Detection of Power Transformer Fault Conditions using Optical Characteristics of Transformer Oil

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Abstract—Power transformers are important in the power transmission and distribution network. A continuous monitoring of the transformer is important in ensuring the prolonged service of the transformer. This paper focuses on the characterization of transformer oil using optical detection method. 10 Transformer oil samples from the main tanks and 11 oil samples from the on-load-tap-changer (OLTC) were obtained for the optical characterization from 200 to 3300 nm. Based on the conventional results interpretation using dissolved gas analysis (DGA) and Duval Triangle, the optical characteristics of the samples in 2120 to 2220 nm clearly demonstrate the detection of electrical discharges of high energy (D2), electrical discharges of low energy (D1) and thermal faults at temperatures above 700°C (T3) faults. This approach provides a quicker and cheaper method to determine the condition of power transformers based on the optical characteristics of transformer oil.

Keywords— main transformer tank; On-load-tap-changer; spectrophotometer; transformer oil aging

I. Introduction

Power transformer plays a vital role in the transmission and distribution network. Unforeseen outages of the transformer due to unanticipated failures are catastrophic. Thus, smooth functioning of the power transformer is crucial in ensuring a hassle free operation of the system.

The majority of power transformers are filled with liquid known as the transformer oil, which is petroleum-based insulating oil. Apart from playing an important role as a cooling and an insulating agent, transformer oil also provides information on the condition of the transformer. This is because during normal operation, the oil is constantly subjected to thermal and electrical stresses, which break a number of carbon-hydrogen (C-H) and carbon-carbon (C-C) bonds in the molecules of the oil. As a result of this mechanism, a trace amount of fault gases are generated along with some changes in the physical appearance of the transformer oil

Many research works were carried out to develop different methods of analyzing and characterizing the transformer oil with the aim of early detection of faults in the transformer. These methods involve conditions such as degree of polymerization (DP), dielectric breakdown voltage [1], color index [2], inhibitor content [3], and dissolve gas analysis (DGA) [4]. Due to higher sensitivity towards various faults in the transformer, DGA was widely accepted as a standard technique for the interpretation of transformer fault conditions [5].

The application of DGA as a fault gas detector had evolved to becoming a method of identifying errors that occur in the transformer [6]. It was identified that low temperature degradation of mineral oils generates large quantity of hydrogen (H_2) and methane (CH_4) gases as well as trace quantities of ethane (C_2H_6) and ethylene (C_2H_4). The thermal decomposition of cellulose, on the other hand generates carbon monoxide (CO), carbon dioxide (CO_2) and water vapor and lastly, acetylene (C_2H_2) gases are developed due to high temperature thermal heating [7].

After many investigations, it was discovered that compared to different concentrations of individual fault gases, different ratios of fault gases are more accurate in determining the fault in the transformer. Thus, many methods were developed to study the ratio of these fault gases. Among the methods established includes, Key Gas, Dornenburg Ratio, Rogers Ratio Method, Nomograph Method, IEC Ratio, CIGRE and Duval Triangle [8-10].

As one of the most commonly used method, Duval Triangle Method uses a triangular map to study three types of gases, namely, CH_4, C_2H_2, and C_2H_4, which are used to determine various types of fault. These faults are, corona partial discharge (PD), electrical discharges of low energy (D1), electrical discharges of high energy (D2), thermal faults of temperature below 300°C (T1), thermal faults at between the temperatures of 300°C and 700°C (T2), thermal faults at temperatures above 700°C (T3) and the combinations of thermal and electrical faults (DT) [11]. Literature suggests that D1 and D2 occur more frequently in the OLTC. This is because OLTC is subjected to high arcing which encourages the build up of

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pyrolitic carbon in the oil. This mechanism results in the occurrence of D1 and D2 faults [12, 13]. However, there are possibilities for these faults to occur in main tank of the transformer.

Thus, the main objective of this paper is to characterize these faults (D1, D2 and T3) in the transformer based on the optical characteristics of transformer oil. The outcome of the investigations showed that the optical characterization of transformer oil could identify the D1, D2 and T3 faults in the transformer.

II. Experimental Details & Results

A total of 21 transformer oil samples were collected from different in-service transformers with different life span. The transformer oil consists of 10 samples which were obtained from the main tank and 11 other samples from OLTC tank. DGA was conducted on all samples using gas chromatography based on the International Electrotechnical Commission (IEC) 60567 [14]. The DGA results obtained were further analyzed using Duval triangle. There are two types of Duval triangle, one for main tank and the other for OLTC tank. However, all the samples were analyzed using the Duval triangles for main tank. This is because it is difficult to obtain oil samples from the main tank with D1 and D2. Nevertheless these faults frequently occur in the OLTC; hence the oil samples were used to represent the oil samples from the main tank with D1 and D2. Table I shows the Duval faults of the transformer based on the DGA of all the transformer oil samples.

TABLE I. Duval Fault Condition Based on Dissolved Gas Limits

Samples from Main Tank	Duval Fault	Samples from OLTC	Duval Fault
MT1	O	OLTC1	D1
MT2	T3	OLTC2	D1
MT3	T3	OLTC3	D2
MT4	O	OLTC4	D1
MT5	O	OLTC5	D1
MT6	O	OLTC6	D2
MT7	T3	OLTC7	D2
MT8	O	OLTC8	D2
MT9	O	OLTC9	D2
MT10	T3	OLTC10	D1
		OLTC11	D1

Optical characterization was carried out using the Agilent Cary 5000 Spectrophotometer. The ultraviolet-visible-near infrared (UV-Vis-NIR) light was passed through the 1cm path-length cuvettes containing the reference oil and the sampled transformer oil. The resulting light is collected by a detector to obtain an optical spectrum. The transformer oil samples were analyzed in the range of 200-3300 nm. The relationship between the absorbance peaks obtained from the optical characterization of the transformer oil and the results of Duval Triangle based on the conventional method was investigated.

The comprehensive analysis and correlation of the optical characteristics with the established fault conditions based on Duval Triangle shows that there is a clear relationship between the optical spectrum in the range of 2120-2220 nm and the fault conditions. Figure 1 shows the optical absorbance spectra of the transformer oil samples with different fault conditions.

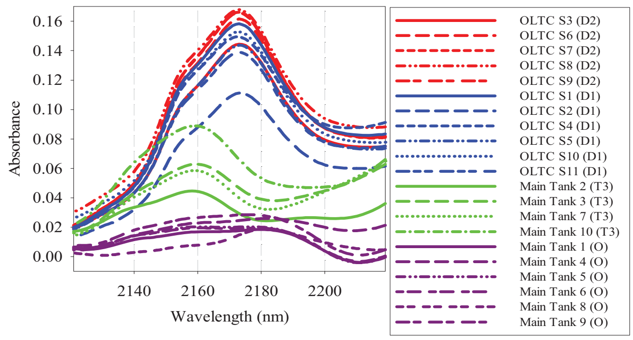

Fig. 1. Absorbance spectrum at 2120-2220 nm wavelengths.

III. Discussion

Based on Figure 1, the peak at 2172 nm shows the fault in the D2 category while the absorbance peak at the same wavelength but with lower absorbance value shows the fault in the D1 category. Absorbance peaks can also be observed at 2160 nm. Peaks at this wavelength indicate the fault in the T3 category. Lastly, there are a few oil samples which have very low absorbance in this wavelength range. They were involved in the detection of fault for less than 300°C or no fault condition, and they are classified as others (O).

According to the graph in Figure 1, a line from D2 (OLTC S3) can be found falling into the D1 region. This phenomenon can occur due to the misinterpretation of the Duval Triangle. Literature suggests that the diagnosis of faults using Duval Triangle has only 89% of accuracy [10]. Therefore, this line can be interpreted as the condition of the transformer oil approaching the D2 region from the D1 region.

Table 2 shows the conditions of transformer based on the Duval Fault [15]. It is clear that the conditions at D2, among the 3 major faults, are the most severe and the transformer at these conditions is approaching to a downfall. D1 conditions appear to be less severe, compared to D2, but the transformer with D1 requires constant monitoring. The condition at T3 region indicates that the transformer is approaching a critical condition and frequent monitoring is advisable. Based on the results in Figure 1, it is also noted that if transformer oil does not produce absorbance peak in the wavelength range, it is either with a much less critical faults (T1 and T2) or with no fault condition. Therefore, by optically characterizing the transformer oil in the 2120-2220 nm would enable the maintenance team to make a quick and accurate decision on the maintenance plan of the transformer.

TABLE II. TRANSFORMER CONDITION BASED ON DUVAL FAULT

Type of Faults	Symbol	Conditions
Electric discharge of high energy	D2	1. Metal fusion, poor contacts in LTC or lead connections. 2. Weakened insulation from aging and electrical stress. Carbonized oil. 3. Paper destruction if it is in the arc path or overheated.
Electrical discharge of low energy	D1	1. Pinhole punctures in paper insulation with carbon and carbon tracking. 2. Possible carbon particles in oil. 3. Possible loose shield, poor grounding of metal objects.
Thermal fault above 700°C	T3	1. Metal discoloration. 2. Thermal fault caused by arching

Based on the results of the experiment, it is clear that the optical characterization is a simpler way to examine the condition of the transformer. It saves the hassle of performing DGA and then analyzing the transformer oil samples using Duval Triangle, which requires a higher cost and longer time. However, the consistency of this method and the range of absorbance values at which the transformer oil can be categorized as T3, D1 and D2 can be established by characterizing more oil samples with these fault conditions.

IV. CONCLUSION

This study focuses on the optical characterization of transformer oil based on the relationship of Duval Fault. The results obtained show that peaks were observed at 2172 nm. The peak at the higher absorbance indicates the fault in the D2 category while the lower absorbance reflects the fault in the D1 category. T3 fault can be observed at a wavelength slightly shifted to the left which is 2160 nm. The optical characterization of oil in the NIR region is a faster and a cheaper alternative to detect D1, D2 and T3 faults in the transformer. However, further studies should be conducted with more oil sample with these faults to establish the exact range or limits of absorbance value for each fault.

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