Vegetable Oil is an Alternative Fluid to Mineral Oil Used in High Voltage Application: An Experimental Study

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Abstract— Most of the high voltage power equipments are filled with dielectric fluid (mineral oil) with a primary function to provide electrical insulation, arc quenching medium and served as a coolant. It is studied that, huge quantity of mineral oil is used for many decades in the power sector for the above purpose. Some of the certain point raised in recent research which is the major concern like biodegradability, low flash point and availability of resources in the future. To overcome the difficulties an alternative dielectric fluids (vegetable oil) are taken into consideration for replacement of mineral oil in the distribution power equipment. The Ultraviolet visible (UV-vis) spectroscopy, Fourier Transform Infrared (FTIR) spectroscopy, and Nuclear Magnetic Resonance (NMR) spectroscopy method has been used and has advantages over the conventional dissolve gas analysis (DGA) technique. However, their performance in the high voltage power transformer is yet to be established and required comprehensive analysis.

Keywords—Partial Discharge; Vegetable Oil; High Voltage; spectroscopy method

I. INTRODUCTION

The incipient faults, if not taken care at the earliest, cause the insulating transformer oil to degrade and transformer failure over a period of time [1-3]. Therefore, monitoring and diagnosing the power transformer has become an inevitable task for its effective functioning. In this work, the two vegetable oil such as soybean oil (SO) and coconut oil (CO) and another mineral oil (MO) are taken as for qualitative analysis with the optical spectroscopic techniques. In this proposed work, thermal analysis on different transformer oil samples has been performed by using optical methods such as ultraviolet-visible spectroscopy, Fourier transform infrared spectroscopy and Nuclear magnetic resonance (NMR) spectroscopy. The obtained results with UV-visible spectroscopy method exhibit proportional degradation of the oil samples with temperature rise. Fourier transform infrared spectroscopy could identify the different functional groups present in the degraded oil samples thereby detecting the dissolved gases developed due to the applied thermal stress. Finally, Nuclear magnetic resonance spectroscopy provided the picture of the hydro-carbon structure in degraded oil samples thus determining the physical and chemical information, as it concentrates at the nuclei and nuclear spins in the molecules. The employed photo spectroscopic methods can be best alternative next to so called dissolved gas analysis method. Along with spectroscopy techniques, the physical and the electrical properties of the oil samples have been inspected, i.e., refractive index and the BDV tests and the obtained results supported all the spectroscopic results in this study.

II. SAMPLE PREPERATION

Though the mineral oil, as an insulating fluid in transformer, has been in use for many decades and has been successful, the current research has raised certain concerns about its biodegradability, low flash point, and the availability of resources in the future. Having known the disadvantages of mineral oil, this proposed work has also been focused on the vegetable oils; SO and CO. The soybean and coconut samples have been prepared and aged with thermal stress of 120 °C at various time durations i.e., 100, 200, 300, and 400 hours to see the degradation. The mineral also has been considered in this study to compare the results with the vegetable oils shown in Fig. 1.

The amount of oil taken for each sample is 500 ml. all the samples have been taken in the glass vials. These glass vials have been thoroughly washed with the neutral detergent and kept in the oven for 45 minutes at 100 °C to do away with any contaminants present. All the aforementioned samples have been taken in glass vials and kept in the heat chamber at constant temperature of 120 °C at different durations.
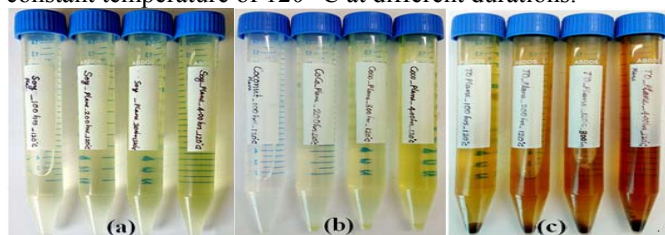

Fig. 1 Thermally-aged samples at 120 °C for 100, 200, 300, 400 hrs (a) Soybean Oil (b) Coconut Oil (c) Mineral Oil

III. EXPERIMENTAL SETUP

All the aforementioned samples have been taken in glass vials and heated at constant temperature of 120 °C in heat chamber at different durations. The aged samples are analyzed with UV-vis, FTIR and NMR spectro-photometric technique.

UV-visible spectrometry technique is an excellent tool to diagnose the health of the transformers such that the fault preventive measures can be taken thereafter [4]. The Agilent Technologies make, Model No.: Carry 100 UV-visible spectrometer is used to perform the experiment.

On the other hand the FTIR spectroscopy provides information by identifying unknown materials. In view of much technology advancements, Infrared is found to be an excellent tool for qualitative and quantitative analysis as it has greater optical throughput [5]. Fourier transform infrared (FTIR) spectrometer (Model: ALPHA, Germany, Bruker GmbH make) is used for this experiment.

Finally, the Nuclear Magnetic Resonance (NMR) spectroscopy on different oil samples has been performed with NMR spectrometer (AV 400 Avance-III 400MHz, Bruker Biospin International, Switzerland). For every 20-22 ml oil, 0.4 ml of CDCl$_3$ has been mixed and have run through the NMR spectrometer for plotting the spectra. NMR deals with the behaviour of the ^{1}H and ^{13}C in the organic compounds [6]. Since the insulating oil samples are of organic nature, the NMR is best suited to acquire the useful information such as the composition of the compound.

IV. RESULT AND DISCUSSION

The obtained results with UV-visible spectroscopy demonstrated that it could qualitatively analyzed the samples by visually showing the degradation and the peaks in all the plots have been obtained in the range 200-380 nm. On the other hand results with FTIR spectroscopy gave the various functional groups present in the soybean and coconut oil samples. Finally the NMR spectra, using the spin states of the protons in the samples, gave the chemical composition present in the samples. To verify the electrical properties of the transformer oil samples the breakdown voltage (BDV) test has been performed as per the standard [7, 8]. The BDV of SO, CO and MO samples has been found 58.6 kV, 59.6 kV and 35 kV respectively.

Considering the obtained graphs for soybean oil samples the absorbance peaks observed are 2.47, 1.87, 1.76, 0.90 at 367, 359, 353, 316 nm wavelength respectively shown in Fig. 2 (a).

The obtained results for coconut oils samples the absorbance peaks identified are 2.44, 2.01, 1.40 at 379, 371, 370 nm wavelength respectively for coconut oil shown in Fig. 2 (b). In all these results the highest absorbance is identified for 400 hour degradation, the fresh oil does not show any observable peaks. The careful investigation of these results show that the degradation is proportional to the accelerated thermal ageing and it is clearly visible in the obtained plots with UV-visible spectroscopy.

The peaks are observed at wavelengths 334, 326 nm for MO sample shown in Fig. 2 (c). The maximum absorbance in

the sample is identified at 3.48 at 334 nm wavelength which is for the 400 hour degradation, whereas the minimum absorbance is observed at 2.26 at 326 nm wavelength which is for the fresh oil.
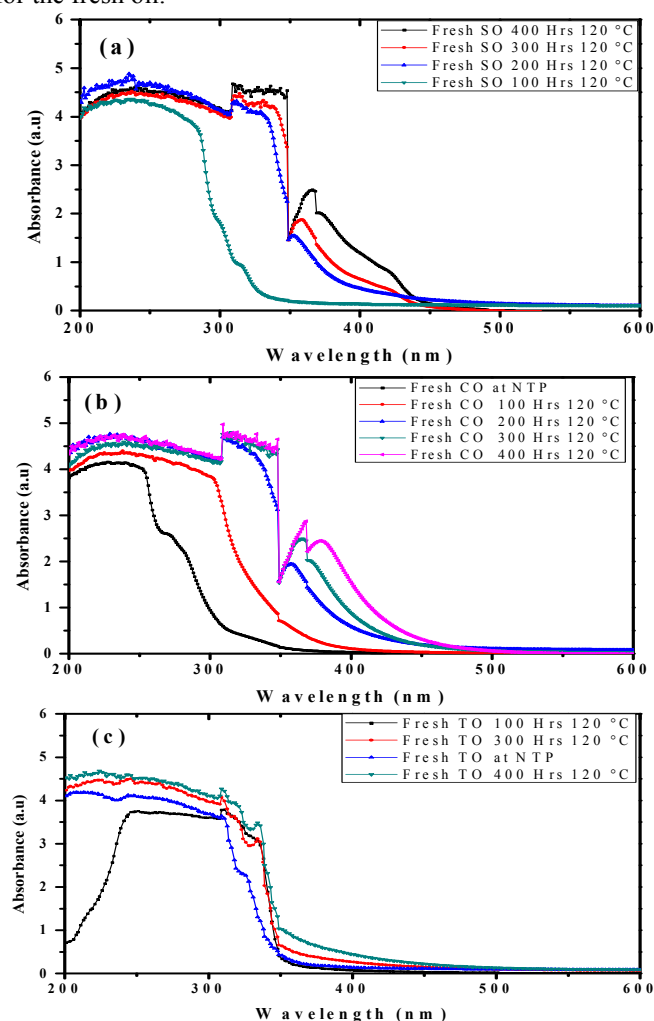

Fig. 2. UV-Visible Spectra of (a) Soybean oil (SO) (b) Coconut oil (CO) and (c) Mineral oil (MO)

All the obtained results render the correlation between the absorbance and the degradation. Moreover, transformer oil is the mixture of paraffinic, naphthenic, and aromatic compounds. Since, the paraffinic and naphthenic compounds do not absorb in UV region i.e., 200-400 nm, there are definitely aromatic compounds which are the resultant of the degraded oil samples. The maximum peak value is found for 400 hour heated oil and minimum for fresh oil or the oil with less temperature effect. The obtained result clearly exhibit the qualitative analysis.

From the plots of soybean oil samples, the transmittance peaks are observed at 721, 1097, 1159, 1236, 1377, 1461, 1742, 2852, 2922, 3008 wavenumbers as shown in Fig. 3 (a). Between 2850-3000 wavenumber, C-H alkane functional groups are identified. In particular, at 2922 and 2852 wavenumbers the alkane C-H stretch (medium or strong bonds) and carboxylic acid O-H stretch (broad and variable) functional groups are observed. The functional groups beyond 3000 and below 3100 wavenumber are of aromatic stretch =C-

H (medium) and the peak at 3008 wavenumber designates it. Further, when it comes to the peak identified at 1742 wavenumber in the IR spectra represents functional groups such as the ketone C=O stretch, ester C=O stretch, and carboxylic acid O-H stretch and these are very strong bonds. The bonds at 1097 and 1461 wavenumbers represent the C-O stretch strong functional group and alkane -C-H stretch bending and C=C functional groups respectively. Finally, the aromatic C-H bending functional groups are identified between 680-860 wavenumber i.e., at 721 wavenumber.

The spectra of the CO samples show that the peaks observed in these samples are almost same as that of the soybean oil samples excluding above 3000 wavenumbers as shown in Fig. 3 (b). The transmittance peaks at 2922 and 2852 represent the alkyl C-H stretch (medium or strong) and carboxylic O-H stretch (broad and variable) functional groups. Generally, the alkane C-H bonds are fairly ubiquitous and therefore less useful in determining the structure of the composition. The strong bonds functional groups identified at 1742 wavenumber are ketone C=O stretch, ester C=O stretch and carboxylic acid C=O stretch. The peaks at wavenumber 1463 represent the alkane –C-H bending (variable) and C=C stretch (medium, weak, and multiple bonds). Investigation also reveals that between 400-1500 cm^{-1} wavenumbers, interpretation of peaks in the fingerprint region is little complicated as number of different vibrations occur here including a wide variety of bending vibrations. Further, the functional groups between 860-680 cm^{-1} that are found at 722 wavenumber are strong aromatic C-H bending vibrations.

Finally, the Fig. 3 (c) shows the results for MO samples with FTIR spectroscopy. For transformer oil samples the transmittance peaks are observed at 722, 1375, 1457, 2852, 2922 wavenumbers. The peaks in FTIR graph represent the different chemical compounds present in the MO samples according to their vibrational energy. In the plot, the conspicuous characteristic absorptivity between 1470-1350, is observed and it shows there are functional groups of C-H alkane stretch which is fundamentally CH_3 bond stretch.

In addition, the observable peaks between 860-680 are functional groups of CH_2 bonds. The spectra also shows there are peaks between 1500-400 wavenumbers, but these peaks are intricate as far as the chemical interpretation concerned because of varied vibration between the molecular bonds of the samples which includes the wide variety of bending vibrations.

Figure 4 presents the NMR results obtained for the MO, SO and CO oil samples heated for 100 hours and 400 hours. Firstly, the results with MO show that there is clear chemical shift difference between the samples heated for 100 and 400 hours and they are shown in Fig. 4 (a) and Fig. 4 (b). From the Fig 4 (a) and 4 (b), the ^{1}H-NMR peak between 6.4 to 7.4 ppm indicating the methyl group (–CH_3) whereas, the peak at 1.281 stand for methylene group (–CH_2) that the aromatic moiety present in compounds.

The identified functionalities tend to combine and form the gases like ethane, methane, ethylene etc. which are actually the by-products of the transformer oil degradation. Basically, the identified Aromatic hydrocarbons are stable unsaturated cyclic compounds owing to chemical reactions that take place during ageing [9].
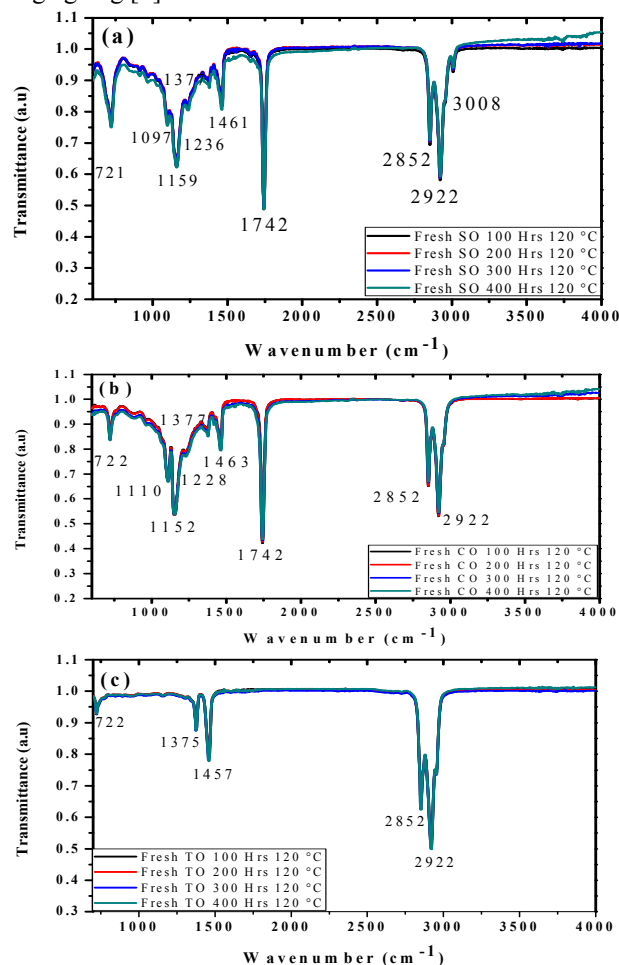

Fig. 3. FTIR Spectra of (a) Soybean oil (SO) (b) Coconut oil (CO) and (c) Mineral oil (MO)

Secondly, the SO sample NMR plot also shows that there is clear variation in the chemical shifts due to the accelerated thermal ageing. From the Figures 4 (c) and 4 (d), it is found that the peaks between 5.2 to 5.5 ppm it is corresponds for the olefin protons. Likewise, in the range 4.0 to 4.5 ppm peaks are corresponds for the -CH_2,- CH, proton nearby ester functional group (O-linked hydrogen) and 2.0 to 3.0 ppm peaks for the -CH_2 proton connected with the ester functional group (C=O -carbon linked hydrogen). Finally, in the range 0.5 to 1.8 ppm are indicating that aliphatic alkyl chain is present in the compounds.

Finally, the CO sample NMR spectra values as shown in Fig 4 (e) and 4 (f) also depict the clear variation from 100 hour ageing to 400 hour ageing. From the figures, in the range 5.4 to 5.5 ppm, the olefin protons are identified. Between 4.0 to 4.5 ppm, and also in the range 1.9 to 2.5 ppm, ester group (-O-CH_2) are confirmed. Further, the functional groups that are present in the range 0.5 to 1.6 are aliphatic protons i.e., hydrocarbon chains. In all the sample there is clear variation in the peak values as they are aged at different temperatures.
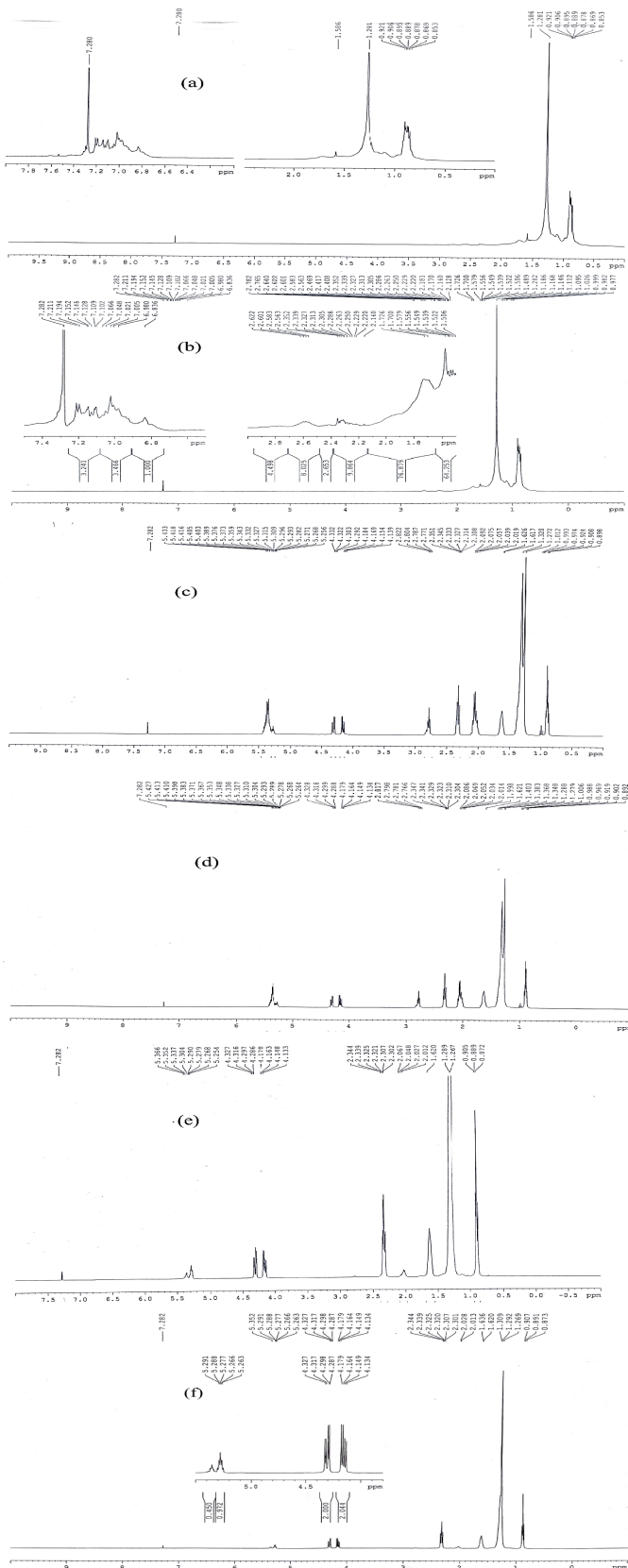
Fig. 4. NMR spectra of different oil samples (a) Mineral oil with 100 hrs degradation (b) Mineral oil with 400 hrs degradation (c) Soybean oil with 100 hrs degradation (d) Soybean oil with 400 hrs degradation (e) Coconut oil with 100 hrs degradation (f) Coconut oil with 400 hrs degradation.

V. Conclusions

The different aged oil samples such as mineral oil, soybean oil, and coconut oil samples have been characterised using various spectroscopy techniques such as UV-visible spectroscopy, FTIR spectroscopy, and NMR spectroscopy. The obtained results with UV-visible spectroscopy clearly established that as the heating period is increased, the degradation of the oil is also increased. Further, the results demonstrated that UV-visible spectroscopy could qualitatively analyse the samples by visually showing the degradation. On the other hand, FTIR spectroscopic results identified the various functional groups present in the aged oil samples along with some gases dissolved in them over a spectral range of 4000-400 cm^{-1} wavenumber. Finally, the NMR spectra, using the spin states of the protons in the samples, gave the chemical composition present in the samples.

The UV-vis method gave the qualitative analysis of the samples whereas, FTIR gave the functional groups present in the samples, and NMR provided the chemical composition in the degraded samples. Further, the procedure is also simple and could quickly analyze the samples. Therefore, as these proposed spectroscopy techniques have great optical throughput and do not cause any harm to the measuring samples, they can be alternative next to well-known DGA method.

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