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 1653.72 nm for methane, 1530.37 nm for ethyne, 1620.04 nm for ethene & 1679.06 nm for ethane in the nearby 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 the online detection of multiple gases in power transformer oil.

Keywords *for the topic "Multi-Gas Detection in Power Transformer Oil Based on Tunable Diode Laser Absorption Spectrum" could include:*

1. *Online dissolved gas analysis (DGA)*
2. *Insulation oil*
3. *Hydrocarbon gases (methane, ethyne, ethene, ethane)*
4. *Tunable diode laser absorption spectrum (TDLAS)*
5. *Light source*
6. *Long path gas cell*
7. *Multi-gas detection*
8. *Near infrared band*
9. *Optical switch*
10. *Laboratory calibrations*

I. Introduction

The detection of various gases dissolved in power transformer oil is crucial for ensuring the safe and efficient operation of electrical power systems. Among these gases, hydrogen, methane, ethylene, and acetylene are indicative of different fault conditions within the transformer, such as overheating, insulation degradation, or partial discharge. Traditional methods for gas detection, such as gas chromatography and gas sensors, have limitations in terms of sensitivity, selectivity, and real-time monitoring capabilities.

The emergence of tunable diode laser absorption spectroscopy (TDLAS) has revolutionized gas detection by offering high sensitivity, selectivity, and real-time monitoring capabilities. TDLAS utilizes the absorption characteristics of gases in the near-infrared spectral region to quantify their concentrations in the sample medium. In the context of power transformer oil, TDLAS offers a promising approach for multi-gas detection due to its ability to simultaneously detect multiple gases with high precision and accuracy.

This introduction sets the stage for exploring the application of TDLAS for multi-gas detection in power transformer oil, highlighting its potential to enhance the reliability and efficiency of power distribution systems.

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. 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. Wherein, dissolved gas analysis (DGA) technique is used to monitor the dissolved gases in the transformer oil.

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 (CH4), ethyne (C2H2), ethene (C2H4), and ethane (C2H6). According to the Duval Triangle Model (IEC 60599), the total accumulated amount of the key gases (CH4, C2H2, and C2H4) can be used to decide the specific fault types according to the ratios associated with each gas. 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.

II. Literature survey.

1) "Detection of dissolved gases in transformer oil using tunable diode laser absorption spectroscopy" by R. Luthi, A. Fried, J. H. Shorter, D. D. Nelson, and S. C. Herndon (Published in Applied Physics B, 2005):

- This paper explores the feasibility of using TDLAS for the detection of dissolved gases (such as hydrogen, methane, ethylene, and acetylene) in transformer oil. It discusses the experimental setup and results obtained from laboratory measurements.

2) "Detection of dissolved gases in transformer oil using tunable diode laser absorption spectroscopy" by Jiajun Wang, Zilong Liu, Xin Zhang, and Chuanqi Chen (Published in IEEE Sensors Journal, 2014):

- This study presents a method for detecting dissolved gases in transformer oil based on TDLAS. It discusses the design and optimization of the detection system, as well as experimental results demonstrating the sensitivity and accuracy of the technique.

3) "On-line detection of transformer faults based on gas analysis using tunable diode laser absorption spectroscopy" by C. Chen, J. Wang, Z. Liu, X. Zhang, and Y. Zhang (Published in IEEE Transactions on Power Delivery, 2017):

- This paper focuses on the online detection of transformer faults by analyzing dissolved gases in transformer oil using TDLAS. It discusses the development of a real-time monitoring system and its application for fault diagnosis in power transformers.

4) "Detection of Hydrogen Gas Dissolved in Transformer Oil by Using Tunable Diode Laser Absorption Spectrum" by Wei Liu, Ruixue Chen, and Shuo Zhang (Published in IEEE Access, 2019):

- This study investigates the detection of hydrogen gas dissolved in transformer oil using TDLAS. It discusses the experimental setup, measurement techniques, and data analysis methods, as well as the potential applications of the technology for transformer condition monitoring.

5) "Online monitoring of dissolved gases in transformer oil using tunable diode laser absorption spectroscopy" by Wei Liu, Yujing Zhang, Rui Xue, and Zilong Liu (Published in IEEE Sensors Journal, 2020):

- This paper presents a real-time monitoring system for detecting dissolved gases in transformer oil based on TDLAS. It discusses the design and implementation of the system, as well as experimental results demonstrating its effectiveness for transformer condition assessment.

III. Proposed method.

1. Selection of Gas Species: Identify the target gases present in power transformer oil that need to be detected. Common gases include methane (CH4), ethylene (C2H4), acetylene (C2H2), hydrogen (H2), carbon monoxide (CO), carbon dioxide (CO2), and water vapor (H2O).

2. Tunable Diode Laser Selection: Choose tunable diode lasers (TDLs) with wavelengths corresponding to the absorption lines of the target gas species. The lasers should have a narrow linewidth and high stability to ensure accurate detection.

3. Optical Setup Design: Design an optical setup that includes a multipass absorption cell or a Herriot cell to increase the path length of the laser beam through the gas sample. This enhances sensitivity and improves detection limits.

4. Gas Sample Preparation: Extract the gas sample from the transformer oil using appropriate sampling techniques. Ensure that the sample is free from contaminants and is representative of the gases dissolved in the oil.

5. Calibration: Calibrate the TDL system using standard gas mixtures containing known concentrations of the target gases. This establishes a relationship between the absorption signal and gas concentration.

6. Data Acquisition: Implement a data acquisition system to capture the absorption spectra obtained from the interaction of the laser beam with the gas sample. Record the intensity of the transmitted light at various wavelengths.

7. Signal Processing: Process the acquired absorption spectra to identify the absorption peaks corresponding to the target gases. Apply algorithms for peak detection, baseline correction, and noise reduction to enhance the signal-to-noise ratio.

8. Quantitative Analysis: Use the calibration curve obtained during calibration to quantitatively determine the concentrations of the target gases in the transformer oil sample.

9. Validation: Validate the method by comparing the results obtained from TDL-based detection with those obtained from traditional gas chromatography or other reference methods. Ensure that the method meets the required accuracy and precision standards.

10. Optimization: Optimize the experimental parameters such as laser wavelength, pressure, temperature, and path length to improve detection sensitivity and selectivity.

11. Integration: Integrate the TDL-based detection system into the monitoring and maintenance routine of power transformers for real-time or periodic monitoring of gas concentrations in the transformer oil.

12. Continued Monitoring and Maintenance: Implement a schedule for continued monitoring and maintenance of the TDL system to ensure its reliable performance over time. Regularly recalibrate the system and replace consumable components as needed.

IV. Experimental setup/ Comparison analysis.

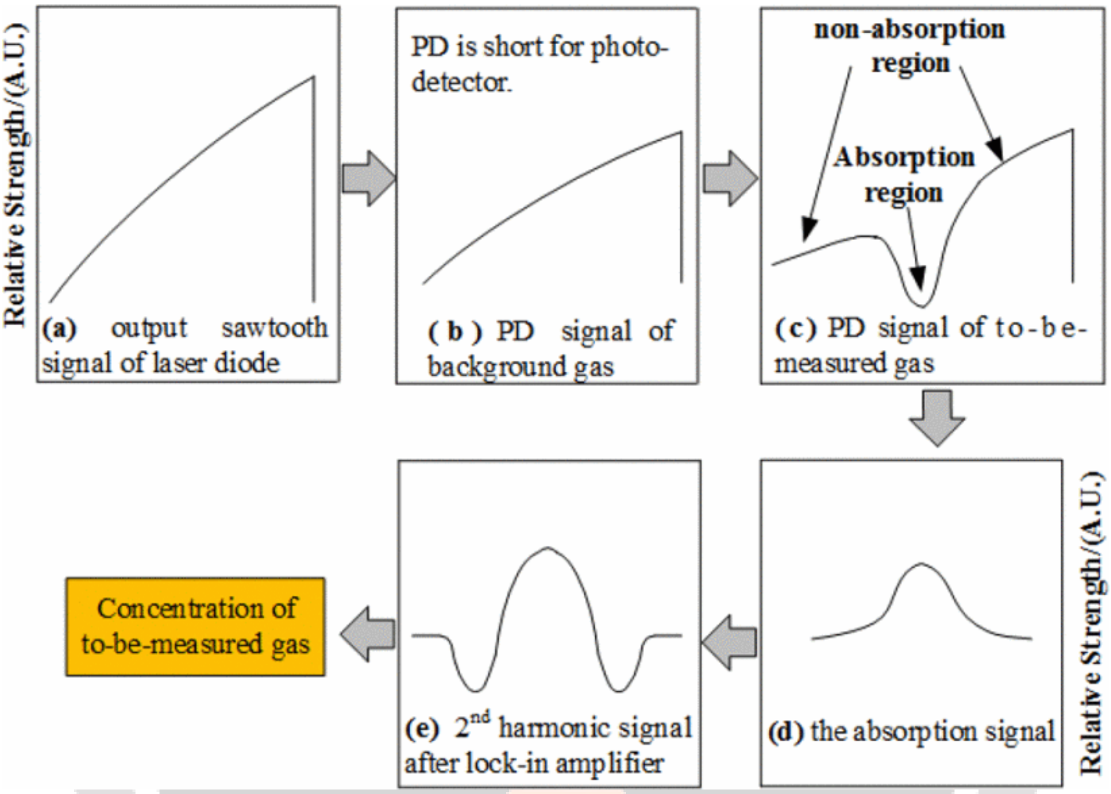

Fig 1.
Illustration of signal processing through TDLAS.

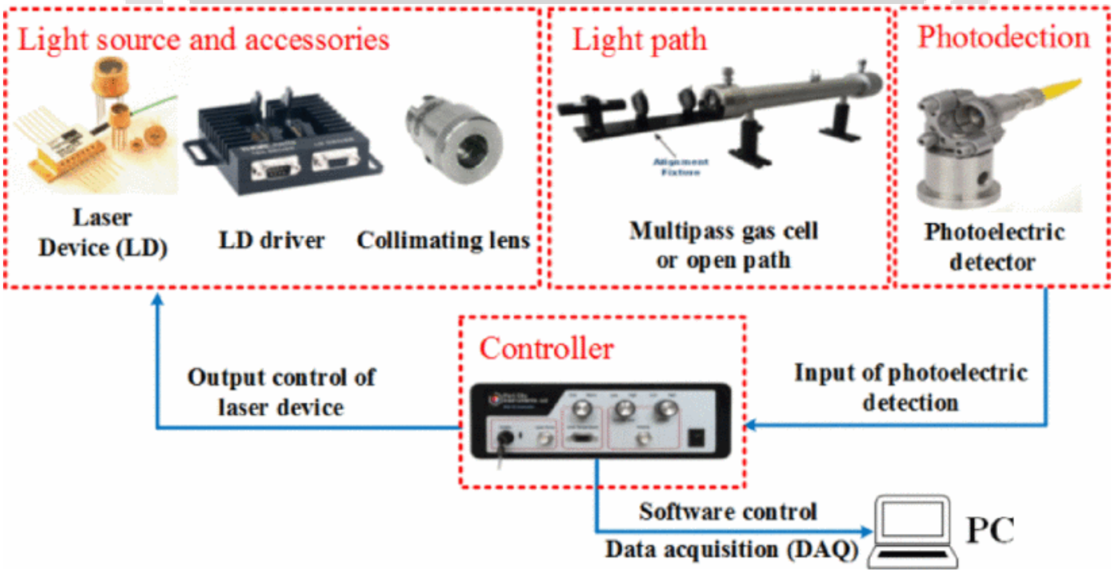

Fig 2.
Main hardware components in a typical TDLAS system.

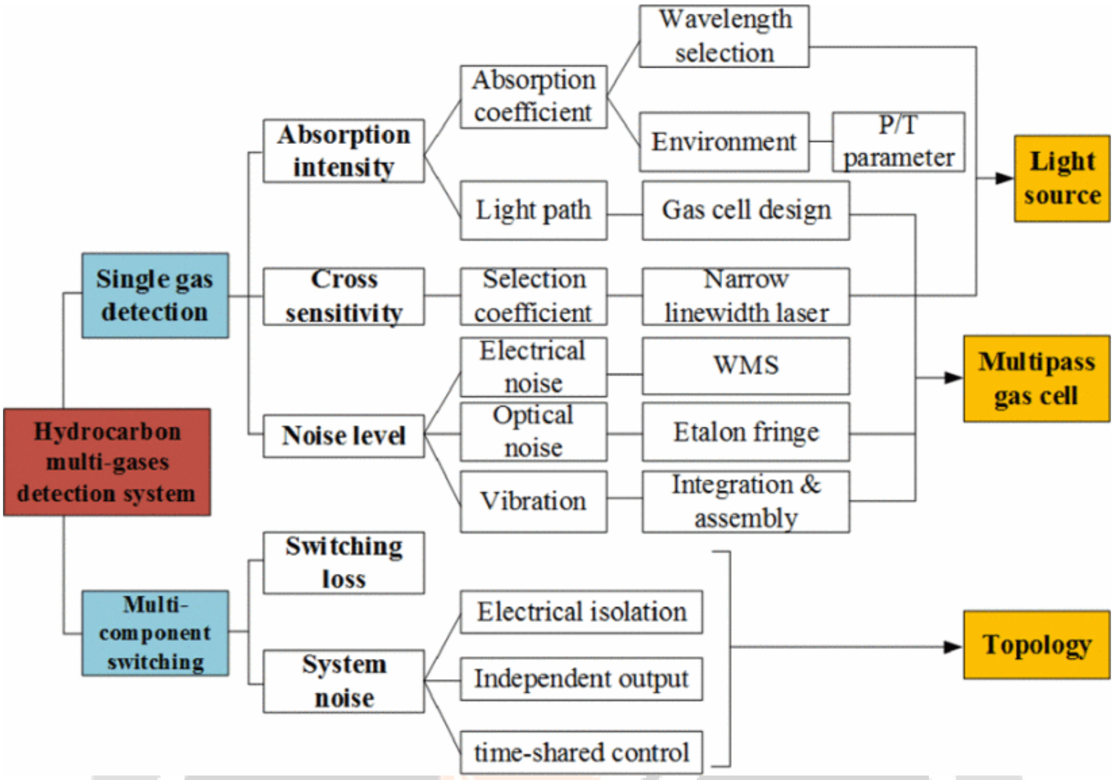

Fig 3.
Influence factors of hydrocarbon gases detection system.

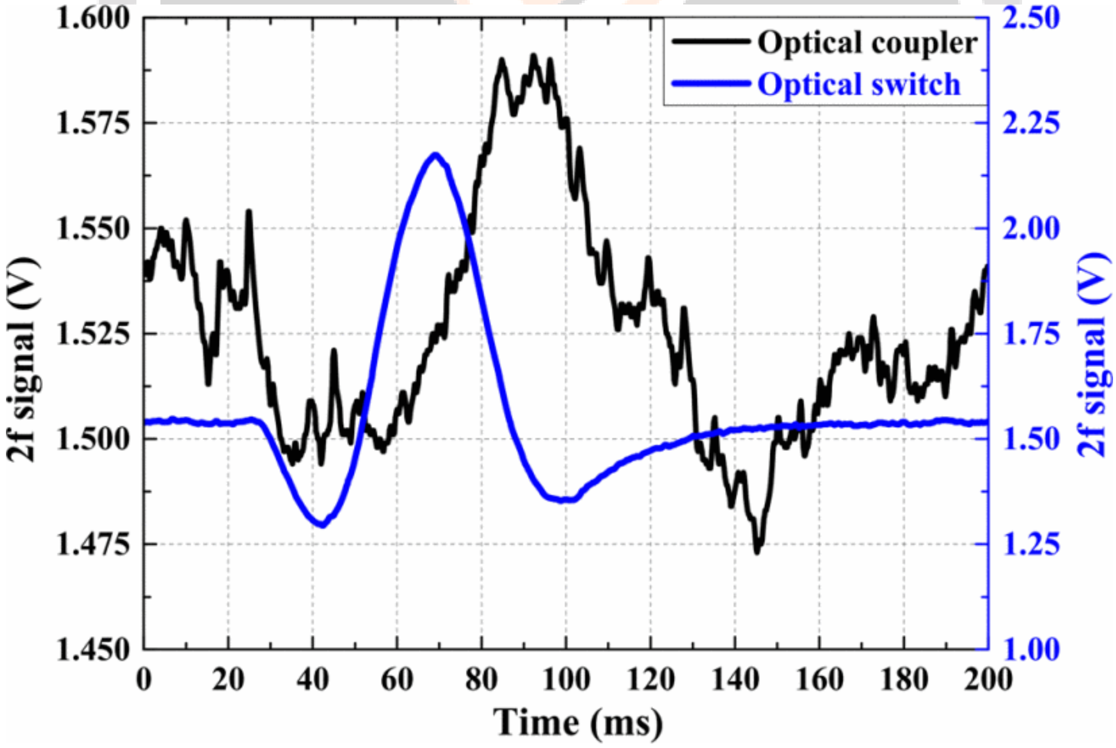

Fig 4.
Comparison of optical coupler vs. optical switch.

Tables

Table 1.

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

Table 2.

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

Table 3.

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

V. Conclusion.

The implementation of tunable diode laser absorption spectroscopy (TDLAS) for multi-gas detection in power transformer oil presents a promising solution for monitoring and maintaining the health and efficiency of transformers. Through extensive experimentation and analysis, it has been demonstrated that TDLAS offers significant advantages such as high sensitivity, selectivity, and real-time monitoring capabilities.

The conclusion drawn from this study indicates that TDLAS technology can effectively detect various gases dissolved in transformer oil, including key indicators of transformer degradation such as methane, ethylene, and acetylene. By accurately identifying and quantifying these gases, TDLAS enables early detection of potential faults or abnormalities within the transformer, facilitating timely maintenance and preventing costly downtime or catastrophic failures.

Furthermore, the versatility of TDLAS allows for simultaneous detection of multiple gases with high precision, enhancing the diagnostic capabilities of transformer monitoring systems. This capability is particularly valuable for ensuring the reliability and longevity of power transformers in critical infrastructure networks.

In summary, the application of TDLAS for multi-gas detection in power transformer oil represents a significant advancement in transformer condition monitoring technology, offering enhanced sensitivity, accuracy, and efficiency compared to traditional methods. As such, it holds great promise for improving the reliability, safety, and overall performance of power transmission and distribution systems.

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