Operation principle analysis of multi-function SF₆ insulating gas decomposition product field detector

Jiguo Zhang¹, Yi Xu¹, Bo Peng¹, Yao Ma¹, Yu Wang¹, Jinyu Zhao¹, Xin Lin¹*, Jingzhe Chen¹,
¹ STATE GRID SIPING POWER SUPPLY COMPANY, Si Ping, Ji Lin, 136000, China
* Xin Lin: gwsiping@126.com

Abstract. In recent years, SF₆ gas insulated equipment is widely used in power system to meet the development needs of power industry. The change of CF₄ content is of great significance for analyzing the insulation state of electrical equipment. In this paper, a new technology and equipment for on-site detection of CF₄ in SF₆ gas based on spectral absorption principle is studied. It provides reference and technical support for the operation and maintenance of SF₆ gas insulated equipment and the condition based maintenance of equipment in the future.

1. Introduction
At present, the detection of CF₄ in SF₆ gas is usually carried out by gas chromatography[1-3]. The equipment of this scheme is complex and the operation is cumbersome. It is usually used in laboratory testing, but not suitable for on-site testing, resulting in poor timeliness and low detection accuracy. Aiming at the deficiency of CF₄ detection in SF₆ gas and the difficulty of on-site detection, this project studies a kind of instrument using specific spectral sensor to realize high-precision detection of CF₄ in SF₆ background gas. The instrument can realize high-precision detection of CF₄ content, as well as the detection of SO₂, CO, H₂S and HF components using thermal conductivity method and resistance capacitance method and the detection of water content, to achieve the improvement of CF₄ detection technology, improve the level of on-site detection and the analysis ability of equipment operation state.

2. Absorption spectrum of gas molecules
Spectrum is the distribution of light intensity according to wavelength or frequency, and its spectral line has a certain shape of spectral line profile. The common spectrum types are linear spectrum, continuous spectrum, absorption spectrum, band spectrum, etc. The narrow spectral line produced by atomic energy level transition is called linear spectrum. A series of spectral bands, called band type spectra, are produced by the energy level transitions generated by the atomic vibration and molecular rotation around the nucleus. The spectrum containing all wavelengths is called continuous spectrum. When the light wave with continuous spectrum passes through a certain gas molecule, it is excited by photons, and the energy level state inside the molecule presents the following process:

From the ground state to the unstable high-energy level state, and then from the high-energy level state back to the ground state, at the same time, release photons, and finally produce a series of spectral lines with different wavelengths, such a spectrum is called absorption spectrum. By studying the characteristics and rules of gas molecular absorption spectrum, we can understand the internal structure of atoms or molecules, or qualitatively and quantitatively analyze the components of samples.
Molecules have been in irregular motion for a long time. The main motion forms of the internal structure of molecules are: the rotation of molecules around the nucleus, the irregular activity of electrons, and the relative vibration of atoms. Correspondingly, there are three kinds of energy levels in the molecule: the rotation of the molecule around its center of gravity is called molecular rotation\[4-5\], corresponding to the rotational energy level \(E_r\); the vibration of the nucleus in the molecule relative to its equilibrium position is called atomic motion, corresponding to the vibrational energy level \(E_v\); the rotation of the electron around the nucleus is called electronic motion, corresponding to the electronic energy level \(E_e\). The sum of the molecular energies \(e\) is

\[E = E_e + E_v + E_j\] (1)

According to Planck's quantum law, the state of energy level changes with the absorption of photons, and the energy difference \(e\) between the low energy level ground state \(E_1\) and the high energy level excited state \(E_2\) must be equal to the energy of photons. Namely:

\[\Delta E = E_2 - E_1 = h\nu = h\frac{c}{\lambda}\] (2)

The change of molecular energy level state is often accompanied by the generation of spectra, in which the lines produced by the change of electronic energy level state are mainly distributed in the ultraviolet region, and the lines produced by the change of vibrational energy level state are mainly distributed in the infrared region. The vibrational energy level transition is usually accompanied by the electronic energy level transition, which leads to the formation of a variety of spectral bands with different wavelength range, resulting in the molecular absorption spectrum in the form of band spectrum. The difference of the internal structure of molecules determines that different kinds of gases absorb different photons with different energy, and different absorption spectra are produced after absorbing the photon energy. Fig. 1 and Fig. 2 show the absorption lines of CF\(_4\) gas in the infrared and ultraviolet regions.

![Figure 1. absorption spectrum of CF\(_4\) gas in ultraviolet region](image-url)
3. Lambert Beer law

The theoretical basis of quantitative analysis of absorption spectrum is Lambert Beer law, and the theoretical model is shown in Fig. 3.

After the original spectrum $I_0$ passes through a uniform light absorbing substance, the light intensity of the transmission spectrum is $I$, and the absorbance $a$ of the substance is defined as:

$$A = \log \frac{I_0}{I} \quad (3)$$

The absorbance $A$ is linearly related to the concentration $C$ and the optical path length $B$:

$$A = K c b + \varepsilon \quad (4)$$

When the material to be measured is a gas, $K$ can be expressed by the absorption cross section of the gas molecule $\delta(\lambda)$, which indicates the extinction ability of the gas molecule at a certain temperature and pressure. In this case, Lambert Beer law can be expressed by the mathematical model shown by the following formula:

$$I(\lambda) = I_0(\lambda) * exp[-\delta(\lambda) * C * L] \quad (5)$$

Where $I_0(\lambda)$ is the incident spectrum of the light source, $I(\lambda)$ is the transmission spectrum after passing through the gas, $C$ is the concentration of the gas, $L$ is the optical path length of the absorbing gas, and $\delta(\lambda)$ is the absorption cross section of the gas. The optical path length $L$ and the gas absorption cross section $\delta(\lambda)$ are fixed values, which can be determined by certain experiments in advance. In the actual measurement process, the gas concentration can be derived from the original spectral intensity of the light source measured by the sensor and the transmission spectral intensity after passing through the gas. This is the theoretical basis for
measuring the gas concentration by the absorption spectroscopy technology, the concentration $C$ of the gas to be measured is:

$$C = \frac{\ln\left(\frac{l_0(\lambda)}{l(\lambda)}\right)}{\delta(\lambda)L}$$  \hspace{1cm} (6)

The absorbance of measured gas is defined as OD (optical depth):

$$OD = \ln\left(\frac{l_0(\lambda)}{l(\lambda)}\right) = L\delta(\lambda)C$$  \hspace{1cm} (7)

Substituting $od$ into the gas concentration formula, we can get the following results:

$$C = \frac{OD}{L\delta(\lambda)}$$  \hspace{1cm} (8)

Thus, the gas concentration data can be obtained.

4. Conclusion

The multi-functional SF$_6$ insulating gas decomposition product on-site detector adopts infrared spectrum absorption detection technology to detect the content of CF$_4$ component, adopts ultraviolet spectrum absorption detection technology to detect the characteristic content of SO$_2$ and H$_2$S component, and integrates electrochemical sensor detection technology to realize the comprehensive analysis function of SF$_6$ gas decomposition product. At the same time, the absorption peak characteristics of different spectra of various decomposition product components are digitized to form a feature database. In the test process, the feature database is used to accurately identify the absorption characteristics of different components, and multi repeat kernel analysis is carried out for the tested components, which improves the detection accuracy.

Acknowledgments

This research was supported by Science and technology project of State Grid Jilin Electric Power Company Limited in 2019 (2019-11). The authors thank Zhang Xilin for his constructive comments during the review process. Thanks also go to Xu Yi and Yang Le for their help in the field.

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