On-line Monitoring of GIS Using Fourier Transform Infrared Spectroscopy

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Abstract. Different decomposition component gases caused by different insulation defects in gas-insulated switchgear will accelerate insulation degradation, which is a major threat to human and equipment safety. In this paper, we proposed online monitoring of GIS based on Fourier transform infrared spectroscopy. Firstly, we analysed the absorption characteristics of infrared light in SO2 and moisture. Secondly, we introduce the design principle and signal stabilization method of the laser. Thirdly, we propose the methods for measuring the concentration of SO2 and moisture. Finally, experiments with various concentration of SO2 and moisture are deployed, which proves that the GIS on-line monitoring method for decomposed gas has small measurement error and can be applied in practical applications.

1. Introduction
Partial discharges in gas-insulated switchgear (GIS) caused by different insulation defects will generate different decomposition component gases. Therefore, the internal insulation situation such as the degree of insulation damage and development trend can be judged by detecting the content and change trend of different decomposition components of SF6 gas, which can prevent early insulation sudden accident caused by failure [1][2][3]. The above-mentioned decomposition products are combined with oxygen to generate substances, which have a strong corrosive effect on metal materials and insulating solids in electrical equipment, thereby accelerating insulation degradation, posing a major threat to human and equipment safety. Therefore, research on real-time monitoring and fault diagnosis of SF6 electrical equipment is urgently needed. In particular, monitoring the content of micro-water and SO2 in SF6 can help improve prevention and reduce losses.

Tominaga S and others found that gas chromatography can be used for accurate qualitative and quantitative analysis of SO2, CF4, CO2 and other products [4]. However, gas chromatography has a long detection time and is susceptible to environmental influences, so it is not suitable for on-line monitoring in the field. Rashmi Mital used mass spectrometer as a detection method to study the discharge decomposition products of SF6 gas under the condition of high voltage arc discharge [5]. However, mass spectrometry has the disadvantages of complicated operation, affecting gas components, and not suitable for on-line monitoring. Weidong Ding designed a carbon nanotube sensor for the detection of SF6 gas decomposition products, and found that its change in conductance has a linear relationship with the internal discharge [6]. However, the performance of carbon nanotube sensors will be affected by factors such as temperature and installation position. When the temperature is too high or too low, its response characteristics will be weakened. Fourier transform infrared spectroscopy (FTIR) method can detect a variety of substances in a short period of time, with high resolution and signal-to-noise ratio. The shape, size and position of infrared absorption spectrum can identify components and quantitative analysis.
In this paper, we proposed online monitoring of GIS operating conditions based on Fourier transform infrared spectroscopy. Firstly, we analysed the absorption characteristics of infrared light in SO\(_2\) and moisture. Secondly, we introduce the design principle and signal stabilization method of the laser. Thirdly, we propose the methods for measuring the concentration of SO\(_2\) and moisture. Finally, it is proved through experiments that the GIS on-line monitoring method for decomposed gas has small measurement error and can be applied in practical applications.

2. Infrared absorption spectrum of SO\(_2\) and moisture
Absorption spectrums of pure SO\(_2\) and moisture are shown in figure 1.

![Figure 1. Infrared absorption spectrum.](image)

Figure 1. Infrared absorption spectrum.

Figure (a) is the infrared absorption spectrum of SO\(_2\), from which we can see that pure SO\(_2\) has three distinct infrared absorption regions and the second group of absorption regions is located at 1058 cm\(^{-1}\) to 1255 cm\(^{-1}\). Considering that the second group of absorptions is caused by the symmetrical stretching of molecular bonds and the absorption in the mid-infrared region of 2.5 to 25 um is caused by the fundamental frequency of chemical bond vibrations, after comparing with the absorption peaks of SF\(_6\), we determined that the absorption peak at 1167 cm\(^{-1}\) and 8.6 um as the research object to test the SO\(_2\) content.

Similarly, figure (b) is the infrared absorption spectrum of moisture, from which we can see that pure H\(_2\)O has three distinct infrared absorption regions. By comparing with the absorption peaks of SF\(_6\) and other decomposition products in this range, we determined that the absorption peak at 1635 cm\(^{-1}\) and 6.1 um as the research object to test the H\(_2\)O content.

3. Detection of SO\(_2\) and moisture in SF\(_6\)

3.1. Driving power of the laser
When the drive power for quantum-cascade laser (QCL) is operating, the operating characteristics of many devices will change with temperature changes, which will eventually cause the fluctuation of the drive current value of the quantum cascade laser and affect the stability of the laser output optical power [7]. Therefore, it is necessary to compensate these error values in the software to reduce the fluctuation of the drive current of the quantum cascade laser. The block diagram of the proportional integral derivative (PID) control system is shown in figure 2.

![Figure 2. Block diagram of PID control system.](image)
The proportional integral derivative (PID) is used as the software control algorithm for the QCL drive power supply, where the digital signal processor (DSP) controls the ADC module to detect the output value $S$, calculates the deviation $e$ and the control variable $y$ at the same time, and outputs it to the constant current source module after the DAC module. Corresponding to the above picture, PID can be calculated as follows.

$$U(t) = K_p * e(t) + K_i * \int e(t) dt + K_d \frac{de(t)}{dt}$$

From the equation above we can see that the proportional control action in the PID controller can reduce the error and the integral control action can eliminate the error, so that the steady-state error is zero, and the differential control action can reduce the overshoot of the output response.

3.2. Fourier transform using interferogram

After the interferogram was obtained with the Michelson interferometer, the Fourier transform was used to transform the interferogram with time as a variable into the spectrum with frequency as a variable [8].

When monochromatic light is incident, the incident light is divided into two coherent beams by the beam splitter, and the interference flux density can be calculated.

$$B(x, \sigma) = 2E_0^2(\sigma)[1 + 2\cos(2\pi \sigma x)]$$

where $\sigma$ is the wave number, $E_0$ is the amplitude, and $x$ is the optical path difference between the two beams. Limited by the scanning length of the moving mirror, the actual interception of the interference signal in the interval of the finite optical path difference $[-L, +L]$, and we can calculate the spectrum map corresponding to the truncated interference pattern.

$$B_r(\sigma) = \frac{1}{2}[\delta(\sigma - \sigma_i) + \delta(\sigma + \sigma_i)][2LSa(2\pi \sigma L)] = B(\sigma) * ILS(\sigma)$$

Where $ILS(\sigma)$ is the instrumental line shape function.

In order to compensate for the error caused by intercepting the interference signal with a finite optical path difference $[-L, L]$, The Happ-Genzel function can be used as a truncation function in the information acquisition part., which can not only effectively suppress the side lobes, but also reduce the reduction of the spectral resolution caused by the introduction of the window function.

3.3. Quantitative analysis of a single gas infrared absorption spectrum

The Lambert-Beer law is used for the quantitative analysis of a single gas infrared absorption spectrum.

$$I(v) = I_0(v) * e^{-\alpha NL}$$

Where $I(v)$ is the light intensity after gas absorption counted by W/sr, and $I_0(v)$ is the background light intensity without gas absorption, and $\alpha$ is the molecular absorption cross section counted by cm$^2$/molecule$^{-1}$, and $N$ is the concentration of the measured substance, and $L$ is the total gas absorption optical path length counted by meters.

According to Lambert's law, when the gas concentration is constant, the absorbance is directly proportional to the optical path length, which means that increasing the optical path of the sample can improve the detection accuracy of the spectrum. Since the detection objects including SO$_2$ and H$_2$O in SF$_6$ are below the ppm level, it is necessary to achieve a long enough optical path to meet the detection needs, and also ensure the detector enough light energy.

Firstly, we use Lambert's law and standard spectrum data to estimate the concentration optical path product to obtain the standard gas concentration for the experiment. Then, the actual concentration optical path product of the gas detection limit can be obtained through experiments. Finally, the optical path length required to reach the detection limit of 1ppm gas can be obtained. The theoretical concentration optical path product are as follows.
(1) Set the optical path $L$ of the gas chamber, the concentration $C$ of the detection gas, and the infrared spectrum obtained from the test gas. The concentration optical path product can be obtained according to the formula.

$$D_{\text{opt}} = C \times L$$ \hspace{1cm} (5)

(2) Obtain the absorbance $A$ at the optimal wavelength of the infrared spectrum, and the value of the absorption coefficient $\vartheta$ of the substance can be obtained according to the formula.

$$A = \vartheta \times D_{\text{opt}}$$ \hspace{1cm} (6)

(3) The value of $D$ can be calculated.

$$D = 5 \times 10^{-4}$$ \hspace{1cm} (7)

3.4. Relationship between infrared absorption and the concentration SO$_2$ and moisture content in SF$_6$

We use gas concentration as input data and the measured infrared spectrum data as output to build a gas analysis model to achieve quantitative determination of components, the results of which are shown in figure 3.

![Figure 3](image)

**Figure 3.** Correspondence between absorbance and target gas concentration.

As shown in the left part of figure 3, the corresponding data of the absorbance of the sample at 1167 cm$^{-1}$ and the concentration of SO$_2$ were fitted to obtain the relationship curve:

$$y = a + bx$$ \hspace{1cm} (8)

Where $y$ is the absorbance of the sample, $x$ is the concentration of SO$_2$ in the SF$_6$ standard sample, $a = 0.03459$, $b = 5.71238 \times 10^{-4}$, so the results are credible.

Similarly, as shown in the right figure, the corresponding data of the absorbance of the sample at 1635 cm$^{-1}$ and the concentration of moisture were fitted to obtain the relationship curve, here $y$ is the absorbance of the sample, $x$ is the concentration of H$_2$O in the SF$_6$ standard sample, $a = 0.03453$, $b = 5.71171 \times 10^{-4}$, so the results are credible.

3.5. GIS failure probability predication

After measuring the content of SO$_2$ and H$_2$O in SF$_6$, a model of the relationship between decomposition products and equipment failure is needed to determine different operating conditions of the equipment. Chengqi Li proposed a Bayesian decision theory based SF6 electrical equipment failure probability estimation model, based on which Weibull, normal, or lognormal distribution are respectively used for Partial Discharge, Abnormal fever and Breaking arc, which is shown in figure 4.
4. Experiments.

The gas concentration changes with pressure, and the gas pressure increases with temperature, which will affect the test results.

Gas calibration samples with SO$_2$ concentrations of 5 uL/L, 50 uL/L, and 500 uL/L were prepared with a dynamic gas calibrator for infrared absorption testing to obtain the absorbance of each sample at 1167 cm$^{-1}$.

| SO$_2$(uL/L) | Deviation | error  |
|--------------|-----------|--------|
| 5            | 0.123     | 2.46%  |
| 50           | 0.621     | 1.24%  |
| 500          | 3.531     | 0.71%  |

As shown in Table 1, the test values of the gas standards are 5.123 uL/L, 50.621 uL/L, and 503.531 uL/L, so the test values at the three concentrations are 2.46%, 1.24%, and 0.71%, respectively, which means that the error is within the allowable range.

Similarly, gas calibration samples with H$_2$O concentrations of 5 uL/L, 50 uL/L, and 500 uL/L were prepared with a dynamic gas calibrator for infrared absorption testing to obtain the absorbance of each sample at 1635 cm$^{-1}$, the detection error of which is also within the allowable range.

5. Conclusions.

In this paper, we proposed online monitoring of GIS based on Fourier transform infrared spectroscopy. Firstly, we analysed the absorption characteristics of infrared light in SO$_2$ and moisture. Secondly, we introduce the design principle and signal stabilization method of the laser. Thirdly, we propose the methods for measuring the concentration of SO$_2$ and moisture. Finally, it is proved through experiments that the GIS on-line monitoring method for decomposed gas has small measurement error and can be applied in practical applications.

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