Characterizing Inhibitor Content of Transformer Oil in the UV-Visible Waveband

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***Abstract*—Over the years, transformer oil has been used in majority of the power transformers to provide a reliable insulating system that is effective against dielectric stresses. Oxidation often occurred in transformer oil in the presence of oxygen and moisture which will affect the stability and insulating properties of the oil. The oxidation process cannot be eliminated but it can be delayed with the presence of inhibitor content. Even though inhibitor content can reduce the oxidation rate, the amount of inhibitor content still depletes over time. Thus, a monitoring system to detect the inhibitor content concentration is very crucial as it will be able to prolong the life span of the transformer. This paper focuses on the optical characterization of inhibitor content in transformer oil by utilizing the ultraviolet-visible (UV-Vis) spectroscopy technique. It was found that oil samples with inhibitor content produce multiple absorbance peaks in the range of 350 nm to 500 nm. A clear difference in peak absorbance near 450 nm indicates the difference in the inhibitor content concentrations. Based on the results of this work, a portable and low cost optical sensing device can potentially be developed for the detection of inhibitor content in transformer oil using UV-Vis spectroscopy.**

Keywords—Inhibitor; Transformer Oil; Power Transformers; Visible spectroscopy

I. INTRODUCTION

A reliable insulation system is very important to the modern power transformers. The insulation system of a power transformer generally consists of transformer oil and insulating paper [1]. During the operation of power transformers, insulating materials are subjected to continuous thermal, and electrical stresses [2], thus degrading the materials and producing polar compounds and oil sludge [3]. Internal insulation failures are considered as the most serious and costly problem for power transformers [4]. Therefore, monitoring the condition of the transformer oil is important as to detect any early signs of fault so that catastrophic failures can be avoided.

The cause of transformer oil degradation is generally due to the oxidation in the presence of oxygen and moisture [1]. Thus, one of the key characteristics for transformer oil is the oxidation stability. Inhibitor content is added into transformer oil to neutralize peroxy radicals responsible in the formation of oxidation by-products [5], resulting in a longer service life of transformer oil [3]. Conventionally, 2,6-ditertiarybutyl-para-cresol (DBPC) is the most commonly used inhibitor as it is approved universally as a highly desirable antioxidant material with excellent properties [6]. However, the amount of inhibitor content depletes over time, and once the inhibitor is used up, the oxidation rate increases and it furthers degrades the oil. Therefore, the monitoring of inhibitor content in transformer oil is crucial.

The optical sensing method has gained increasing interest recently as it is a noninvasive method of checking the oil condition. This monitoring method has been proposed on various conditions such as interfacial tension (IFT) [7], furan content [8], and dissolved gases [9]. For inhibitor content, Percherancier et al. [10] has proposed to use Fourier transformed infrared (FTIR) spectroscopy to detect inhibitor content, specifically DBPC, by measuring the spectrum of the inhibitor content and then performed a quantitative analysis based on the spectrums obtained. IEC 60666 [11] and ASTM D2668-07 [12] were then developed to determine DBPC in transformer oil using FTIR spectroscopy. It was determined that the major absorption band of the inhibitor content is at a wavenumber of 3650 cm^{-1} due to the phenolic OH stretch [10-12]. This method of measurement is currently used to determine the concentration of inhibitor content in transformer oil. However, the method involves expensive equipment, which requires yearly maintenance. The measurements can only be conducted in a laboratory environment since it involves sample preparation and the instrument is large in size. To solve this problem, Hontert [13] has developed a portable infrared analyzer such that measurement can be carried out on-site to determine the concentration of inhibitor content without the need of transporting the oil sample to a laboratory for test.

Furthermore, it is noted that the phenolic OH stretch also has vibration overtone bands in the near-infrared (NIR) region. By investigating crystalline phenol using conventional and photoacoustic spectroscopy, Ishiuchi et al. [14] reported that peaks at wavenumbers of 7143 cm^{-1} , 10461 cm^{-1} and 13612 cm^{-1} are assigned to the first, second and third OH stretch overtones respectively. Authors of this work have done an investigation of

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inhibitor content in transformer oil using optical detection in the NIR region [15]. We reported that an absorption peak can also be seen at a wavelength of 1403 nm (equivalent to wavenumber of 7127 cm^{-1}) if inhibitor content is present in the transformer oil. The absorbance peak belongs to the first OH stretch overtones for DBPC. However there are other OH stretch overtones that can be investigated and these optical absorbance peaks can be useful for easier and cheaper detection of DBPC in transformer oil. Therefore, this paper investigates the optical characterization of inhibitor content in the UV-Vis region.

II. Experimental Details and Results

A. Methodology

Transformer oil samples were collected from different in-service power transformers with different life span. The color index of the oil and the inhibitor content concentration were measured in a laboratory using color comparator in accordance to ASTM D1500 [16] and FTIR spectroscopy in accordance to IEC 60666 [11] respectively. The oil samples were then optically characterized using the Agilent Cary 5000 spectrophotometer. The Cary 5000 is a laboratory-based double beam UV-Vis-NIR spectrophotometer. The general concept of double-beam spectroscopy experimental setup is shown in Figure 1.

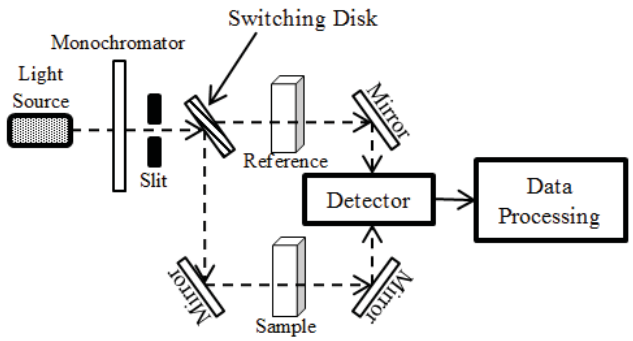

Fig. 1. Basic experimental setup for double-beam spectrophotometer.

Generally, radiation from the light source passes first through a monochromator and slit so that only a narrow band of wavelength of light beam passes through. The light beam is then focused on a switching disk where it switches between three distinct positions. One position allows the light beam to pass through, striking the 1 cm path-length quartz cuvette containing the reference sample, and then reaches the detector for measurement. The switching disk then switches to the second position which has a mirror surface, where light beam is reflected 90 degree, and then strikes the sample in the 1 cm path-length quartz cuvette. Lastly, the switching disk switches to the third position where it has a black surface, thus no light beam can pass through. This is done to ensure that the instrument measures the dark current, so that background noise can be subtracted from the overall measurement. By applying the Beer-Lambert's Law [17] as shown in (1), the absorbance value of the measured spectral response was calculated.

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$$Abs = -\log_{10}(S_\lambda - B_\lambda / R_\lambda - B_\lambda) = \varepsilon_\lambda \cdot c \cdot l \quad (1)$$

where, Abs is the absorbance, S_λ is the transmittance of light passing through the sample in sampling slot, R_λ is the transmittance of light passing through the sample in reference slot, B_λ is the baseline, ε_λ is the absorbance coefficient of the absorbing sample at a certain wavelength, c is the concentration of the absorbing sample, and l is the path length traversed by the light.

B. Results

The collected oil samples were measured in the visible range from 300 nm to 700 nm to obtain their respective absorbance spectral response. Figure 2 shows the absorbance spectral response of several samples with their details summarized in Table I.

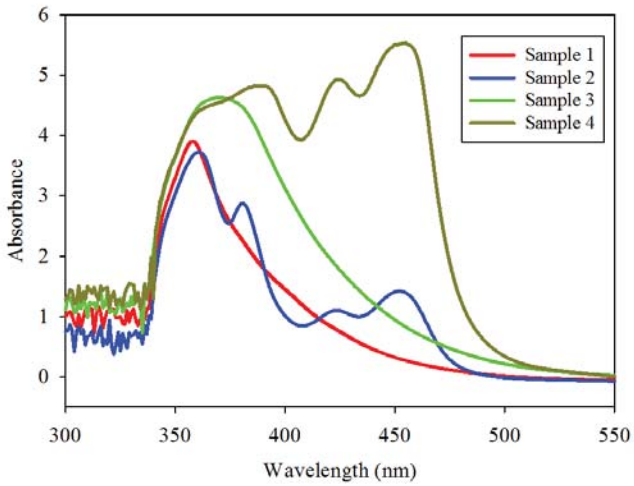

Fig. 2. Absorbance spectral response of 4 transformer oil samples.

TABLE I. Details of Oil Samples

Sample	*Color Index*	*Inhibitor Content Concentration (%)*
Sample 1	1.5	0.0
Sample 2	1.5	0.23
Sample 3	2.5	0.0
Sample 4	2.5	0.33

It is noted that the inhibitor content concentration is measured in terms of weight percent, where it is derived as the ratio of the weight of inhibitor content to the sum of weight of the oil sample and inhibitor content. Spectrum of 4 oil samples are chosen for Figure 2 to visualise the distinct difference in curve.

III. Discussions

From our previous reported work [18], it was clearly demonstrated that there was a clear correlation between the color index of the oil samples and their spectral response in the UV-Vis waveband. However, based on Figure 2, it is clear that even though oil samples have the same color index, it produced

different absorbance spectrum. After carry out a thorough investigation and analysis, it was established that this difference is due to the presence of inhibitor content in the oil samples. The results suggest that the absorbance spectral response for Samples 2 and 4 contain two pieces of information, which are the color index and inhibitor content concentration, while the spectra of Samples 1 and 3 only contain the information on color index. Subtraction was applied between the two plots (Sample 2 with Sample 1, and Sample 4 with Sample 3), since samples 1 and 2 are having the same color index of 1.5, and samples 3 and 4 are having the same color index of 2.5. The resulting plot shall carry only the information on the inhibitor content concentration, as shown in Figure 3.

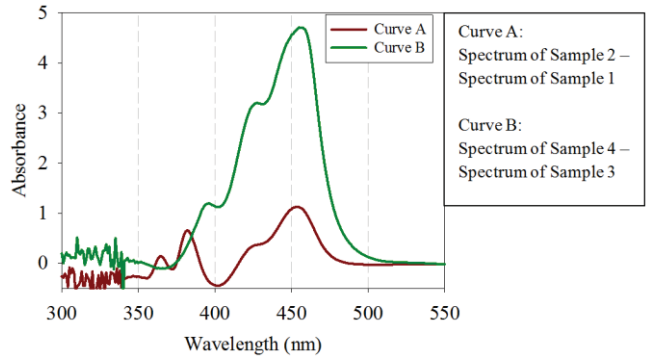

Fig. 3. Subtraction curves of transformer oil samples.

Based on Figure 3, Curve A is the subtraction of spectral response of Sample 2 with Sample 1, while Curve B is the subtraction of spectral response of Sample 4 with 3. It can be observed that there are multiple absorption peaks within the range of 350 nm to 500 nm. There is a clear difference in peak absorbance near 450 nm compared to other wavelengths. According to the laboratory test results, Samples 2 and 4 show inhibitor content concentration of 0.23 % and 0.33 % in weight percentage, respectively. The difference in peak absorbance near 450 nm indicates the difference of inhibitor content concentrations. Sample 4 has a higher inhibitor content concentration compared to Sample 2, and thus producing a higher peak absorbance near 450 nm. Further research work is needed by preparing a set of controlled oil samples with the same color index but different inhibitor content concentrations, to clearly demonstrate that the absorbance peak at 450 nm can be used to determine the inhibitor content concentration in transformer oil.

IV. Conclusion

Inhibitor content in transformer oil can be characterized optically in the UV-Vis region as multiple peak absorption can be observed. The difference in peak absorbance near 450 nm suggests the difference in inhibitor content concentration in transformer oil. However, further work with more controlled oil samples are needed to fully establish a clear relationship between the peak absorbance at 450 nm and the inhibitor content concentration of transformer oil. The results of this work demonstrate the potential of detecting inhibitor content in transformer oil at very low cost by utilizing Silicon photodetector for the UV-Vis optical sensing system.

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