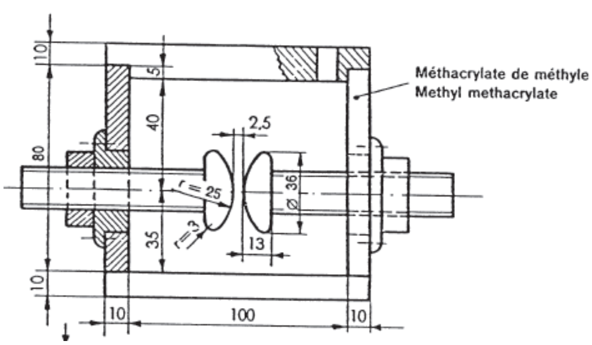

Figure-1: Dimensions of the breakdown voltage test cell which comply with the MS IEC 60156:2012 standard

b) Fourier transform infrared (FTIR) spectrometry

FTIR spectrometry is widely used in research and testing of various solid and liquid materials, and it is typically used to analyse the physical and chemical bonds of lubricants. In recent studies, a number of researchers have analysed the reaction of mineral oil under oxidation (Hadjadj *et al*., 2013) and reaction of palm oil-based insulating oil in the presence of moisture (Suleiman *et al*., 2014) using FTIR spectrometry. The American Society for Testing and Materials (ASTM) has developed two test

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standards specifically for examining electrical insulation oils by means of infrared absorption: (1) ASTM D2144-07(2013): Standard practices for examination of electrical insulating oils by infrared absorption, and (2) ASTM D2668-07(2013): Standard test method for 2,6-di-tert-butyl- p-cresol and 2,6-di-tert-butyl phenol in electrical insulating oil by infrared absorption. In FTIR spectrometry, the infrared (IR) radiation is passed through the sample. The molecular fingerprint of the sample is represented by the resultant spectrum which reveals information on the molecular absorption and transmission of radiation by the molecules in the sample. FTIR spectrometry provides information on the identity of an unknown material, and enables the analyst to determine the quality or consistency of a sample, as well as to determine the amount of components in a mixture. Figure-2 shows the basic principle of FTIR spectrometry.

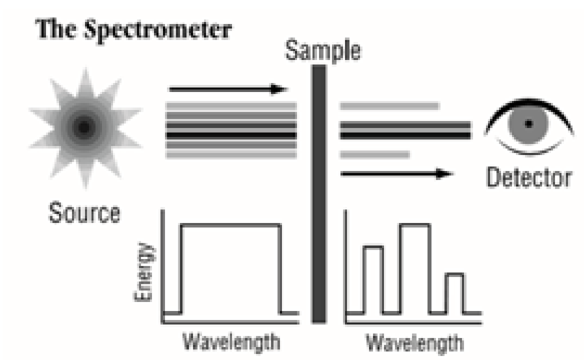

Figure-2. Basic principle of fourier transform infrared spectrometry (Thermo, 2001).

A FTIR spectrometer consists of a source, interferometer, a compartment in which the sample is placed, and a computer. The IR is emitted by the source, which is then passed through the sample via the interferometer. The radiation is detected by a detector, and an interferogram is then generated. This signal is then sent to a computer which performs Fourier transform and generates the FTIR spectrum of the sample, which is a plot of the transmittance (in %) versus the wavenumber. The operating principle of the FTIR spectrometer is illustrated in Figure-3.

FTIR spectrometers are developed in order to overcome the limitations encountered with dispersive IR spectrometers. The sample (which in this study is a solution) makes it possible to measure all of the IR frequencies simultaneously. The interferometer itself is a very simple optical device, consisting of a beam splitter, which splits the incoming IR beam into two beams with different directional paths. One beam is reflected off a flat mirror that is fixed in place (stationary mirror), whereas the other beam is reflected off a flat mirror which moves a very short distance away from the beam splitter – typically a distance of a few millimetres. This mirror is the movable mirror. These two beams are recombined when they meet again at the beam splitter. The resultant signal that exits the interferometer is known as an interferogram since the two beams 'interfere' with each other. The interferogram is unique since each data point that constitutes the signal contains information on the IR frequency emanating from the source. The interferogram is then encoded using a mathematical technique known as Fourier transform, which is carried out by the computer which enables one to easily analyse the signals.

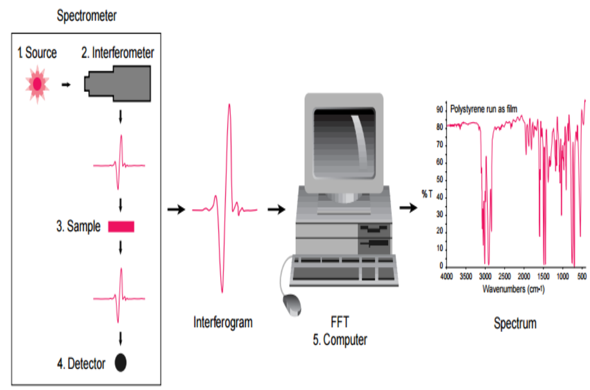

Figure-3. Operating principle of a fourier transform infrared spectrometer (Thermo, 2001).

METHODOLOGY

The methodology adopted in this study is described briefly in this section. Megger OTS60PB portable oil test set equipped with semi-spherical electrodes and capable of testing a 350 ml liquid sample is used to conduct the breakdown voltage test. JASCO FT/IR-6100 spectrometer is used to measure the FTIR spectra of the oil samples within a wavenumber range of 4000–400 cm^{-1}. The instrument is equipped with IR analyser, which is a software package that enables one to search and access reference IR spectra and thus, analyse the chemical structures of the sample under investigation. The effects of moisture content is investigated by varying the amount of distilled water added into the oil sample from 1 to 5 ml, with an increment of 1 ml (Du *et al.*, 2001). Figure-4 shows the flow chart of the methodology used in this study. The mineral inulation oil used in the experiments is Hyrax Hypertrans (uninhibited mineral oil) which is sourced from Hyrax (M) Sdn. Bhd. while the PFAE oil is sourced from Lion Corporation, Japan.

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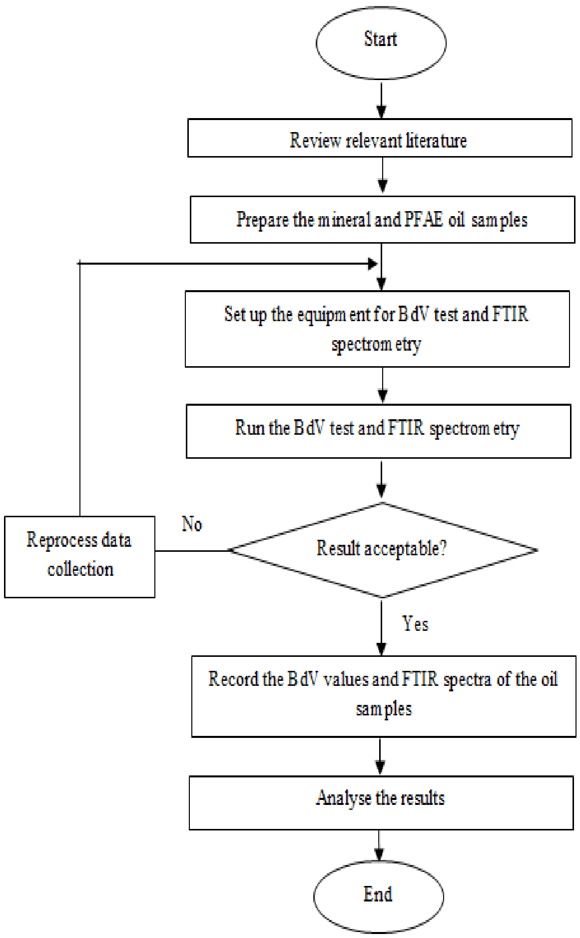

Figure-4. Flow chart of methodology used in the study.

RESULTS AND DISCUSSION

Breakdown voltage test

The results of the breakdown voltage test are presented in this section. The mean BdV values for the mineral and palm oil-based insulation oil samples with various moisture content are summarized in Table-2. Figure-5 shows the trend of the mean BdV value with respect to the moisture content for both types of oil.

Table-2. Mean breakdown voltage of the mineral and palm fatty acid ester oil samples with various moisture content.

Moisture (ml)	Mineral oil (kV)	PFAE oil (kV)
0	60	60
1	18	14
2	14	12
3	10	11
4	10	12
5	8	13

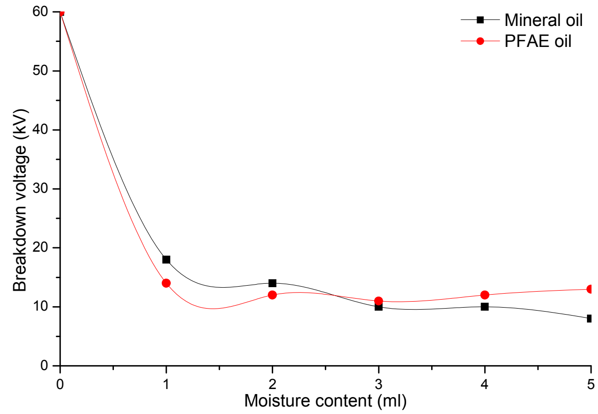

Figure-5. Trend of the mean breakdown voltage of mineral and palm fatty acid ester oil samples.

Based on the results shown in Table-2, it can be seen that the mean BdV is high for the new mineral oil sample, with a value of 60 kV, which indicates that the oil fulfils the requirement of 'good' transformer oil. However, the mean BdV decreases significantly to 18 kV upon the addition of 1 ml of distilled water, and the value decreases further to 14 kV when 2 ml of water is added into the mineral oil sample. However, it is found that the mean BdV is equal for the mineral oil samples containing 3 and 4 ml of distilled water, with a value of 10 kV. The mean BdV is the lowest upon the addition of 5 ml of distilled water, with a value of 8 kV.

It can be seen from Table-2 that the mean BdV is also high for the new PFAE oil sample (i.e. sample with zero moisture content) at constant temperature and relative humidity, whereby the value is 60 kV. Similarly, the mean BdV decreases drastically to 14 kV upon the addition of 1 ml of distilled water into the PFAE oil sample. The mean BdV value decreases further to 12 and 11 kV when the moisture content is 2 and 3 ml, respectively. Interestingly, there is a slight increase in the mean BdV upon the addition of 4 and 5 ml of distilled water into the PFAE oil sample, with a value of 12 and 13 kV, respectively.

It can be observed from Figure-5 that the mineral oil sample shows a declining trend in the mean BdV value with an increase in moisture content. Likewise, the PFAE oil sample first shows a declining trend in the mean BdV value – however, there is a slight increase in the BdV value when there is 4 and 5 ml of moisture in the oil samples. The results indicate that the presence of moisture influences the dielectric strength of both conventional mineral oil and PFAE oil – however, the effect is more pronounced for mineral oil. The minor increase in the mean BdV value observed upon the addition of 4 and 5 ml of distilled water into the PFAE oil indicates that this oil has the capability to absorb moisture from the oil to a certain extent. These results correspond to the findings of Suleiman *et al*. (2014).

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Fourier transform infrared (FTIR) spectra

According to the ASTM D2144 standard, the absorption band within a wavenumber range of 3570–3700 cm^{-1} is ascribed to carboxylic acid O-H and amide N-H stretching vibrations. Figure-6 shows that there is a change in the spectral characteristics of the mineral oil samples with an increase in moisture content, as an absorption band is detected within a wavenumber range of 3570–3700 cm^{-1}, which is attributed O-H and N-H stretching vibrations. The peak of the absorption band occurs at a wavenumber of 3621 cm^{-1}. The new mineral oil sample has a transmittance of 0.970% at 3621 cm^{-1}, as indicated by the black solid line in Figure-6. In contrast, the mineral oil sample has a transmittance of 0.940, 0.950, 0.978, 0.966 and 0.920% when the moisture content in the oil sample is 1, 2, 3, 4 and 5 ml, respectively. It is apparent that the FTIR spectrum shifts downwards with an increase of moisture content in the mineral oil.

Figure-7 shows the analysis of the FTIR spectrum for the mineral oil sample having a moisture content of 4 ml. The spectrum is analysed using the IR analyser in order to determine the compounds present in the mineral oil (in other words, the chemical composition of the oil) upon the addition of 4 ml of distilled water. The spectrum of this oil sample is compared with the selected region from the built-in compound database available in the IR analyser, as shown in Figure-7(a). Figure-7(b) shows the selected fragment structure while Figure-7(c) shows the compound present in the mineral oil sample based on its FTIR spectrum, which includes the classification of the compound, functional group, chemical bond, wavenumber range and intensity of the absorption band. Based on the spectral analysis at a wavenumber of 3615 cm^{-1} (Figure-7(a)), the compound that is present in the oil sample is water vapour (moisture) and is classified as ‘impurities’, as shown in Figure-7(c). The chemical bond is OH and the intensity of the absorption band is medium, as indicated by the letter ‘M’.

It shall be highlighted here that there are no standards available to verify which region of the FTIR spectra is indicative of the problem for palm fatty acid ester insulation oils. For this reason, the findings of Suleiman *et al*. (2014) are used as a reference to verify the FTIR spectra for the PFAE oil samples in this study. It is expected that the chemical composition of PFAE oil will be different from that for mineral oil since PFAE oil is biodegradable and thus, it does not have detrimental impact on the environment. According to Suleiman *et al*. (2014), the absorption band which appears at a wavenumber range of 1000–1250 cm^{-1} is attributed to C-OH stretching vibrations, as shown in Figure-8. The peak of the absorption band occurs at 1170 cm^{-1}. The transmittance of the new PFAE oil sample is found to be 0.520% at 1170 cm^{-1}, as indicated by the black solid line. It can be observed that the transmittance of the PFAE oil samples with a moisture content of 1, 2 and 3 ml is close to the transmittance of the new PFAE oil sample at this wavenumber, with a value of 0.526, 0.518 and 0.517%, respectively. This corresponds to a difference in transmittance of roughly 0.006, 0.002 and 0.001, respectively. In contrast, the transmittance at 1170 cm^{-1} of the PFAE oil samples with a moisture content of 4 and 5 ml differs significantly from the other four samples, with a value of 0.716 and 0.714%, respectively. It can be deduced from Figure-8 that there is a change in the chemical structure of the carboxylic acids and alcohol within a wavenumber range of 1000–1250 cm^{-1} for these two samples.

Figure-9 shows the analysis of the FTIR spectrum of the PFAE oil sample having a moisture content of 1 ml. Figure-9(a), 9(b) and 9(c) shows the spectral analysis of the sample, the selected fragment structure, and the list of compounds present in the PFAE oil sample, respectively. Based on the spectral analysis at a wavenumber of 1169.6 cm^{-1} (Figure-9(a)), the compound present in the PFAE oil sample is alcohol-IR, and the corresponding functional group and chemical bond is (R)3C-OH and C-O, respectively. The intensity of the absorption band is strong, as indicated by the letter ‘S’, as shown in Figure-9(c). The results indicate that the chemical structures of the PFAE oil are not significantly influenced by moisture content since the FTIR spectra of the PFAE oil samples (specifically those with a moisture content of 1, 2 and 3 ml) are close to that for the new PFAE oil sample. Hence, it can be deduced that PFAE oil is suitable to be use as a substitute for mineral insulation oils for two reasons: (1) the chemical-makeup of PFAE oil is not significantly influenced by moisture content, and (2) PFAE oil has the capability to absorb more moisture. Previous studies have also shown that PFAE oil is capable of absorbing moisture, ensuring that the kraft paper is always in dry condition (Suleiman *et al*., 2014; Martins, 2010).

Key findings

The key findings of this study are highlighted in this section. In general, the mean BdV of the mineral oil sample decreases with an increase in moisture content. In the FTIR spectrum of the mineral oil sample shifts downwards with an increase in moisture content, indicating that there is a change in the chemical composition of the oil, specifically within a wavenumber range of 3570–3700 cm^{-1}. In contrast, the mean BdV of the PFAE oil sample first decreases with an increase in moisture content, and then increases slightly when the moisture content is increased to 4 and 5 ml. Analysis of the FTIR spectra within a wavenumber range of 1000–1250 cm^{-1} shows that the chemical composition is the same for the PFAE oil samples with a moisture content of 1, 2 and 3 ml since the spectra are nearly coincident with each other. However, the spectrum shifts upwards when the moisture content is increased to 4 and 5 ml. Analysis of the FTIR spectra within the wavenumber range of 3570–3700 cm^{-1} reveals the presence of moisture in the new PFAE oil sample even though distilled water is not added into this sample, as shown in Figure-10. Hence, this region (3570–3700 cm^{-1}) is not suitable to determine the effects of moisture content in PFAE oil samples.

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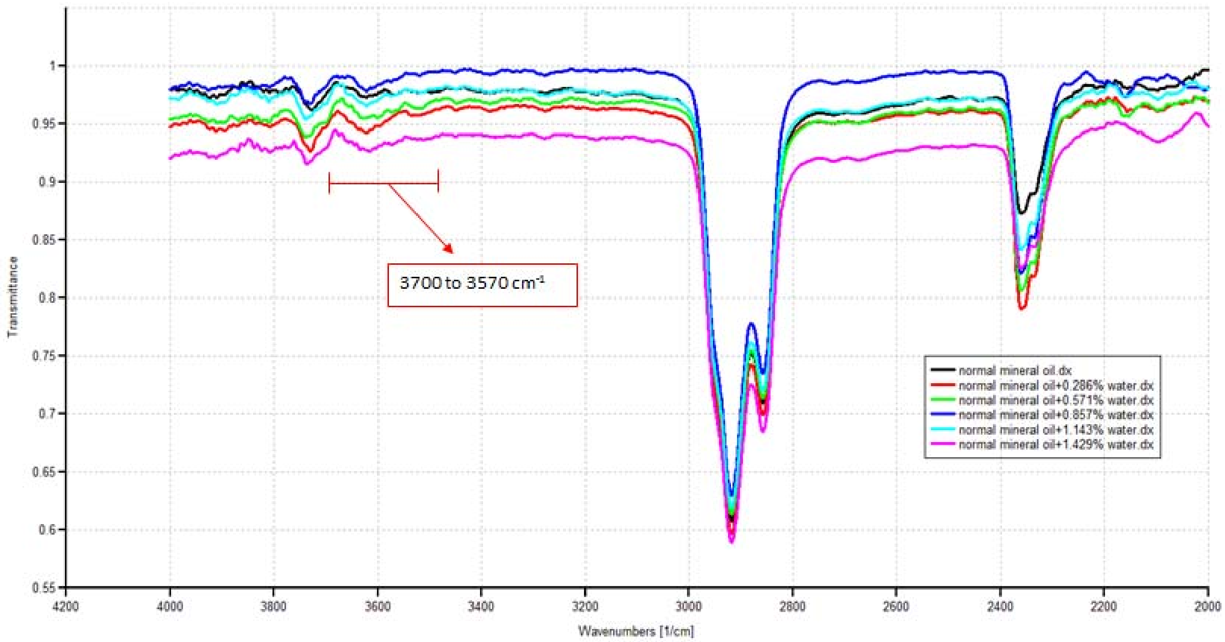

Figure-6. Fourier transform infrared spectra of the mineral oil samples, whereby the absorption band within the wavenumber range of 3570–3700 cm^{-1} is attributed to O-H and N-H stretching vibrations.

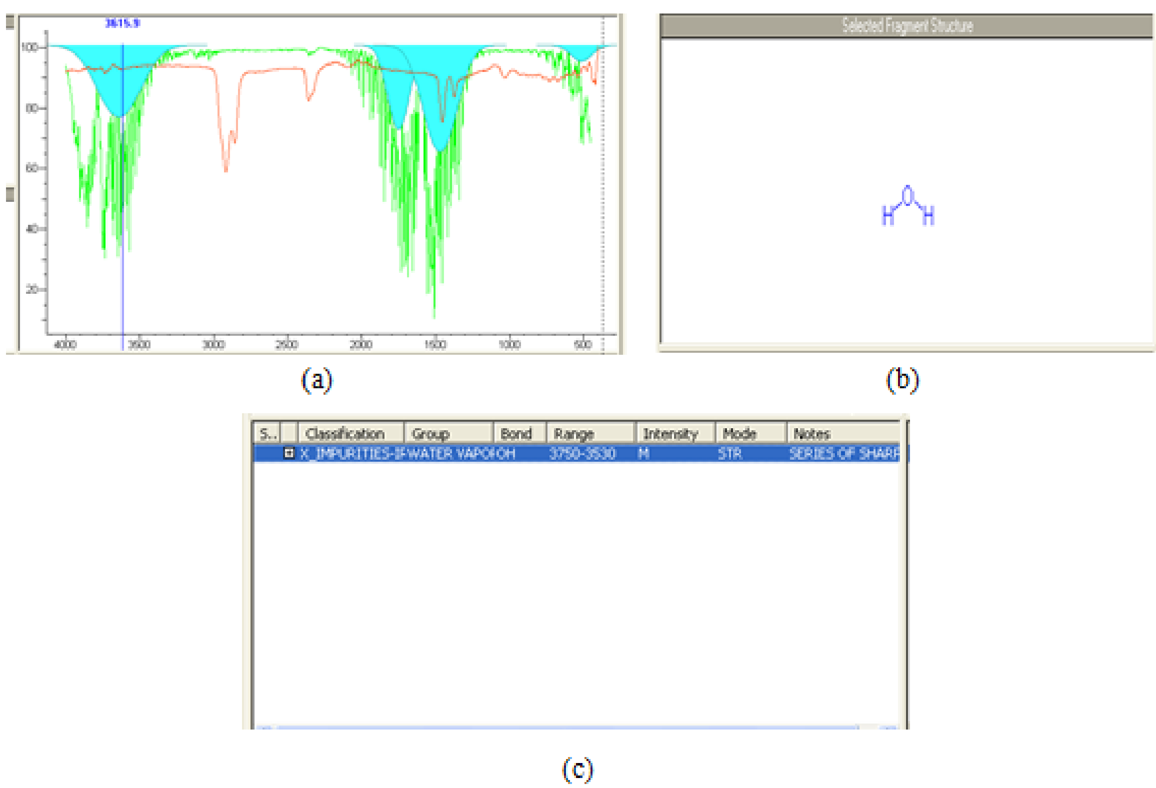

Figure-7. Analysis of the compounds present in the mineral oil sample with a moisture content of 4 ml using the IR Analyser: (a) spectral analysis (b) selected fragment structure, and (c) list of compound.

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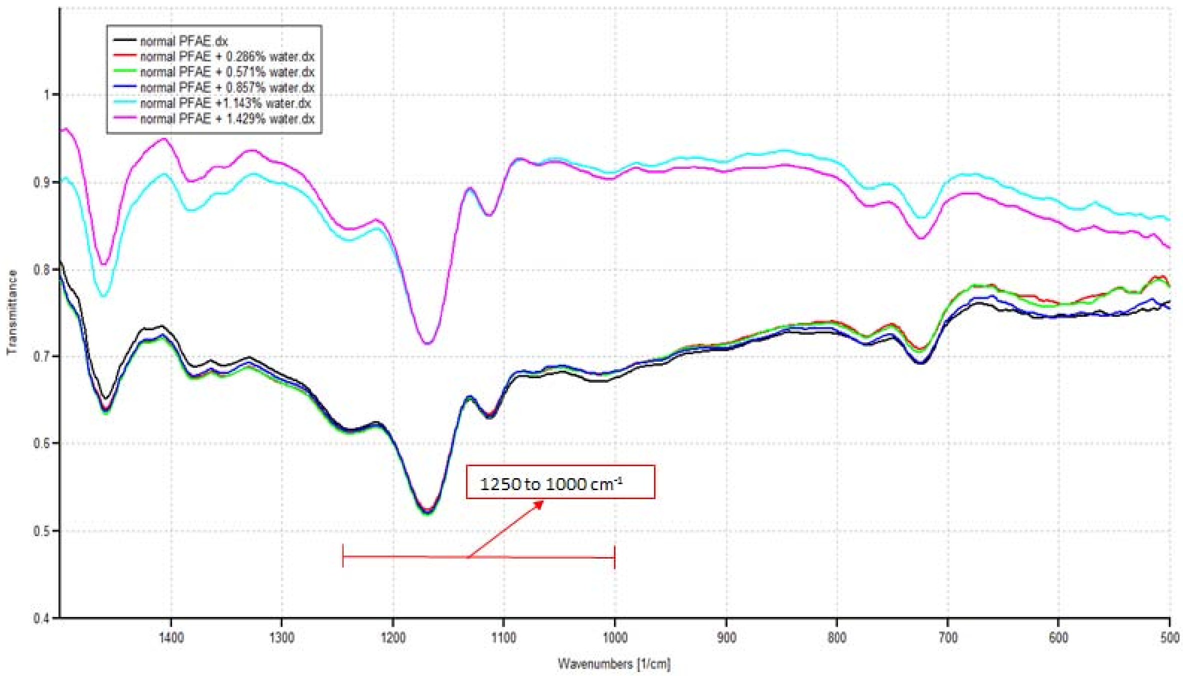
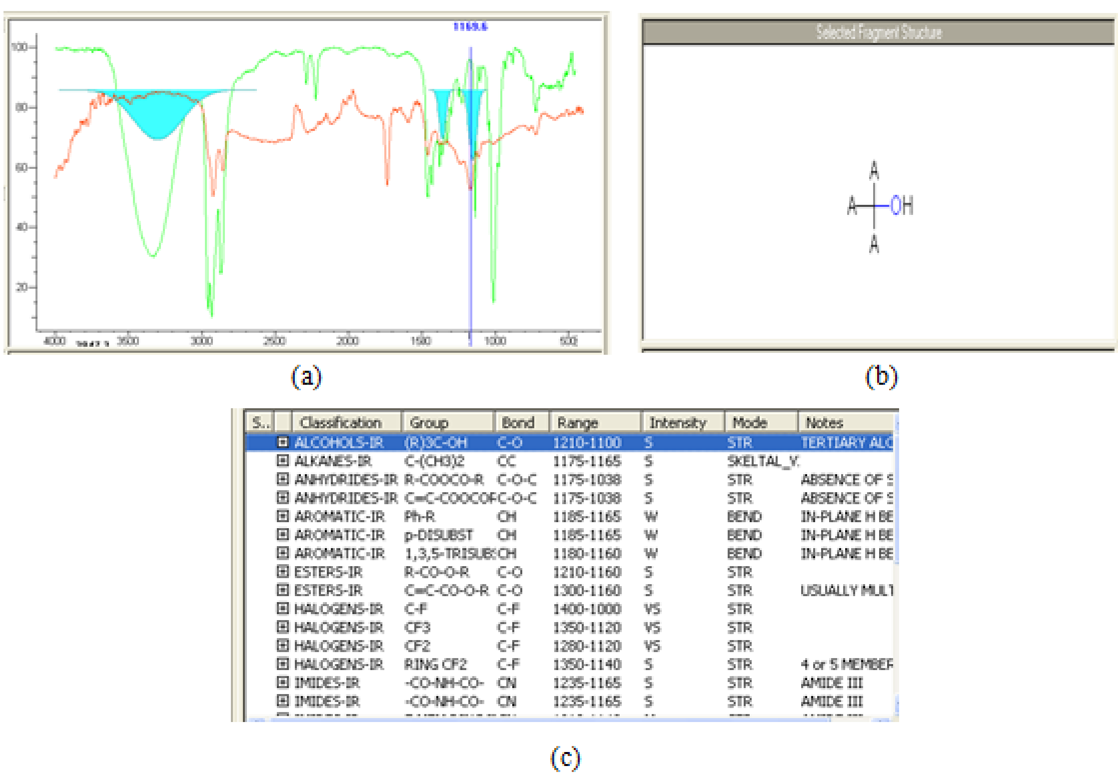


Figure-8. Fourier transform infrared spectra of the palm fatty acid ester oil samples, whereby the absorption band within the wavenumber range of 1000–1250 cm^{-1} is attributed to C-OH stretching vibrations.



S..	Classification	Group	Bond	Range	Intensity	Mode	Notes
	ALCOHOLS-IR	(R)3C-OH	C-O	1210-1100	S	STR	TERTIARY ALC
	ALKANES-IR	C-(CH3)2	CC	1175-1165	S	SKELTAL_V.	
	ANHYDRIDES-IR	R-COOCO-R	C-O-C	1175-1038	S	STR	ABSENCE OF S
	ANHYDRIDES-IR	C=C-COOCOF	C-O-C	1175-1038	S	STR	ABSENCE OF S
	AROMATIC-IR	Ph-R	CH	1185-1165	W	BEND	IN-PLANE H BE
	AROMATIC-IR	p-DISUBST	CH	1185-1165	W	BEND	IN-PLANE H BE
	AROMATIC-IR	1,3,5-TRISUB	CH	1180-1160	W	BEND	IN-PLANE H BE
	ESTERS-IR	R-CO-O-R	C-O	1210-1160	S	STR	
	ESTERS-IR	C=C-CO-O-R	C-O	1300-1160	S	STR	USUALLY MULT
	HALOGENS-IR	C-F	C-F	1400-1000	VS	STR	
	HALOGENS-IR	CF3	C-F	1350-1120	VS	STR	
	HALOGENS-IR	CF2	C-F	1280-1120	VS	STR	
	HALOGENS-IR	RING CF2	C-F	1350-1140	S	STR	4 or 5 MEMBER
	IMIDES-IR	-CO-NH-CO-	CN	1235-1165	S	STR	AMIDE III
	IMIDES-IR	-CO-NH-CO-	CN	1235-1165	S	STR	AMIDE III

Figure-9. Analysis of the compounds present in the palm fatty acid ester oil sample with a moisture content of 1 ml using the IR Analyser: (a) spectral analysis, (b) selected fragment structure and (c) list of compounds.

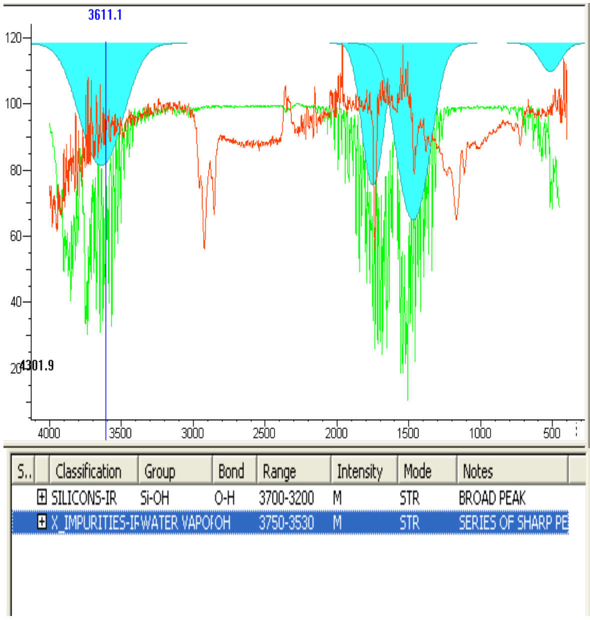


Figure-10. Analysis of the compounds present in the new palm fatty acid ester oil sample using the IR Analyser *Note that water vapour (moisture) is detected even though distilled water is not added into the sample, indicating that the wavenumber range of 3570–3700 cm^{-1} is not suitable to analyse the effects of moisture content for palm fatty acid ester oil.

CONCLUSIONS

The effects of moisture content on the breakdown voltage and FTIR spectral characteristics of mineral and palm oil-based transformer insulation oils have been investigated in this study. The moisture content of the oil samples is varied by the addition of distilled water, ranging from 1 to 5 ml. The following conclusions can be drawn based on the findings of this study. Firstly, there is an abrupt decrease in the mean BdV for both mineral and PFAE oil samples having a moisture content of 1 ml. The mean BdV decreases further as the moisture content is increased for the mineral oil samples. However, the mean BdV shows a different trend for the PFAE oil samples since the value increases slightly when the moisture content is increased to 4 and 5 ml. The breakdown voltage test results indicate that the effect of moisture content is more pronounced for mineral oil samples compared to PFAE ones. Secondly, analysis of the FTIR spectra within a wavenumber range of 3570–3700 cm^{-1} indicates that there is a change in the chemical composition of the mineral oil samples upon the addition distilled water, whereby water vapour (moisture) is detected in the oil samples. However, water vapour is detected in the new PFAE oil sample within the same wavenumber range even though it is obvious that distilled water is not added into the sample. This indicates that the chemical composition between mineral and PFAE insulation oils is inherently different. For this reason, effect of moisture content on the chemical composition of PFAE oil samples is examined at a different wavenumber range, i.e. 1000–1250 cm^{-1}, based on the findings of previous studies. Finally, it can be concluded that both breakdown voltage test and FTIR spectrometry are useful tools to determine the performance or degradation of transformer insulation oils in the presence of moisture.

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