Comparative study of mineral and soya bean oil at faulty temperature for transformer application

Rishabh Roy* and Srikant Prasad

Department of Electrical & Electronics Engineering, O.P Jindal University, Chhattisgarh, India

*Corresponding author’s e-mail address: rishabhroy.980@gmail.com (R. Roy)

Abstract. Mineral oil is one of the most important insulating materials used for electro insulating & cooling of transformers. For monitoring & diagnosing the incipient fault in power transformers, dissolved gas analysis (DGA) technique is used. DGA have some drawbacks such as it requires regular instrument calibration, standard carrier gas and so on. To overcome these drawbacks, Fourier transform infrared spectroscopy (FTIR) & UV-Visible spectroscopy are used to determine dissolved gas present & ageing of oil. Once the gases are quantified from the FTIR result they can be interpreted using various diagnostic methods mentioned in IEEE Std.C57.104-2008. Also, absorption spectroscopy is considered for condition assessment tool to inspect the oil. By adopting Ultraviolet absorption technique, transformer health assessment is developed: UV-Visible spectroscopy is used. As in search of solution to the harmful & ecological problems, due to non-biodegradability & toxicity by mineral oil, the soya bean seed oil was carried out for the production of transformer insulating oil. In this proposed work, we carried out results from both FTIR & UV-Vis spectroscopy for both mineral oil & soya bean oil & compared both oil by preparing samples heated at 150 °C for 24hrs & 48hrs.

1. Introduction
The transformer is very costly, indispensable, and most important equipment of any electric power system. Almost all of the large power transformers in power delivery systems around the world are still being insulated with mineral-based insulating oil [1-2]. Power transformers play an important role in the field of power transmission and distribution. But they are always under the influence of electrical, thermal, mechanical and environmental stresses. Due to these stresses, insulating oil degrades, leading the operation of the transformer to fail over a period of time. These stresses cause generation of gases from decomposition of insulating oil [3-5]. For many years the method of analysis of gases dissolved in the oil has been used as a tool in transformer diagnostics in order to detect incipient faults, to supervise suspect transformers, to test a hypothesis or explanation for the probable reasons of failures or disturbances which have already occurred and to ensure that new transformers are healthy. Dissolved gas analysis (DGA) technique is used for monitoring and diagnosing the incipient faults in power transformers. However, DGA has some drawbacks like it cannot localize the fault, no mistakes are okay while taking samples from the transformer, regular instrument calibration, cleaning of instrument after every test, maintenance cost is high, requires standard carrier gases and so on. An optical diagnostic method like Fourier transform infrared (FTIR) spectroscopy and UV-Visible spectroscopy are considered to overcome these drawbacks as they show greater ability to diagnose transformer health...
conditions [6]. FTIR spectrometer has capability to identify the C-H and C-O chemical bond [6-8]. The released gases are Hydrogen (H\textsubscript{2}), Methane (CH\textsubscript{4}), Ethane (C\textsubscript{2}H\textsubscript{6}), Ethylene (C\textsubscript{2}H\textsubscript{4}), Acetylene (C\textsubscript{2}H\textsubscript{2}), and Carbon monoxide (CO), Carbon dioxide (CO\textsubscript{2}) if cellulose also involves [7-9]. Also UV-Visible spectroscopy analysis method is proved and very much useful to be qualitative measurement of gases dissolved in transformer oil. Comparative results show that absorption spectra obtained by wavelet transmission are consistent to those with their real background and are independent of the spectrometer. Through UV-Visible Spectroscopy ageing of oil can be determined [10-12]. Oil constitutes a major component of power transformers. Conventionally, mineral or synthetic oils have been used. In an attempt to overcome some of the drawbacks with mineral oils, vegetable oil has been considered as an alternative. Used in the industry for several decades it has proved to be a viable alternative to mineral oil and has several advantages over mineral oil. As mineral oil is non- biodegradable, researchers find alternative oil for this purpose. Cooking oil can be used instead of mineral oil. Use of soya bean oil and palm kernel oil can be used as alternative to mineral oil in transformer insulation. Crude samples of these oils and their blend in varied proportions were tested for dielectric strength, pour point, flash point, kinematic viscosity, density and moisture content. The results showed that soya bean oil and palm kernel oil have good properties to act as insulating and cooling liquid in a transformer. These properties could be further improved when the oils are refined and purified [13-16]. In terms of economic costs and environmental considerations, soya bean oil and palm kernel oil appear to be viable alternatives to transformer oils. In this work, we are showing and comparing results of FTIR & UV-Visible spectroscopy for mineral and soya bean oils heated at 150 °C (faulty temperature) in the laboratory.

2. Spectroscopy method for oil analysis

Infrared (IR) spectroscopy is a very useful method for detecting the characteristic bonds of many functional groups through their absorption of infrared light. If you shine infrared light on a molecule, it is possible that the molecule absorbs energy from light. Absorbed energy can cause a bond to stretch or bend. We call that a stretching or bending vibration. These vibrations occur only at specific frequencies, which correspond to the frequency of IR light. When the frequency of IR light matches the frequency of a particular vibrational mode, the IR light is absorbed, and you can tell which frequencies are absorbed by looking at your infrared spectrum. Different kinds of bonds vibrate at different frequencies, so they absorb different frequencies of IR light, so it is possible to determine the functional groups present.

IR spectra can be divided into two main regions:

1) Diagnostic region – generally has fewer peaks and provides the clearest information. This region contains all signals that arise from all bonds in a molecule.
2) Fingerprint region – contains signals resulting from the vibrational excitation of most single bonds (stretching and bending).

Since the fingerprint region generally contains many signals and is more difficult to analyze, we can ignore it. Such spectra will be the same in the diagnostic region, but in the fingerprint region won’t. Thus this region is called a fingerprint because each compound has a unique pattern of signals in this region, much the way each person has a unique fingerprint.

![IR diagram showing Diagnostic and Fingerprint region.](image-url)
3. Ultraviolet–Visible spectroscopy

Ultraviolet-visible spectroscopy or ultraviolet-visible spectro-photometry (UV-Vis or UV/Vis) refers to absorption spectroscopy in the ultraviolet-visible spectral region. This means it uses light in the visible and adjacent (near-UV and near-infrared (NIR)) ranges. UV/Vis spectrophotometer is used in the quantitative determination of concentrations of the absorber in the solutions of transition metal ions and highly conjugated organic compounds.

![UV-Visible spectroscopy model- labindia UV 3092.](image1)

The UV-Visible spectroscopy analysis has been done on different transformer oils like in-service aged oil, laboratory aged and fresh transformer oils. The method is very much useful and proved to be qualitative measurement of gases dissolved in transformer mineral oil. Comparative results show that absorption spectra obtained by wavelet transmission are consistent to those with their real background and are independent on spectrometers.

4. Fourier transform infrared spectroscopy

FTIR spectroscopy converts raw data into the actual spectrum. It is a non-destructive technique which is used to acquire an infrared spectrum of absorption of a solid, liquid and gas by collecting spectral data in a wide spectral range. When IR radiation is passed through a collected sample, some of it is absorbed by the sample (Absorption) and some of it is transmitted (Transmission) creating a molecular fingerprint of the sample. FTIR spectroscopy provides information by identifying unknown materials. It also determines quality of a sample and amount of components. In fact FTIR identifies a fingerprint of a sample with absorption peaks that correspond to the frequency of vibrations between the bonds of molecular structure of the sample. 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. This is developed mainly to overcome the limitation with dispersive instruments. It produces a unique type of signal which encodes all the infrared frequencies into it.

![Bruker alpha-2 spectrometer.](image2)
Basic principal - Molecular bonds vibrate at various frequencies depending on the elements and the type of bonds. For any given bond, there are several specific frequencies at which it can vibrate. According to quantum mechanics, these frequencies correspond to the ground state (lowest frequency) and several excited states (higher frequencies). One way to cause the frequency of a molecular vibration to increase is to excite the bond by having it absorb light energy. For any given transition between two states the light energy (determined by the wavelength) must exactly equal the difference in the energy between the ground state and the first excited state.

5. Absorption spectroscopy

Many atoms emit or absorb visible light. In order to obtain a fine line spectrum, the atoms must be in a gas phase. This means that the substance has to be vaporized. The spectrum is studied in absorption or emission. Visible absorption spectroscopy is often combined with UV absorption spectroscopy in UV-Vis spectroscopy. According to Beer-Lambert relationship, the change in light intensity due to absorption is determined by the number of absorbing types. The Beer-Lambert relationship states that there is a logarithmic dependence between the transmission, of light through a substance and the product of the absorption coefficient of the substance, \( \alpha \), and the distance the light travels through the material i.e. the path length ‘\( l \)’.

### Table 1. The major properties of soya bean and castor bio-transformer oil compared with ASTM limits of conventional transformer oil.

| Properties          | Soya bean Bio-transformer oil | Transformer oil |
|---------------------|-------------------------------|-----------------|
| Flash point (°C)    | 250                           | 140             |
| Pour point          | -16                           | -7              |
| Viscosity(cst) at 27 °C | 7.29                         | 9.3             |
| Specific gravity at 27 °C | 0.88                         | 0.89            |
| Density (g ml⁻¹)    | 0.9404                        | 0.89            |
| Dielectric strength (KV) | 21                           | 24              |

\[
A = -\log T = \log \frac{I}{I_0} = a, c, b \quad (1)
\]

Where \( A \) is the absorbance, \( T \) is the transmittance defined as \( \frac{I}{I_0} \), \( I \) is the incident light intensity & \( I_0 \) is the transmitted light intensity, \( c \) is the concentration of the absorbing types (gm/l), \( b \) is the path length traversed by the light, \( a \) is the absorptivity of the absorbing types.

6. Experimental Setup

This experiment is carried out by UV-Visible spectroscopy and FTIR spectroscopy by taking two different types of oil namely – Mineral oil and Soya bean oil respectively and heated them at 150 °C (faulty temperature for transformer oil) for 24hrs and 48 hrs. Also, we try to mimic the internal condition of a transformer by adding copper pieces and insulation paper in them during heating. Here 4 beakers are taken and named them Beaker A, B, C, & D. Where, Beaker A- consists of 500ml of fresh mineral oil heated at 150 °C for 24hrs and 48hrs. Beaker B- consists of 500ml of fresh mineral oil + 10 gram of insulation paper + 30 gram of pure copper pieces heated at 150 °C for 24hrs and 48hrs.
Beaker A consists of 500ml of fresh mineral oil (right) & beaker B consists of 500ml of fresh mineral oil + 10 gram of insulation paper + 30 gram of pure copper pieces (left).

Beaker C- consists of 500ml of fresh soya bean oil heated at 150 °C for 24hrs and 48hrs. Beaker D- consists of 500ml of fresh soya bean oil + 10 gram of insulation paper + 30 gram of pure copper pieces heated at 150 °C for 24hrs and 48hrs.

Beaker D- consists of 500ml of fresh soya bean oil + 10 gram of insulation paper + 30 gram of pure copper pieces heated at 150 °C for 24hrs and 48hrs.

From these beakers we have taken out 15ml of oil from each of them after 24hrs and 48 hrs of heating.

Figure 4. Beaker A consists of 500ml of fresh mineral oil (right) & beaker B consists of 500ml of fresh mineral oil + 10 gram of insulation paper + 30 gram of pure copper pieces (left).

Figure 5. Beaker C consists of 500ml of fresh soya bean oil (right) & beaker D consists of 500ml of fresh soya bean oil + 10 gram of insulation paper + 30 gram of pure copper pieces (left).

Figure 6. Sample A1= fresh mineral oil heated at 150 °C for 24hrs. Sample A2= fresh soya bean oil heated at 150 °C for 24hrs. Sample A3= fresh mineral oil + 10 gram of paper + 30 gram of copper pieces heated at 150 °C for 24hrs. Sample A4= fresh soya bean oil + 10 gram of paper + 30 gram of copper pieces heated at 150 °C for 24hrs.
pieces heated at 150 °C for 24hrs.

Figure 7. Sample B1= fresh mineral oil heated at 150 °C for 48hrs.Sample B2= fresh soya bean oil heated at 150 °C for 48hrs.Sample B3= fresh mineral oil + 10gram of paper+30gram of copper pieces heated at 150 °C for 48hrs.Sample B4= fresh soya bean oil+ 10 gram of paper + 30 gram of copper pieces heated at 150 °C for 48hrs.

7. Result and its analysis
For analysis of results we follow Infrared spectroscopy table to find chemical bond in each peak. We observe only alkanes, alkynes, alkenes (CH, CH-O, C=C etc).

7.1 For FTIR Spectroscopy

Sample A1-

Figure 8. Result of Fresh mineral oil heated at 150 °C for 24 hrs.

Peaks observed and its analysis =  
At range 3000-2500 cm-1, 2950.87, 2917.43, 2849.18 = medium intensity, C-H stretching, alkane. At range 1600-1300 cm-1, 1458.30, 1375.35 = medium intensity, C-H bending, alkane, methyl group. At range 1000-650 cm-1, 721.57 = strong intensity, C=C bending, alkene, disubstituted (cis).
Sample A2-

Figure 9. Result of Fresh Soya bean oil heated at 150 °C for 24 hrs.

Peak observed and its analysis=
At range 3000-2500 cm⁻¹, 3005.08 = medium intensity, C-H stretching, alkene & 2919.22, 2849.97 = medium intensity, C-H stretching, alkane. At range 2000-1650 cm⁻¹, 1741.64 = weak intensity, C-H bending, aromatic compound, overtone. At range 1600-1300 cm⁻¹, 1460.91 = medium intensity, C-H bending, alkane, methylene group & 1375.36 = medium intensity, C-H bending, alkane, methyl group. At range 1400-1000 cm⁻¹, 1234.77 = strong intensity, C-O stretching, vinyl ether, 1158.10 = strong intensity, C-O stretching, tertiary alcohol & 1096.86 = strong intensity, C-O stretching, secondary alcohol. At range 1000-650 cm⁻¹, 965.58 = strong intensity, C=C bending, alkene, disubstituted (trans), 912.85 = strong intensity, C=C bending, alkene, monosubstituted, 721.00 = strong intensity, C=C bending, alkene, di-substituted (cis).

Sample A3-

Figure 10. Result of fresh mineral oil + 10gram of paper+30gram of copper pieces heated at 150 °C for 24hrs.
Peak observed and its analysis=
At range 4000-3000 cm\(^{-1}\), 3667.15 = strong intensity, O-H stretching, alcohol, free. At range 3000-2500 cm\(^{-1}\), 2954.54, 2920.74, 2852.99 = medium intensity, C-H stretching, alkane. At range 1600-1300 cm\(^{-1}\), 1460.18 = medium intensity, C-H bending, alkane, methylene group & 1376.29 = medium intensity, C-H bending, alkane, methyl group. At range 1000-650 cm\(^{-1}\), 722.95 = strong intensity, C=C bending, alkene, disubstituted.

**Sample A4**

![Graph](image1)

**Figure 11.** Result of fresh soya bean oil+ 10 gram of paper + 30 gram of copper pieces heated at 150 °C for 24hrs.

Peak observed and analysis =
At range 3000-2500 cm\(^{-1}\), 3005.01 = medium intensity, C-H stretching, alkene, 2919.24, 2849.95 = medium intensity, C-H stretching, alkane. At range 2000-1650 cm\(^{-1}\), 1741.55 = weak intensity, C-H bending, aromatic compound, overtone. At range 1600-1300 cm\(^{-1}\), 1459.47 = medium intensity, C-H bending, alkane, methylene group & 1375.23 = medium intensity, C-H bending, alkane, methyl group. At range 1400-1000 cm\(^{-1}\), 1234.92 = strong intensity, C-O stretching, alkyl aryl ether, 1158.07 = strong intensity, C-O stretching, tertiary alcohol & 1096.70 = strong intensity, C-O stretching, secondary alcohol. At range 1000-650 cm\(^{-1}\), 965.51 = strong intensity, C=C bending, alkene, monosubstituted & 720.90 = strong intensity, C=C bending, alkene, disubstituted (cis).

**Sample B1**

![Graph](image2)

**Figure 12.** Result of fresh mineral oil heated at 150 °C for 48hrs.
Peak observed and analysis =  
At range 3000-2500 cm\(^{-1}\), 2951.01, 2917.34, 2849.29 = medium intensity, C-H stretching, alkane. At range 1600-1300 cm\(^{-1}\), 1458.88 = medium intensity, C-H bending, alkane, methylene group & 1375.41 = medium intensity, C-H bending, alkane, methyl group. At range 1000-650 cm\(^{-1}\), 721.79 = strong intensity, C=C bending, alkene, disubstituted (cis).

**Sample B2**

![Image](image1.png)

**Figure 13.** Result of fresh soya bean oil heated at 150 °C for 48hrs.

Peak observed and analysis =  
At range 3000-2500 cm\(^{-1}\), 3004.90 = medium intensity, C-H stretching, alkene & 2919.32, 2849.92 = medium intensity, C-H stretching, alkane. At range 2000-1650 cm\(^{-1}\), 1741.52 = C-H bending, aromatic compound, overtone. At range 1600-1300 cm\(^{-1}\), 1459.54 = medium intensity, C-H bending, alkane, methylene group & 1375.98 = medium intensity, C-H bending, alkane, methyl group. At range 1400-1000 cm\(^{-1}\), 1235.53 = strong intensity, C-O stretching, alkyl aryl ether, 1157.98 = strong intensity, C-O stretching, tertiary alcohol & 1096.95 = strong intensity, C-O stretching, secondary alcohol. At range 1000-650 cm\(^{-1}\), 965.68 = strong intensity, C=C bending, alkene, disubstituted (trans) & 720.68 = strong intensity, C=C bending, alkene, disubstituted (cis).

**Sample B3**

![Image](image2.png)

**Figure 14.** Result of fresh mineral oil + 10gram of paper+30gram of copper pieces heated at 150 °C for 48hrs.
At range 3000-2500 cm\(^{-1}\), 2950.87, 2917.58, 2849.21 = medium intensity, C-H stretching, alkane. At range 1600-1300 cm\(^{-1}\), 1512.07 = strong intensity, N-O stretching, nitro compound, 1460.17 = medium intensity, C-H bending, alkane, methylene group & 1375.48 = medium intensity, C-H bending, alkane, methyl group. At range 1000-650 cm\(^{-1}\), 721.08 = strong intensity, C=C bending, alkene, disubstituted (cis).

**Sample B4**

*Figure 15.* Result of fresh soya bean oil + 10 gram of paper + 30 gram of copper pieces heated at 150 \(^\circ\)C for 48hrs.

Peak observed and analysis =

- At range 3000-2500 cm\(^{-1}\), 3004.92 = medium intensity, C-H stretching, alkene, 2919.25 = medium intensity, C-H stretching, alkane & 2849.92 = medium intensity, C-H stretching, alkane. At range 2000-1650 cm\(^{-1}\), 1741.46 = weak intensity, C-H bending, aromatic compound, overtone. At range 1600-1300 cm\(^{-1}\), 1459.94 = medium intensity, C-H bending, alkane, methylene group & 1375.39 = medium intensity, C-H bending, alkane, methyl group. At range 1400-1000 cm\(^{-1}\), 1235.05 = strong intensity, C-O stretching, alkyl aryl ether, 1157.99 = strong intensity, C-O stretching, tertiary alcohol & 1096.69 = strong intensity, C-O stretching, secondary alcohol. At range 1000-650 cm\(^{-1}\), 965.72 = strong, C=C bending, alkene, monosubstituted, 912.15 = strong, C=C bending, alkene, monosubstituted & 720.65 = strong, C=C bending, alkene, disubstituted (cis).

7.2 For UV-Visible spectroscopy

**Sample A1**

*Figure 16.* Result of fresh mineral oil heated at 150 \(^\circ\)C for 24hrs

Peak observed at 318 nm.
Sample A2

Figure 17. Result of fresh mineral oil heated at 150 °C for 24hrs.

Peak observed at 339 nm.

Sample A3-

Figure 18. Result of fresh mineral oil + 10 gram of paper + 30 gram of copper pieces heated at 150 °C for 24hrs.

Peak observed at 319.5 nm.

Sample A4-

Figure 19. Report of fresh soya bean oil + 10 gram of paper + 30 gram of copper pieces heated at 150 °C for 24hrs.

Peak observed at 347.5 nm.
Sample B1-

Figure 20. Result of fresh mineral oil heated at 150 °C for 48hrs.

Peak observed at 319.5 nm

Sample B2-

Figure 21. Report of fresh soya bean oil heated at 150 °C for 48hrs.

Peak observed at 341 nm.

Sample B3-

Figure 22. Report of fresh mineral oil + 10gram of paper+30gram of copper pieces heated at 150 °C for 48hrs.
Peak observed at 332.5 nm.

Sample B4-

**Figure 23.** Result of fresh soya bean oil+ 10 gram of paper + 30 gram of copper pieces heated at 150 °C for 48hrs.

Peak observed at 361nm.

**Comparison graph =**

1) All mineral oil samples

**Figure 24.** Comparison graph of all mineral oil samples.

2) All soya bean oil samples

**Figure 25.** Comparison graph of all soya bean oil samples.
8. Conclusion
FTIR Spectroscopy Gases formed in insulating oils in a transformer due thermal and electrical stresses are H2 (Hydrogen), CH4 (Methane), C2H2 (Acetylene), C2H4 (Ethylene), C2H6 (Ethane), CO (Carbon monoxide), CO2 (Carbon dioxide).
As we know FTIR spectroscopy shows excellent diagnostic capability to identify the C-H and C-O chemical bond [6]. Due to various stresses, gases formed shows incipient faults, to find out the gases quantitatively as well as qualitatively IR spectroscopy is used. From the result analysis we observed:-

| Table 2. Peak observed by FTIR at different range by different oil. |
|---------------------------------------------------------------|
| Different oils | Peak observed(cm\(^{-1}\)) at range | Heating time |
| Mineral oil | 4000-3000, 3000-2500, 1600-1300, 1000-650 | 24hrs |
| Mineral oil | 3000-2500, 1600-1300, 1000-650 | 48hrs |
| Soya bean oil | 3000-2500, 2000-1650, 1600-1300, 1400-1000, 1000-650 | 24hrs |
| Soya bean oil | 3000-2500, 2000-1650, 1600-1300, 1400,1000, 1000-650 | 48hrs |

Once gases are quantified, the quantified gases can be further interpreted using various no of diagnostic method in IEEE Std. C57.104-2008 [6]. From the analysis of obtained results we can clearly see the transmittance of IR at different wavelength by sample oils. That shows amount of gases releases in both soya bean and mineral oil samples which were heated at different time period, the degradation of oil takes place. From the analysis FTIR results of different samples of oil we see that soya bean oil transmit/absorb more shows higher level of gases release.

UV-Visible spectroscopy
Main aim for any absorption spectroscopy is to obtained and measure how well a sample absorbs light at each wavelength. Many monochromatic beam of light of different wavelength passes through samples repeatedly to observe how light is absorbed by sample in a UV-Visible spectrometer. In this work, UV-Vis spectrometer is used to determine the decomposition and ageing of two different kind of oil in different condition and heated at different time period. Here we can see that absorption take place in between 300nm to 370nm wavelength. Below table shows different oil’s absorption in different time period. In the region 300 to 320 nm wavelength which means decomposition of oil takes place. For mix mineral oil samples for 24hrs and 48 hrs is 319.5 nm and 332.5 nm which means absorb value increase than the mineral oil samples, and also as time increases the decomposition of oil is more.
Table 3. Observed results in UV-Visible spectroscopy for different samples.

| Sample Oil | Peak observed at wavelength (nm) for 24 hrs | Peak observed at wavelength (nm) for 48 hrs |
|------------|---------------------------------------------|---------------------------------------------|
| Mineral oil 500ml heated at 150 °C. | 318 | 319.5 |
| Mineral oil 500 ml + 10 gram of paper + 30 gram of copper pieces. | 319.5 | 332.5 |
| Soya bean oil 500 ml heated at 150°C. | 339 | 341 |
| Soya bean + 10 gram of paper + 30 gram of copper pieces | 347 | 361 |

As compared to mineral oil samples, soya bean oil shows more absorption which means decomposition of oil is more than mineral oil. From the above results we clearly see that for 24 hrs and 48 hrs heated fresh soya bean oil shows peaks at 340 nm and 339 nm. Where for mix soya bean oil for 24hrs and 48hrs shows absorption peak at 347 nm and 361 nm, by which we can say that decomposition of these sample gets higher due to increment of time period. From the comparison graph of fig no-24 and fig no 25 we clearly see the differences. As UV-Visible spectroscopy gives the clear results, it can be used as a tool for investigating the Transformer oil for its deterioration and ageing due to electrical and thermal stresses [9].

Hence, Bio transformer oil is made for actual use of soya bean oil in transformer by adding solvent to refined soya bean oil [12].

References
[1] Palmer J A, Wang X, Shoureshi R A, Mander A, Torgerson D and Rich C 2000 Effect of aging on the spectral response of transformer oil Conference Record of the 2000 IEEE International Symposium on Electrical Insulation. p 460-464
[2] Suleiman A A, Mohamad N A B, Alghamdi A S and Aizam M 2012 Improving Accuracy of DGA Interpretation of Oil-filled Power Transformers Needed for Effective Condition Monitoring 2012 IEEE International Conference on Condition Monitoring and Diagnosis. A 374
[3] Gray I A R 2005 Transformer, A GUIDE TO TRANSFORMER OIL ANALYSIS.
[4] Skelly D 2012 Photo-acoustic spectroscopy for dissolved gas analysis: Benefits and Experience 2012 IEEE International Conference on Condition Monitoring and Diagnosis. pp. 29-43
[5] IEEE Std. C57.104 IEEE 2008 Guide for the Interpretation of Gases Generated in Oil -Immersed Transformers.
[6] Hussain K and Karmakar S 2015 Incipient Fault Diagnosis in Oil-filled Power Transformers using Fourier Transform Infrared Spectroscopy. International Conference on High Voltage Engineering and Technology (ICHVET-2015) 9654 p 29
[7] Tang X, Wang W, Zhang X, Wang E and Li X 2018 Energies 11 3192
[8] Meena R R, Chaki S, Khimani A J and Deshpande M P 2018 Petroleum and Coal 60 872
[9] Hussain K and Subrata Karmakar 2014 Condition Assessment of Transformer Oil using UV-Visible Spectroscopy, In 2014 Eighteenth National Power Systems Conference (NPSC), p 1-5. IEEE
[10] Thakur N and Rahi O P 2011 International Journal of Electronics Signals and Systems. 1 134
[11] Karthik R, Raja T S R and Shunmugam S S 2014 Acta Scientiarum Technology. 36 245
[12] Zhang W, Li N, Feng Y, Su S, Li T and Liang B 2015 Food Chem. 2015. 185 326
[13] Egbuna C N 2016 International Journal of Engineering Sciences and Research Technology. 5
105

[14] Ursula Biermann and Jürgen O. Metzger 2013 Application of Vegetable Oil-Based Fluids as Transformer Oil, Oleo chemicals under Changing Global Conditions *International Journal of Engineering Research & Technology (IJERT)*. 2 1

[15] Rycroft M 2014 *Energize* 4 37

[16] Bandara K, Ekanayake C, Saha T and Ma H 2016 *Energies* 9 258

[17] M. A. Usman, O. O. Olanipekun and U. T. Henshaw 2012 *Journal of Emerging Trends in Engineering and Applied Sciences* 3 33