Optical charged sensing detection technology for H2S, SO2, CS2 and CF4 gas of sulfur hexafluoride decomposition products

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Abstract. In view of the current situation that it is difficult to prevent and control in advance the generation of trace H2S, SO2, CS2 and CF4 gases by SF6 gas insulation equipment under fault conditions, there is no effective monitoring method and detection device. This paper studies the gas detection technology based on the UV spectrum and non-dispersive infrared analysis, deeply studies the spectral characteristics of low concentration H2S, SO2, CS2 and CF4 gas with the SF6 as background gas, and simulates the spectral absorption capacity. According to the absorption spectrum line and its variation with temperature and pressure, the concentration inversion algorithm is fitted to improve the effective detection ability of the instrument. Using optical fiber sensing technology, an optical path structure suitable for on-line detection of high-voltage equipment is designed. Using the characteristics that the optical signal is free from electromagnetic interference, the transmission of optical signal by optical fiber is studied, and finally the on-line analysis of the trace H2S, SO2, CS2 and CF4 gas components in the high-voltage equipment is realized. The high-voltage switch model is constructed through three-dimensional modeling, and its fault tolerance and anti-interference ability are analyzed. The stray light and space light are analyzed by simulation software, and the effects caused by vibration and deformation are simulated. The on-line optical fiber sensing detection method of H2S, SO2, CS2 and CF4 gas in high-voltage GIS equipment is proposed. The optical noise suppression technology suitable for the field is studied, the optical path system is designed to withstand the gas pressure of high-pressure equipment, and the influence of field vibration and temperature change of high-pressure equipment on the optical path structure is solved. The on-line gas detection experiment was carried out, and the automatic calibration simulation device of the optical path system was calibrated to ensure the accuracy and stability of H2S, SO2, CS2 and CF4 gas detected by the optical path system.

1. Introduction
As an excellent insulation and arc extinguishing medium, sulfur hexafluoride (SF6) gas is widely used in various electrical equipment such as sulfur hexafluoride gas insulated circuit breaker, gas insulated sub station (GIS), transformer, transformer and power cable. Most of the high-voltage switches with SF6 gas as the insulation medium in China have gradually entered the disassembly and maintenance period since they were put into operation[1-3]. In long-term operation of electrical equipment, SF6 gas will decompose under the action of high-voltage arc or high-energy factors to produce hydrogen fluoride (HF), carbon tetrafluoride (CF4), sulfur dioxide (SO2), hydrogen sulfide (H2S), carbon disulfide (CS2), sulfurous fluoride (SOF2), sulfurous fluoride (SO2F2) and other compounds. The
above decomposition products are harmful to different parts of human body, and their corrosivity has an adverse impact on electrical equipment and affects the safe and stable operation of power equipment. According to the research, H2S, SO2, CS2 and CF4 gases first appear in electrical faults. Online detection of the above four gases can provide rich and reliable data support for the study of electrical equipment fault mechanism. The existing detection methods for H2S, SO2, CS2 and CF4 gas can only be analyzed offline, and can not be measured online. Due to its strong adsorption, active chemical properties and easy reaction with other substances, it is difficult to effectively detect H2S, SO2, CS2 and CF4 gases by off-line measurement[4,5]. At present, there is a lack of means to conduct quantitative analysis in the power field, resulting in a large number of high-voltage equipment faults cannot be detected in the early stage, and the early test data can not be obtained when faults occur, so that the accident experience can not be effectively accumulated.

This achievement is the first time to carry out the in-depth research on optical charged sensing and detection technology based on ultraviolet spectrum and non dispersive infrared ray, mainly to develop a set of on-line measurement device to measure single or several absorption lines of molecules that are very close and difficult to distinguish by using the characteristics of narrow line-width and wavelength of the tunable semiconductor laser changing with the injection current. Using the advantages of non-destructive measurement of optical fiber sensing technology, after the successful development of research results, it can realize the on-line measurement of H2S, SO2, CS2 and CF4 gases, achieve good sensitivity and wide detection range, and have the characteristics of low cross sensitivity, high reliability and stability, long service life, etc[6,7]. It is suitable for on-line accurate measurement of H2S, SO2, CS2 and CF4 gas in high-voltage switches, circuit breakers and other electrical equipment in the fields of scientific research and power system (H2S reaches 10^{-6} detection accuracy, SO2 reaches 10^{-6} detection accuracy, CS2 reaches 10^{-9} detection accuracy and CF4 reaches 10^{-6} detection accuracy), so as to realize the safe operation of power equipment, It has good economic and social benefits to ensure the life safety of power equipment operation and maintenance personnel and reduce the occurrence of insulation fault accidents of SF6 electrical equipment.

2. Detection principle of dual channel NDIR Technology

Ultraviolet and infrared H2S, SO2, CS2 and CF4 gas detection systems are based on non-dispersive infrared (NDIR) detection technology[8]. Taking CF4 as an example, ultraviolet and infrared beams pass through the gas chamber, and CF4 gas will absorb specific wavelength ultraviolet and infrared light. By querying hitran2008 database, it can be seen that the main absorption bands of CF4 are between 1275 ~ 1290cm^{-1}, which basically do not overlap with the main absorption bands of SF6 gas and other decomposition products. This band can be selected as the key research band of CF4 gas. The test principle of SO2, CS2 and H2S gas is similar to that of CF4 gas. The absorption spectra of the main decomposition components of H2O and SF6 are shown in Figure 1.

Figure 1 Absorption spectra of SF6 and its main decomposition components
The light intensity attenuation of the characteristic infrared wavelength follows the Lambert Beer law, and the absorbance $A$ is directly proportional to the concentration $C$ of the gas to be measured and the thickness $L$ of the absorption layer, that is:

$$ A = \ln \frac{I_n(\lambda)}{I_out(\lambda)} = k(\lambda)cL $$

(1)

$$ I_out(\lambda) = I_in(\lambda) \times \exp[-k(\lambda)cL + \beta] $$

(2)

Where: $I_{in}(\lambda)$ is the incident light intensity, $I_{out}(\lambda)$ is the outgoing light intensity, $L$ is the total distance from the incident point to the exit point, $k(\lambda)$ is the molar absorption coefficient, $c$ is the concentration of the gas to be measured. According to formula (1), if $k(\lambda)L$ is known, the gas concentration $C$ to be measured can be deduced by detecting the incident light intensity $I_{in}(\lambda)$ and the outgoing light intensity $I_{out}(\lambda)$[9,10]. The gas concentration $C$ can be detected by measuring the energy $I$ of infrared radiation absorbed by CF4 gas and the initial energy $I_0$ of infrared radiation. In practical measurement, the differential detection method of single light source and double detectors is often used, that is, the infrared light emitted by the light source is divided into measurement light and reference light, which enter the gas chamber through two wavelength filters for infrared absorption. Set up $\beta_1$ and $\beta_2$ is the interference factor of the measurement light and reference light, $I_{M-in}(\lambda)$ and $I_{R-in}(\lambda)$ incident light intensity of measurement light and reference light, the $I_{M-out}(\lambda)$ and $I_{R-out}(\lambda)$ are the outgoing light intensity of the measuring light and the reference light respectively.

$$ I_{M-out}(\lambda) = I_{M-in}(\lambda) \times \exp[-k(\lambda_1)cL + \beta_1] $$

(3)

$$ I_{R-out}(\lambda) = I_{R-in}(\lambda) \times \exp[-k(\lambda_2)cL + \beta_2] $$

(4)

The gas concentration can be inversed from the above formula, as shown in formula (3). Because the measurement light and reference light have common interference factors, so $\beta_1=\beta_2$. Mediation input light makes $I_{M-in}(\lambda)=I_{R-in}(\lambda)$. In the reference channel, the gas to be measured has no absorption of infrared radiation, so $k(\lambda_2)$ is approximately zero, the formula (4) can be derived continuously:

$$ c = \frac{1}{k(\lambda_1) - k(\lambda_2)} \left\{ \ln \frac{I_{M-in}(\lambda)}{I_{R-in}(\lambda)} - \ln \frac{I_{M-out}(\lambda)}{I_{R-out}(\lambda)} - (\beta_2 - \beta_1) \right\} $$

(5)

$$ c = \frac{1}{k(\lambda_1) - k(\lambda_2)} L \ln \frac{I_{R-out}(\lambda)}{I_{M-out}(\lambda)} = \frac{1}{kL} \ln \frac{SB}{SA} $$

(6)

Where SA and SB are the feedback values of the output signals of the measurement sample channel and the reference channel respectively. The value of $SB/SA$ represents the infrared light intensity detected by the detector after the gas in the gas chamber absorbs the light source. According to formula (6), the gas concentration to be measured can be calculated and inversed by measuring SA and SB.
3. Research on phase sensitive detection technology based on digital phase locking

Phase locked amplifier is the core component of the harmonic detection. The traditional phase locked amplifier is realized by the analog period such as multiplier and low-pass filter. The combination of the wavelength modulation technology and the harmonic detection technology can greatly reduce the interference of the low-frequency noise and improve the detection sensitivity. Loading low-frequency saw-tooth wave and phase-locked amplifier, loading high-frequency sine wave to drive and modulate the laser, and effectively obtain the emission frequency of the laser[11]. Therefore, this achievement simulates and studies the design and implementation of digital phase-locked amplifier, and studies the influence of digital phase-locked parameter setting on phase-locked results. The principle of dual fiber laser harmonic detection technology is shown in Figure 2.

![Figure 2 Double fiber laser harmonic detection technology](image)

When the harmonic signal is sine wave, the demodulated signal amplitude is the largest. However, it is sometimes difficult to generate the synchronous sine wave in the embedded system, and it is a better choice to use the square wave generated by hardware PWM to be shaped into the saw-tooth wave after RC filtering. The system simulates the saw-tooth wave for frequency scanning and superimposes the triangular wave for frequency tuning, which is mathematically superimposed, as shown in Figure 3.

![Figure 3 Schematic diagram of harmonic drive signal generation](image)

![Figure 4 Harmonic signal sampling data](image)
The frequency of the analog saw-tooth wave signal is about 1Hz, the level amplitude is 0.5V, the DC component is 1.5V, the superposition harmonic amplitude is 0.2V and the frequency is 5kHz. The system simulates an ADC with a sampling rate of 1MHz and a resolution of 12bit. At the harmonic frequency of 5kHz, up to 100 samples can be taken in one cycle. Due to the division problem and considering the calculation efficiency, 128 sampling times per cycle are selected and the harmonic frequency is adjusted to 7.812kHz. In order to improve the detection accuracy, 8 periods of data are sampled for each harmonic point, and the sampling data is shown in Figure 4. According to the fitting Lorentz absorption curve data, the simulation data shown in Figure 4 is fitted and absorbed. The calculation formula of the simulated received signal is as follows, where is total number of sampling harmonics, the number of internal harmonic samples, the sampling time and the random noise.

\[
f^2(t) = 0.4 + \frac{0.2}{n \times k} \times t + 0.1 \times \sin \left(\frac{2\pi}{k}\right) + n(t)
\]

(7)

The original signal is substituted into the Lorentz absorption function to obtain the absorption ratio, and the absorption ratio is multiplied by the original data to obtain the absorbed signal.

\[
y(t) = f^2(t) \times (1 - f_1(f^2(t)))
\]

(8)

Simulating optical fiber sensing system, the absorption line is Lorentz line, and the half height width of the absorption line is 1/16 of the scanning period. Set the noise amplitude as 20mV. Set the harmonic amplitude as 50mV. Set the sampling frequency to 524K[12]. Set the scanning amplitude to 200m. In this case, set different phase angles between the reference signal and the original signal, simulate the phase-locked process, and obtain 8 groups of experimental data, as shown in Table 1.

| ° | Phase locked data | ° | Phase locked data |
|---|---|---|---|
| 0 | ![Image](image1.png) | 10 | ![Image](image2.png) |
| 20 | ![Image](image3.png) | 30 | ![Image](image4.png) |
| 40 | ![Image](image5.png) | 60 | ![Image](image6.png) |

Table 1 Comparison of phase locked data under different phase difference
It can be seen from Table 1 that although the phase-locked result has no deviation, and when the phase difference is 0, the phase-locked result is almost the same as the cosine signal. However, in the case of different phase difference, the amplitude of two orthogonal phase-locked signals changes greatly. It is required to use two orthogonal signals for digital processing when the phase difference cannot be guaranteed to be 0. Based on the phase sensitive detection technology of digital phase locking, this achievement puts forward the quantitative analysis algorithm of SF6 decomposition gas generation device under overheating fault defects and the mixed components of SO2, CS2, CF4 and H2S under laboratory conditions, as shown in Figure 5. The spectral data of SO2, CS2, CF4 and H2S single gas under each concentration are experimentally studied and analyzed. Based on smoothing technology, wavelet transform, FFT transform and least square method, the relationship between the concentration and eigenvalue of each gas is determined, which is used as the basis for the inversion of various gas concentrations.

Figure 5  Ray tracing simulation and design of optical path cell for experiment

4. Experimental study on gas analysis based on laser spectroscopy
Theoretical verification and algorithm design experiments are carried out on the test platform. The test platform includes the high-performance workstation for the data sampling and storage, phase sensitive detection technology of digital phase-locked, programming implementation of quantitative inversion process and high-precision calculation execution. Phase locked amplifier (ametek7270) is used for harmonic extraction of sampling signal. The function generator is used for generating the laser driving waveform. The laser controller LDC-3900 is used to drive, protect and control the laser. Pci-4474 acquisition card is used for data acquisition. DFB laser diode, near infrared detector, laser fixture, optical console, optical fiber and various connectors, etc. The whole system platform is used for the experimental demonstration, the parameter adjustment and the optimization before the prototype trial production. The system block diagram is shown in Figure 6(a), and the physical photos of the built experimental platform are shown in Figure 6(b).
In the harmonic absorption experiment of SO2, CS2, CF4 and H2S gas, a saw-tooth wave signal and a triangular wave signal are generated by the signal generator. The triangular wave signal is used as the input signal of signal generator and superimposed with the saw-tooth wave signal. The superimposed signal is input to the laser driver as an excitation source. The laser driver generates the tunable current signal according to the input signal to drive the laser and generate the wavelength tunable laser source. The generated laser signal is absorbed by the InGaAs sensor after being absorbed by the gas pool, and the signal is amplified by the pre-amplifier and then enters the phase-locked amplifier. The lock-in amplifier uses triangular wave signal generated by the signal generator as the synchronization signal for lock-in. The lock-in output results directly enter the PCI data acquisition card and are collected into digital signals.

Different concentrations of SO2, CS2, CF4 and H2S were obtained by the SF6 local superheated gas mixture generation device. The four gases were studied based on the second harmonic absorption signal by using the experimental platform. During the experiment, the gas chamber was purged with high-purity nitrogen, then the research gas of 1ppm, 2ppm, 3ppm, 4ppm and 5ppm was proportioned in turn, and the gas was introduced into optical path cell with an optical path of 10cm to analyze the absorbed signal. Collect 100 groups of data for each group of absorption signals, as shown in Figure 7.

Figure 6 Establishment of experimental system platform

Figure 7 SO2, CS2, CF4 and H2S gas absorption spectrum under various defect types
It can be seen from Figure 8 that under the condition of 10cm optical path, the detection limit of various gases can be less than 0.5ppm. Based on Lambert Beer's law in the above theoretical analysis, the corresponding detection limit will be reduced in the equal proportion after the optical path is lengthened. Under 1m optical path, the second harmonic method and FFT spectrum analysis are used to infer that the detection limit of SO2, CS2, CF4 and H2S gas is less than 50ppb.

5. Conclusion
This achievement has made a systematic theoretical and Experimental Research on the optical charged sensing detection technology of sulfur hexafluoride decomposition products H2S, SO2, CS2 and CF4. The main innovative achievements and conclusions are as follows:

a) Build an experimental platform, simulate and study the absorption capacity, spectral line broadening and gas cross interference performance of H2S, SO2, CS2 and CF4 gases with SF6 as the background under the high pressure, and establish the spectral map database corresponding to each component. Based on the spectrum database, the corresponding absorption spectrum law is determined according to the UV spectrum and non dispersive infrared characteristics of the typical trace decomposition gas of SF6, and the suitable characteristic peak is selected as the qualitative and quantitative detection basis of the spectral technology. The cutting-edge embedded processing technology is applied to design the processing algorithm combined with the experimental data to improve the detection ability of low concentration gas in the system.

b) Using the optical charged sensing detection technology, an optical path structure suitable for on-line detection of high-voltage equipment is designed. Using the characteristics that the optical signal is free from electromagnetic interference, the optical signal is transmitted through optical fiber to realize the on-line analysis of trace H2S, SO2, CS2 and CF4 gas components in high-voltage GIS equipment. The high-voltage switch model is constructed through three-dimensional modeling, its fault tolerance and anti-interference ability are analyzed, the stray light and the space light are analyzed by simulation software, and the effects caused by the vibration, the deformation and other factors are simulated to reasonably avoid the interference between other gases in SF6 decomposition components and the characteristic components to be measured, and quantitative inversion algorithm of multi-component and low concentration gases is studied, the optical charged sensing technology of H2S, SO2, CS2 and CF4 gas in high voltage GIS equipment is proposed.

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