Methane Detection at Low Concentration Based on 2f Harmonic Signal

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Abstract. This paper presents the methane detection at low concentration based on 2f harmonic signal to achieve highly sensitive monitoring. Since methane is the characteristic gas in power transformer oil once a thermal fault at low temperature (<300°C). Based on wavelength modulation and tunable diode laser absorption spectroscopy(TDLAS) technique, the specific mathematical modeling of infrared gas absorption process, the input signal and the second harmonic signal after the methane gas through the absorption is calculated. Especially, the phase-sensitive detector lock-in amplifier is adopted to improve the sensitivity. Finally, the performance of the proposed methane detection schedule is simulated at the low hydrogen concentration. The results prove that the proposed optical detection has a high sensitivity of 0.052V at every 1 μL/L.

Introduction

Dissolved gas analysis (DGA) is the study of dissolved gases in transformer oil [1-3]. Insulating materials within transformers and electrical equipment break down to liberate gases within the unit.

Thermal faults are detected by the presence of by-products of solid insulation decomposition. The solid insulation is commonly constructed of cellulose material. The solid insulation breaks down naturally but the rate increases as the temperature of the insulation increases. When an electrical fault occurs it releases energy which breaks the chemical bonds of the insulating fluid. Once the bonds are broken these elements quickly reform the fault gases. Oil overheating results in breakdown of liquid by heat and formation of methane, ethane and ethylene [4,5].

A small amount of decomposition occurs at normal operating temperatures. As the fault temperature rises, the formation of the degradation gases change from Methane (CH4) to Ethane (C_2H_6) to Ethylene (C_2H_4). A thermal fault at low temperature (<300°C) produces mainly Methane and Ethane and some Ethylene [6,7]. So it is very important to detect the methane in power transformer oil.

Principle of harmonic detection

The basic principles of harmonic detection is performed by wavelength modulation (e.g., sinusoidal modulation) with a related frequency signal. The signal is scanned to cover the measured signal. Then a frequency-multiplied signal modulation frequency or the modulation frequency is acted as a reference signal to be input into the lock-in amplifier. The information of the harmonic signal is recorded. The theoretical basis of harmonic detection principle is the Fourier transform and the feature object to be measured can be described by a certain mathematical model. When the gas absorption coefficient is known, it can be analyzed to give a concentration of gas. The schematic of wavelength modulation spectroscopy (WMS) is shown in Fig. 1.

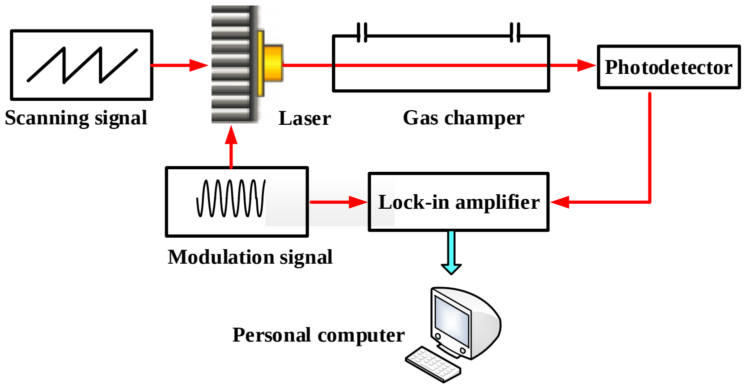

Fig. 1 Schematic of wavelength modulation spectroscopy

When the center frequency of the light output is accurately locked on the gas absorption peak, that is to say, $u_0 = u_c$. The detected signal can be obtained as:

$$I = I_0[1+n\sin wt - \frac{a_0 c L}{1+w^2\sin^2 wt}] \tag{1}$$

$$w = \frac{u_f}{{}_{\Delta}u} \tag{2}$$

where , I_0 is the input signal amplitude,

n is the light intensity coefficient,

c is the measured gas concentration,

L is the effective optical path,

ν_f is the frequency modulation amplitude,

Δn is the half width at half maximum (HWHM).

Eq. 1 can be expanded into Fourier series sequence. Since the higher harmonic amplitude is too small to be ignored in this situation. And the second harmonic (2f) coefficients is shown as Eq. 3

$$I_{2f} = -\frac{2[2+w^2-2(1+w^2)^{0.5}]}{w^2(1+w^2)^{0.5}} a_0 c L I_0 \tag{3}$$

It is can be concluded that the amplitude of the second harmonic signal intensity is related to initial gas concentration, thus the gas concentration information can be obtained by extracting second harmonic signal.

Calculation and simulation of the methane detection

A low frequency sawtooth (sawtooth frequency 10Hz) superimposing a high-frequency sine (sine wave frequency 5kHz) modulation signal is adopted as the laser driving signal. According to the description of Eq. 1, infrared gas abides by Beer Lambert law absorption principle. The gas absorption signal is obtained after the signal is fed to lock-in amplifier. Reference signal is a square wave signal, and the frequency of the square wave signal is superimposed cosine (or sine) signals of the second harmonic. In addition, integral operation is taken to analog low-pass filter function. The laser drive waveform shown in Fig. 2. As well, Gas absorption waveform modeling (no intensity modulation) is shown in this figure.

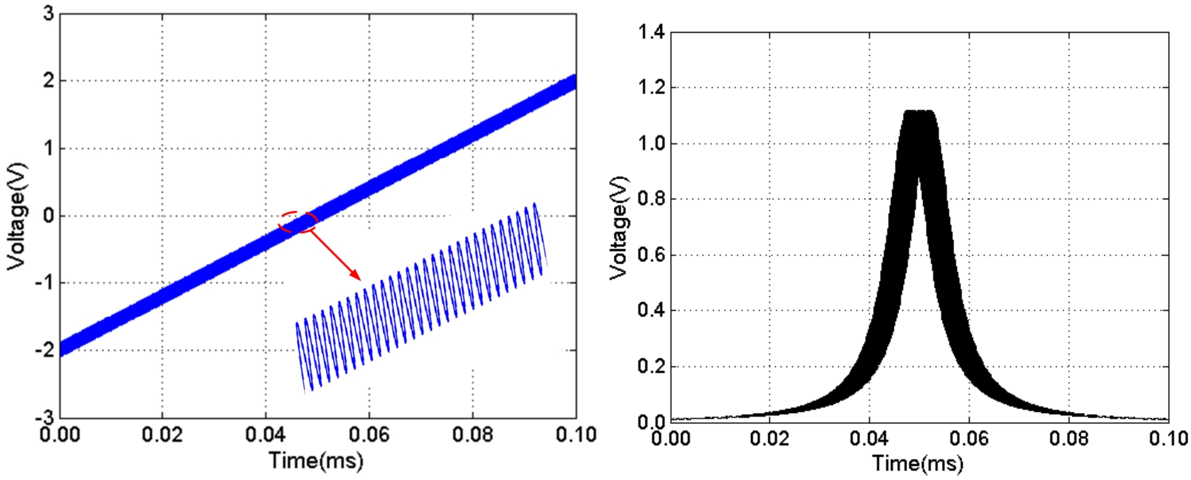

Fig. 2 The laser drive waveform and Gas absorption waveform (without intensity modulation)

The methane gas concentration value is changed in the program, and they are taken as the concentration $c_1 \sim c_5$. Then the second harmonic signal is output, and the second harmonic amplitude can be calculated. Second harmonic signal at different concentrations is shown in Fig. 3.

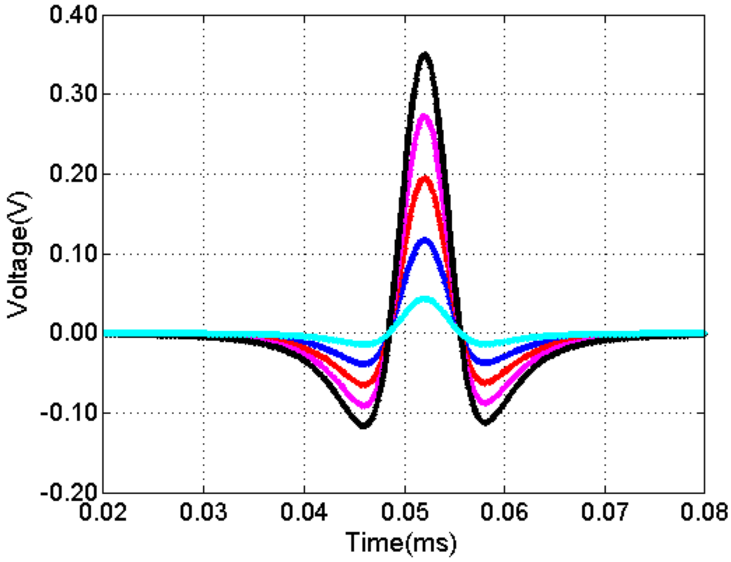

Fig. 3 The second harmonic signal at different methane concentrations

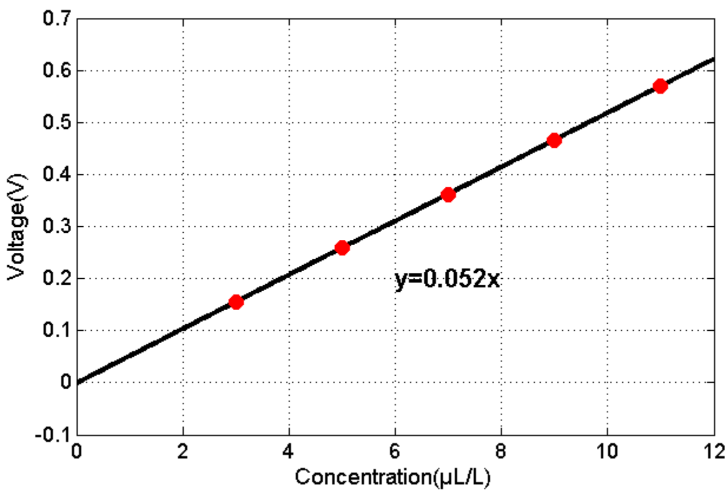

Fig. 4 Fitted curve at different concentration of methane

Through the above five sets of data, it shows that gas concentration is in a proportional relationship to the magnitude of the second harmonic signal and within a certain range. Fitted equation is as follows:

$$y = 0.052c(CH_4) \quad (4)$$

Where c is the methane concentration (μL/L), and y is the amplitude of 2f signal (V).

The methane detection based on 2f harmonic signal had good linearity and good sensitivity according to the test data. The wavelength increases 0.052 V when hydrogen density increases 1 μL/L

Conclusion

In the paper, the basic principles of gas detection is described, comprising an infrared absorption spectrum theory, TDLAS technical principles, harmonic detection principle and the principle of phase-sensitive detector lock-in amplifier. Based on the above principles and the specific mathematical modeling of infrared gas absorption process, the input signal and the second harmonic signal after the methane gas through the absorption is calculated. The simulation and analyses proves that the second harmonic signal is proportional to the gas concentration. This article provides a theoretical basis for the subsequent circuit design TDLAS gas detection in the second harmonic with the help of lock-in amplifier.

Acknowledgements

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