Dielectric and Design and Experimental Study of GIS Gas Chamber HF and Micro Water Dual Fiber Laser Detection System

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Abstract. HF gas and trace moisture content, as the primary characteristic by-products of SF6 gas decomposition reaction, are of great significance to the fault diagnosis of high voltage SF6 gas insulated high voltage power equipment. In this paper, the typical discharge fault types in GIS are analyzed, and the decomposition products corresponding to different discharge types are summarized. The physical and chemical mechanism of HF generation in the early dissociation process of SF6 and under certain micro water and micro oxygen conditions is explained, and the experimental platform is built to carry out the simulation generation experiment of HF gas and micro water. The results show that choosing the best target absorption line suitable for sensitive and selective gas sensing can eliminate interference, simplify the system and reduce the cost. Furthermore, under the experimental conditions, the self-developed TDLAS online detection technology is used to realize the effective detection of HF gas and trace water in GIS discharge room. The 1278nm and 1392nm laser sources are selected respectively, and the TDLAS technology based on dual fiber time-sharing multiplexing is feasible for HF and trace water measurement. The stability and reliability of the technology are verified, which can provide effective technical support for on-line detection of HF gas in GIS, and has good engineering application value.

1. Introduction

Typical insulation defects such as metal protrusion, air gap and insulator surface pollution exist in the process of the manufacturing, installation and operation of SF6 gas insulated high voltage power equipment, resulting in decomposition of SF6 gas to produce products such as HF, H2S and SO2. Therefore, typical decomposition products can effectively characterize the types of insulation defects of SF6 gas insulated high voltage power equipment [1,2]. Because of its symmetrical octahedral molecular structure and the largest electron affinity of fluorine atom, SF6 gas has very strong electron adsorption ability, so it has ideal arc extinguishing and insulation properties. As an insulating medium, SF6 gas is widely used in totally enclosed switch-gear (GIS). When high-voltage electrical equipment fails, HF gas, as the first decomposition product, has been an important research object of high-voltage electrical equipment fault diagnosis [3-5]. At present, on-line detection method of HF gas is limited, and the traditional electro-chemical method and gas chromatography analysis method are lagging behind. The detection method which can realize real-time, fast and high sensitivity detection of HF gas content in the GIS is particularly important. On the other hand, the different discharge voltage and environmental factors (SF6 gas pressure, micro water content, etc.) have different effects on the formation of HF gas and micro water in GIS.
This paper first introduces the principle of dual fiber laser detection system, which provides theoretical guidance for on-line detection of HF gas in GIS switch-gear. An on-line detection system for HF and H2O in GIS gas chamber is designed and developed. The host module of the detection system adopts the principle of time-sharing multiplexing to realize the regular work of the two lasers, and the signal transmission between the detection host and the gas path is realized through double optical fibers. In the hardware system, the laser driving circuit and temperature control circuit are designed effectively. TDLAS detection technology is used to dynamically monitor the generation process of HF gas and trace water under different voltages, and detect the HF gas concentration and trace water concentration of high-voltage switch-gear under field conditions. The stability and reliability of TDLAS detection technology are verified, which has strong industrial application value and is important for identifying and judging the insulation condition of the high-voltage electrical equipment.

2. Principle of dual fiber laser detection system

The combination of the wavelength modulation technology and harmonic detection technology can greatly reduce the low-frequency noise interference and improve the detection sensitivity. The laser is driven and modulated by loading the low frequency saw-tooth wave and lock-in amplifier and high frequency sine wave, the emission frequency $v$ of the laser is obtained[6-9]:

$$v = v_0 + \sigma \cos 2\pi f t$$  

(1)

Where, $v_0$ is the center frequency, $f$ is the modulation frequency, and $\sigma$ is the amplitude of the modulation signal. By Fourier series expansion of equation (1), we can get:

$$I_v = I(v_0,t) = \sum_{n=0}^{\infty} A_n(v_0) \cos(n2\pi f t)$$  

(2)

Where $A_n(v_0)$ is the $n^{th}$ cosine Fourier series expansion coefficient of the transmitted light of the laser, the attenuated light signal after absorption is received by the detector, and the second harmonic amplitude expression is obtained after phase-locked amplification:

$$A_2(v_0) = \frac{l_0 CL}{4} \sigma^2 \left. \frac{d^2 \sigma(v)}{dv^2} \right|_{v=v_0}$$  

(3)

The concentration of the gas to be measured can be obtained by the DC component $I_0$ of light intensity and the second harmonic amplitude:

$$C = \frac{A_2(v_0)}{I_0 KL}$$  

(4)

Where $k$ is the calibration constant, and it can be seen from equation (4) that the gas concentration $C$ is proportional to the second harmonic amplitude. Through standard gas calibration, the determined gas concentration can be retrieved.

3. Spectrum line selection and cross interference analysis

Choosing the best target absorption line for sensitive and selective gas sensing can eliminate the interference, simplify the system and reduce the cost. Compared with mid infrared laser, near infrared distributed feedback laser (DFB) has the advantages of low power consumption and simple operation. Therefore, 1278nm and 1392nm laser chips are selected as the laser source to measure HF and H2O in GIS gas chamber. In order to simulate the interference of other components in GIS gas chamber on HF and H2O absorption, Figure 1 (a) and Figure 1 (b) show the spectral absorption profiles of HF and H2O in the range of 7820-7830cm$^{-1}$ and 7180-7186cm$^{-1}$, respectively. For HF gas, the absorption line intensity is the strongest at 7823.83cm$^{-1}$ (1278.1nm), and the order of magnitude is $10^{-37}$. At the same time, the Lorentz spectrum simulation is carried out at 20cm$^{-1}$ optical path, 1atm and 300K, and the possible CO, CO2, SO2, H2S and H2O gases in GIS gas chamber almost have no interference. Similarly, for H2O gas, the absorption line strength is the strongest at 7181.15cm$^{-1}$ (1392.5nm), the
order of magnitude is $10^{-20}$, and the possible HF, CO, CO2, SO2 and H2S gases in GIS gas chamber almost have no interference. It can be seen that it is feasible to choose 1278nm and 1392nm laser sources respectively and realize HF and micro water measurement based on TDLAS technology of dual fiber time division multiplexing.

![Absorption lines of HF in the spectral range of 7821-7828 cm$^{-1}$](image1)

![Absorption lines of H$_2$O in the spectral range of 7180-7186 cm$^{-1}$](image2)

Fig.1 Simulation of line intensity and absorption spectrum of HF and H$_2$O at 7823.83 cm$^{-1}$ and 7181.14 cm$^{-1}$, respectively
4. HF and Micro Water Dual Fiber Laser Detection System

The principle of the detection system is shown in Fig. 2. The Irish DFB laser is used, of which the HF laser is EP1278-DM-B, the central wavelength range is 1260~1288nm, the current and temperature tuning coefficients are 0.014nm/mA and 0.1nm/℃ respectively; the micro water laser is ep1392-dm-tp39, the central wavelength range is 1378~1400nm, the current and temperature tuning coefficients are 0.01nm/mA and 0.1nm/℃, respectively. Typical threshold current is 20mA and 15mA respectively. The model of InGaAs photodetector is OD-PD-1000-TO46-F, the spectral response range is 1000 ~ 1700nm, and the diameter of photosensitive surface is 1000μM. The sampling card is pci-4474, and the highest sampling rate is 102.4kS/s. In order to obtain a higher detection degree and ensure the normal entry and diffusion of the gas to be measured in the GIS gas chamber, the system adopts a Herriott gas absorption cell with a turn back optical path. The length of the absorption cell is 10cm, the optical path is 20cm, three rows of 11 air inlets are set, and two collimators are used in the gas chamber for laser emission and reception respectively. There is no laser return to the laser, which can effectively reduce the optical noise[10,11]. STM32 MCU generates a low-frequency sawtooth wave signal and a high-frequency sinusoidal modulation signal to ensure that the output wavelength of the laser can completely scan the selected absorption spectrum of the gas to be measured. After gas absorption and reflection, the laser is focused on InGaAs photodetector. After lock-in amplification and data acquisition, it is finally converted into electrical signal for subsequent processing. In order to realize the on-line detection of HF and H2O in GIS gas chamber, the host module of the detection system adopts the principle of time-sharing multiplexing to realize regular work of the two lasers, and realizes the signal transmission between detection host and gas path part through double optical fibers.

![Fig.2 Structure diagram of double fiber laser detection system](image1)

![Fig.3 Optical structure of optical cavity](image2)

Figure 3 shows that the light has good collimation in the optical cavity. The light can form several refractions inside the optical cavity, thus extending the length of the light propagation path, and making the detection of HF and H2O more accurate.
5. System hardware design
The laser current modulation drive circuit is shown in the figure below. The adder circuit is composed of operational amplifier U1D. Sinusoidal signal and slope signal generated by MCU are superimposed to form a modulation signal. The modulation signal is formed by the current source composed of U1C and Q2[12]. The current signal finally drives the laser to produce a modulation laser optical signal. In order to realize the multiplexing of driving signal and drive two-way laser, this design adopts the principle of time division multiplexing, and uses MCU to generate control signal to control the on/off of MOS transistor Q11 and Q12, that is to realize the selection of laser channel.

Fig.4 Laser driving circuit

Fig.5 Temperature control circuit
The temperature control circuit of the laser is shown in the figure below. The temperature control circuit includes temperature signal differential operational amplifier circuit, voltage controlled PWM wave control signal generation circuit, H-bridge drive circuit and over-current protection circuit. The temperature differential operational amplifier circuit amplifies the difference between the voltage value corresponding to the set temperature and the real-time voltage sampling value of the laser thermistor. The differential signal is output to the MCU control chip. The MCU controls the duty cycle of the PWM wave according to the AD sampling value of the voltage to generate two PWM pairs, which are respectively output to the H-bridge drive control chip, and each H-bridge drive chip is output to the H-bridge circuit Up and down bridge output. The duty cycle of PWM can control the on/off of the upper and lower MOS transistors, and then control the flow direction of the control current through TEC, so as to realize the cooling and heating of TEC. The current protection circuit collects the voltage of TEC current sampling resistor, and turns off the H-bridge control chip when the voltage is too large.

6. Results and discussion
At room temperature, HF laser is controlled by optical switch. Wavelength modulation spectroscopy (WMS) is used to test the linearity of hf-sf6 gas with different concentrations. According to equation (4), the gas concentration $C$ is proportional to the second harmonic intensity $2f$ when the measured parameters of the system remain unchanged. In the measurement process, the scanning frequency is 10 Hz, the modulation frequency is 10kHz, and the modulation current is 70-120Ma, so that the peak value of the second harmonic is stabilized at a certain value. After that, six bottles of standard samples such as 10ppm, 30ppm, 50ppm, 70ppm, 90ppm and 100ppm are measured. Before the test, high purity nitrogen was used to purge the gas chamber to eliminate the influence of air background in the gas chamber, and nitrogen was used as the base. In order to further eliminate the influence of noise on the second harmonic spectral line, the multiple sampling average method is adopted. The number of sampling points is 400, and 99 groups of data are collected under each concentration. After weighted average, the relationship between the gas concentration (0~100ppm) at the sampling point 294 and the harmonic amplitude $2F$ intensity is obtained. As shown in Figure 5, the harmonic amplitude intensity increases with the increase of gas concentration $C$, and the waveform center remains unchanged, which is linear fitting. The fitting coefficient $R^2$ is 0.9997.

$$2f = 10.5c - 55.7 \quad (5)$$
In order to further verify the anti-interference ability of the laser measurement system, the simulated gas chamber of GIS is taken as the test object, and the SF6 decomposition product multi group distribution gas system is used to prepare 100ppm H2S, SO2, CO and CO2 as the interference gas under the SF6 background[13]. After the test, there is no harmonic spectrum at the sampling point 294, and the anti-interference performance is good.

Using the humidity generator as the air source, the dew point interval of the humidity generator is 10 ℃, and 8 groups of data are set in the range of -70 ~ 0 ℃ respectively for system input verification. Similarly, using the optical switch to control the micro water laser, the number of sampling points is 400, 298 groups of data are collected under each dew point, and the second harmonic $2f$ signals corresponding to different dew point D are obtained after weighted average. As shown in Fig. 7, with the increase of dew point, the second harmonic intensity increases, the center of the waveform remains unchanged, and the nonlinear fitting coefficient $R^2$ is 0.999, which changes in the form of first-order index, which is consistent with that reported in reference[3]. The fitting linear equation is as follows:

$$2f = 15205.94\exp\left(\frac{d}{12.67}\right) - 101.77$$  \hspace{1cm} (6)

**Fig.7** 2f signal and fitting curve of H2O at -70 ~ 0 ℃

7. Conclusion
(1) For HF gas, the absorption line intensity is the strongest at 7823.83cm$^{-1}$ (1278.1nm), and the order of magnitude is $10^{-37}$. At the same time, the Lorentz spectrum simulation is carried out at 20cm$^{-1}$ optical path, 1atm and 300K, and the possible CO, CO2, SO2, H2S and H2O gases in GIS gas chamber almost have no interference. Similarly, for H2O gas, the absorption line strength is the strongest at 7181.15cm$^{-1}$ (1392.5nm), the order of magnitude is $10^{-20}$, and the possible HF, CO, CO2, SO2 and H2S gases in GIS gas chamber almost have no interference. It can be seen that it is feasible
to choose 1278nm and 1392nm laser sources respectively and realize HF and micro water measurement based on TDLAS technology of dual fiber time division multiplexing.

(2) The system uses Herriott gas absorption cell with turn back optical path. The length of the absorption cell is 10cm, the optical path is 20cm, three rows of the 11 air inlets are set, and two collimators are used in the gas chamber for laser transmitting and receiving respectively. There is no laser return to the laser, which can effectively reduce the optical noise. With the increase of dew point, the second harmonic intensity increases, the center of waveform remains unchanged, and the nonlinear fitting coefficient $R^2$ is 0.999, which changes in the form of first-order exponential. The interference gases of 100 ppm H2S, SO2, CO and CO2 in SF6 background were prepared by SF6 decomposition product multi group distribution gas system at the same time. After the test, there was no harmonic spectrum at 294 position of sampling point, and the anti-interference performance was good.

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