Research and Development of NDIR Sensor and Its Application In On-Line Detection of CF4 Gas

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Abstract—Due to the excellent insulation and arc extinguishing properties of SF6 gas, it is widely used in the production and use of high voltage GIS. However, due to the breakdown of discharge and overheat, SF6 gas decomposes and produces a variety of low fluorine sulfides. Therefore, the concentration of CF4 gas in the high-voltage switch state can be effectively determined by detecting high-voltage GIS. This paper puts forward a kind of semiconductor laser based gas detection (NDIR) technology, the flange fixed installation in high voltage switch, optical fiber sensing structure can realize remote, real-time online monitoring of CF4 gas content. The experiment shows that the flange fiber optic sensor on-line monitoring device can realize the effective measurement of CF4 gas. The research results show that maximum field intensity on the surface of basin insulator is 10.788 kV/mm, which is lower than the control field strength of 20kV/mm under the SF6 gas insulation condition, therefore the E-field near the basin insulator does not affect the operation of the optical fiber sensor. In the case of 1m light path, the detection limit of CF4 gas near 1312nm is less than 0.5 ppm. The results of this study can provide an entirely new scheme for on-line monitoring of high-pressure open-light SF6 gas decomposition products, which can realize real-time on-line monitoring of the internal gas of the high voltage GIS equipment.

1. INTRODUCTION

With the construction and development of UHV smart grid in China, State Grid Corporation of China has made great efforts to promote the operation state detection and life assessment of large-scale power main equipment in the 14th five year plan[1-4]. At present, the state detection and diagnosis technology of SF6 gas insulated high-voltage combined electrical appliances and other key power equipment has become research hot-spot in the field of electrical science. Sulfur hexafluoride (SF6) gas has excellent insulation and arc extinguishing performance, so it is widely used in gas insulated circuit breakers, gas insulated combined electrical appliances and other electrical equipment. Because SF6 gas insulation equipment may have various defects during manufacturing, installation or operation, and then discharge and overheat faults occur, resulting in the decomposition of SF6 gas and the formation of a variety of low fluorine sulfides. If the discharge occurs near the solid insulating medium, the decomposition products such as CF4, CO and CO2 will also be formed. Its content and generation rate are closely related to the internal insulation deterioration of the equipment, which can be used as the basis for judging the early latent failure of the insulation equipment. GB/T 12022-2014, the national standard of people's Republic of China, sulfur hexafluoride for industry, clearly proposes to detect carbon tetrafluoride gas in the decomposition products of SF6[5-8]. The existing detection methods for carbon tetrafluoride gas can only do off-line analysis, not on-line measurement. At present, there is a lack of
effective means for quantitative analysis of carbon tetrachloride gas in the field of electric power, resulting in a large number of high-voltage equipment failures can not be detected in the early stage.

In view of this, the non dispersive infrared technology (NDIR) is applied to on-line detection of carbon tetrafluoride gas for first time. Software and theoretical analysis: in-depth study of the spectral characteristics of SF6 as background gas and low concentration CF4 gas, combined with simulation platform to simulate the spectral absorption capacity and the refined distribution of electric field of internal insulation parts of typical high-voltage power equipment. According to the quantitative measurement data of absorption spectrum and spectrum line changing with temperature and pressure, the mixture algorithm of RBF neural network and NSGA-II is used to invert the concentration of CF4 gas[9,10]. Hardware and device development: develop a set of on-line measurement device to realize quantitative analysis of carbon tetrafluoride gas, optimize the design of optical path system to solve the impact of high-voltage equipment on the structure of optical path caused by high-frequency vibration and large temperature difference on the site. Debug 220kV SF6 GIS true type test platform for gas insulation, and use NDIR technology in the platform for the on-line detection of carbon tetrafluoride gas[11,12]. The on-line measurement method based on NDIR technology can realize the high sensitivity and wide concentration range detection of carbon tetrafluoride gas. It is suitable for the on-line accurate measurement of carbon tetrafluoride gas in the high-voltage combined switch-gear and other equipment in the field of power system, so as to realize the safe operation of power equipment, with good economic and social benefits.

2. PRINCIPLE OF CF4 ONLINE OPTICAL FIBER SENSING SYSTEM

2.1 Principle of CF4 online optical fiber sensing system

Compared with the traditional infrared spectrum technology, the characteristic of NDIR is that the spectrum width of the semiconductor laser source is much smaller than that of the gas absorption line. Therefore, NDIR technology with single-mode laser has very high spectral resolution[13], which can analyze the specific spectral line of gas absorption spectrum and obtain measured gas concentration (often referred to as single line spectral analysis technology), as shown in Figure 1.

![Figure 1. Principle of CF4 online optical fiber sensing system.](image)

Compared with traditional infrared absorption spectroscopy, the characteristic of NDIR gas analysis technology is that the spectral width of the semiconductor laser source is much smaller than that of the gas absorption line. For example, the spectral line-width (<10MHz) of the semiconductor distributed feedback laser (DFB-LD) is much smaller than that of the gas absorption laser (tens to hundreds of MHz). Therefore, NDIR technology with single-mode laser has very high spectral resolution, which can analyze the specific spectral line of gas absorption spectrum and obtain measured gas concentration.

The NDIR gas spectrum detection technology is applied to CF4 online monitoring research in CF4 online optical fiber sensing technology of this project, and the principle is shown in Figure 2. Advantages are: using the good monochromaticity of semiconductor laser, adopting “single line spectrum” technology to avoid the interference of background gas absorption, non-contact measurement, not affecting the gas components inside the high-voltage switch, no active device, not subject to strong electromagnetic interference of the high-voltage switch. It has the advantages of good reliability, high sensitivity and automatic compensation of temperature and pressure.
In the early stage of high-pressure equipment failure, the concentration of CF4 gas is low, which is difficult to be detected. This project needs to study the CF4 detection method, improve the detection ability of the system, meet the requirements of effectively detecting CF4 gas under the low concentration conditions, and further study the low concentration CF4 gas monitoring technology under the background of high-pressure equipment SF6, so as to improve the effective detection ability of the instrument. The NDIR is the abbreviation of non dispersive infrared technology, it is based on the beer Lambert law[14]. When infrared light source emits infrared light in a wide wavelength range through the measured gas, the measured gas selectively absorbs the infrared light, resulting in light intensity attenuation. The degree of light intensity attenuation is directly proportional to the concentration of the measured gas. Therefore, the attenuation of the measured gas can be obtained by measuring the attenuation of the light intensity concentration.

2.2 Monitoring principle of low concentration CF4 gas

When the infrared light passes through the gas to be measured, these gas molecules have absorption to the infrared light of the specific wavelength, and the absorption relationship obeys Lambert Beer absorption law. Let the incident light be the parallel light, its intensity is $I_0$, the intensity of the outgoing light is $I$, and the thickness of the gas medium is $L$. According to Lambert Beer’s law of absorption: $dI/I = -kNC$, where $k$ is the proportional constant. By integration, $\ln I = -kNC + \alpha$, where $n$ is the total number of molecules absorbing the gas medium and $\alpha$ is the integration constant. Obviously, $n \propto C$ is the gas concentration. The above formula can be written as:

$$I = I_0 e^{-kNC} = I_0 e^{-\mu LC} = I_0 e^{-\mu eL}$$  \hspace{1cm} (1)

Formula (1) shows that the light intensity decreases exponentially with the concentration $C$ and the thickness $L$ in the gas medium. The absorption coefficient depends on the gas characteristics, and the absorption coefficients $\mu$ of various gases are different from each other. For the same gas, $\mu$ varies with the incident wavelength. If there are $N$ absorption gases in the absorption medium, formula (1) should be changed to:

$$I = I_0 e^{-L \sum_{i=1}^{N} \mu_i e}$$  \hspace{1cm} (2)

Therefore, for variety of mixed gases, in order to analyze the specific components, the narrow-band filter suitable for analyzing gas absorption wavelength should be installed in front of the sensor or infrared light source, so that the signal change of the sensor only reflects the change of the measured gas concentration[15]. Compared with the traditional infrared absorption spectrum technology, NDIR adopts the electric modulation infrared light source, which saves the mechanical modulation components in the traditional method. At the same time, it adopts the high-precision interference filter integrated infrared sensor and the single beam dual wavelength technology, together with the detachable gold plating chamber and data acquisition system. This project is based on the research of on-line CF4 gas sensing technology based on NDIR technology, and applies NDIR gas detection technology to on-line CF4 monitoring research. Its advantages include: the single beam dual
wavelength infrared measurement technology, strong anti-interference ability; non-contact measurement, no impact on the internal gas components of high-voltage switch; micro structure, low power consumption, good reliability, high sensitivity, can realize automatic compensation of temperature and pressure; the implementation of this project will affect the development direction of CF4 gas on-line decomposition product monitoring technology, and will produce better economic benefits and practical value.

NDIR is a new technology, which can reach ppm or even ppb level. It adopts wavelength modulation spectroscopy and the harmonic detection technology. Wavelength modulation spectroscopy technology can suppress noise bandwidth by selecting modulation frequency, while harmonic detection technology (i.e. lock-in amplification technology) can obtain harmonic signal proportional to the concentration of the measured gas, and move the detection frequency to the high frequency with low noise, so as to effectively suppress external interference and low-frequency noise, thus achieving high detection sensitivity[16]. This technology uses the high frequency sine wave as the modulation wave to modulate the sawtooth wave current with the tunable laser frequency of $f_0$ and low frequency.

The laser emission frequency is as follows:

$$V = V_0 + \sigma_V \cos 2\pi ft$$

(3)

$V$ is the instantaneous frequency of laser, $V_0$ is the center frequency of laser, $\sigma_V$ is the modulation amplitude, $f$ is the sine wave frequency, $t$ is the time. Take formula (3) into formula (4) and carry out the Fourier series expansion to get:

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

(4)

In this way, the amplitude of $N_{th}$ harmonic signal is:

$$A_n(v_0) = \frac{2}{\pi} \int_0^\infty I_0(v_0 + \sigma v, \cos 2\pi ft) \exp[-\sigma(v_0 + \sigma v, \cos 2\pi ft)L] \cos(n2\pi ft) d(2\pi ft)$$

(5)

In an ideal case, $I_0$ is a constant independent of $V$, that is, there is no amplitude modulation:

$$A_n(v_0) = \frac{2I_0 c L}{\pi} \int_0^\infty \cos(n2\pi ft) d(2\pi ft)$$

(6)

In the case of very small absorbance:

$$A_n(v_0) = \frac{2I_0 c L}{\pi} \int_0^\infty -\sigma(v_0 + \sigma v, \cos 2\pi ft) \cos(n2\pi ft) d(2\pi ft)$$

(7)

If an $(V_0)$ is expanded by Taylor series, we can get:

$$A_n(v_0) = \frac{I_0 c L 2^{n-1}}{n!} \left[ \sigma(v) \right]_{v=0}$$

(8)

It can be seen from formula (8) that the $n$-th harmonic amplitude value is directly proportional to the $n$-th derivative of the original light intensity $I_0$ and $\sigma_v$, the optical path length $L$ and the absorbed substance concentration $C$. In practical application, the second harmonic technology is usually used, taking $n=2$. The expression of second harmonic component is as follows:

$$A_2(v_0) = \frac{I_0 c L}{4} \left[ \sigma(v) \right]_{v=0}$$

(9)

Therefore, as long as the second harmonic signal and the DC component $I_0$ of the light intensity are measured, the gas concentration can be obtained by analysis.
Central control system: the main function is to control the laser driver and process the data uploaded by the signal acquisition system; laser drive system: control the laser wavelength emitted by the laser source through the way of temperature and harmonic modulation, so as to accurately find out the position of the whole characteristic absorption peak and improve the measurement accuracy. Optical path cell: this part involves the processing and grinding of many optical devices. Its processing technology directly affects the measurement results, so it is an important part of the system platform. Its schematic diagram is shown in Figure 4.

After the system platform is built, the exhaust channel is designed to ensure personal safety, and the reliability of the test platform is verified. The test data provided by the test platform provides the basis for determining the best scanning frequency, harmonic frequency and amplitude, scanning frequency and other parameters. The built system platform is shown in Figure 5.

3. Principle and Device of High Voltage Experiment

Studied the detection method of CF4 gas in SF6 based on NDIR technology, and completed the off-line detection of CF4 gas in laboratory conditions. In the early stage, we studied the detection method of CF4 gas based on NDIR technology, studied the optical absorption characteristics of CF4 gas, and carried out a series of laboratory evaluation experiments on CF4 gas test platform, as shown in Figure 6.
State Grid Chongqing Electric Power Research Institute established 220kV SF6 GIS true type test platform in 2017. After design and calculation, the overall layout of 220kV SF6 GIS true type test platform is shown in Figure 7. The bay includes circuit breaker, dis-connector, voltage and current transformer. When the circuit breaker is in the on and off state, the voltage withstand test is carried out for the whole GIS true interval. During the test, the resonance frequency $f$, the quality factor $Q$ and the current value $I$ of the whole series resonant circuit are focused on. During the test, two-stage step-up technology is adopted: after the power frequency 220V voltage of the distribution transformer is increased to 10kV, the voltage is increased to $10Q$ kV through the series resonance technology. When the circuit breaker is closed, the frequency of the whole circuit reaches resonance state $f_1=123.11\text{Hz}$; when the circuit breaker is open, the frequency of the circuit reaches resonance state $f_2= 136.83\text{Hz}$. The power supply of the whole true type test platform is a series resonance system, which can be boosted from power frequency 220V to 680kV, with rated current of 1.2A. The whole device is SF6 gas insulated, with high voltage generated by resonance circuit and adjustable frequency in the range of 18-300Hz. The compact design of the device overcomes the limitation of the traditional open series resonant high voltage generator due to corona loss, and its local discharge is lower than 2pC, and the series resonance coefficient is 45. Figure 8 shows the overall physical diagram of the 220kV true type test platform, which can effectively simulate the electrical stress and thermal stress borne by GIS equipment in actual operation. GIS equipment includes basin insulator, tube bus insulation support and other insulation parts. It provides SF6 gas field fault gas body and insulation parts fault solid products for the physical and chemical analysis platform for SF6 fault gas composition analysis and fault solid product element analysis.
Figure 8. Global map of GIS true interval.

The establishment of the 220kV SF6 GIS true test platform provides the better hardware application environment for the on-line detection of SF6 decomposition product carbon tetrafluoride based on NDIR. Assuming that the solid insulation parts for GIS are subjected to long-term withstand voltage test by high-voltage AC series resonance equipment and CF4 gas is generated, the recovery voltage $u_{0-1}$ after arc extinguishing can be characterized by equation (11) due to the flash-over of insulation defects of solid samples:

$$u_{0-1} = \cos(\omega t) - [\cos(\beta t) + \alpha \sin(\beta t) / \beta] \exp(-\alpha t)$$  \hspace{1cm} (11)

In equation (11), $\beta = \sqrt{1/(LC) - R^2 / (4L)^2}$, $\alpha = R / (2L)$. Loop resistance $R$ is mainly the equivalent resistance caused by the corona loss of the resonance loop in consideration of:

$$\beta = \sqrt{\omega^2 \left[ \omega^2 / (4Q^2) \right]} = \omega \sqrt{1-1/(4Q^2)} \approx \omega$$ \hspace{1cm} (12)

$$\alpha = R / (2L) = \omega / (2Q)$$ \hspace{1cm} (13)

Therefore, equation (11) can be rewritten as equation (14):

$$u_{0-1} = \cos(\omega t) - [\cos(\omega t) + \sin(\omega t) / (2Q)] \exp(-\omega t / (2Q))$$ \hspace{1cm} (14)

Since $1/(2Q)$ is very small, equation (14) can be further rewritten as equation (15):

$$u_{0-1} \approx \left[1 - \exp\left(-\omega t / (2Q)\right)\right] \cos(\omega t)$$ \hspace{1cm} (15)

It is assumed that the capacitance of the tested object is $C=8000\text{pF}$, the inductance of the reactor is $L=600\text{H}$, the frequency is $f=50\text{Hz}$, and the loop resistance is $r=1.5$. The typical waveform of the recovery voltage $u_{0-1}$ after flashover and arc extinguishing of the tested object is calculated by the above theoretical formula as shown in Figure 9. It can be seen that the flash-over instantaneous voltage of the tested object is zero, and the voltage between the tested objects gradually increases to the test voltage after arc extinguishing. Therefore, the series resonant circuit is applied to the solid insulation of GIS during the voltage withstand test of the edge parts, no over-voltage is generated at the flashover moment. This change rule makes series resonance circuit have better safety and possibility of secondary flashover is low.
Figure 9. Typical waveform of recovery voltage $u_{0.1}$ after flash-over and arc extinguishing.

The optical path of the flange type monitoring device designed in CF4 gas online monitoring is 1m, and its internal structure and optical path are shown in Figure 10. The incident laser enters the gas absorption pool through the optical fiber incident end, and is collimated by optical fiber collimator installed on internal disk structure, with the collimating light number of 1, which is transmitted to the optical fiber collimator in the right direction, and introduced to the number 2 through the optical fiber coupling transmission, the laser is emitted, and so on. Finally, the laser is emitted at No. 10 and coupled to the inside of the optical fiber. The output end of the optical fiber transmits the signal with the gas concentration information to processing terminal to realize the real-time online monitoring of the CF4 gas concentration in the high-voltage switchgear.

Figure 10. France type sensor in CF4 gas on-line monitoring.

Electric field distribution of the installation environment of the flange type optical fiber sensor online monitoring device after actual processing and optical path adjustment is shown in Figure 10. The inside of the device is sealed by the corrosion-resistant and high temperature resistant sealing ring, and some openings are treated with sealant. There are 20 optical fiber collimators installed on the inner ring structure of the gas chamber. The flange optical fiber sensor on-line monitoring device is installed on the 220kV SF6 gas insulation GIS true test platform instead of the original flange cover to verify the on-line monitoring of CF4 gas content in the high-voltage switchgear.

The laser driver is used to drive the laser, and the laser is generated through the 0/1m optical path gas absorption pool and the 100/1m optical path pool, where 0 represents no CF4 gas, 100 represents CF4 gas, and the concentration is 100. After the test, two groups of directly absorbed signals are obtained, and 100 groups of signals are collected respectively, and the number of data sampling points of each group is kept at 500 points. When there is no CF4 gas, there is no absorption near 1312nm. When there is CF4 gas, there is an obvious absorption peak near 1312nm. The absorption spectrum lines without CF4 gas and with CF4 gas are shown in Figure 11 and Figure 12 respectively.
Figure 1. \(0 \mu L/L\) CF4 gas absorption line (Amplitude/nm)

Figure 12. \(100 \mu L/L\) CF4 gas absorption line (Amplitude/nm)

Figure 13 shows that when the CF4 gas concentration is 0, the amplitudes of 100 groups of sampled signals are low and there is no significant peak value, and the signal waveforms are disordered. The burr in the signal is mainly from external interference, and there is basically no effective signal component. When the concentration of CF4 gas is 100, the amplitude of signal waveform is high, and 100 groups of signals are basically the same, which proves that CF4 gas absorption spectrum has good repeatability, and there is a significant absorption peak near the amplitude of 1312nm.

Figure 13. 100 sets detected data (Amplitude/nm)

Through the configuration of low concentration CF4 gas with gas distribution instrument, CF4 gas based on NDIR second harmonic absorption signal is studied using experimental platform. In the experiment, the gas chamber is first purged with high-purity nitrogen, and then 1, 2, 3, 4, 5 CF4 gas is proportioned in turn, and CF4 gas is introduced into the optical path pool with optical path of 1m to analyze the signal after absorption. 100 groups of data are collected from each group of absorption signals. The collected data is shown in Figure 13. It shows that the amplitude at the peak point increases with the increase of CF4 gas concentration, and the position of peak appears basically unchanged. The data collected when the high-purity nitrogen gas is introduced shall be accumulated and averaged as the
zero point data, and the absorption data shall be obtained by subtracting five groups of absorption data from the zero point data, as shown in Figure 14.

Figure 14. Subtract the background data to obtain the experimental data(Amplitude/nm)

Five groups of 100 times of absorption data are respectively weighted and accumulated, and the accumulated data is shown in Figure 15. It can be seen from the data that when the valve concentration of the valve instrument is changed, the absorption data increases and decreases obviously, and the amplitude tends to be stable with the time extension. Discard the first 50 groups of data with obvious data changes, quantize the last 50 groups of accumulated data into gas concentration, analyze the concentration data, and take three times of standard deviation as the detection limit. The sensitivity or detection limit of the five groups of measurement data is shown in Figure 16. It can be seen from the data that the detection limit of CF4 gas is less than 0.5 near 1312nm in the case of 1m optical path.

Figure 15. Absorption area

Figure 16. Detection capability

4. CONCLUSION

(1) In this paper, the flange optical fiber sensor on-line monitoring method for CF4 gas detection of high-voltage switch is proposed. Based on laser spectrum technology, a flange optical fiber sensor
device is designed, which can be directly installed on the high-voltage switch to monitor the gas inside the high-voltage switch in real-time.

(2) In the true type test platform, the maximum field strength along the surface of the basin insulator appears in the contact area between the solid insulator and the high potential, and the maximum field strength on the surface of the basin is 10.788kV/mm, which is lower than the requirement of 20kV/mm control field strength under the SF6 gas insulation condition. The calculation results show that the electric field near the basin insulator does not affect the operation of the optical fiber sensor after the flange optical fiber sensor online monitoring device is connected to the GIS equipment.

(3) Through the detection of different concentrations of CF4 gas, its absorption spectrum has good repeatability. In the case of 1m optical path, the detection limit of the CF4 gas near 1312nm can be less than 0.5. In the later stage, the measurement accuracy can be further improved by improving the internal coating of flange and increasing the length of optical path.

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