Transformer Working Condition Assessment using Laser Raman Spectroscopy

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Abstract: Analyses of dissolved gas and furfural in the insulating oil are a very efficient tool for assessing the working conditions of transformer. We propose the in-situ transformer health diagnosis without the need for oil sampling by measuring the Raman signals from C₂H₂ and furfural concentrations present in transformer oils. Raman signals in oil at ~1972 cm⁻¹ and ~1705 cm⁻¹ originating from C₂H₂ and furfural, respectively, were detected. The results show that laser Raman spectroscopy is a useful alternative method to diagnose the transformer faults.

1 INTRODUCTION

Transformers are important components in any power system and their condition monitoring is essential for ensuring reliable operation of the system. In general, power transformer coils are insulated with a cellulose paper and immersed in mineral oil. Under the normal operating conditions, insulating mineral oils in the transformers include small amounts of gases, but failure of the transformer is known to be preceded by significant evolution of hydrogen(H₂), carbon monoxide(CO), carbon dioxide(CO₂), methane(CH₄), ethylene(C₂H₄), and acetylene(C₂H₂) gases caused by corona discharges, overheating, and arcing. Therefore, a dissolved gas analysis (DGA) of the insulating oils has become the most widely used method for investigating incipient faults in transformers (Duval, 1989). Dissolved gases extracted from oil aliquots due to pressure reduction or substitution by inert gases are measured by gas chromatography. In addition, it is known that furfural in oil comes only from the decomposition of insulation paper. So the furfural content in insulation oil is an important indicator for assessing the degradation of insulating paper in transformer (Morais et al., 1999). Furfural concentration in oil was generally extracted by methanol and measured by high performance liquid chromatography. These methods usually offer sensitive detection limits at ppm levels that are suitable for monitoring the transformer conditions, but require time consuming preprocessing steps and include risks of sample contamination during sampling.

We recently reported detections of C₂H₂ dissolved in the insulation oil using laser Raman spectroscopy technique (Somekawa et al., 2013). C₂H₂ is mainly produced at very high temperatures that occur in presence of arcing. C₂H₂ is not detected in transformers during normal operation, but concentrations as high as 1% are detected in presence of huge arcing (Duval and dePablo, 2001). Therefore, C₂H₂ is introduced as an effective indicator. Our approach does not require gas separation in oils and the gas content in the insulating oil is directly measured by irradiating laser. Based on this technique, on-line and in-situ detection of dissolved gases and byproduct materials can be adapted for diagnosis of transformer faults.

In this paper, we demonstrate that C₂H₂ and furfural in insulating oils can be directly detected by Raman spectroscopy. We found that Raman signals of C₂H₂ (~1972 cm⁻¹) and furfural (~1705 cm⁻¹) can be used for monitoring the transformer condition with no interfering peaks overlapping from the insulating oil. Hence, Raman spectroscopy could be a useful technique for in-situ transformer health diagnosis without the need for oil sampling.
2 EXPERIMENTAL

2.1 Raman Spectroscopy

Figure 1 shows the schematic diagram of Raman spectroscopy. The laser was a standard Q-switched Nd:YAG laser (Continuum, Surelite: 10 ns pulse-width with 100 mJ pulse energy at 10 Hz repetition rate) operating at its second harmonic wavelength of 532 nm. A non-focused laser beam having about 8 mm diameter was used to avoid laser induced damage of oil sample. The Raman signals from samples are collected using an achromatic lens at an angle of 25° from the forward direction of the laser beam. This design provides a longer optical path length than a conventional detection geometry at 90°, offering an order of magnitude increase in Raman scattering intensity. After passing through the edge and notch filters at 532 nm, the Raman signal is coupled into an optical fiber bundle by using an achromatic lens. The collected Raman signal is dispersed by a spectrometer (Acton, SpectraPro-2300i) with an entrance slit width set to 15 μm and detected with a liquid nitrogen-cooled charge-coupled device (CCD) camera (Princeton Instruments, SPEC-10). The exposure time was 90 ms. Accumulation numbers of C₂H₂ and furfural measurements were 3000 and 500, respectively. Higher accumulation number in the C₂H₂ detection was required to reduce the random noise in Raman spectra and improve the S/N ratio. The spectral resolution of this system was estimated to be about 5 cm⁻¹.

2.2 Sample Preparation

The insulating oil used in this work was a mixture of naphthenic(41.6%), paraffinic(50.0%), and aromatic(8.4%) oils. The used insulating oil samples were optically clear in visible region. The insulating oils were stored in glass bottles with diameters of 3 cm. We confirmed that the glass bottles had no effect on Raman spectra. After complete degassing in vacuum for 4 hours, high-purity C₂H₂ gas (more than 99%) was introduced via a gastight syringe. The C₂H₂ concentrations of the samples under the investigation were measured by the gas chromatography and had 1.9%, 5.7%, and 10% concentrations, respectively.

Furfural is only slightly soluble in this oil. Therefore, toluene solvent is added to oil. The concentration of toluene in oil was constant at approximately 9% for quantitative analysis. Furfural used in this experiment becomes yellow on exposure to air and light, but the spectrum obtained using 532 nm excitation is not dominated by fluorescence.

3 RESULTS AND DISCUSSION

3.1 Raman Spectrum of Oil

Figure 2(a) shows the Raman spectra of oil. In short and long edges of the spectrum, it exhibits numerous features that are specific to complex oil structures (Somekawa et al., 2013), however, it has no large Raman spectral features and relatively low background baseline between 1700 to 2500 cm⁻¹ range. The large peak centered at 1450 cm⁻¹ corresponds to CH₃-CH₂ bending mode, and the set of peaks at 1302 and 1350 cm⁻¹ corresponds to paraffin C-H twisting modes. The peak at 1610 cm⁻¹ is due to an aromatic C=C stretching mode. The band at 2725 cm⁻¹ can be assigned to the C-H stretching mode. In higher wavenumber side not shown here, the Raman spectrum of oil shows only C-H stretching mode around 3000 cm⁻¹, but no signals in the region between 3100 and 4200 cm⁻¹.

Figures 2(b) and 2(c) show the Raman spectra of furfural and toluene, respectively, as discussed below.

3.2 Raman Spectrum of C₂H₂ Dissolved in Oil

Figure 3 shows the spectra of C₂H₂ gas at different concentrations dissolved in the insulation oil. These Raman spectra were normalized at ~2191 cm⁻¹ Raman signal intensity peaks. Weak Raman signals were detected at 2191 cm⁻¹, which were assigned to the oil-derived Raman signal since its Raman peak intensity remained almost unchanged as the C₂H₂ concentration increased in the oil. On the other hand, Raman peak intensity of relatively sharp line at ~1972 cm⁻¹ increased linearly versus increasing C₂H₂ concentration. We assign the peak around 1972...
Figure 2: Raman spectra of (a) oil, (b) furfural and (c) toluene.

\[ \text{Raman shift (cm}^{-1}\text{)} \]

\[ \begin{align*}
0 & \quad 1000 \quad 1100 \quad 1200 \quad 1300 \quad 1400 \quad 1500 \quad 1600 \quad 1700 \quad 1800 \quad 1900 \quad 2000 \quad 2100 \quad 2200 \quad 2300 \quad 2400 \quad 2500 \quad 2600 \quad 2700 \\
\text{Intensity (arb. unit)} & \quad 0 \quad 0.2 \quad 0.4 \quad 0.6 \quad 0.8 \quad 1
\end{align*} \]

Figure 3: Raman spectra of C\(_2\)H\(_2\) gas at different concentrations dissolved in the insulation oil.

Figure 4: Raman peak intensity ratio \(I_{1972cm^{-1}}/I_{2191cm^{-1}}\) as a function of dissolved C\(_2\)H\(_2\) concentration in oil.

is degraded due to the variation in the excitation laser intensity and changes in the sample matrix. The oil-derived Raman signals at \(\sim 2191 \text{ cm}^{-1}\) were used for these analyses. Figure 4 shows Raman peak intensity ratios, \(I_{1972cm^{-1}}/I_{2191cm^{-1}}\), as a function of C\(_2\)H\(_2\) concentration. The error bars were evaluated using the standard deviation of 10 consecutive spectra. The slope of the linear fit is 0.0825. Therefore, the C\(_2\)H\(_2\) concentration is determined by this slope and the Raman peak intensity ratio. Also, we estimated the detection limit of the present system to be \(3\sigma_{C_2H_2}~0.37\%\), where \(\sigma_{C_2H_2}\) is the standard deviation of the Raman spectra from C\(_2\)H\(_2\) free oil sample (0%) in 1952-1977 cm\(^{-1}\) spectral range. Thus, the high C\(_2\)H\(_2\) concentrations (~1%) observed in actual insulating oils are detectable with current Raman system. On the other hand, the detection limits could be improved by using longer path length oil sample, higher average power CW laser, and more sensitive CCD detector.
3.3 Raman Spectrum of Furfural in Oil

Figure 2 shows the Raman spectra of (b) furfural and (c) toluene. The furfural Raman spectrum shows a H-C-C/O bending mode at 1372 cm\(^{-1}\), C-C stretching mode at 1398 cm\(^{-1}\), C=C stretching modes at 1478 and 1573 cm\(^{-1}\), C=O stretching modes at 1675-1705 cm\(^{-1}\) (Kim et al., 2011). As shown in Fig. 2(c), the measured Raman spectrum of toluene includes no spectral interferences caused by Raman band overlap over ~1600 cm\(^{-1}\). Detailed toluene mode assignments can be found elsewhere (Hameka and Jensen, 1996).

Figure 5 shows Raman spectra of furfural at different concentrations in oil in the presence of toluene (~9%) as a solvent.

The furfural spectrum clearly shows an additional C=O stretching mode at 1675-1705 cm\(^{-1}\), which is not found in oil. Thus, we can easily distinguish furfural from oil using this Raman band. Figure 5 shows Raman spectra of furfural at different concentrations in oil, in the presence of toluene (~9%) as a solvent. Raman peak intensity at ~1705 cm\(^{-1}\) increased linearly versus increasing furfural concentration. The spectral shape differences between Fig. 2(b) and Fig. 5 can be observed at 1675-1705 cm\(^{-1}\), which may be due to strong solvent interference (Allen and Bernstein, 1955).

Figure 6 shows Raman peak intensity ratios, \(I_{1705\text{cm}^{-1}}/I_{1608\text{cm}^{-1}}\), as a function of furfural concentration in oil. The Raman ratio at 1705 cm\(^{-1}\) shows a linear dependence on the furfural concentration in contrast to the non-linear relationship between the Raman ratio at 1687 cm\(^{-1}\) and furfural concentration. In this study, as a furfural-concentration-invariant signal, we choose the Raman peak of oil and toluene mixture at 1608 cm\(^{-1}\). The error bars were evaluated using the standard deviation of 5 consecutive spectra and were hidden in the plot symbols. These ratios can be reasonably well fitted by a line with a slope of 0.643. We estimated also the detection limit of the present system to be \(3\sigma_F\sim 65\) ppm, where \(\sigma_F\) is the standard deviation of the Raman spectra from 0.08% furfural sample between 1720 to 1750 cm\(^{-1}\) range. However, the permissible concentrations of furfural in oil are 1.5 and 15 ppm at caution and danger levels, respectively (Okabe et al., 2013). Therefore, further development of the measurement system is needed to improve sensitivity.

4 CONCLUSIONS

We demonstrated in-situ application of Raman spectroscopy for detection of C\(_2\)H\(_2\) and furfural in the insulating oil to diagnose the transformer health. Our method also has the advantage of simplicity, time savings and non-requirement of sample preprocessing. In addition, the Raman spectroscopy could simultaneously monitor multi-trace gases and byproduct materials to get relevant information about the transformer condition.

In future research, sensitivity improvements of our Raman spectroscopy system will be performed. We believe it can be generally applied for assessing the transformer conditions.

REFERENCES


