Multi-Gas Detection in Power Transformer Oil Based on Tunable Diode Laser Absorption Spectrum

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ABSTRACT

Online dissolved gas analysis (DGA) is an effective technique to obtain the health status information of insulation oil in power transformers. The typical hydrocarbon gases (methane, ethyne, ethene, ethane) decomposed from insulation oil, are the key indicators to diagnose the fault type and severity. To realize contactless and field measurement, a multi-gas detection system based on tunable diode laser absorption spectrum (TDLAS) is proposed in this paper. Critical technique problems on the light source, long path gas cell, and the topology for multi-gas detection are investigated. Individual central wavelengths of hydrocarbon gases are set at as 1653.72 nm for methane, 1530.37 nm for ethyne, 1620.04 nm for ethene and 1679.06 nm for ethane in the near infrared band. A 10.13 m long multi-pass gas cell is developed with the advantage of anti-vibration design. To share the optical absorption path, an optical switch is adopted to merge the multi-gas detection system. The high sensitivity of the TDLAS multi-gas detection system was demonstrated in the laboratory calibrations, with ethyne detection reaching sub-parts per million level, and the other hydrocarbon gases achieving ppm level. Furthermore, the comparison detection in the real 220 kV power transformer gave evidence to the effective monitoring of DGA, proving it an alternative approach to online detection of multiple gases in power transformer oil.

Index Terms — **insulation oil, power transformers, gas detectors, optical beams, infrared measurements**

1 INTRODUCTION

OIL-IMMERSED power transformers are the most critical and costly equipment in the power grids, which is often regarded as the "heart" of the power system. Transformer oil is an important medium for the normal operation of transformers, playing a significant role of insulation, cooling, and extinguishing arcing [1-3]. Unexpected failures at any period in the transformer lifecycle have serious consequences. To decide when, what and how to maintain the power apparatus, the strategy of condition based maintenance (CBM) has received widespread recognition [4, 5]. Wherein, dissolved gas analysis (DGA) technique is used to monitor the dissolved gases in the transformer oil [6].

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Transformer oil, mainly composed of hydrocarbons, contains carbon (C) and hydrogen (H) atoms linked by C-C and C-H chemical bonds. The chemical bonds are easily broken when thermal or electrical faults are stressed over the time. Active H atoms and hydrocarbon fragments are rearranged to form small molecular hydrocarbon gases, typically, methane (CH_4), ethyne (C_2H_2), ethene (C_2H_4), and ethane (C_2H_6). According to the Duval Triangle Model (IEC 60599), the total accumulated amount of the key gases (CH_4, C_2H_2, and C_2H_4) can be used to decide the specific fault types according to the ratios associated with each gas [7, 8]. Thus, it is no doubt that the precise detection of dissolved gases is the cornerstone of reliable judgement on the potential defects in power transformer oil.

Various techniques for detection of dissolved gases in transformer oil have been proposed and implemented. Gas

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chromatography (GC) method is mostly used as quantitative measurement in the laboratory and default off-line routine tests [5, 9]. With regard to online DGA detectors, there are mainly two categories: physical/chemical techniques and optical methods. Generally, physical and chemical gas detectors include thermal conductivity detectors (TCD), flame ionization detectors (FID), semiconductor detectors, electrochemical detectors, catalytic combustion detectors, palladium gate FET (field effect transistor) detectors, array gas sensors, etc. [10] The manufacturing processes of these detectors are relatively mature and the mass production costs are low. However, the regular replacement and calibration will increase the workload of operation and maintenance due to the relatively poor long-term stability of physical/chemical detectors. In addition, most physical/chemical techniques rely on the external carrier gases. In recent years, with the development of related technologies, solid oxide fuel cell sensors [11], carbon nanotube sensors [12], and nano metal-oxide semiconductor sensors [13] have been proposed and researched. Part of the detector performance has been improved. But the problems, such as being susceptible to aging, saturation, electromagnetic compatibility and impurity contamination, have to be considered in the future exploration.

Optical techniques came into the field of DGA owing to their superiority of non-contact measurement and immunity to electromagnetic interference. Especially, photoacoustic spectroscopy (PAS) devices, based on the photoacoustic principle, have been developed and installed [14, 15]. It has been verified that the optical techniques can detect multiple components simultaneously without consuming the fault gases [16, 17]. Gas chromatographic columns, which are often used to separate different types of gases in physical/chemical occasions, are unnecessary in the optical techniques. Nevertheless, PAS is susceptible to many factors, such as noises, incident laser power and temperature. Especially, vast noise sources are difficult to eliminate and control in the actual application, which can affect the detection sensitivity. Several optical techniques are researched as well. Chen *et al* [18] carried out optical detection of DGA based on laser Raman spectroscopy (LRS). Based on Fourier transform infrared spectroscopy (FTIR), Tang *et al* [19] utilized algorithms to enhance the measurement. Although the high sensitivity had been achieved, the complex and fragile components are not suitable to the field application. In addition, fiber Bragg gratings (FBG) also has been tried to detect dissolved hydrogen [20], but it is inapplicable to hydrocarbon gases due to the lack of corresponding sensing materials. To solve the problems of current optical techniques, tunable diode laser absorption spectroscopy (TDLAS) technique has been proposed to complete methane and ethyne detection [21], showing the advantages of real-time detection, high signal-to-noise ratio, high reliability, sample-free and non-destructive measurement, etc. However, only single-component detection is available, it's hard to meet the actual needs [14, 22]. Particularly, the information of multiple components are essential in DGA to diagnose the exact status of insulation oil.

In this paper, based on the TDLAS principle, a multi-gas (methane, ethyne, ethene, and ethane) optical detection system is proposed and researched. There are mainly three problems need to be analyzed and solved: light source, long path gas cell and the topology. To avoid the cross interferences, specific central wavelengths of different gases are considered and selected in the near infrared bands. Long light path is essential to sensitive detection, which is vulnerable to vibration in actual use. This issue is also focused in the manuscript. A time-sharing tropology for multiple gases is put forward to merge the optical path. In the laboratory, each hydrocarbon gas is calibrated. Then the field application and tests have been implemented.

2 PRINCIPLE OF TDLAS DETECTION

2.1 TUNABLE DIODE LASER ABSORPTION SPECTROSCOPY TECHNIQUE

TDLAS technique is an alternative of direct absorption spectrum by measuring a high-resolution target spectral region with a tunable sweeping diode laser source. Since ro-vibrational absorption lines of different gases locate at specific spectral bands, the characteristic absorption finger print of a particular species of interest should be identified. According to the Lambert-Beer absorption law, the incident/emitted intensity variation is related to the path of the laser beam and concentration of the species in specific wavelength, neglecting scattering and reflection process. The quantified expression of laser output and gas concentration is given by Equation (1) [23].

$$I(\tilde{\upsilon})=I_0(\tilde{\upsilon})\cdot\exp[-\alpha(\tilde{\upsilon})\cdot c\cdot L] \tag{1}$$

where

$\tilde{\upsilon}$ is wavenumber, which indicates the number of light waves per unit length (1 cm) in the direction of light propagation, cm^{-1}, $I_0(\tilde{\upsilon})$ and $I(\tilde{\upsilon})$ are initial intensity and transmitted intensity of the laser beam after traversing the medium respectively, mw, c is the number density or the average concentration of absorbing gas, μL/L, L is the traversing distance of the laser beam in the absorbing medium, m and $\alpha(\tilde{\upsilon})$ is the absorption cross-section of the absorbing gas of interest, cm/mol.

The exponential term can be seen as the absorbance coefficient of the gas, δ , related to the line strength and lineshape function at the specific temperature and pressure,

$$\delta=\text{-In}(\frac{I(\tilde{\upsilon})}{I_0(\tilde{\upsilon})})=\alpha(\tilde{\upsilon})\cdot c\cdot L \tag{2}$$

Due to the line strength of gas medium is extremely weak ($10^{-5}\sim 10^{-7}$), the transmitted intensity is calculated as

$$I(\tilde{\upsilon})=I_0(\tilde{\upsilon})\cdot\exp(-\delta)\approx I_0(1-\delta) \tag{3}$$

Since the light intensity signal received by the detector is mixed with a large amount of background noise signals, it is not conducive to directly measuring the concentration. The laser beam is proportional to the drive current. To achieve the harmonic modulation of the transmitted signal, the cosine modulation of the injection current of the laser is adopted,

$$_{\Delta}I\cos\omega t\rightarrow(I_0+{}_{\Delta}I\cos\omega t)(1-\delta) \tag{4}$$

The $\alpha(\tilde{\upsilon})$ is expanded into Fourier series to get the expression as:

$$\alpha(\tilde{\upsilon})\Big|_{\tilde{\upsilon}=\upsilon_0} = \alpha(\upsilon_0 + {}_{\Delta}\upsilon\cos\omega t) = \sum_{n=0}^{\infty} H_n(\upsilon_0)\cos n\omega t \quad (5)$$

where

H_n is the order of n harmonic modulation coefficient Fourier component, which can be detected through lock-in amplifier at the frequency of $n\omega$.

Then the transmitted intensity is:

$$I(\tilde{\upsilon})\Big|_{\tilde{\upsilon}=\upsilon_0} = I(\upsilon_0)[1 - c\cdot L\sum_{n=0}^{\infty} H_n(\upsilon_0)\cos n\omega t] \quad (6)$$

It is possible to establish the relationship between the gas concentration and the harmonic signal. Due to the amplitude of high order of harmonic component, the second harmonic signal (2f) is preferred to be detected and calculated [24]. The signal processing was illustrated in Figure 1. When there is no gas of interest absorbed in the light path, PD output is proportional to the modulated intensity of tunable laser source, as shown in Figure 1(a) and (b). Once there exists the gas of interest, the absorption region appears during the PD detection cycle, and the absorption signal is easy to be obtained through lock-in amplifier, as shown in Figure 1(c) and (d). Since the output intensity of laser is varied with the injected modulation current, the 2f harmonic signal in Figure 1(e) is actually asymmetric around the central position.

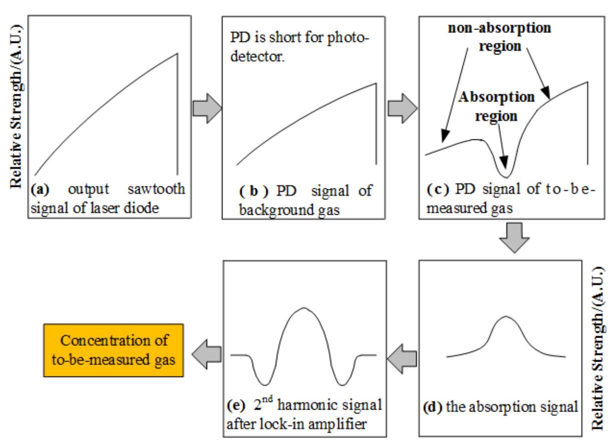

Figure 1. Illustration of signal processing through TDLAS, the horizontal axis of figure (a) ~ (d) is the wavelength (nm) and the horizontal axis of figure (e) is time (ms).

2.2 ESTABLISHMENT OF MULTI-GAS SYSTEM

Generally, a typical TDLAS hardware system is mainly composed of light source and its drive unit, gas cell (absorption light path), photodetector, control and DAQ device, as shown in Figure 2. It is relatively mature to utilize the TDLAS system to detect industrial gases in various applications. However, multiple gases measurement, cross-interference, high sensitivity and vibration of practical application should be taken into consideration, it is not possible to apply the similar device to online dissolved gases detection in power transformer directly.

To analyze the influence factors of hydrocarbon multi-gas detection system, single component detection and multi-component switching part are taken into consideration respectively. For single gas detection, the detection is closely related to gas absorption intensity, cross sensitivity and noise level. Among them, the absorption intensity is determined by absorption coefficient and light path, depending on the laser source and gas cell ultimately. The mind map and logic analysis is illustrated in Figure 3. To achieve the multiple gases detection and improve the measurement effect, there are three problems need to be solved.

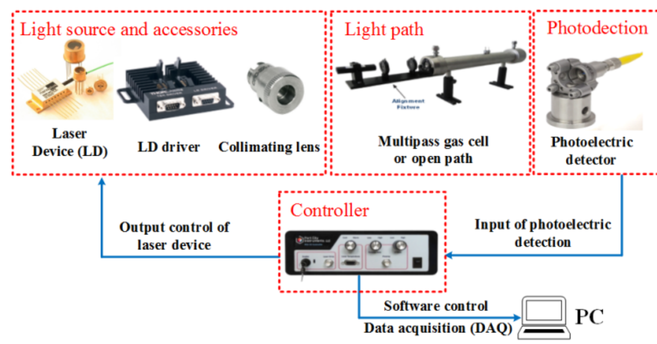

Figure 2. Main hardware components in a typical TDLAS system.

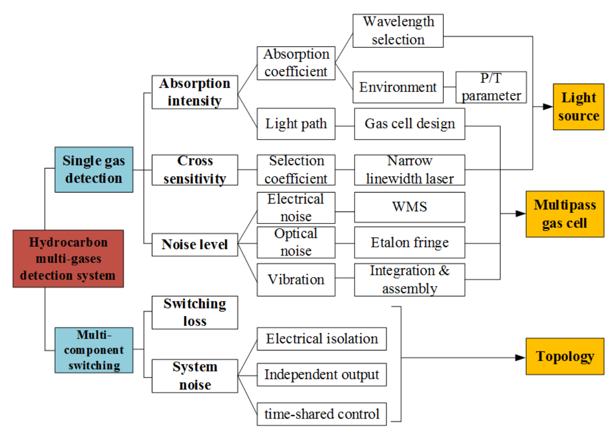

Figure 3. Influence factors of hydrocarbon gases detection system.

(3) Switching topology. Since the individual laser is adopted to multiple hydrocarbon gases, output and temperature of each laser source should be controlled independently to avoid mutual interference. Using optical switch or coupler is an approach to merge the multiple fiber channels into one through time-sharing strategy.

(1) Laser source. In order to improve the selectivity of single-component gas detection and avoid cross-interference of hydrocarbon gases, high-performance and narrow-line-width laser light sources should be selected.

(2) Gas cell. To increase the effective absorption of laser beam, design and integration of long optical path gas cell is critical. Meanwhile, different from the laboratory tests on optical platform, vibration issue should be considered in the real application.

3 EXPERIMENTAL SETUP OF TDLAS SYSTEM

3.1 OPTICAL LASERS

In the TDLAS system, the laser is not only a light source, but also a guarantee of spectral subdivision. This requires the spectral width of the laser to be much smaller than the width of the absorption peak, as shown in Figure 4. Rapid tuning (higher than 1kHz) can be adopted to obtain the information of the entire absorption peak. When it comes to the selection of light source, the following issues are considered in this study.

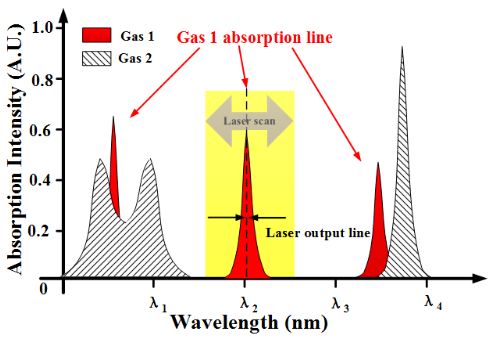

Figure 4. Schematic diagram of absorption line selection.

(1) Transmission band. Basic gas absorption bands are generally located in the mid-infrared (MIR) region. High detection sensitivity can be obtained using mid-infrared lasers. However, different gases have different absorption peaks, making the system complicated, expensive, and difficult to integrate. Near-infrared (NIR) lasers can operate at room temperature and can cover various absorption bands, but the gas absorption intensity is weak. Long-path absorption cells and wavelength-modulation spectroscopy techniques can be used to increase detection sensitivity. Therefore, the near-infrared region (defined by the ASTM Working Group on NIR as 780 nm to 2526 nm) is preferred in this research. Last but not least, the transmission loss of the fiber is relatively low in NIR, especially optical telecom bands (O band: 1260-1360 nm; E band: 1360-1460 nm; S band:1460-1530 nm; C band: 1530-1565 nm; L band: 1565-1625 nm; U band: 1625-1675 nm), as shown in Figure 5. With the aforementioned consideration, absorption lines in telecom bands are focused in this study.

(2) Central wavelengths. In the selection of absorption lines, two factors are mainly considered: one is the intensity of the absorption line, and the other is to avoid mutual interference between lines of the gases dissolved in the transformer oil. For example, the E-band represents the water peak region, the wavelength in this band won't be selected. As a result, the following central wavelengths: 1653.72 nm for methane, 1530.37 nm for ethyne, 1620.04 nm for ethene and 1679.06 nm for ethane, are selected.

(3) Linewidth. The linewidth of a laser is a parameter to indicate the width (typically the full width at half-maximum, FWHM) of its optical spectrum. Lasers with very narrow linewidth, implying high degree of monochromaticity, are preferred in this application.

(4) Optical output. Low optical output is unbeneficial to the absorption process. The mW level lasers are used in this case.

(5) Laser type. DFB (Distributed Feedback Laser) is chosen due to its advantages of better dynamic-single stability, lower noise operation and smaller volume.

3.2 MULTI-PASS GAS CELL

In the trace gas detection, the light path design of TDLAS system has a great influence on the system performance. Beer-Lambert Law indicates that, for a certain gas, the signal attenuation caused by gas absorption and gas concentration are positively correlated. By increasing the optical path, the intensity of the attenuated signal can be effectively increased. Therefore, a long optical path gas cell should be established for the high sensitivity.

Traditional multiple-reflection long-range gas chambers mainly include Herriott cells and White cells. Compared to the White cell, the Herriott cell consists of only two spherical mirrors, and the optical system is relatively simple. The design of the long optical path gas chamber can also be realized within a short distance and its optical path is easy to adjust. Although its aperture angle is smaller than that of the White cell, it does not make any difference since the light source is laser type in this system. Therefore, Herriott structure is preferred in our case. However, when the ambient temperature and gas pressure in the cell vary, the spectral width and amplitude of the to-be-measured gas will change, resulting in

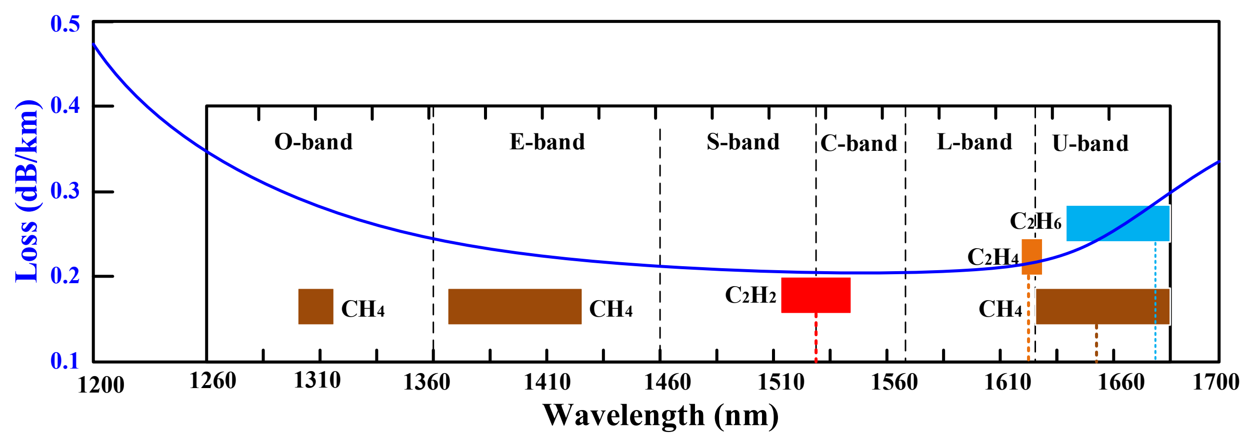

Figure 5. Absorption wavelength distribution of four hydrocarbon gases.

the deviation of the measured gas concentration. In addition, the vibration of the cell is inevitable in the field application. Thus, it is necessary to design a specialized Herriott cell with the consideration of temperature, pressure and vibration.

To control the ambient parameters, pressure and temperature sensors are utilized in the Herriott cell. Since the vacuum degassing is an effective technique in the oil-gas separation, the pressure in the cell is expected to be lower than normal atmosphere. Honeywell 19 Vacuum Gage series sensor is mounted on the gas cell, which is compatible with 316 stainless steel. The special Vacuum Gage series sensors are specifically designed for applications that can be exposed to vacuum. As well, temperature sensor and heating belt are designed around the cell, to maintain a stable temperature.

To reduce the influence of vibration, it is essential to keep the optics relatively fixed. In this way, we make the photodetector (PD), collimator and gas cell as a whole through mechanical connection. Last but not least, a flexible pipeline is used from the cell to the vacuum pump to keep away from the vibration. A customized Herriott gas cell was developed in our study. Long optical path of 10.13 m was achieved within 0.34 m mechanical length, as shown in Figure 6. Detail parameters of the gas cell are shown in Table 1.

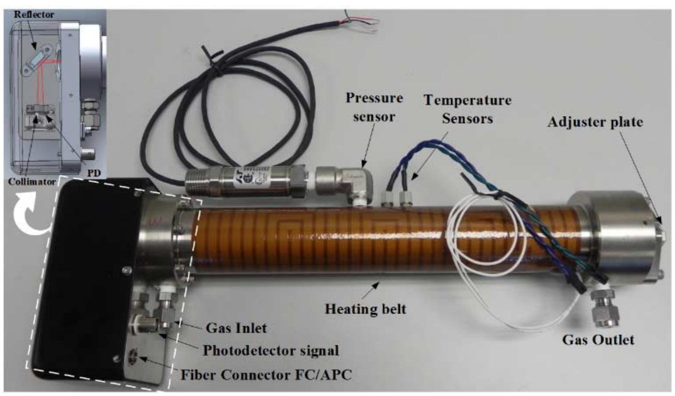

Figure 6. Structure view of the specialized long-path Herriott cell.

Table 1 Technical parameters of the specialized Herriott cell.

Items	Specifications
Optical path length	10.13 m
Volume of gas cell	0.24 L
Number of reflections	34
Reflectance of reflector	≥98.5%
Angle of incidence	2.07°
Diameter of coupling hole	3.3 mm
Maximum beam diameter	3.0 mm
Surface accuracy of mirror	1/10 Wavelength
Surface roughness of mirror	20~10
Mirror coating	Gold (HfO_2)
Length of gas cell	340.0 mm

3.3 TOPOLOGY OF MULTI-GASES DETECTION

Due to the different central wavelengths of the hydrocarbon gases are selected, four individually controlled lasers are used. Four thermoelectric (TEC) controller modules and FPGA (field programmable gate array) boards are utilized to drive and control each of them independently. The TEC is to maintain the temperature stability of laser and the FPGA is to precisely control the laser output and to record the measurement data. Single gas cell configuration is more favorable since the wavelengths of the four lasers are close to each other. It means that there are four incident light and one output light. Thus, an optical coupler or a fiber switch is essential to switch the laser channels in sequence to the Herriott cell. The results of two optical components are compared in the same condition, as shown in Figure 7. The fiber switch is selected since the optical switch scheme has a much better signal-to-noise (SNR) performance.

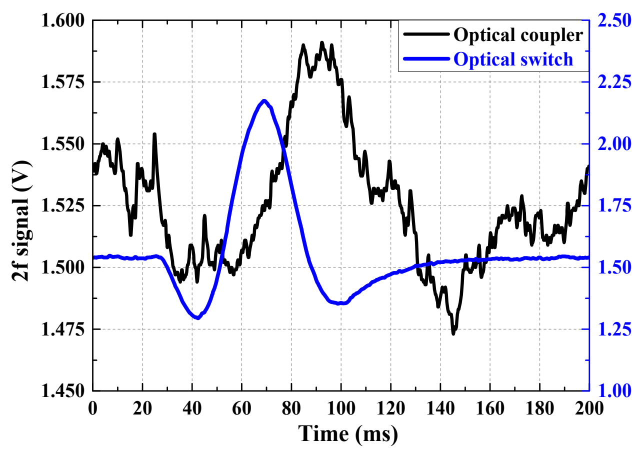

Figure 7. Comparison of optical coupler vs. optical switch.

The configuration of the TDLAS-based hydrocarbon gases detection system is shown in Figure 8. The entire system consists of four parts: the light source control unit, the laser launch and receive unit, the gas cell and gas path, and the data acquisition unit. The light source control unit comprises four FPGAs, four TECs, four DFB lasers, and an optical switch. The light source control unit realizes the modulation output of the light sources. The light launch and receive unit includes an optical fiber collimator and a photodetector, to complete the light source's collimated output and light intensity detection. Gas cell and gas path unit contains specialized Herriott cell, gas inlet pipe, outlet pipe, pressure/temperature sensor, auxiliary temperature control module, etc. The data acquisition unit, which mainly includes a lock-in amplifier, a preamplifier, a data acquisition device NI-USB-6341 and a computer, completes the collection, recording and gas concentration inversion of harmonic signals. In order to improve the integration and stability of the system, the modulation signal generator, controller, preamplifier and lock-in amplifier are all integrated on a single FPGA printed circuit board (PCB).

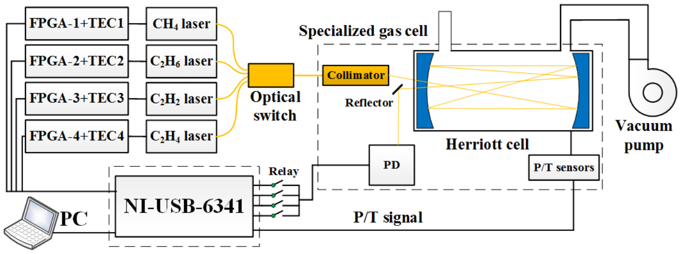

Figure 8. System configuration of TDLAS for hydrocarbon gases in transformer oil.

In our study, the basic sinusoidal sine wave (1f modulation) frequency is set to 31.4 kHz to avoid the low frequency noises. Consequently, the frequency of FPGA-based 2f demodulation is 62.8 kHz.

4 RESULTS AND ANALYSIS

4.1 LABORATORY TESTS

Measurements of spectral absorption of methane, acetylene, ethylene, and ethane were conducted in the laboratory to identify their detection sensitivity. Mass flow controller (MFC) was utilized to obtain different concentration of hydrocarbon gases, such as 50, 100, 200, and 500 μL/L. Nitrogen (N_2) was selected as the balance gas since it is chemically stable and has no spectral absorption. The mixed gases were pumped into the specialized Herriott gas cell respectively.

Typically, the 2f signal of the absorption spectrum (CH_4 as an example) is shown in Figure 9. As aforementioned, the residual amplitude modulation (RAM) phenomenon occurred and the peak-to-peak voltage value (PPV) reflected the absorption strength.

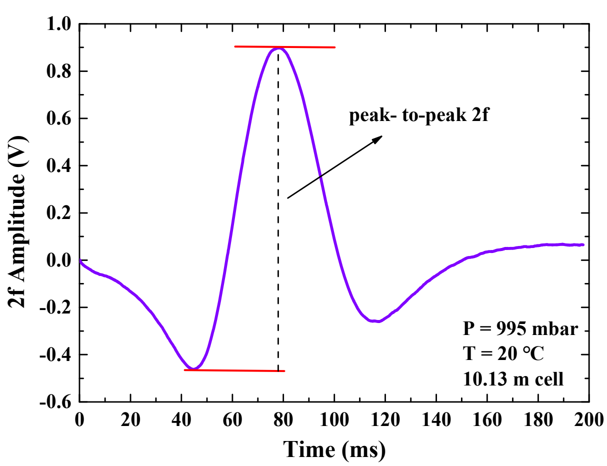

Figure 9. Typical absorption spectrum of methane.

PPV of 2f signal of methane, ethyne, ethene, ethane with different concentrations and the linear relationship between them are shown in Figures 10–13.

As shown in Figures 10–13, PPV is the peak-to-peak value of the second harmonic voltage detected by the sensing device in the unit of V; the unit of each gas concentration is μL/L. The fitting curves indicate that the sensor has good linearity and good sensitivity. Take methane measurement as an example, the concentration of methane increases by 100 μL/L and the voltage increases by 0.086 V.

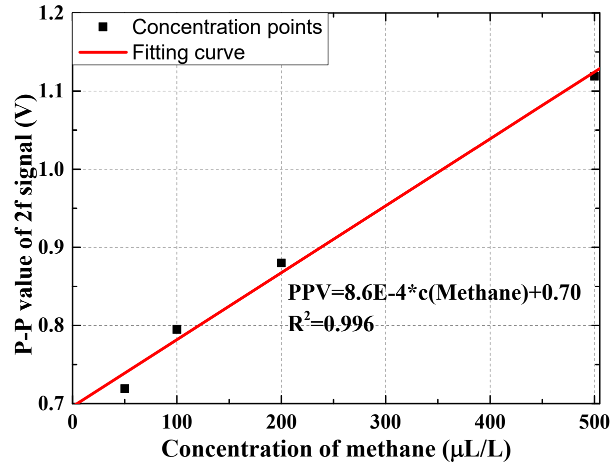

Figure 10. 2f signals of methane at different concentrations.

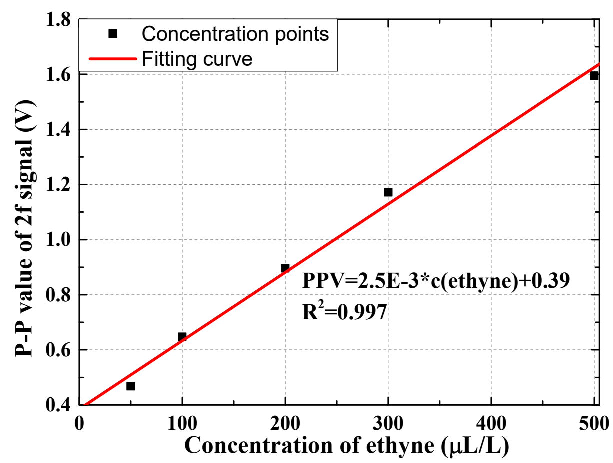

Figure 11. 2f signals of ethyne at different concentrations.

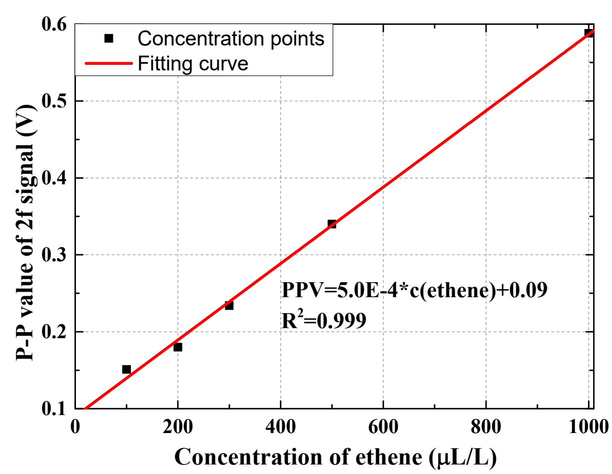

Figure 12. 2f signals of ethene at different concentrations.

To investigate the detection performance of the various gases, the noise level and signal-to-noise ratio (SNR) are essential to be considered. As to the gas detection, the noise amplitude is controlled at mV level. Accordingly, the detection sensitivity of methane and ethyne reaches 1.2

(μL/L)/mV and 0.4 (μL/L)/mV respectively. And the sensitivity of ethene and ethane is measured to be 2.0 (μL/L)/mV and 2.86 (μL/L)/mV.

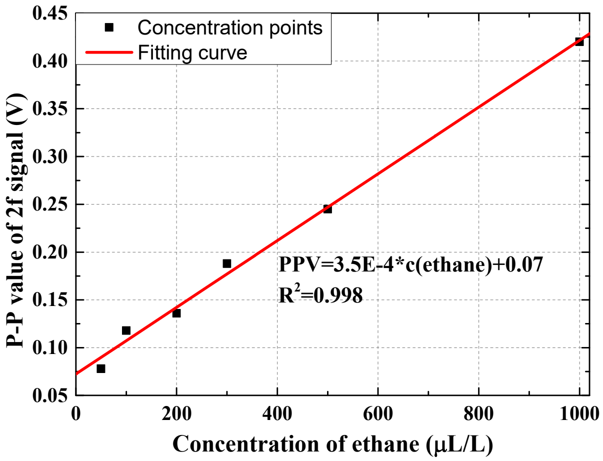

Figure 13. 2f signals of ethane at different concentrations.

In summary, the high linearity and high sensitivity seen in the calibrations demonstrates the effectiveness of the proposed TDLAS based multi-gas detection system, satisfying the requirement of the latest IEEE Guide for the Interpretation of Gases Generated in Oil-Immersed Transformers [25]. In particular, the sub-ppm level sensitivity for the detection of ethyne, which is the indicating gas of high intensity discharges, helps to find incipient faults in power transformers.

4.2 FIELD APPLICATION

Online dissolved gas analysis based on the proposed optical sensing technique was deployed in China Southern Power Grid (CSG), Zhaoqing city. The system was installed in # 1 main transformer, Duanzhou 220kV substation, integrated with TDLAS based hydrocarbon gases sensing system. A high-reliability cable is used to connect to the communication module.

To ensure the reliability and stability of the system, the optical module was placed in a compartment with properly controlled temperature and humidity. Mechanical structure of the multi-gas detection system was designed and assembled to control the oil & gas path, as illustrated in Figure 14. Additionally, a specific software was compiled and combined with the warning information to build an online monitoring and fore-warning system.

On-line detections of transformer dissolved gases with our TDLAS technique based equipment, as shown in Figure 15, have been conducted. A comparison test between developed online DGA device and existed DGA equipment were carried out in the same circulating oil path of the main transformer.

The field test results of our TDLAS device were compared with the original DGA equipment of the transformer, as shown in Table 2. Four hydrocarbon gases and the total hydrocarbons (THC) value were listed.

The high consistence of the field tests data and the high agreement of the TDLSA results to that of the reference DGA manifests the practicality of our TDLAS based DGA device in monitoring symbol gases concentration of transformer oil in the field.

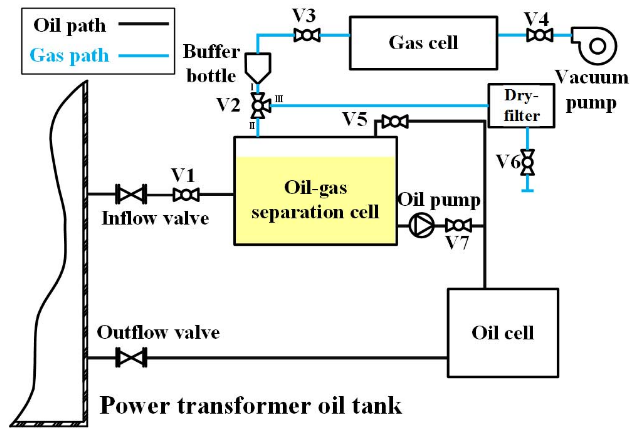

Figure 14. Mechanical structure of multi-gas detection system in the field.

(a) appearance of on-line DGA equipment (650mm*500mm*400mm)

(b) inside view of the equipment

Figure 15. Developed on-line DGA equipment in the field (served for 220 kV power transformer).

Table 2. Comparison results of developed equipment vs. existed system in the field.

Tests	CH_4 (μL/L)	C_2H_6 (μL/L)	C_2H_4 (μL/L)	C_2H_2 (μL/L)	THC (μL/L)
1	0.551	1.470	1.887	0.093	4.000
2	0.384	1.070	1.398	0.022	2.874
3	0.555	1.407	1.508	0.059	3.529
Average	0.497	1.316	1.598	0.058	3.468
Reference DGA	2.03	0.75	1.53	0.00	4.31

According to P.R. China Electric Power Industry Standard DL/T 722-2014 *Guide to the analysis and the diagnosis of gases dissolved in transformer* and National Standard GB/T 7252-2001 *Guide to the analysis and the diagnosis of gases dissolved in transformer oil*, the error limit and alert concentrations of dissolved gas in 220 kV power transformer, are shown in Table 3.

Table 3. Contrastive analysis of gases concentration detected by developed equipment.

Items	C_2H_2 (μL/L)	THC (μL/L)
Developed equipment	0.058	3.468
Reference DGA system	0.000	4.310
Error value	0.058	0.842
Error limit	1.0	—
Alert value	5	150

It is also shown that the error criteria of the Standard DL/T 722-2014 and GB/T 7252-2001 are met with our proposed DGA equipment. The test results truly reflected the working conditions of the transformer, verifying that the developed optical detection system could complete the monitoring and early warning of dissolved gas in real power transformer.

5 CONCLUSIONS

In summary, we report an optical technique based on tunable diode laser absorption spectroscopy (TDLAS) principle that provides multiple hydrocarbon gases detection for the health status of power transformer oil in this paper. Different from single-component measurement, three technical problems are researched: light source, long path gas cell and the topology. Specific central wavelengths of the hydrocarbon gases are analyzed and determined: methane (1653.72 nm), ethyne (1530.37 nm), ethene (1620.04 nm) and ethane (1679.06 nm). Moreover, an optical integrated and customized Herriott gas cell, with a light path of 10.13 m (0.34 m physical length), was designed and developed to minimize the vibration effect from the field application. In addition, to share the optical path, a time-sharing tropology for multiple gases was put forward with the help of optical switching. The calibration tests showed that the detection sensitivity of methane, ethene and ethane was 1.2 (μL/L)/mV, 2.0 (μL/L)/mV, and 2.86 (μL/L)/mV, respectively. Particularly, the sensitivity of the critical fault gas ethyne reached as high as 0.4 (μL/L)/mV. Furthermore, on-line detection in a 220 kV main power transformer with a developed equipment based on TDLAS technique, has been conducted and it showed that the error criteria of the relevant standards was met. Laboratory calibration and field tests have demonstrated the effectiveness of using TDLAS approach to diagnose health conditions for power transformers.

Further research will be focused on the expansion of more fault components and long-term reliability of the online optical monitoring system.

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