New Approach to Estimate Furan Contents in Transformer Oil Using Spectroscopic Analysis

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***Abstract*— The presence of furan derivatives in aged-transformer oil has been one of the key indicators for solid dielectric deterioration. Identification and quantification of furan derivatives are currently performed using high performance liquid chromatography (HPLC) or gas chromatography-mass spectrometry (GC/MS) based on ASTM D5837 standard. Although these techniques are well developed, they call for an expert personal to conduct the test and to analyse its results. Moreover, the test is relatively expensive and the analysis of oil sample may take days as most utilities sending transformer oil samples to external laboratories to be tested. This paper introduces a novel approach to determine the furan concentration within power transformer dielectric oil through ultraviolet to visible (UV-Vis) spectroscopic analysis for oil samples. Furan concentration in transformer oil would determine the absorption intensity in UV-Vis spectral range and hence the correlation between furan concentration and spectral response of transformer oil can be identified. Experimental results show that the new technique is reliable, economic and easy to be implemented on site to identify the furan concentration level in transformer oil instantly.**

***Index Terms*— Transformer oil, Furan derivatives, Spectral response.**

I. Introduction

Power transformers are vital links within any transmission and distribution networks. Condition monitoring and diagnostic techniques are essential to decrease the maintenance cost and to improve the reliability of the equipment. At present, there are several chemical and electrical diagnostic techniques applied for power transformers [1]. Furans are the main chemical compounds that are produced as the paper insulation ages and degrades due to the thermal and electrical stresses that a transformer experiences during its operation. Paper insulation is a critical component in oil-immersed transformers as in general; transformer operational life span is equivalent to the solid dielectric aging.

The research on identifying furans in transformer oil started over the last three-decades and reported that the thermal degradation of cellulosic insulation material within paper insulation results in 5 furan compounds namely; 2-furaldehyde, 5-hydroxymethyl-2-furaldehyde, 2-acetylfuran, 5-methyl-2-furaldehyde and 2-furfurol. These products dissolve in insulation oil and decreases paper and oil dielectric strength [2]. Dielectric strength of paper insulation can be accurately assessed by measuring its degree of polymerization (DP). However, it is impractical to acquire the paper samples from an operating transformer especially paper samples from the hot-spot location that is usually located in the centre of the transformer winding. There has been a lot of research in the literature that concludes a strong correlation between the DP and furan derivatives concentrations [1]-[5]. The advantage of furan measurement compared to DP is that oil samples can be conveniently collected from an operating transformer without causing any damage to the transformer.

An increase in furan concentration in transformer oil corresponds to a decrease in the tensile strength and the DP of the insulation paper. Furan level in a transformer can be correlated with the paper DP, and therefore an in-service assessment of the mechanical strength of the paper insulation can be made. De Pablo reported the following relation between the furfural and DP based on viscosity (DP_V) [6, 7].

$$DP_V = \frac{7100}{8.88 + 2FAL} \qquad (1)$$

where, 2FAL is the 2-furfural concentration in mg/kg of oil.

The correlation between the 2-FAL and DP with respect to the solid insulation extent of damage is listed in Table I which depicts the insulation paper dielectric and mechanical properties. When the DP test reveals a value of 250 or less, the paper is considered to have lost all its mechanical strength, and the transformer has reached its end of life [8].

TABLE I
CORRELATION BETWEEN 2-FAL AND DP VALUE [8]

2-FAL (ppm)	DP Value	Significance
0-0.1	1200-700	Healthy Insulation
0.1-1.0	700-450	Moderate Deterioration
1-10	450-250	Extensive Deterioration
> 10	< 250	End of Life Criteria

ASTM D5837 is a commonly used guideline by the industries to determine the furan derivatives concentration in the transformer oil using high performance liquid chromatography (HPLC) or gas chromatography-mass spectrometry (GC/MS) [12]-[15]. Since this method requires specific skills and expensive equipment to conduct the test and

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to analyse its results, most utility companies outsource the furan test to the relevant service companies.

This paper proposes an alternative and cost effective technique to estimate the furan concentration in transformer oil using ultraviolet-to-visible (UV-Vis) spectroscopy. In this context, series of laboratory-based tests were conducted on different transformer oil samples of different furan concentration. A custom-designed Matlab algorithm is developed based on the parameters taken from the UV-Vis spectral response curve to estimate the furan concentration within transformer oil samples.

II. Mechanism of Furan Formation

The furanic compounds in transformer oil that are detectable with the current available technologies namely; 2-furfural (2-FAL), 2-Furfurol (2-FOL), 5-Hyroxy methyl-2-furfural (5-HMF), 5-Methyl-2-furfural (5-MEF), and 2-Acetylfuran (2-ACF) are shown in Fig. 1. It is widely accepted that furans arise from insulating paper degradation but the actual mechanism of formation has not been fully understood accurately yet. However, it has been proposed that furans are produced from pyrolysis mechanism of levoglucosane (LG) and hydrolytic degradation of cellulose in the paper [10]. LG, the precursor of furanic compounds, is the by product due to thermal degradation of cellulosic paper at temperatures higher than 130 °C [9]. It is well investigated by Scheirs *et al.,* [10] that the LG leads to the production of all five types of furan derivatives. On the other hand, hydrolytic thermal degradation that contributes to the chain scission of cellulose is also an important factor of furanic derivatives generation at the transformer normal operating temperature of 80 °C ~ 120 °C [11].

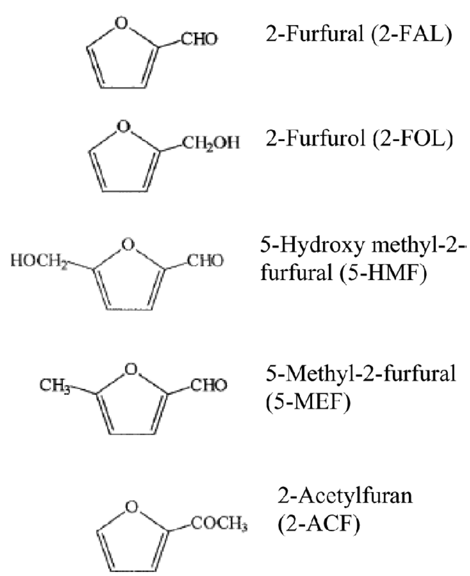

Fig. 1. Furanic compounds detectable in transformer oil that has been in contact with degraded cellulosic insulation [10].

Furans may also be generated in transformer oil during the normal operating temperature due to the existence of moisture in the paper and air that leads to oxidative hydrolysis of the cellulose. Hohlein had proven that the hydrolysis degradation mechanism is the major contributor for 2-FAL in transformer insulating oil at the normal service temperature. Among all furan compounds, 2-FAL is always considered as the main compound in the analysis because of its relatively higher generation rate and stability inside a transformer and all other derivatives can be ignored [2-3].

TABLE II
SELECTED OIL SAMPLES TEST CONDUCTED BY GC/MS

Test Samples	2-FAL (ppm)	2-FOL (ppm)	2-ACE (ppm)	2-FAL (ppm)	2-FAL (ppm)
Lab. aged	<0.01	<0.01	<0.01	<0.01	<0.01
In-service	3.1	<0.01	0.01	0.01	<0.01
In-service	5.1	<0.01	0.02	0.01	<0.01
In-service	10.0	<0.01	0.03	0.03	<0.01
In-service	15.0	0.01	0.05	0.05	<0.01

Table II shows each furanic derivative concentration in the selected oil samples expressed in parts per million (ppm) or mg/l measured by following the standard of ASTM D 5837. The table of results also includes the furan analysis for a laboratory aged oil sample. The test results indicate that furan content is dominated by 2-FAL which is consistent with findings by many other researchers around the globe [4, 7, 10]. Therefore, it is possible to use 2-FAL as a cellulosic insulation degradation indicator for the rest of the experiment.

III. Experimental Set Up and Measurements

For measurement, several sets of transformer oil samples were collected from different in-service power transformers with different operating conditions and life span. Furan concentration in each set of oil sample was identified using GC/MS in accordance to ASTM D 5837 (B) [12]-[15]. Each test sample was pre-treated with acetonitrile prior to extraction for test specimen that was then arranged into GC/MS for furanic derivatives identification and quantification.

The spectral response (light absorbance) of oil samples were measured using a laboratory-based UV-Vis spectroscopy setup as shown in Fig. 2. The objective of this measurement is to find the correlation between the conventional furan measurement method and the proposed alternative method (spectral response area underneath the light absorbance curve). For this measurement, the concepts of accelerated aging of transformer oil samples are performed in reference to the standard of IEC 61125 [12], ASTM D 923 [13], ASTM D 5837 [14] and ASTM E 275 [15].

The UV-Vis spectroscopy test procedure was developed in reference to the ASTM E 275 [15]. Furan derivatives in oil sample affect the amount of UV-Vis light absorbed by the specimen which is calculated using the following equation.

$$A_\lambda = -\log_{10}\left(\frac{S_\lambda - D_\lambda}{R_\lambda - D_\lambda}\right) \tag{2}$$

where, A_λ is the light absorption, S_λ is the sample intensity, D_λ is the dark intensity and R_λ is the reference intensity at wavelength λ.

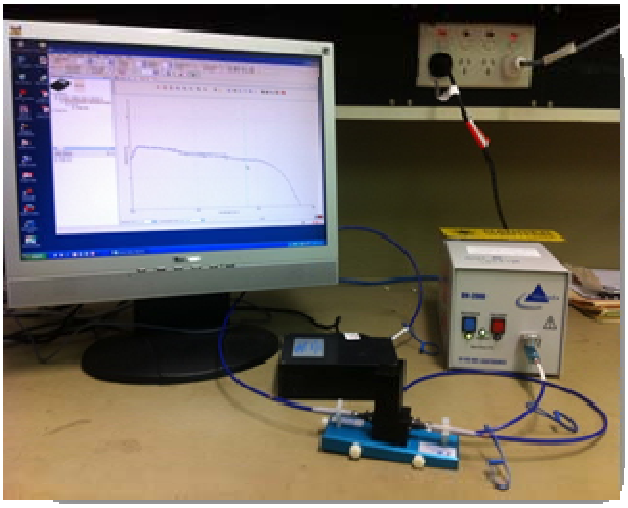

Fig. 2. Experimental setup for light absorbance measurement of transformer oil samples using the UV-Vis spectroscopic system.

The experimental setup for the light absorbance measurement of transformer oil using UV-Vis spectroscopy is shown in Fig. 2. The light source transmits the input light via an input optical fiber into a cuvette located in a cuvette holder. This input light interacts with the transformer oil sample and the output optical fiber carries the output light from the transformer oil sample (cuvette holder) to the spectrometer which is connected to the computer as shown in Fig. 2.

IV. Results and Discussions

Fig. 3 shows the absorption spectra for various 2-FAL contents (in ppm) of power transformer oil measured by the UV-Vis spectroscopy. For this test, several sets of oil samples whose furan contents were identified using GC/MS are included for the absorption test. As can be seen in Fig. 3, the oil UV-Vis spectral response strongly correlates with its furan content. It is clear that the new oil with 2-FAL of 0 ppm has the lowest spectral response area compared to the samples with higher level of furan content. Fig. 3 also reveals that the new oil with 2-FAL of 0 ppm has the shortest bandwidth and lowest absorbance peak. As the 2-FAL concentration increases, the spectral response bandwidth is becoming wider and maximum absorbance peak is becoming higher. The spectral response has also displayed spikes characteristic at wavelength around 350 nm when furans content level increases in transformer oil. It is observed that all the maximum peaks appear within the range of 260 nm to 280 nm. The zero crossing points are different for different furan content levels, such as, from 350 nm to 475 nm (spectral bandwidth).

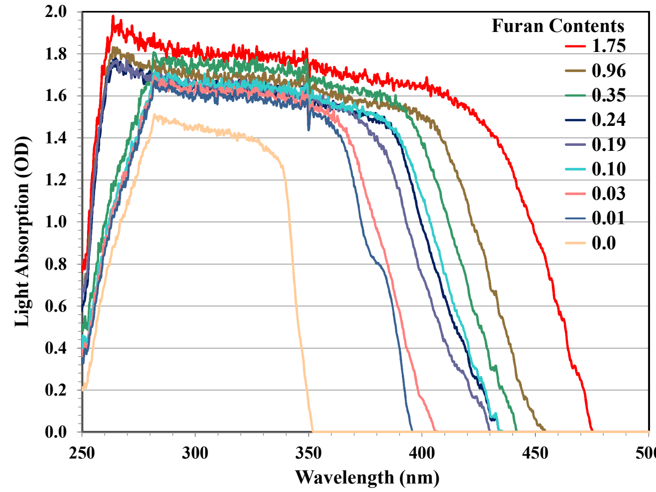

Fig. 3. Absorption spectra for various furan contents of power transformer oil measured by the UV-Vis spectroscopy.

Fig. 4 shows a plot between the spectral response area and furan concentration of transformer oil samples. Fig. 4 shows clearly that there is strong correlation between spectral response area and furan concentration in power transformer oil samples. The mathematical correlation between the spectral response area and furan concentration of power transformer oil can be estimated using curve fitting as below.

$$Y_f = 2\times10^{-19} A_s^{\,7.528} \tag{3}$$

where, Y_f is the estimated furan contents of oil sample in ppm, A_s is the spectral response area underneath the absorbance spectra.

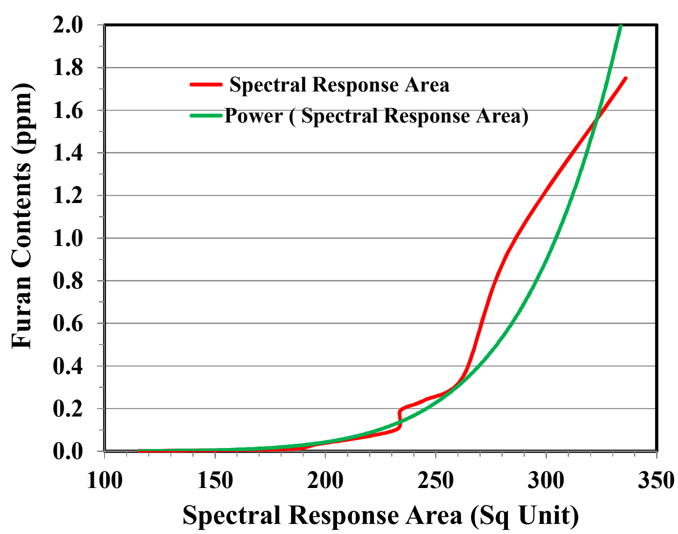

Fig. 4. Spectral response area versus furan contents characteristics of power transformer oil measured by the UV-Vis spectroscopy.

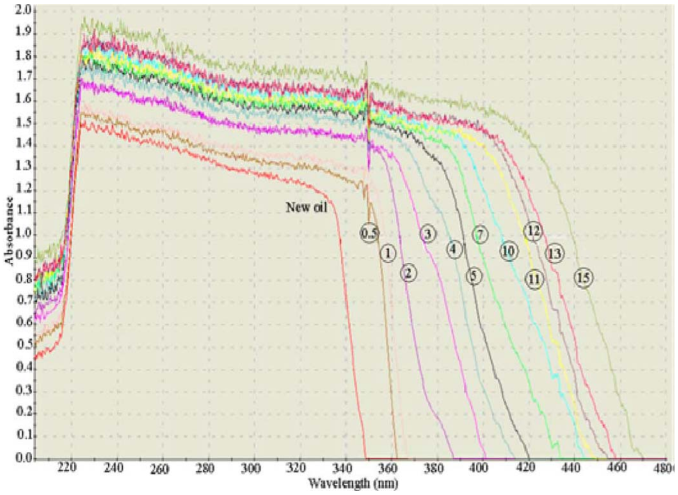

Fig. 5. UV-Vis absorption spectra at various furan content levels [16].

To validate the estimated mathematical expression of (3), another set of spectral response with pre-known 2-FAL concentration as shown in Fig. 5 is used [16]. The area under each curve in Fig. 5 is calculated and is used in (3) to estimate furan concentration in each relevant oil sample. The estimated furan content along with the measured value for sets of samples is shown in Table III.

TABLE III
COMPARISON BETWEEN CALCULATED AND MEASURED AREAS

Furan (Measured)	Spectral Response Area (sq. unit)	Furan (Calculated using (3))	Error
0.01	223.14	0.096	-0.086
0.5	270.06	0.403	-0.097
1.0	302.86	0.955	-0.045
3.0	350.59	2.873	-0.127
4.0	368.15	4.15	0.15
5.0	380.29	5.298	0.298

Table III show that results of the estimated correlation between the area under the absorbance characteristic of oil sample and its 2-FAL content are very close to the furan measured values. The absolute error between calculated and measured values is less than 0.1 for furan levels less than 1 ppm. This error is increasing with higher furan contents. This won't affect the calculated results for oil samples with high furan concentration as the transformer is considered to exhibit extensive deterioration for furan concentration higher than 1 ppm as shown in Table I. The mean square error between the calculated and measured values is found to be 0.024.

V. CONCLUSION

This paper introduces a new technique to quantify furan concentration in transformer oil using its spectral response. Results show that, more furan contents in transformer oil is corresponding to higher bandwidth and peak absorbance in its specral response. A mathematical relation to estimate furan concentration in oil sample based on the area under its absorbance specral charactaristic is deduced. Validation of the estimated mathematical correlation is performedand the mean square error between the calculated and measured values is 0.024. Although the absolute error is becoming higher for furan contents more than 1 ppm, the estimated correlation can still be applied as the exact furan concentration level above 1 ppm is not necessarily required because transformer is considered in extensive deterioration condition for any furan level above 1 ppm.

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