An On-Line Monitoring Device for Dissolved Gas in Transformer Oil Based on Spectrum Technology

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Abstract. On-line monitoring of dissolved gas in transformer oil can effectively judge the early fault of transformer. The existing monitoring devices are generally based on gas chromatography, which need to be replaced carrier gas and calibrated periodically, therefore, the maintenance work is heavy. In recent years, photoacoustic spectrum technology with the advantages of high accuracy and no carrier gas required is gradually stressed, but its measurement accuracy is susceptible to mechanical vibration and noise, and its main components such as modulation disk is prone to failure. For this reason, this paper proposes an on-line monitoring device for dissolved gas in transformer oil based on spectrum technology, which doesn't need carrier gas and maintenance during operation. The device is simpler and lighter in structure and better in performance. The device can on-line monitor 7 kinds of dissolved gas in transformer oil, and has functions such as transformer fault diagnosis, remote alarm, local man-machine interaction, local storage, and supports multiple communication modes such as IEC61850 protocol. The field application shows that the device can provide the basis for transformer fault diagnosis.

1. Introduction

Dissolved Gas in transformer oil Analysis (DGA) can be used for fault diagnosis while the transformer is in operation, and is not affected by electric field and magnetic field. DGA has been recognized as one of the most effective ways of monitoring and diagnosing of oil-filled power transformers [1].

At present, gas chromatography is widely used, but this method has the following disadvantages: ① the gas chromatograph devices will consume carrier gas, so it is necessary to replace the carrier gas periodically; ② the performance of the chromatographic column and sensor will change over time, leading to a decline in the measurement accuracy, therefore, on-field calibration of the device is required [2].

Due to the advantages of high accuracy and no need of carrier gas, photoacoustic spectroscopy has attracted people's attention gradually [3], but some problems have also been exposed: ① measurement accuracy is susceptible to mechanical vibration and noise; ② high failure rate of mechanical rotating components such as modulating disk; ③ The length of pipeline is about 10m to 30m, which has safety risks.
In view of the above problems, this paper designs a kind of on-line monitoring device for dissolved gas in transformer oil based on spectrum technology, which doesn't need carrier gas, consumables, maintenance, and has strong anti-interference ability, compact structure and high stability, and provides a new idea for on-line monitoring of dissolved gas in transformer oil.

2. Gas Detection Principle based on Spectrum Technology

When a gas is irradiated with infrared light, the gas molecules absorb a certain frequency of infrared light due to vibration or rotational transitions, thus obtaining infrared absorption spectrum [4], which shows that there is a corresponding relationship between the gas composition and the infrared frequency, as long as the infrared frequency is known, the gas composition can be derived backwards. This process is the qualitative analysis of the gas. There is also a corresponding relationship between the gas concentration and the infrared absorption intensity. The process of calculating the gas concentration by analyzing the infrared absorption intensity is the quantitative analysis of the gas.

The theoretical basis of quantitative analysis is Beer-Lambert Law [4], which can be expressed as: when a beam of light passes through a sample, the absorbance \( A(\nu) \) at a wavenumber \( \nu \) is directly proportional to the concentration of the sample \( C \), and is directly proportional to the optical path length \( L \). The mathematical expression is:

\[
A(\nu) = \ln \frac{I_0(\nu)}{I_t(\nu)} = \ln \frac{1}{T(\nu)} = k(\nu)LC
\]  

(1)

Where, \( I_0(\nu) \) is the intensity of incident light, \( I_t(\nu) \) is the intensity of transmission light, \( T(\nu) \) is the transmittance, and \( k(\nu) \) is the absorption coefficient of the tested sample, which is related to temperature and pressure. For gas, the above equation can also be expressed as:

\[
A(\nu) = k(\nu)PL
\]  

(2)

Where, \( P \) is the partial pressure of the gas sample.

The absorbance shows superposition when the tested sample contains multiple components. The absorbance \( A_i(\nu) \) of the mixed component at the wavenumber \( \nu \) is the superposition of the component in \( i \):

\[
A(\nu) = \sum_{i=1}^{n} A_i(\nu) = \sum_{i=1}^{n} k_i(\nu)L
\]  

(3)

The establishment of Beer-Lambert Law must satisfy the following premise:

1. There is no interaction between the particles that absorb the photons;
2. The substance absorbing the photons is uniformly distributed;
3. The substance only absorbs radiation, and there is no fluorescence, scattering light and other phenomena;
4. Constant temperature and pressure conditions.

3. Design and Implementation of the Device

3.1. Overall design

The device is based on spectrum technology, and doesn’t contain any mechanical rotating components, which is small in size, light in weight, simple in structure and can be directly installed on the transformer body.

The device is composed of Oil Sample Acquisition Unit, Oil and Gas Separation Unit, Gas Detection Unit based on Spectrum Technology, Data Acquisition Unit, Control and Processing Unit, Storage Unit, Communication Unit and Man-machine Interaction Unit.

The structure diagram of the device is shown below.
The transformer oil enters the device through the Oil Sample Acquisition Unit, and the oil sample enters the Oil and Gas Separation Unit for oil and gas separation, and then the dissolved mixed gas in the oil is obtained. Next, the mixed gas enters the Gas Detection Unit based on Spectrum Technology for gas detection. After the detection, the component of mixed gas and the concentration of each component can be obtained, which are transmitted to the Data Acquisition Unit. The Data Acquisition Unit converts analog signals into digital signals and transmits them to the Control and Processing Units.

Control and Processing Unit filters the digital signal in the first place, and then the concentration of dissolved gas in transformer oil is obtained by calculation, at last, Three-Ratio Method, Duval’s Triangle Method are used to diagnose transformer fault. The device alarms immediately through the Communication Unit if there is any abnormal. Besides the above functions, the Control and Processing Unit also has the functions of controlling Oil Sample Acquisition Unit, Oil and Gas Separation Unit, Gas Detection Unit based on Spectrum Technology and Data Acquisition Unit to work properly.

The measurement data, diagnostic results and working parameters of the device are all stored in the Storage Unit. The Man-machine Interaction Unit is composed of LCD display and keys, which is used to realize man-machine interaction.

3.2. Gas Detection Method
The Gas Detection Unit based on Spectrum Technology is composed of Near-infrared Generator, Gas Room, Electronic Grating and Photoelectric Sensor, Hydrogen Sensor, Pressure Sensor and Temperature Sensor, Gas Inlet and Gas Outlet.

The block diagram of Gas Detection Unit based on Spectrum Technology is shown below.

The mixed gas is injected into the Gas Room from the Gas Inlet. When the infrared beam generated by the Near-infrared Generator passes through the mixed gas in the Gas Room, the mixed gas will absorb a certain frequency of infrared light, and the remaining infrared light will be transmitted to Electronic Grating and Photoelectric Sensor.

The role of the electronic grating is to select specific frequency of infrared light, and the selected specific band infrared light is converted into electrical signal by the photoelectric sensor.
Because spectrum technology can't effectively detect hydrogen, the device is equipped with the Hydrogen Sensor to detect the concentration of hydrogen in the mixed gas. Pressure Sensor and Temperature Sensor is used to detect the pressure and temperature in the Gas Room. The Gas Detection Unit based on Spectrum Technology needs to be kept at a constant temperature and pressure condition during operation, otherwise the measuring results will be affected. After the measurement, the mixed gas is discharged from the Gas Outlet.

3.3. Software Architecture

The device software is divided into three layers: Hardware Drive Layer, Operating System Layer and Application Layer. The Application Layer includes four functional units: Transformer Oil Detection Functional Unit, Transformer Fault Diagnosis Functional Unit, Data Upload and Alarm Functional Unit, and Man-machine Interaction Functional Unit.

The software architecture diagram of the device is shown below.

The Transformer Oil Detection Functional Unit realizes the detection of dissolved gas in transformer oil: CH4, C2H4, C2H6, C2H2, H2, CO and CO2.

The Transformer Fault Diagnosis Functional Unit integrates Three-Ratio Method, Duval’s Triangle Method [5, 6].

The Data Upload and Alarm Functional Unit supports a variety of communication access methods, including Ethernet, RS485 and IEC61850, etc., and the Man-machine Interaction Functional Unit has local display, parameter setting.

The software flow of the device is shown below.

![Flow chart of the device software.](image-url)
After a measurement, the device analyses the measuring results. If the transformer has a fault, alarm will be given immediately and the alarm data will be stored at the same time. Otherwise, the device stores the measuring results and responds to man-machine interaction and communication.

4. Design Verification

4.1. Laboratory Test
The device to be tested is calibrated in advance. The composition of the standard sample gas is CH4, C2H4, C2H6, C2H2, H2, CO and CO2, and the concentration of each component gas is shown in the table below.

| Components   | CH4 (ppm) | C2H4 (ppm) | C2H6 (ppm) | C2H2 (ppm) | H2 (ppm) | CO (ppm) | CO2 (ppm) |
|--------------|-----------|------------|------------|------------|----------|----------|----------|
| Concentration of the standard gas | 59.5      | 59.8       | 60.1       | 59.6       | 101.1    | 100.7    | 991.4    |
| Measurement data of the device   | 53.2      | 64.1       | 69.5       | 57.5       | 108.7    | 90.4     | 914.5    |

According to the above table, the device can detect seven gases including CH4, C2H4, C2H6, C2H2, H2, CO and CO2, and the measuring result of each component is close to the standard gas concentration.

4.2. Field Application
The device is tested in the 220kV substation, which is installed at the backup oil outlet valve of No.2 main transformer, and uploads the monitoring data to Transformation Equipment Condition Acquisition Controller (CAC), and then CAC uploads the data to the main station.

The device is small in size and installed directly on the transformer, through only a single flange plate. There is no risk of tubing damage or oil leakage, and there is no need of mounting bracket. Installation diagram of the device is shown below.

![Figure 5. Installation diagram of the device.](image-url)
Figure 6. Field application photos of the device.

The monitoring data trend of the device on site is shown below. It can be seen from the trend chart that the variation trend of each component is relatively stable, with no significant abrupt change, and the concentration values are all within the safe range, indicating that the transformer works well.

The measuring results of the device can reflect the variation trend of dissolved gas in the transformer oil and can assist to monitor transformer working condition.

In addition, during the application, the device is in good condition and without personnel maintenance.

Figure 7. Concentration versus measurement data.

5. Conclusion
In this paper, an on-line monitoring device for dissolved gas in transformer oil based on spectrum technology is realized, which can reflect the variation trend of the dissolved gas in transformer oil.

The device is based on spectrum technology, which not only overcomes the disadvantages of gas chromatographic devices that need to be maintained and calibrated periodically, but also overcomes the disadvantages of photoacoustic spectrum devices, such as poor anti-interference ability and short life.

In addition, the device is compact and convenient for engineering construction.
Laboratory testing and field application prove that the device can monitor the variation trend of dissolved gas in transformer oil on line and provide the basis for transformer fault diagnosis.

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