Spectrochimica Acta Part A: Molecular and Biomolecular Spectroscopy 136 (2015) 884–889

Contents lists available at ScienceDirect

Spectrochimica Acta Part A: Molecular and Biomolecular Spectroscopy

journal homepage: www.elsevier.com/locate/saa

Fourier transform infrared spectroscopy quantitative analysis of SF_6 partial discharge decomposition components

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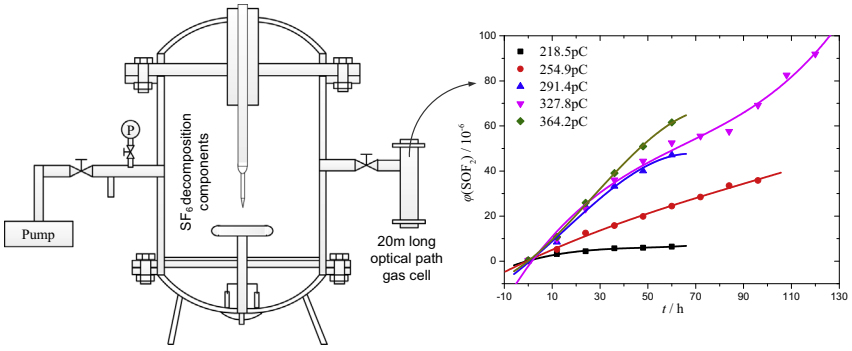
HIGHLIGHTS

- We have studied the SF_6 PD decomposition components by FTIR.
- Quantitative detection experiments on four characteristic components were conducted.
- The four components volume fraction variation with PD time were analyzed.
- Gas production rate variation with PD time and PD quantity was analyzed.

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:
Received 20 April 2014
Received in revised form 11 September 2014
Accepted 13 September 2014
Available online 2 October 2014

Keywords:
Fourier transform infrared spectroscopy
Quantitative analysis
SF_6
Decomposition components
Partial discharge

ABSTRACT

Gas-insulated switchgear (GIS) internal SF_6 gas produces specific decomposition components under partial discharge (PD). By detecting these characteristic decomposition components, such information as the type and level of GIS internal insulation deterioration can be obtained effectively, and the status of GIS internal insulation can be evaluated. SF_6 was selected as the background gas for Fourier transform infrared spectroscopy (FTIR) detection in this study. SOF_2, SO_2F_2, SO_2, and CO were selected as the characteristic decomposition components for system analysis. The standard infrared absorption spectroscopy of the four characteristic components was measured, the optimal absorption peaks were recorded and the corresponding absorption coefficient was calculated. Quantitative detection experiments on the four characteristic components were conducted. The volume fraction variation trend of four characteristic components at different PD time were analyzed. And under five different PD quantity, the quantitative relationships among gas production rate, PD time, and PD quantity were studied.

Introduction

Sulfur hexafluoride (SF_6) gas is widely applied as an electrical insulator as well as an arc-quenching medium in gas-insulated switchgear (GIS). Pure SF_6 is a colorless, tasteless, non-poisonous, and non-combustible inert gas, the dielectric strength of which is thrice that of air at atmospheric pressure [1]. SF_6 gas produces minimal decomposition components under normal operation circumstances. However, when partial discharge (PD), a spark, an arc, or overheating occurs in SF_6 gas, some SF_6 molecules decompose and produce SF_4, SF_3, SF_2, S_2F_{10}, and some other low-fluoride sulfides. These low-fluoride sulfides have very active chemical properties and react with impurities, such as H_2O and O_2 in SF_6 gas. Thus, different types of decomposition products are generated; these products include SOF_2, SOF_4, SO_2F_2, SO_2, HF, and H_2S [2–5]. Fig. 1 shows the chemical reaction of SF_6 decomposition.

The hydrolysis products of SF_6 decomposition components, such as HF, H_2SO_3, and SO_2, have a corrosive effect on GIS internal

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http://dx.doi.org/10.1016/j.saa.2014.09.109
1386-1425/

insulation. Owing to this effect, the speed of insulation degradation increases, and the level of PD intensifies; thus, equipment faults occur. Preliminary study indicates that PD caused by different types of insulation fault yields different SF_6 decomposition products with different volume fractions and generation rates [6,7]. Accordingly, such information as the type, property, and level of equipment internal insulation degradation can be obtained by detecting the element of SF_6 gas decomposition components.

The main international methods of detecting SF_6 gas decomposition components are gas chromatographic, detector tube, gas sensor, and Fourier transform infrared spectroscopy (FTIR) methods [8]. The gas chromatographic method can detect most components, such as SOF_2, SO_2F_2, SO_2, and CF_4 [9] with detection precision that can reach μL/L. However, the sample injection time of this method is extremely long, and the chromatographic columns have to be cleaned regularly; thus, this method is unsuitable for online monitoring. For the detector tube method, when commercial detector tubes are applied to detect SF_6 gas composition components, only some types of composition products, such as SOF_2, SO_2, and HF, can be detected [10]. Although the detection precision of a detector tube can also reach μL/L, its stability is easily affected by temperature and humidity, and the cross interference problem also exists. A gas sensor has the advantages of high speed, high efficiency, and so on [1]; however, because of the chemical reaction between the gas to be detected and the sensor, sensor poisoning occurs after long-term use and thus affects the sensitivity and detection precision of the gas sensor.

The FTIR method has the advantages of high detection speed, capability to detect numerous types of components, high detection precision, strong capacity for resisting disturbance, and repeated detection of the same sample [11,12]. This method is thus suitable for online monitoring with prospects for powerful future applications [13]. Quantitative research on SF_6 decomposition components was conducted in this study based on the FTIR method. The absorption coefficients of several types of SF_6 decomposition components were confirmed, and the quantitative relationships among gas production rate, PD time, and PD quantity were studied.

Detection platform

FTIR involves the use of the spectral characteristic of gas molecules for gas detection [14]. The infrared absorption spectroscopy has an inherent relationship with the structural characteristic of gas molecules [15]. The infrared absorption spectroscopy of different gases varies, and so does the absorption intensity of the same type of gas with different concentrations to the same absorption peak. Not all gas molecules can produce an infrared absorption spectroscopy; only gas molecules with vibration transition that is accompanied with the changing of the dipole moment can produce such spectroscopy. These gas molecules are called infrared active molecule.

Gas infrared absorption spectroscopy quantitative detection mainly occurs according to the Beer–Lambert law. When monochromatic light passes through a medium (gas) with a certain thickness and is absorbed by the medium, the intensity of the light decreases. The medium volume fraction, thickness, and intensity of the light satisfy Eq. (2.1) [16–18].

$$I = I_0 \exp(-\alpha c l) \tag{2.1}$$

I_0 is the intensity of incident light, I indicates the intensity of emergent light, α is the absorption coefficient, c is the volume fraction, and l is the thickness of the medium (length of the optical path). By transforming Eq. (2.1), Eq. (2.2) is obtained.

$$A = \log_{10}\frac{I_0}{I} = K \cdot l \cdot c \tag{2.2}$$

where A expresses the absorbance, K is the absorption coefficient, and c is the volume fraction of the medium.

SF_6 gas partial discharge decomposition experiments were conducted in the experimental apparatus shown in Fig. 2. The needle-plate electrode defect model is used to simulate the extremely nonuniform electric field caused by PD in the GIS and the distance between electrodes is 10 mm. After the experimental apparatus was evacuated and flushed by pure SF_6 gas, pure SF_6 gas was charged into the apparatus until the pressure reached 0.3 MPa. Then a high voltage was applied on the needle-plate electrode. Laboratory used the Nicolet 6700 Fourier transform infrared spectrometer in conjunction with the gas cell of 20 m long optical path to analyze the samples.

Absorption peak and coefficient

Optimal absorption peak selection

The absorption peaks and decomposition products of SF_6 are mainly distributed at 2000–480 cm^{-1} [4,19–22]. The standard infrared absorption spectroscopy of the standard gas was measured in the laboratory, as shown in Fig. 3(a)–(d), to identify the optimal absorption peak of SF_6 gas characteristic decomposition components. Fig. 3 shows the standard spectra of SO_2F_2, SOF_2, SO_2, and CO. The circled portion of Fig. 3 is enlarged in a diagram to better distinguish between the gas absorption peak of the standard gas and that caused by the interference of residual SF_6. In Fig. 3(a) and (b), other peaks are caused by the residual SF_6 beyond the circled point.

Eq. (2.2) indicates that the volume fraction of the gas to be detected and the intensity or area of the absorption peak have a

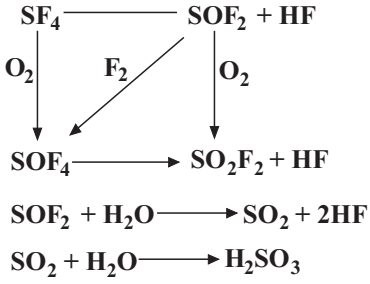

Fig. 1. Schematic of SF_6 decomposition.

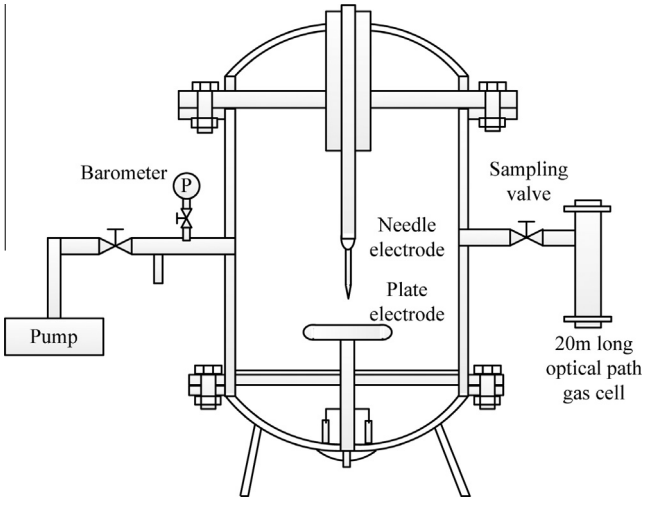

Fig. 2. Schematic diagram of the SF_6 gas decomposition experimental apparatus.