Compact QEPAS humidity sensor in SF₆ buffer gas for high-voltage gas power systems

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A B S T R A C T

In SF₆ insulated high-voltage gas power systems, H₂O is the most problematic impurity which not only decreases insulation performance but also creates an acidic atmosphere that promotes corrosion. Corrosion damages electrical equipment and leads to leaks, which pose serious safety hazards to people and the environment. A QEPAS-based sensor system for the sub-ppm level H₂O detection in SF₆ buffer gas was developed by use of a near-infrared commercial DFB diode laser. Since the specific physical constants of SF₆ are strongly different from that of N₂ or air, the resonant frequency and Q-factor of the bare quartz tuning fork (QTF) had changed to 32,763 Hz and 4173, respectively. The optimal vertical detection position was 1.2 mm far from the QTF opening. After the experimental optimization of acoustic micro-resonator (AmR) parameters, gas pressures, and modulation depths, a detection limit of 0.49 ppm was achieved for an averaging time of 1 s, which provided a powerful prevention tool for the safety monitoring in power systems.

1. Introduction

Sulfur hexafluoride (SF₆) is a man-made insulating gas, which is odorless, non-toxic, nonflammable, nonexplosive, and chemically inert in the normal state. SF₆ gas has been widely used in commercial and scientific research applications in the recent century, such as power systems, semiconductors, airplane tires, wind supersonic, medical and scientific research applications in the recent century, such as power systems, semiconductors, airplane tires, wind supersonic, medical.

trace SF₆ decompositions may react with other inevitable gas impurities (mainly H₂O, O₂ and N₂) or materials (electrodes and equipment surfaces), and produce undesirable toxic or corrosive compounds [7–13]. For example, disulfur decafluoride (S₂F₁₀) can be produced due to the arcing or corona insulating faults, which is a highly toxic gas with the toxicity of four times that of phosgene. Besides, the accumulate of these chemically active decomposition gases with the action of H₂O will corrode electrodes and reduce the insulating performance of the electrical equipment, and may ultimately pose an assault to industrial safety. It has been experimentally verified that the SF₆ decomposition gas concentrations and formation rates are associated with the different partial discharge insulating faults [14–16]. Moreover, Tang et al. [17] in 2012 found that the production of CF₄ was inhibited, but the generation of SOF₂ and SO₂F₂ was promoted with the increasing of O₂ concentration. In 2015, Zeng et al. [18] reported that the H₂O molecules created favorable conditions for generating SO₂F₂ and SOF₂ molecules but consumed intermediate by-products (CF₂ and CF₃) and restrained CF₄.

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generation. As a result, the SF₆ decomposition gas concentrations and evolution rates are closely related to the H₂O and O₂ gas concentrations in SF₆ buffer gas. The accurate detection and monitoring of H₂O and O₂ concentrations are crucially important for the association study of SF₆ decompositions and internal fault diagnosis in a high-voltage gas power system.

In electrical equipment, trace concentration of H₂O is the most power impurity in the SF₆ buffer gas, since the gradual release of water vapor from the inner surface and electrode material or the untight seal assembly of electrical equipment. The water vapor reduces the recombination of sulfur and fluoride (or F atom) into SF₆ and creates acidic gases that promotes corrosion. The rate of damage in SF₆ gas insulation equipment depends on the humidity content. To make sure there is no safety hazard, the H₂O in SF₆ buffer gas needs to be kept below 800 ppm. Therefore, the humidity content must be monitored and minimized during the operation process for the long-term and trouble-free safe service.

In recent decades, various kinds of sensitive humidity sensors [19] have been reported in the literature by adopting new technologies, such as optical fiber sensor [20], MEMS-based micro-cantilever [21,22], mass spectrometry [23], tunable diode laser absorption spectroscopy (TDLAS) [24], scanning spectra [25]. However, none of these moisture measurement techniques are well adapted to the continuous monitoring of H₂O in SF₆ gas-insulated switchgears. The most frequently used humidity sensor in SF₆ gas insulation equipment is the chilled mirror technology, which is highly sensitive but high-priced, complex, and time-consuming [19]. Furthermore, it is hard to distinguish dew or frost ice when the mirror surface temperature stays between –20 ℃ and 0 ℃, due to the appearance of the supercooling effect. Another commonly used method is a capacitive polymer sensor, which is quick measuring and much cheaper than chilled mirror technology [26]. On the downside, the short service life, poor selectivity, and limited operating temperature range limit its performance in practical application.

The laser-based photoacoustic spectroscopy (PAS) technology has been developed rapidly for the qualitative and quantitative detection of trace gas since it offers the advantage of high sensitivity, high selectivity as well as real-time monitoring capability. The basic principle of the PAS technology is to detect the periodic acoustic waves, which are generated by the non-radiative relaxation process [27–32]. The acoustic waves generated in the gas molecules can be detected by different kinds of spectrophones, such as condensers, electret microphones, fiber tips, and piezoelectric quartz tuning forks. A unique advantage of the PAS technique is the excitation wavelength independence, therefore various optical excitation sources in different wavelength ranges have been adopted for the trace gas detection including the electronic (UV-Vis), vibrational overtone (1–2.5 μm), fundamental transition (3–12 μm) and even rotational (THz range) spectral ranges [33–37]. For the detection of water vapor molecules, its absorption lines have already been extensively investigated in the HITRAN database. In the near-IR and mid-IR spectral regions, the H₂O molecule absorption lines exist strong intensities and can be used as the targeted absorption lines in the PAS technology [38,39]. However, the developed humidity sensors were all operated in N₂ or air buffer gas and can’t be used directly in SF₆ buffer gas, since the specific physical constants of SF₆ are strongly different from that of N₂ or air. Therefore, a sensitivity humidity gas sensor was designed by using the quartz enhanced PAS (QEPAS) technology with a capability of analyzing trace gas samples of a few mm³ in volume in this manuscript. A commercial and standard quartz tuning fork (QTF) was employed as a resonant acoustic transducer. Taking advantage of the resonant frequency of the acoustic wave in SF₆ buffer gas, the third harmonic acoustic standing wave in the acoustic micro-resonator (AmR) was experimentally observed for the first time to our knowledge, since the curtail length of the AmR in SF₆ buffer gas. The resonant frequency, detection position, AmR parameter, modulation depth, and gas pressure were optimized to achieve a sub-ppm level detection limit of H₂O in SF₆ buffer gas.

2. Photoacoustic sensor system

A sensor system basic diagram is depicted in Fig. 1 for the trace H₂O detection in SF₆ gas-insulated equipment. A near-infrared commercial distributed feedback (DFB) diode laser operating at 1368.6 nm was employed as the excitation source. According to the HITRAN database, the H₂O targeted absorption line of 7306.75 cm⁻¹ was selected with a line strength of 1.8 × 10⁻²⁰ cm/molecule, and which is far away from the absorption lines of SF₆ decomposition gases (such as CO, CO₂, H₂S, SO₂, CF₆). A 14-pin butterfly package containing a thermoelectric controller (TEC) was used to inspire the laser. The DFB laser output wavelength can be controlled by the temperature and the injection current. The experimentally measured temperature and current tuning coefficients were –0.48 cm⁻¹/°C and –0.061 cm⁻¹/mA, respectively.

To obtain a higher detection sensitivity, a 2 f wavelength modulation spectroscopy (WMS) technology was employed in the experiment. The DFB laser wavelength modulation was achieved by a ramp signal with a low frequency of 0.1 Hz and a sinusoidal dithered signal operating at half of the QTF resonance frequency (f/2). A fiber focuser (OZ Optics, model 163426) with a beam waist radius of 50 μm was used to focus the laser beam and pass through the on-beam QEPAS spectrophone without touching the inner surface [40]. The laser output power was monitored by a power meter (Ophir Optronics Solutions, Ltd, model 3A-ROHS) behind the spectrophone. A standard commercial QTF with a resonant frequency of ~32.8 kHz was employed as the acoustic transducer, which had an extremely high Q-factor of 6.8 × 10⁵ when it was vacuum-sealed. An AmR made of two stainless-steel tubes was employed to carry out the on-beam QEPAS sensor system and increase the detection sensitivity. A low noise trans-impedance amplifier (TA) with a feedback resistor of 10 MΩ was used to gather and transmit the QTF signal to a lock-in amplifier (Stanford Research Systems, Inc. model SR830), which was operated in the 2 f demodulation mode. The amplifier filter slope and time constant were set as 12 dB/oct and 1 s, respectively, which corresponded to a detection bandwidth of 0.25 Hz. A LabVIEW-based program was written to record laser power and QEPAS signals simultaneously.

As shown in Fig. 1, a highly purified SF₆ gas (99.99%) was divided into two mass flow meters (MFCs). A silicone hollow fiber membrane module (PermSelect, model PDMSXA-2500) was placed behind one of the MFC to humidify the SF₆ gas. A chilled mirror hygrometer (Edgetech Instruments Inc. model 52773) was used to measure the gas humidity. The maximum absolute humidity was 2.4% at room temperature, which was determined by the performance of the hollow fiber membrane. The desirable humidity levels can be obtained by adjusting the gas flow rates of the two MFCs. A compact diaphragm pump (KNF Technology, model N816.3), a pressure controller (MKS Instruments, model 649B), and two needle valves (NV) were used cooperatively to control and keep the desired gas flow rate and gas pressure.

3. Optimization of the sensor system

The mechanical and electrical properties of QTF are coupled via the piezoelectric effect. The accumulated electric charge resulting from the in-plane flexural of each QTF prong is collected by the metal coating and transferred out by two electrodes. Unlike in the vacuum condition, the gas damping phenomena can be observed when the QTF operates in a viscous matrix, especially in the SF₆ buffer gas. Since SF₆ gas concentration in the electric power system is usually > 99.8%, numerous physical constants of SF₆, such as gas density, thermal conductivity, velocity, and viscosity are different from N₂ or air [5]. Due to the large molar mass (146.07), the density of SF₆ gas (6.52 kg/m³) is relatively higher than N₂ at room temperature and standard pressure. Besides, the molar mass of the SF₆ molecule is ~146 g/mol, and the velocity of sound through the gas is ~134 m/s at room temperature. For comparison, the molar mass of air, which is ~80% N₂ and 20% oxygen (O₂), is approximately 30 g/mol and leads to a velocity of sound of 343 m/s.
For the QEPAS based sensor, the QTF resonant frequency, the Q-factor, the optimal vertical position of the focused laser beam, and the AmR geometrical parameters (length, outer diameter, and inner diameter) are closely related to these physical constants of the buffer gas. The optimization of the QEPAS sensor system with a 1.5% H$_2$O vapor was carried out in the following experiments.

### 3.1. Resonant frequency and Q-factor

The QTF can be treated as two quartz cantilevers with the shape of the tuning fork and the low-loss quartz bridge. The natural frequency of QTF can be described by the Euler Bernoulli beam theory [41]. With the increase of the buffer gas effective mass, the QTF fundamental resonant frequency $f_0$ can be expressed as:

$$f_0 = f_{vac} \frac{mP}{\rho_w w t}$$

where $m$ is the added mass due to the buffer gas, $P$ is the gas pressure, $w$ and $t$ are prong width and thickness, $\rho_w$ is the quartz density. Therefore, the resonant frequency decreases when the QTF immerses in SF$_6$ gas. In Fig. 2, the standard QTF frequency response curves were experimental achieved in SF$_6$ and N$_2$ gas at standard atmospheric pressure. A frequency shift of 27 Hz was obtained when the buffer gas changed from pure N$_2$ to pure SF$_6$ buffer gas.

In addition, the change of buffer gas also causes energy dissipation and reduces the resonance quality factor $Q$. The $Q$-factor is equal to the ratio between the energy accumulated and the energy loss per cycle. A typical QTF Q-factor is $> 100,000$ in vacuum and $> 10,000$ in the atmosphere. The QTF energy loss mechanisms have resulted from gas damping, support loss, and thermoelastic damping. In pure SF$_6$ buffer gas, the main energy dissipation is from the QTF prongs interaction with the surrounding viscous medium, which can be expressed as:

$$Q_{gas} = \frac{4 \rho \mu f_{vac} t^4}{3 \pi \mu w + 3/4 \pi t^2 \sqrt{4 \pi \rho_{vac}}}$$

where $\mu$ is the gas viscosity, $\rho$ is the buffer gas density. For a standard QTF, the ratio of $Q_{gas}$ in N$_2$ and SF$_6$ buffer gas is 2.1 by using the theoretical model. As shown in Fig. 2, the measured $Q$-factors in SF$_6$ and N$_2$ buffer gas were 4173 and 11,909, respectively. More energy dissipation resulted from the support loss and thermoelastic damping of the QTF [40].

### 3.2. Optimal vertical position of the focused laser beam

In N$_2$ buffer gas, the optimal vertical position to detect the photoacoustic signal is below the QTF opening of 0.7 mm, as observed in the case of on-beam configured QEPAS gas sensors [42]. However, the maximum photoacoustic signal amplitude moves with the change of buffer gas, since the physical constants of SF$_6$ molecule are strongly different from that of N$_2$ at 20°C and 1 atm [3]. For the QEPAS system, the photoacoustic source can be supposed to be located between the two QTF prongs. A detailed theoretical model for the determination of the beam position of the laser beam that maximizes the photoacoustic signal was proposed by N. Petra. and P. Patimisco [43,44]. In order to experimentally achieve the optimal detection position, the DFB laser output...
wavenumber was locked at 7306.75 cm\(^{-1}\). A travel translation stage was employed to move the laser focuser from the top of the QTF opening to the bottom of the prongs. The zero position was defined as the opening of the QTF. As shown in Fig. 3, the maximum signal was obtained when the laser beam was positioned 1.2 mm below the QTF opening, where the center position of the AmR was installed in the following experiments. The heavy gas damping makes the optimal detection position moved toward the junction of the QTF [45], since the heavy SF\(_6\) gas density.

3.3. Optimization of the AmR geometrical parameters

For QEPAS based gas sensors, AmR provides a significant improvement on the photoacoustic signals [46–48]. The optimal full AmR length (sum of two tube lengths) was \(\lambda/2 < L < \lambda\) for the on-beam configuration, where \(\lambda\) is the acoustic wavelength. In N\(_2\) buffer gas, the wavelength \(\lambda_{N_2}\) can be calculated by the ratio of the sound velocity and resonant frequency \(\lambda_{N_2} = c_{N_2}/f_{N_2} = 10.37\) mm. However, the acoustic wavelength in SF\(_6\) buffer gas is 4.05 mm, which means the length of each stainless-steel tube is < 2 mm for the first harmonic standing wave. The pretty short tube length increases the assembly difficulty. In Fig. 4, the QEPAS photoacoustic signal to noise ratio (SNR) and corresponding \(Q\)-factor were recorded with the increase of full AmR length. The AmR inner diameter (ID) was 0.4 mm and the outer diameter (OD) was 0.7 mm. The largest SNR was achieved when the AmR length was 3.6 mm (close to \(\lambda\)), indicating the first harmonic acoustic standing wave in the tube was formed. A signal gain factor of 9.7 was obtained relative to the bare QTF. An appreciable SNR was also observed when AmR length was 12.0 mm (close to 3\(\lambda\)), which was only 7% smaller than the largest SNR. In this spectrophone configuration, the third harmonic acoustic standing wave was achieved in the one-dimensional (1D) resonator. Moreover, a sharp decrease of \(Q\)-factor was observed when the AmR length got close to the integral multiple of the acoustic wavelength, which indicated that the AmR tubes provide stronger acoustic coupling with the QTF because the high-Q QTF loses energy primarily via coupling to the low-Q AmR oscillator. The photoacoustic signal phase in the two tubes was opposite when the AmR length got close to 2\(\lambda\). The antiphase signal resulted in the photoacoustic signal amplitude close to zero.

As shown in Fig. 5, a tube with a large ID of 0.55 mm and an OD of 0.8 mm was also employed to measure the photoacoustic SNR and \(Q\)-factor. The largest SNR was obtained when the AmR length got close to 3\(\lambda\). The SNR of the first harmonic acoustic standing waves was 4\% smaller than that of 3\(\lambda\). The SNRs were comparable for the odd times of acoustic wavelength. Since the beam waist radius of laser source was 50 \(\mu\)m in this work, which was far less than the AmR inner diameter. The assembly difficulty of acoustics tubes takes precedence over the laser alignment. Therefore, the optimal AmR length of 5.9 mm of the third harmonic acoustic standing wave was selected for each resonant tube, since the first harmonic acoustic standing wave with an AmR length of 1.9 mm was difficult to assemble in actual application. The short AmR length of 1.9 mm provided a potential application for the excitation light source with poor beam quality, such as the ultraviolet LED or THz laser. The signal amplitude also gets close to zero when the AmR length is close to 2\(\lambda\).

Five different AmRs were chosen to assess the impact of OD and ID of the tube on the photoacoustic signal. The length of each resonant tube

Table 1

| AmR #1 | AmR #2 | AmR #3 | AmR #4 | AmR #5 | Bare QTF |
|--------|--------|--------|--------|--------|----------|
| OD (mm) | 1.00   | 0.9    | 0.8    | 0.7    | 0.6      |
| ID (mm) | 0.70   | 0.55   | 0.55   | 0.4    | 0.35     |
| Signal | 13.28  | 17.95  | 18.04  | 25.29  | 23.59    |
| Q-factor | 1749   | 2303   | 2241   | 2268   | 2187     |
| Gain  | 4.7    | 6.4    | 6.4    | 9      | 8.4      |
| \(Q\)-factor | 4173   | 2.82   | 1      |

Fig. 3. QEPAS signal of a bare QTF as a function of laser focuser position. The zero position is the opening of the QTF.

Fig. 4. QEPAS photoacoustic SNR and corresponding \(Q\)-factor with the increase of full AmR length. The AmR consists of two thin tubes with a 0.4 mm ID and a 0.7 mm OD.

Fig. 5. QEPAS photoacoustic SNR and corresponding \(Q\)-factor with the increase of full AmR length with a 0.55 mm ID and a 0.8 mm OD.
was 5.9 mm. The geometrical parameters of each AmR and corresponding SNR and Q-factor were listed in Table 1. The AmR #4 exhibited an optimal signal gain factor of 9 and served as the best geometrical parameter of spectrophone resonators in the following experiments.

3.4. Optimization of gas pressures and modulation depths

Since the 2f wavelength modulation technology was employed, the sensor performance depends on the gas pressure. The highest signal amplitude can be achieved when the laser modulation amplitude is close to the absorption line width. According to the theoretical model, the best modulation amplitude is \( \sim 2.2 \) times the half-width at half maximum of the Lorentzian-shaped absorption line [33,49]. The QEPAS SNRs were depicted in Fig. 6 at different gas pressures and current modulation depths. The maximum SNR was obtained at the pressure of 200 Torr with a modulation depth of 5 mA. In actual application, a gas sampling mechanism consisting of solenoid valves, pressure meters, pressure relief valves and a gas pump was employed to control and maintain the QEPAS gas sensor pressure at 200 Torr. An SNR gain factor of 16.2 was achieved compared with the bare QTF. A high Q-factor of 6823 was obtained when the gas pressure was 200 Torr, which resulted in a highly sensitive QEPAS gas sensor.

4. Experimental results and discussions

The linearity of the H\(_2\)O sensor was evaluated by measuring the photoacoustic signal amplitude from 0.14% to 2.37% H\(_2\)O vapor in SF\(_6\) buffer gas. The humidity of the gas mixture was calibrated by a chilled mirror hygrometer. The laser output wavelength was locked at the peak of the H\(_2\)O absorption line. A 5 min interval was performed to replace the gas mixture with different concentrations. As shown in Fig. 7, a linear fitting with an R-square value of 0.9996 confirmed that the gas sensor responded linearly to the H\(_2\)O concentration. A signal amplitude of 3.3 mW was obtained in 0.14% H\(_2\)O, and a noise level (\( \sigma \)) of 1.16 \( \mu \)V occurred. An SNR of 2845 can be calculated, resulting in a detection limit of 0.49 ppm, which was far below the detection requirement in high-voltage gas power systems. Since the different physical properties of SF\(_6\) gas, the resonant frequency of bare QTF turned from 32,790 Hz to 32,763 Hz, the corresponding Q-factor reduced \( \sim 2.8 \) times than that in pure N\(_2\) buffer gas. The optimal detection position moved downward \( \sim 0.5 \) mm to the base of the QTF. The SNR and Q-factor concerning the AmR length were experimentally obtained from the first to third harmonic standing wavelength by using the two pairs of thin tubes with an ID of 0.4 mm, an OD of 0.7 mm, and an ID of 0.55 mm, an OD of 0.8 mm. The comparable signal amplitude was observed when the AmR length was close to the acoustic wavelength \( \lambda \) and 3\( \lambda \) in SF\(_6\) buffer gas. However, the antiphase signal in two tubes resulted in the photoacoustic signal amplitude close zero when the AmR length close to 2\( \lambda \). After the optimization of gas pressures and modulation depths, an SNR gain factor of 16.2 was achieved when the pressure was 200 Torr and the modulation depth was 5 mA. A gas sensor detection limit of 0.49 ppm was obtained, which was sufficient for humidity monitoring in high-voltage gas power systems. The reduced Q-factor in SF\(_6\) buffer gas led to a faster sensor response time \( t = Q/\pi f_{SF_6} \) of 66.3 ms, which was almost an order of magnitude faster than the standard QEPAS sensor system in the atmosphere [50]. The highly sensitive and quick-response humidity sensor provides a new approach for safety monitoring in SF\(_6\) insulated high-voltage gas power systems.

5. Conclusions

In this work, a low-cost, compact, and sub-ppm level QEPAS-based H\(_2\)O sensor system was developed and established for SF\(_6\) insulated high-voltage gas power systems. Since the different physical properties of SF\(_6\) gas, the resonant frequency of bare QTF turned from 32,790 Hz to 32,763 Hz, the corresponding Q-factor reduced \( \sim 2.8 \) times than that in pure N\(_2\) buffer gas. The optimal detection position moved downward \( \sim 0.5 \) mm to the base of the QTF. The SNR and Q-factor concerning the AmR length were experimentally obtained from the first to third harmonic standing wavelength by using the two pairs of thin tubes with an ID of 0.4 mm, an OD of 0.7 mm, and an ID of 0.55 mm, an OD of 0.8 mm. The comparable signal amplitude was observed when the AmR length was close to the acoustic wavelength \( \lambda \) and 3\( \lambda \) in SF\(_6\) buffer gas. However, the antiphase signal in two tubes resulted in the photoacoustic signal amplitude close zero when the AmR length close to 2\( \lambda \). After the optimization of gas pressures and modulation depths, an SNR gain factor of 16.2 was achieved when the pressure was 200 Torr and the modulation depth was 5 mA. A gas sensor detection limit of 0.49 ppm was obtained, which was sufficient for humidity monitoring in high-voltage gas power systems. The reduced Q-factor in SF\(_6\) buffer gas led to a faster sensor response time \( t = Q/\pi f_{SF_6} \) of 66.3 ms, which was almost an order of magnitude faster than the standard QEPAS sensor system in the atmosphere [50]. The highly sensitive and quick-response humidity sensor provides a new approach for safety monitoring in SF\(_6\) insulated high-voltage gas power systems.

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