



Application of fluorescence emission ratio technique for transformer oil monitoring



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ABSTRACT

In this work a new fluorescence emission measurement technology was introduced and experimentally compared with other measurement methods, such as the titration method and IR spectroscopy, to validate it for the oil oxidation measurement of electrical insulating oil. The oxidation characteristics of insulating oil were found to be fairly represented by the titration method and IR spectroscopy, and the results are comparable to a change in the fluorescence emission ratio that is defined as the shift in fluorescence intensity in the measured wavelength range. The result also shows that by the measurement of fluorescence emission ratio, it is possible to detect the oxidation of oil relatively earlier than by other methods. This study suggests that the developed technology can provide sufficient information for evaluating the insulating oil quality, and that the developed FER sensor can be used as an effective condition monitoring device of electrical insulating oil oxidation.

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1. Introduction

The analysis of insulating oils provides lots of information about the oil, and also enables the detection of other possible problems, including contact arcing, aging insulating paper and other latent faults. Thus it is an indispensable part of a cost-efficient electrical maintenance program [1].

By accurately monitoring the condition of the oil, sudden faults can be discovered in a timely fashion and outages can potentially be avoided. Furthermore, an efficient approach to maintenance can be adopted and optimum intervals determined for necessary replacement.

Similar to industrial oils, transformer oils are oxidized under the influence of excessive temperature and oxygen, particularly in the presence of small metal particles that act as catalysts and which, result in an increase in the (total) acid number, owing to the formation of carboxylic

acids [2]. Further reactions can result in sludge and varnish deposits, and additionally, in increased acidity formation, which has a damaging effect on cellulose paper.

It is known that oil degradation also produces charged by-products, such as acids and hydro peroxides, which tend to reduce the insulating properties of the oil. An increase in the acid number is often accompanied by a decrease in dielectric strength and increased water content [3]. For these reasons, oxidation of electrical insulating oil needs to be monitored while it is in operation.

Methods of analyzing physical and chemical parameters of insulating oil, such as basic appearance (color), water content, and the acid number, have been used to determine oil degradation. These methods have formed a core part of the preventive maintenance of electrical insulating oil thus far [4]. Nonetheless, these methods are limited to off-line analyses for laboratory use, whereby it is not possible to provide an early warning before any failure due to the oxidation of electrical insulating oil occurs. Therefore, on-line monitoring technology for evaluating insulating oil degradation is crucial. Nowadays a number

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of new techniques are under development to satisfy the requirements of off-line and on-line transformer oil monitoring. Particularly fluorescence spectroscopy is one of them [5,6].

In this work, an apparatus is developed to measure the oxidation of electrical insulating oil. The apparatus can be mounted onto mechanical devices for detecting the intensity of fluorescence light reflected from the oil in real time, and this detected intensity is an indication of the extent of oil oxidation. The developed apparatus evaluates the degree of oil oxidation of test oils, based on the UV fluorescence emission ratio. The test results obtained herein are compared with those obtained from other measurement methods such as the titration method and IR spectroscopy.

2. Fluorescence emission ratio technique and detector for oil oxidation monitoring

Transformer oils are mainly refined from petroleum. They are very complex mixtures and may consist of as many as 2900 paraffinic, naphthenic and aromatic hydrocarbon molecule types, 25% of these being aromatic which are fluorescent molecules [7].

The phenomenon of fluorescence in organic matter occurs due to the emission of photons by fluorophores when excited by electromagnetic radiation. Fluorophores are able to absorb incident energy, which allows electron transfer from a fundamental energy state to an excited state. The return to the ground state may then produce a luminescence phenomenon such as fluorescence when the time scale is sub-nanosecond. This de-excitation mechanism is not the only one possible, and its efficiency depends on the chemical nature of the compounds and their structural environment. Fluorescence of molecules is related to the energy transition phenomenon in the π -orbitals of the C=C bonds. Moreover, the conjugated π -systems require a lower energy than isolated bonds because of higher π -electron mobility and are therefore readily activated. These considerations designate the aromatic and polyaromatic compounds as the main source of fluorescence properties of the sedimentary organic matter [8]. Oxidation of aromatic molecules leads to an overall increase in polarity, and it results in a relative increase in the absorption and emission at high wavelengths and, therefore, causes a spectral shift of emission intensity.

We propose that this shift of the intensity of fluorescence emission phenomenon be used to evaluate oil degradation. The ratio of intensity at long to short wavelengths referred to as the fluorescence emission ratio (FER). Using fresh oil as a reference baseline, the shift phenomenon characterizing oil degradation is observed as a change in the FER parameter. The FER technique is based on measuring fluorescence intensities in three wavelength ranges, and it consists of the following steps. For fresh oil, the fluorescence emission in red ($\lambda_R = 590\text{--}750\text{ nm}$), green ($\lambda_G = 490\text{--}610\text{ nm}$), and blue ($\lambda_B = 400\text{--}510\text{ nm}$) (RGB) wavelengths are measured using color sensor output currents (I) in red I_R , green I_G , and blue I_B wave ranges. The two largest values of $I_{\lambda_{\text{long}}}$ and $I_{\lambda_{\text{short}}}$ are determined, where $I_{\lambda_{\text{long}}}$ is the long wavelength color output current similar to

I_R or I_G and $I_{\lambda_{\text{short}}}$ is the short wavelength color output current similar to I_G or I_B as shown in Fig. 1. The FER parameter is calculated from the color sensor output current (I) as follows [3,9,10]:

$$\text{FER} = \frac{I_{\lambda_{\text{long}}}}{I_{\lambda_{\text{short}}}}. \quad (1)$$

The higher FER value should correspond to a higher level of oxidation. The obtained FER (Eq. (1)) is compared with a predetermined threshold, and if the obtained FER is below the threshold, then the oil is in good condition; otherwise, the oil condition is unacceptable. This method was used to evaluate the degree of oil oxidation level, and in this measurement, absorption of optical radiation by the oil and temperature influence on test results do not need to be accounted for.

Since transformer oils are derivatives of petroleum crude obtained from different sources and are complex mixtures of additives, they have different characteristics. Thus, no unique fluorescence characteristic can be ascribed to transformer oil in general and monitoring of transformer oil characteristics needs to be done starting with the measurement of FER_{fresh} of the fresh oil. Then oil oxidation level is estimated as difference,

$$\Delta\text{FER} = \text{FER}_{\text{used}} - \text{FER}_{\text{fresh}}.$$

A low cost device based on this shifted phenomenon, as shown in Fig. 2, was developed in this work with a three-color sensor as photo-receiver that detects optical light intensity in three wavelengths ranges—red, green, and blue (RGB sensor).

The radiation from the UV diode (1) passes through the bifurcated optical fiber and optical window (9) to the test oil. A ball lens (5) is used to focus the UV diode radiation at the optical fiber end. The optical fibers are mounted in the fiber holder (13), which is inserted into housing (12). An optical window is fixed to the housing (12) by a nut (8). The optical fiber transmits the fluorescent emission from the test oil to the RGB sensor (14). A photodiode (2) is applied in feedback loop of stabilization of UV radiation. The UV diode, RGB sensor, and feedback diode are cable-connected to an electronic block (not shown in Fig. 2). O-rings (7) and (11) prevent oil leakage into the sensor. A cover (4) is used to protect the detector. The electronic microcontroller, amplifier and power PCBs, and an LCD panel are housed in a box, cable-connected to the detector probe (15). The fluorescence emission from the test oil is

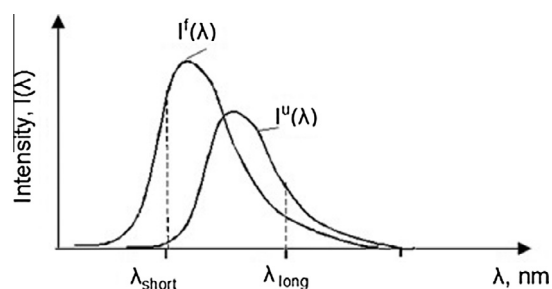


Fig. 1. Fluorescence spectra of fresh $I^f(\lambda)$ and used $I^u(\lambda)$ oil [3].

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