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New near-infrared absorbance peak for inhibitor content detection in transformer insulating oil

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ABSTRACT

Monitoring the condition of transformer insulating oil has been considered as a crucial and effective measure for preventive maintenance of power transformers. Various properties of the oil can be monitored such as the dissolved gases, furan content, and inhibitor content. This paper focuses on the inhibitor content in insulating oil. Currently, Fourier transform infrared (FTIR) spectroscopy in accordance with the IEC 60666 standard is used for the measurement of inhibitor concentration in insulating oil. However, this technique involves site sampling, transportation to a laboratory and an expensive instrument. This work proposes the characterization of inhibitor content in insulating oil in the near-infrared (NIR) waveband, which would lead to the design of a faster and cheaper detection system for inhibitor content. It was found that the inhibitor content exhibits an optical absorbance peak at 1403 nm, which was not reported in any previous work. A mathematical model was then created to describe the relationship between the concentration of inhibitor, the area under the absorbance spectrum and the peak optical absorbance. The model was verified, and the results showed a root mean square error (RMSE) of 0.0458.

1. Introduction

Preventive maintenance of power transformers is crucial to ensure that the power transformer is operating under optimal conditions. Any early signs of fault detected in the transformer will be addressed so that catastrophic failures can be avoided. Typical preventive maintenance programs consists of three tasks, including routine equipment inspections, maintenance tasks and repairs [1]. One of the maintenance tasks is the monitoring of the condition of the insulating oil in the power transformers [2–4].

Insulating oil, also known as transformer oil, is one of the main components in power transformers. It serves as a coolant to regulate the temperature of the power transformer so that overheating does not occur during operation. Insulating oil also electrically insulates the windings and core due to its good electrical insulation properties. Furthermore, noise due to the vibration of the transformer can be reduced. More importantly, insulating oil acts as an information carrier in that it holds information on the physical and chemical condition of the transformer. After years of service, the insulating oil is subjected to continuous thermal, electrical and mechanical stresses [5–7]. These stresses will change the properties of the oil, thus degrading it. Therefore, monitoring of the insulating oil condition is important to ensure reliable and safe operation of power transformers.

Various properties of insulating oil, such as acidity, color, water content, furan content, interfacial tension (IFT), inhibitor content and dissolved gases [8,9], are commonly monitored during routine maintenance. This paper focuses on the concentration of inhibitor content (*%IC*) in the insulating oil. Inhibitors are organic chemical compounds used to decrease the oxidation process in insulating oil [10]. They are also known as antioxidants or oxidation inhibitors. There are various types of inhibitors for transformer oil such as 2, 6-di-tertiarybutyl phenol (DBP), 2,6-ditertiarybutyl-*para*-cresol (DBPC), 1,2,3-Benzotriazol (BTA), dibenzyl disulfide (DBDS), 2-*tert*-butyl-*p*-cresol (2-t-BPC), *N*-phenyl-1-naphthylamine and methylated-BTA [11]. However, DBPC is the most commonly used inhibitor and is approved universally as a highly desirable inhibitor material with excellent properties [10] that minimize any oxidation process in transformer oil during operation.

It is commonly known that insulating oil is subjected to degradation during operation and that the inhibitors deplete with time. According to the IEC 60422 standard (Mineral insulating oils in electrical equipment – supervision and maintenance guidance), if the inhibitor content drops below 40% of its initial level, either close

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Table 1
Summary of the techniques for the measurement of inhibitor concentration based on IEC60666 [13].

Techniques	FTIR Spectroscopy	HPLC	GC–MS
Test Method	• Does not require trained personnel to conduct experiment • Need to prepare reference sample by solid phase extraction using silica gel • Non-destructive test	• Require trained personnel to conduct experiment • Complex sample preparation required. • Destructive test	• Require trained personnel to conduct experiment • Sample preparation required • Complex experimental setup • Destructive Test
Precision	• Unable to detect trace levels of inhibitor in insulating oil • Results can be affected for used oil samples due to oxidation by-products in oil	• Capable of detecting trace levels of inhibitors in insulating oil • Results can be affected during sample preparation.	• Capable of detecting trace levels of inhibitors in insulating oil • Results can be affected during sample preparation

observation of the transformer is needed or additional inhibitor must be added [8]. These actions are necessary because once the inhibitor amount is below the minimum level, the oil starts to degrade at a higher rate. To increase the useful life of the insulating oil to an acceptable period of time, monitoring and replenishment of inhibitor content in insulating oil must be carried out [10].

The ASTM D2668 (Standard Test Method for DBPC and DBP in Electrical Insulating Oil by Infrared Absorption) and IEC60666 (Detection and determination of specified additives in mineral insulating oils) standards are commonly used for the detection and measurement of the concentration of inhibitor content in insulating oil [9,12]. The ASTM D2668 standard covers the determination of inhibitor content using Fourier transform infrared (FTIR) spectroscopy, while the IEC60666 standard covers several techniques to determine the concentration of inhibitor content such as FTIR spectrophotometry, high-performance liquid chromatography (HPLC) and gas chromatography-mass spectrometry (GC–MS) [12,21]. Table 1 shows the comparison of each technique described in the IEC 60666 standard.

Among the three techniques, FTIR spectroscopy is most commonly used for measuring the *%IC* in insulating oil for routine maintenance. Although the technique lacks the precision to measure inhibitor content at the trace level, it does not require trained personnel to conduct complex sample preparation and measurement, which saves time and cost. Furthermore, it is a non-destructive test, as the technique involves optical spectroscopy.

Optical spectroscopy studies the interaction between matter and electromagnetic (EM) radiation. When an EM wave interacts with matter, the matter absorbs, reflects, refracts, diffuses or even emits EM waves of different wavelengths. Depending on the objectives of a research study, different properties are investigated. Recently, optical spectroscopy has been popular among researchers in exploring new techniques for monitoring the condition of transformer oil [14–20]. In this paper, optical absorption by the inhibitor content is investigated. Theoretically, each substance will have unique spectral properties that are discernible from the properties of all others [21]. The region of detection used to determine the concentration of DBPC inhibitor content is the phenolic OH stretch at a wavenumber of 3650 cm^{-1} (equivalent to a wavelength of 2739.73 nm) [13].

However, this FTIR spectroscopy technique still requires relatively expensive equipment, and oil sampling with transportation to a laboratory is still necessary, which incurs additional running cost. Therefore, a more convenient and affordable method is needed. Thus, this paper reports on the optical characterization of inhibitor content in the NIR region, which enables the possibility of designing a cost-effective and portable detection system. A mathematical model that describes the relationship between the optical response of the inhibitor in the NIR region and the *%IC* was formulated and verified.

2. Experiment details

In this research work, a set of transformer oil samples was taken from 40 different operating power transformers. Each sample was collected and transported properly in accordance with the IEC 60475 standard [22]. This procedure requires careful handling of the samples to ensure that there is no contamination or modification of the samples that will jeopardize the analysis. The oil samples were collected in two amber glass bottles, of which one was sent to the accredited laboratory for inhibitor content analysis using FTIR in accordance to the IEC 60666 standard, while the other bottle was analyzed using a laboratory-based NIR spectrophotometer. This method was carried out to ensure that there was no large time gap between the accredited laboratory analysis and the experiment conducted in this study. In the NIR spectrophotometer study, oil samples were divided into two sets: 70% of the oil samples tested with inhibitor content were used for the mathematical modeling, while the remaining 30% of the oil samples were used for verification of the model.

The laboratory-based NIR spectrophotometer used was the Agilent Cary5000 UV–vis-IR spectrophotometer. The Cary5000 is a high-performance double-beam spectrophotometer with good photometric performance in the 175–3300 nm range. Fig. 1 shows the basic working principles of the double-beam spectroscopy.

Radiation from the light source passes first through a monochromator and a slit so that only a narrow band of light passes through. The light beam is then focused on a switching disk. The role of the switching disk is to switch among 3 distinct positions, for which light will either pass through, be reflected or blocked. At the first position, the light beam passes through the disk, directly shines onto a 1-cm path-length quartz cuvette containing the oil samples (Sample cell), and then reaches the detector for measurement. The disk subsequently switches to the second position, for which the light beam shines on the mirror surface to be reflected at 90°. The light then shines through another 1-cm path-length quartz cuvette containing the reference sample (reference cell) and then reaches the detector for measurement. In this experiment, clean, new uninhibited transformer oil was used as the reference sample. Finally, the disk switches to the third position, for which the light beam strikes the black surface, thus ensuring that no light passes through the disk to reach the detector. This part of the cycle is essential for the instrument to measure the dark current so that it can be subtracted from the overall light measurement made by the system. For every measured wavelength, there will be three measurements taken at the three different positions of the switching disk. The process is repeated until it covers the entire range of wavelengths.

The measured results were recorded as transmittance and then converted to absorbance values by applying the Beer-Lambert's Law [24] as in Eq. (1).

$$Abs = -\log_{10}(S_i - B_i/R_i - B_i) = \varepsilon_\lambda \cdot c \cdot l \quad (1)$$