Optical sensors for power transformer monitoring: A review

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Funding information
National Natural Science Foundation of China, Grant/Award Numbers: 51677070, 51807088; State Key Laboratory of Alternate Electrical Power System with Renewable Energy Sources, Grant/Award Number: LAPS1901; Beijing Natural Science Foundation, Grant/Award Number: 1841001; CAST, Grant/Award Number: YESS20160004; Fok Ying-Tong Education Foundation for Young Teachers in the Higher Education Institutions of China, Grant/Award Number: 161053; China Scholarship Council (CSC); Fundamental Research Funds for the Central Universities, Grant/Award Number: 2019MS006

1 | INTRODUCTION

The fast growth of the renewable electricity results in new challenges in electrical grids and power transformers. Although electricity generation from coal and gas fired power plants remains to be the major electric power source, renewable energy already encompassed 36.6% of China’s total installed electric power capacity and 26.4% (1,692,100 GWh) of total power generation in 2017. According to Energy Production and Consumption Revolution Strategy 2016–2030 [1, 2], by 2030, 50% of China’s total electric power generation will be generated from non-fossil energy sources [1, 2]. However, most renewable energy sources are located in the north and west of China. As such, the long-distance transfer of electric power by renewable energy is critical. Recently, ultrahigh voltage grids have been built in China to connect the northern and western electric power sources to the densely populated eastern region of China.

Large power transformers (LPTs), required for stepping up or down the voltage level, are the most important equipment in long distance ultrahigh voltage grids. Any failures of the power transformer might induce a serious blackout [3, 4]. Therefore, keeping and in situ monitoring the healthy performance of transformers are necessary. Currently, regular interval maintenance for transformers is required to check the potential risks of transformer failure by using a conventional diagnostic method. However, the significant high cost of regular maintenance presents a big problem for ultrahigh voltage electric grids. Hence, there is an urgent demand to develop convenient and low-cost monitoring tools to assess the health conditions of the power transformers.

Moreover, many power transformers are ageing in the developed countries. The average service life of LPTs in the United States is approximately 40 years, and 70% of LPTs are serviced 25 years or more. In some extreme cases in the United States, some units are still using even over 70 years operating time [5]. It should be noted that these transformers are typically warranted by the manufacturers for approximately 30–35 years [5]. A power transformer failure might affect the power supplies...
for thousands to millions of people. Furthermore, the costs of transformer failure and maintenance can be up to millions of dollars [6]. It is well-known that the failure rate of power transformers increases non-linearly with their ages [7–9]. Therefore, it is of particular importance to monitor the ageing power transformers to ensure grid reliability [7, 10, 11].

The conventional methods to diagnose transformers are conducting dissolved gas analysis (DGA) and partial discharge (PD) detection with electric sensors [6, 12]. However, such sensors often work well only in the laboratory and subject to strong electromagnetic disturbances in field applications [6, 12]. In recent years, a gradually rising approach to solve the above matters is to apply optical sensors [13, 14]. Optical sensors are immune to electromagnetic interference. What is more, optical sensors provide in situ diagnostics and better sensitivity by installing inside the power transformers [13, 15].

Although many optical sensors have been developed for the diagnostics of power transformers in recent years, most researchers and engineers in electric power discipline are still not familiar with these new techniques due to the lack of optical physics knowledge. Since existing studies in power transformer monitoring are mainly focused on the traditional electric methods [3, 6, 10–12], despite of the great benefits in the optical sensors, a big research and knowledge gap needs to be filled for better understanding and designing new monitoring tools for power transformers using optical sensors.

This study provides a detailed overview of optical sensors for power transformers over past years and aims to inspire future research to develop innovative optical sensors for ultrahigh voltage transformers. The study is structured as following: In Section 2, the main measurement principles of optical sensing methods are introduced. In Section 3, various measurement methods of PD in power transformer are presented. In Section 4, optical sensing methods for the detection of gases dissolved in a power transformer are introduced. In Section 5, local and distributed optical temperature sensors are reviewed. In Section 6, optical monitoring methods for other key parameters of power transformers such as winding deformation, vibration, and moisture are reviewed. In Section 7, existing challenges and future research directions of fibre-optic sensors are discussed. Finally, in Section 8, a brief conclusion is drawn.

2 | MEASUREMENT PRINCIPLES

The developments of optical sensors used in transformer online monitoring are mainly focused on fibre grating, optical interferometers, and laser absorption. The principles are introduced in the sub-sections below.

2.1 | Fibre Bragg grating

A fibre Bragg grating (FBG) is an optical component in which the Bragg reflector is constructed in a short segment of optical fibre. The FBG reflects light of specific wavelengths and transmits all others (as shown in Figure 1). The basic principle of FBG sensing is based on the modulation of the reflection wavelength of FBGs in response to the change of temperature and mechanical strain. In FBGs, a relative shift in the Bragg wavelength, $\Delta \lambda_B / \lambda_B$, as a function of an applied strain ($\Delta \epsilon$) and a change in temperature ($\Delta T$), is approximately given as [16]:

$$
\frac{\Delta \lambda_B}{\lambda_B} = (\alpha_f + \xi) \Delta T + (1 - p_s) \Delta \epsilon \quad (1)
$$

where $p_s$ is the strain optic coefficient, $\xi$ is the thermo-optic coefficient, $\alpha_f$ is the thermal expansion coefficient of the optical fibre.

Thus, the FBGs can be selected as the direct sensing elements in strain and temperature measurements. Besides that, FBGs can serve as transduction elements for other parameters which generate strain changes in elastic elements.

2.2 | Optical interference

Optical interferometers are the instruments that rely on the interference of two or more superimposed laser beams. Generally, the initial light is split into two arms by a beam splitter (or a coupler for optical fibres), forming a reference arm and a sensing arm. Then, the two beams are recombined and detected by an optical electric device, including an optical amplifier or a charge-coupled device et al. The difference between optical paths of two arms, which is induced by variation of the sensing parameters (temperature, gas concentration, and acoustics), leads to a relative phase change of two beams. Thus, the sensing parameters can be retrieved based on the different amplitudes of the recombined beams.

Four representative types of fibre-optic interferometers are widely used for power transformer monitoring, including the Fabry–Perot, Mach–Zehnder, Michelson, and Sagnac [17, 18]. Schematic diagram of the working principle of four fibre-optic interferometers is shown in Figure 2.

2.3 | Laser absorption

While passing though gas, light intensity decays when the light at a specific wavelength gets absorbed by target gases. This phenomenon indicates the changes in gas concentration can be diagnosed by measuring the changes in light intensity, which is called the Beer–Lambert Law, as shown in Figure 3. And the
relationship between the light intensity and the gas concentration can be expressed as [19].

\[ I(\lambda) = I_0(\lambda) \cdot \exp[-\alpha(\lambda) \cdot c \cdot L] \]  

(2)

Where \( I(\lambda) \) and \( I_0(\lambda) \) are intensities of incident and emitted laser respectively, \( W/m^2 \). \( c \) is the concentration of target gas, \( mol/L \). \( L \) is the optical absorption path length, \( m \). And \( \alpha(\lambda) \) is the absorption coefficient per unit distance and per unit concentration of the gas, \( L/(mol \cdot m) \).

3 | PARTIAL DISCHARGE DETECTION

In LPTs, high levels of PD activity may lead to an insulation failure. If PD activities could be monitored effectively and efficiently before the insulation failures occur, the transformer could be repaired or replaced before any transformer failures. With the advantage of anti-electromagnetic interference, the acoustic method is a very attractive way for PD detection in power transformers. However, the ultrasonic signals of PD attenuate greatly during transmission, and the traditional piezoelectric transducers (PZT) sensors are difficult to meet the requirements of sensitivity and distributed detection.

In recent years, many efforts have been made to develop the fibre-optic ultrasonic sensors. Compared with the PZT, the fibre-optic ultrasonic sensors have the advantages of good insulation performance, small size, anti-electromagnetic interference, and so forth. Therefore, the fibre-optic sensors can be implanted in the interior of the power transformer for PD detection, which can avoid the attenuation of the ultrasonic signal at the liquid-solid interface. At present, the fibre-optic ultrasonic sensors for PD detection in a power transformer mainly include the interferometric configurations of Fabry–Perot, Michelson, Mach–Zehnder and Sagnac, as well as FBG ultrasonic sensors.

3.1 | Fabry–Perot interferometer

Fabry–Perot (F–P) interferometer is a kind of commonly used optical fibre ultrasonic sensor. A.B. Wang et al. [20] designed an fibre-optic acoustic sensor system for on-line detection of PD inside high voltage power transformers, as shown in Figure 4. A silica diaphragm was used as a mirror at the end of an optical fibre to form an F–P interferometer. The results showed that the sensors were able to detect the acoustic signals propagating in transformer oil. And the sensor was very sensitive at high frequency (220 kHz). In 2008, they [21] worked out another novel sensor to monitor PD inside the power transformer, especially in a high electric field strength region. They presented a side-hole fibre-based extrinsic Fabry–Perot interferometric (EFPI) sensor. To achieve the goal of in situ online monitoring, the interference cavity was filled with SF6, which provided a high dielectric strength. Results showed that the sensor filled with SF6 was able to withstand electric stress of at least 10 kV/mm in transformer oil. Thus, this kind of sensor could be installed inside the transformer winding for weak PD detection.

To further decrease the thickness of the sensing membrane and improve the sensor sensitivity, X.D. Wang et al. [22] reported an fibre-optic sensor fabricated with Micro-electromechanical System (MEMS). A silicon membrane with a thickness of 25 µm and a side length of 2 mm was designed and manufactured by MEMS technology for the sensor. And the experiments showed that the pressure measurement resolution of the sensor was about 2.8 Pa. Then, the sensor was installed on the inner surface of an oil tank wall to measure PD-induced acoustic waves. The results showed the sensor not only had an inherent capability of high signal-to-noise ratio, but also was able to achieve reliable positioning of the PD sources inside power transformers [23]. Moreover, some researchers designed an EFPI ultrasonic sensor to study the angle between the acoustic emission source and the F–P sensor [24]. The results indicated that the receiving angle of the sensor was nearly 90°.

In order to locate a PD fault, an acoustic sensor array based on four EFPI was introduced by W. Wang et al. [25]. The
sensor array was used for PD localization in a real 35 kV transformer. A localization error less than 5 cm was achieved.

3.2 Other interferometers

Although the F–P ultrasonic sensors have been confirmed to be useful for PD detection, the production process of sensors is complex and fragile. Researchers also developed some intrinsic fibre-optic ultrasonic sensors for PD detection in power transformers, including Michelson, Mach–Zehnder and Sagnac interferometric configurations.

T.R. Blackburn et al. [26] first proposed a fibre-optic sensor based on the Michelson interferometer to detect the ultrasonic signals in high voltage power transformers. A fibre sensor head was constructed from a 150 m length of single mode fibre (SMF) in a coil. Preliminary results proved that the sensor could work effectively. And they thought that the sensor could have a higher sensitivity than normal tank piezoelectric sensors, for the longer the fibre length used in the sensor head, the higher the sensitivity will be. However, fibre with an excessive length may increase the noise due to the back-scattered light in the fibre of the Michelson interferometric sensing system. In addition, two Faraday rotating mirrors are usually required, which increases the complexity of sensing system. Therefore, many researchers focused on the Mach–Zehnder interferometric configurations for PD detection in power transformer.

M. Macalpine et al. [27, 28] introduced an acoustic sensing system based on Mach–Zehnder interferometer, and a fibre coil was used as a sensor head in large oil-immersed power transformers. They also developed a mathematical model of optical fibre coil for analysing sound pressure sensitivity and examined the relationship between coil size and frequency response. Moreover, a multi-layered optical fibre coil with an inner diameter of 10 mm, an outer diameter of 14 mm and a height of 2 mm was designed. The sensor was capable to monitor an acoustic sound pressure wave of 1 Pa under optimal operating conditions. A similar study was carried out by J. P Roman et al. [29]. A multiple-layered optical fibre coil was used as the sensing unit for Mach–Zehnder interferometer, which was used for PD detection in power transformer. As shown in Figure 5, the sensor was made by coiling a multi-layer fibre with a 30 mm diameter. The fibre in the coil was 17 m long and was arranged in five layers of 5 mm width. The performance test with real PD signals indicated that the fibre-optic sensor had a desirable sensitivity of 1.1 mrad/Pa at 9 cm from a 150 kHz PD signal. It could provide enough resolution to detect acoustic sound pressure as low as 1.3 Pa.

However, a multi-layered fibre coil may reduce the performance improvements associated with increasing fibre length, because the outer fibre can weaken the effect of sound waves on the inner fibre. Some researchers took a SMF with a length of about 8 m, forming a single layer fibre coil with a diameter of 25 mm [30]. A Mach–Zehnder interferometric sensing system was built up. The experimental results showed that the optical fibre sensor could be applied for PD detection in power transformers. And the sensor has a sensitivity about 500 mrad/Pa at 20 cm away from a PD signal. Unfortunately, the sensitivity of the single layer fibre coil was examined at 28 kHz which was different from that in Reference [29]. Therefore, the sensitivity of single-layer and multi-layer fibre coils cannot be directly compared. Whether a single-layer or a multi-layer fibre coil is more suitable for PD detection in oil is still unclear.

Although the Mach–Zehnder interferometric sensors have been extensively studied for ultrasonic sensing in power transformers, the stability of the sensing systems is still a challenge. One of reasons is that the Mach–Zehnder interference requires separating the sensing fibre in the transformer from the reference fibre outside the transformer (the same is true for Michelson interference). External noise on reference fibre can affect the stability of the system. Moreover, in order to reduce the phase noise in sensing system, for both Michelson interference or Mach–Zehnder interference, light sources with very narrow linewidth are required for the lengths of the sensing fibre and reference fibre are difficult to be made equal.

On the other hand, for Sagnac interference, broadband light sources are allowed, which can reduce the cost of the sensing system greatly. Because the two beams of the interference light are transmitted in the same fibre coil, the stability of the sensing systems can be significantly improved. In the latest research, H. Chen et al. [31] built up a Sagnac interferometric with an optical fibre sensing coil for PD detection in power transformers. Using the tone burst technique that adapted a commercially available PZT as benchmark, the performance of the sensor was tested. The results indicated that the optical fibre sensor performed better than PZT at 20~130 kHz. But the sensitivity of optical fibre sensor in Sagnac interferometric system was not examined.

3.3 Fibre Bragg grating

From the discussions above, it can be found that the interferometric fibre-optic ultrasonic sensors were suitable for PD detection in power transformers. However, these interferometric sensors were difficult to achieve multiplexing for
distributed detection. Due to the potential advantages of fibre grating sensing in distributed detection, some related studies have been conducted for developing FBG ultrasonic sensors.

The first work with FBGs for sensing ultrasonic pressure fields was reported in 1996 [32]. It was shown that in-FBGs may be used to sense high frequency (MHz) ultrasonic waves. In order to realize the online monitoring for PD detection of power transformer, P. Kung et al. [33] developed a broadband FBG sensor with the capability of measuring a range of ultrasonic frequencies from 30 to 300 kHz in power transformers. B. Sarkar et al. [34] presented a novel intensity-modulated fibre-optic PD sensor based on FBG. The proposed sensor was designed to be placed inside the high voltage equipment and could detect high frequency acoustic waves. One of the main merits in this approach is that the sensor's output is intensity modulated. Although it is an FBG-based sensor, it is inherently temperature insensitive due to the intensity modulation of the sensor's output.

As the authors know, the signal detected by FBG ultrasonic sensing system is demodulated by an edge filter. In this method, a tunable laser source is adjusted into the linear region of the spectrum of an FBG sensor. The ultrasonic signals can be analysed by detecting the reflected light of the FBG. Therefore, the slope of FBG spectrum has a large impact on the sensitivity of the sensing system.

To improve the sensitivity, a method using a phase-shifted FBG (PS-FBG) which has a steep slope has been proposed. In 2013, U. Lima et al. [35] reported an optical fibre sensor based on PS-FBG for the acoustic detection of internal incipient faults in oil-immersed power transformers. The sensor had a flat frequency response (ripple of about 10 dB) in the range from 60 to 230 kHz. Unfortunately, at higher frequencies, the signal declined greatly (≈20 dB).

What is more, based on four PS-FBGs, G.M. Ma et al. proposed a novel distributed PD detection system for power transformers [15]. In term of the sensitivity, the results of frequency response experiments showed that the PS-FBG ultrasonic sensor had a better sensitivity than the conventional ultrasonic sensors (8.46 dB higher). Besides, a PD detection experiment, in which sensors were immersed in oil, indicated that the sensitivity of the PS-FBG was 17.5 times higher than that of a PZT sensor. In addition, the feasibility of multiplexing and positioning of the proposed distributed PD detection system were verified.

Moreover, some researchers used fluorescent fibre to detect the PD signals in transformer [36]. However, due to the negative impact of transformer oil on the light, this method has great limitations in application for actual transformers. Therefore, it will not be described in detail in this review.

3.4 Advantages and disadvantages

We have completed a survey of the recently published results for the PD detection in power transformers and the comprehensive information are summarized in Table 1.

![FIGURE 5](image_url) Details of the effective sensitive zone of the sensor at the desired frequency. Adapted from [29]

The advantages of the FPI ultrasonic sensors are their high sensitivity to weak ultrasonic signals, and small size for installing in transformers. But it may cause tip discharge due to the use of cavity. Reference [21] proposed an idea of filling the cavity with SF₆ to increase the insulation strength and avoid the discharge in cavity. Another disadvantage of the F–P sensor is that the fabrication method is complex and expensive compared to the other methods.

The Michelson, Mach–Zehnder and Sagnac interferometric ultrasonic sensors are insulated and easily to be manufactured. But to improve the sensitivity, a long fibre is needed. The comparisons of the above three types of interferometric ultrasonic sensors are as follows. There is no back-scattering light in the Mach–Zehnder interferometric sensor. The Michelson interferometric sensor can achieve dual optical path detection by using the same length of optical fibre with a Mach–Zehnder or Sagnac interferometric sensor to improve the sensitivity, but the back scattering should be addressed to decrease the noise. As the lengths of the two arms of the Sagnac interferometric sensor are the same, the phase noise induced by the arm length difference does not exist in the Sagnac interferometric sensor. Further developments of the interferometric ultrasonic sensors should consider their merits and drawbacks. Moreover, the low frequency noise generated by temperature variation or random vibration should be reduced to improve the interferometric ultrasonic sensors' stability. Furthermore, the implementation of multiplexing of interferometric sensors is difficult, which has not been well addressed systematically in previous studies.

Compared to the optical interferometric sensors, FBG sensing systems are simple and easy to implement for distributed detection. However, the sensitivity of the FBG sensor for PD detection in transformers needs to be improved.

4 GAS DETECTION

At present, LPTs mainly are oil-immersed transformers [10]. The internal insulation system is a composite insulation structure composed of transformer oil and insulating paper. And the most common transformer oil is the mineral oil [38].
Under normal operating status, mechanical stress, electricity and heat are insufficient to destroy the molecular chemical bonds of transformer oil and insulating paper, and small molecule gases (e.g. methane, ethane, ethylene, acetylene, hydrogen etc.) will be formed [39–41]. And then, gases will continuously get dissolved in transformer oil. Several recommended concentration limits of individual gas values and total dissolved combustible gas (TDCG) recorded in IEEE standards [42] have been summarized in Table 2. A four-level criterion shown in Table 2 is used to classify the operating health status to power transformers.

DGA with gas chromatography (GC) is the most recognized monitoring methods [43–45]. GC belongs to an off-line detection method. The whole detection process is trivial and complicated, and the detection time is long. It is difficult for the operation personnel to grasp the operation status in time. Therefore, gas sensors using optical techniques are gaining popularity [46].

### 4.1 Infrared absorption spectroscopy

Infrared absorption spectroscopy is based on the feature of different gases having different vibration and rotation absorption lines [47, 48]. Gas molecules will absorb photons at a special frequency, which will result in a light intensity attenuation. Different methods based on infrared absorption spectroscopy are investigated in this paper, which includes spectrophotometry, Photoacoustic spectroscopy (PAS) and some other technologies.

#### 4.1.1 Spectrophotometry

The determination of absorption lines and absorption coefficients is very important for the gas detection. Thus, W.G. Chen et al. [49] investigated the absorption coefficients, main absorption bands locations, central wavenumbers and peak absorption coefficients of the characteristic dissolved gases in transformer oil. The variation of peak absorption coefficients with pressure and temperature was analysed. The results were important for infrared absorption spectroscopy when conducting gas detection.

According to the Beer–Lambert Law, the minimum detection limit is proportional to the absorption pathlength. However, most of the long-path gas cells currently have the problem of large sizes. In order to increase the absorption path length while keeping a compact size for higher detection sensitivity, X.X. Zhang et al. [50] designed a system with a gas absorption cell containing a series of reflectors. Within a certain volume range of C2H2, a good linear relationship between the absorbance and the concentration of C2H2 was realized. The minimum detection limit was about 10 ppm. In order to further improve the performance of optical sensors for dissolved gas in transformer oil, F. Wan et al. [51] reported a new gas sensing method based on the frequency-
locking absorption spectroscopy technique with the use of quantum cascade lasers (QCL). The minimum detection limits could reach ppt levels.

For reducing the size of gas cells while ensuring enough absorption pathlength, gas cells in new form should be taken into consideration. Therefore, hollow core photonic bandgap fibre (HC-PBF) could be used as a gas cell for its special structure. For lengthening the optical path, A.M. Cubillas et al. [52] demonstrated CH$_4$ sensing with a 1670 nm band HC-PBF. The gas cell was a HC-PBF with a length of 5.1 m, the minimum detection limit was 10 ppm.

Spectrophotometry has the advantages of good selection, high sensitivity, and rapid response. It is very practical for the detection of dissolved gas in transformer oil. It uses the unique characteristics of the gas absorption to conduct gas detection. Thus, spectrophotometry can well detect the composition and concentration of the target gases.

### 4.1.2 Photoacoustic spectroscopy

PAS-based sensors differ from spectrophotometry sensors in the way that how the absorbed light gets detected. PAS is mainly based on the photoacoustic effect, and the absorbed light is measured directly [53–55]. The broadband light is filtered to obtain an infrared light at a predetermined wavelength. The filtered light will get absorbed by specific gas molecules. After absorbing the infrared light, the molecules will transit from the ground state to an excited state. After the light getting chopped or modulated, an acoustic signal will be generated, and the gas concentration can be converted by the intensity of the sound wave detected by the microphone [53, 55].

Y.X. Yun et al. [56] designed a portable and tunable PAS system to detect the dissolved CH$_4$ in transformer oil with a distributed feedback (DFB) laser. The detection limit was about 5.05 ppm. This system could be a reference for online monitoring of CH$_4$. For multi-gas sensing, J.P. Besson et al. [57] proposed a sensor using tunable laser based on PAS for trace gas sensing. In their sensing system, an optimized resonant configuration (resonant frequency $f = 1$ kHz) based on an acoustic longitudinal mode was introduced. The detection limit was 80 ppb for trace gas of CH$_4$. What is more, the system had the advantages of high reliability and compactness.

The absorbed power is direct proportion to the PAS signal, which is also directly proportion to the incident laser power. To increase the sensitivity, Q.D. Zhang et al. [58] presented a new method using a Q-switched fibre laser. In this system, laser power got increased by an EDF-based fibre laser. And a PAS cell (resonant frequency $f = 5.3$ kHz) was placed inside the fibre cavity. When detecting the concentration of C$_2$H$_2$, an excellent linear response was shown in the range of 400–7000 ppm, and the minimum detection limit was 8.4 ppm, which was about 94.2 times lower than a conventional system.

But the systems based on PAS are susceptible to noise interference. In order to improve the anti-noise performance for better analysis of the dissolved gases in transformer oil qualitatively and quantitatively, Z.Y. Wu et al. [59] designed a system based on the second harmonic PAS with a tunable fibre laser. This system could detect multiple dissolved trace gases in transformer oil simultaneously.

There are some commercial applications for gas detection based on PAS nowadays. A portable online detection device manufactured by Kelman Company of the United Kingdom based on PAS is able to detect gas in oil [60].

PAS can eliminate the need to separate each gas species and detect the mixed gases directly. Also, the sensitivity is high, and the detection speed is fast [54, 61]. However, PAS is susceptible to the environmental noise interference. Due to the presence of motor rotation, electromagnetic noise, and so forth, the sound wave intensity collected by the microphone is much smaller than the environmental noise, so PAS is susceptible to the interference [54, 62].

### 4.1.3 Other technologies based on infrared absorption spectroscopy

In this part, some new technologies based on absorption spectroscopy for gas sensing are introduced.

G.M. Ma et al. [63, 64] proposed a tunable diode laser absorption spectroscopy (TDLAS) sensing system (shown in Figure 6). In this system, a DFB laser was selected to ensure high spectral resolution. An integrated Herriot cell was used to reduce the optical interference and system noise. Also, the integrated Herriot cell increased the effective path length, and then the absorption intensity got enhanced greatly. This system shortened the oil and gas separation time and achieved the minimum detection limit of 0.49 ppm for C$_2$H$_2$.

**Figure 6** Experimental setup of TDLAS measurement [63]. TDLAS, tunable diode laser absorption spectroscopy
J. Wei et al. [65] introduced a fibre-optic trace gas monitoring system based on photo-thermal interferometry and HC-PBF. The sensing system has the advantages in compactness, sensitivity, selectivity, and ability for utilizing in harsh environments. It could be well applied for its remote, multiplexing, multi-point detection abilities, which could achieve 2 ppb C2H2 detection limit and nearly six orders of magnitude dynamic measurement range.

4.2 Laser Raman spectroscopy

Laser Raman spectroscopy is a spectroscopy technique that analyzes the structure and properties of a substance by directly measuring the Raman scattered light from the laser irradiation [66, 67].

Electrons (in gas molecule) will transition from the ground state to the virtual energy state after absorbing the photons of the incident light whose energy equals to $h\nu_0$, where $h$ is the Planck constant and $\nu_0$ is the incident light frequency. By analysing the frequency variation $\Delta\nu$ (in Figure 7) and peak intensity of the Raman spectra generated by gases, the composition and concentration of different gases can be determined and the analysis of the dissolved gas can be realized [67–69].

G.C. Stevens et al. [70] introduced an insulation evaluation method for electrical equipment by Raman spectroscopy and chemometrics. The model by using spectral data to predict the insulation status of electrical equipment was established.

For in situ detection of C2H2 without gas separation in transformer oil, T. Somekawa et al. [71] proposed a method using Raman Lidar technique. The laser used in the system was a frequency doubled Q-switched ND: YAG laser. The spectral resolution was about 5 cm$^{-1}$. The Raman detection limit was 3700 ppm for C2H2. However, it cannot meet the need for the detection of dissolved gases in transformer oil. And in his further work, he used LRS technique to analyse the furfural in transformer oil [72].

X.Y. Li et al. [73] set up an integrated sensing system for detecting multiple dissolved gases in transformer oil based on LRS. For the propose of promoting the sensitivity of the system, a near-confocal cavity was applied, and the Raman scattering got enhanced greatly. However, the minimum detection limits still need to be further lowered.

In order to analyse the dissolved gases in transformer oil accurately and eliminate the interference of the Raman scattered light generated by gas cells, W.G. Chen et al [68, 69] demonstrated a LRS platform based on confocal Raman technique with silver-plated quartz glass tubes. The detection limit of C2H2 reached 5 ppm. Also, samples of multiple gases mixture were tested. The results were satisfactory. However, the Raman scattering cross-section area of gas is extremely small, which resulting in the Raman scattering intensity is too low. In order to improve the detection limits, they further investigated the vibration mode and the Raman spectrum mechanism of double-atomic and polyatomic molecules [74]. With the Pd surface enhancement technique, the Raman scattering cross-sectional area got increased. And with the use of the Allan variance time domain analysis, the detection limit improved about 12.8 times, and the detection accuracy reaches 96%.

Compared with traditional online monitoring technology, LRS has advantages in the application of characteristic gases analysis for transformer faults: (1) no need to separate the mixed gases; (2) the detection of multiple gases could be conducted simultaneously; and (3) a good repeatability. However, for the field application of LRS to detect dissolved gases in transformer oil, it is still necessary to improve the sensitivity. In addition, some optical components such as Raman spectrometers, Raman probes are not suitable for implanting inside transformers. Therefore, LRS technology needs further development for practical field application.

4.3 Hydrogen sensing based on FBG

The principle of FBG-based hydrogen sensors is to monitor the central wavelength shift of the reflected Bragg spectrum [75–78]. When the hydrogen sensitive material is coated on the outer surface of the FBG, the hydrogen concentration in the environment can be figured out when the hydrogen sensitive material expands and generates strain. Main hydrogen sensing materials includes rare earth alloys, magnesium-based alloys, Ti, Pd and Zr [78, 79].

L. Coelho et al. [80] demonstrated a new type of hydrogen sensor with two inline FBGs in one fibre. The cladding of the two FBGs were etched by chemical treatment. One FBG was coated with Pd, while the other one was uncoated. The sensor was able to make a good response to the concentration of H2 in the range of 0%–1% at atmospheric pressure. The sensitivity was better than 20 pm%/%. T. Mak et al. [81] showed a Mg–Ti thin film deposited fibre-optic hydrogen sensor with a polytetrafluoroethylene protection layer. It can be applied for measuring the dissolved hydrogen in transformer oil. The detection range was greatly large, which was 5~15 ppm at 21°C, 5~30 ppm at 40°C, 5~130 ppm at 60°C, and 5~1500 ppm at 80°C.

![Figure 7](image.png)
Absorption spectroscopy has been utilized in gas sensing (NH$_3$, H$_2$S, NO etc.) for a long time, but it is new for the dissolved gas detection. For Spectrophotometry, the spectral absorption intensity has been greatly improved by effectively lengthening the absorption path. Compared with the broadband measurement, narrowband technique has a better signal-to-noise ratio. But multiple lasers are required for all specific gas detection in narrowband gas sensing.

PAS has the advantages of short optical path length, high detection sensitivity, wide detection range and fast detection speed. However, PAS is susceptible to noise and temperature variations, which is common in substations. Thus, even though PAS has many advantages mentioned above, its vulnerability to interference makes it difficult to utilize in substations.

The detection sensitivity of sensors based on LRS has been improved a lot, which could reach the order of a few of ppm or 10s of ppm. But for the field application in dissolved gases sensing, there are still some aspects need to be further improved. For example, some optical components are not suitable for utilizing in online monitoring. Therefore, LRS technology needs further development for field applications.

Nowadays, hydrogen could be detected successfully by sensors made by FBG with specific gas sensitive materials coated. And the minimum detection limit can meet the requirements for practical application in sites. Limited by gas sensitive materials, it is temporarily unable to detect dissolved gases other than hydrogen by FBG.

The biggest demerit for most optical gas sensors is requiring separation process of oil and gas. The separation process increases the response time. The second demerit is its cost. Compared with other sensors, such as electrochemical sensors, optical sensors cost more. Besides that, the detection accuracy is vulnerability to the stability of the optical devices. Thus, improvements are required before actual application.

4.4 | Advantages and disadvantages

This section mainly discussed techniques in dissolved gas sensing. Detailed information is summarized in Table 3.

Comparing with the traditional gas sensing methods such as pellistors and electrochemical devices, optical techniques have the merits of non-contact measurement, immunity to electromagnetic interference, and no needs for calibration. Optical gas sensors can be self-referenced, so it is easy to realize whether there are any faults in sensing system. Also, optical gas sensors have a rapid response time. Taking C$_2$H$_2$ sensing as an example, a schematic diagram of the minimum limit of detection and response time of different types of methods is shown in Figure 9. The merits and demerits of optical method are as follows.

FIGURE 8 | Structure of side-polished FBG hydrogen sensor
(a) Lateral view of the side-polished FBG segment and (b) cross-sectional view of different layers. Adapted from [82]. FBG, fibre Bragg grating

5 | OPTICAL TEMPERATURE MONITORING

Long-term researches have shown that the operational reliability of LPTs depends on their insulation status [85, 86]. Although a combination of factors results in the ageing of main insulation, the life of which is determined mainly by its thermal ageing. Insulating paper with cellulose as a main component will undergo thermal degradation, which will reduce its insulation properties [87, 88]. The mechanical strength of the conductor and structural insulation will also be decreased under high temperature, which results in a reduced ability to withstand transient currents, even permanent deformations [9, 89]. According to the IEC Loading Guide, the deterioration rate of mechanical properties doubled for each 6° C rising [90]. Economically, in the process of dynamic capacity increase, the hot-spot temperature of the insulated conductor is also strictly restricted [89, 91]. Therefore, temperature monitoring is significant for delaying insulation ageing, increasing service life of power transformers, and improving the transmission capacity of the power grid.
Traditional transformer temperature monitoring methods have insurmountable drawbacks. The infrared method is a non-contact and convenient measuring method, but it is difficult to monitor the internal temperature of transformers and is subject to interference. Electronic temperature sensors based on thermistors and thermocouples are widely used, but such sensors are susceptible to electromagnetic interference. More importantly, due to the complex insulation problems, they cannot be implanted into the transformer to measure the temperature of the internal structure.

On the contrary, the merits of optical fibre temperature sensors of anti-electromagnetic interference and better insulation performance are particularly suitable for direct measurement of the internal temperature. At present, the optical fibre temperature sensing methods are mainly based on fluorescent fibre, FBG and distributed fibre sensing.

### 5.1 Temperature sensing based on fluorescent fibre

Fluorescent fibre is a special kind of fibres. In its core, a small amount of fluorescent substance is doped, which has the characteristic of selectively absorbing a low-light signal at
a specific wavelength band and emitting fluorescence [92–94]. Depending on the way of the fluorescent signal processed, fluorescent fibre temperature sensors are generally classified into three types: intensity, intensity ratio and lifetime. Due to the stronger anti-interference ability and better accuracy, the fluorescent fibre sensors applied for transformer windings temperature measurement are all fluorescence lifetime type [95]. With a pulsed light input, the fluorescence is attenuated exponentially. The fluorescence lifetime is decreased with the increase of temperature due to the phonon scattering process.

K.A. Wickersheim et al. [96] embedded eight fluorescent fibre-optic temperature sensors directly onto the windings of a three-phase LPT to monitor the hot spot temperatures under seven different loading conditions. This was the first study in temperature monitoring of transformers by using fibre-optic sensors. The system was single channelled, and the probes were made by plastic clad silica fibre. The mean difference between the inserted probe and the embedded thermocouple was 1.5°C over a temperature range of 3°C to 105°C.

Aiming to facilitate detection and simplify the installation process, a direct reading hot-spot detector for industrial applications was developed [97]. The system was upgraded to four channels and could collect data automatically over a long period. The sensing range was from -150°C to 400°C with ±2°C accuracy without calibration. The researchers also proposed two approaches to improve the ease of installation. One with metal-sheathed cables and double compression gland feed-throughs of the Conax type. The other one with rigidly welded pipes and connectors at both ends.

After 25 years of innovation, as a main partner of Reference [96, 97], Luxtron developed a commercial transformer winding temperature fibre monitoring system WTS-22 in 2001 [98]. The system directly measured the hot spot temperature of a high voltage power transformer, with 4 to 16 sensors input in one package. The system successfully provided a temperature measurement resolution of 1.0°C over a range of \(-30°C\) to \(+200°C\), and the accuracy was \(\pm 2°C\) without calibration. The fibre-optic probe was made of a special material to adapt to the high oil temperature of transformers. This system is widely used in transformers of ABB, GE and other companies.

Since then, the principles and structures of the temperature sensing system based on fluorescent fibre have not changed significantly, while the subsequent researchers made efforts in the practical application. C. Wang et al. [99] encapsulated the fluorescent fibre-optic probe in a transparent glass tube to meet the mechanical strength requirements. A hole was made in the insulating block based on the size of the sensor, and the fluorescent fibre temperature sensor was installed in the transformer winding together with the insulating block. The actual measurement showed that the accuracy of the sensor can reach \(\pm 0.3°C\) in the temperature range of \(-50°C\) to \(240°C\). Furthermore, 32 sensors were used to the internal temperature distribution monitoring of a 500 kV oil-immersed transformer.

Using the measured results to correct the theoretically calculated temperature distribution is an important purpose for direct measurement. H.Y. Wang [95] verified the applicability of the monitoring system by directly measuring the temperature of the windings, the top oil and the middle oil of a 220 kV oil-immersed power transformer. The monitoring system had a temperature detection range of \(-40°C\) to \(260°C\) with an accuracy of \(\pm 2°C\) and a temperature resolution of \(0.1°C\). Up to 16 sensors could be simultaneously worked.

Fluorescent fibre-optic sensor is a mature and widely used temperature sensor that can be used to directly measure the transformer winding temperature. Since this method is a single point measurement, it is hard to measure temperature distribution. It is necessary to increase the number of sensors to find the hottest location, which often leads to complex maintenance and high costs.

### 5.2 Temperature sensing based on FBG

The FBG temperature sensors have a special advantage, that is, wavelength modulation. The merit of that is the measured signal may not be easily interfered by the instability of the light source and is susceptible to the signal loss caused by fibre bending [94, 100]. Multiple FBGs can be connected along one fibre for multi-point measurement by wavelength division multiplexing (WDM) and time division multiplexing (TDM) [101, 102]. Also, the FBG temperature monitoring system is easy to be installed, maintained, and expanded.

A.D. Stokes et al. [103] used a temperature-compensated FBG sensor to improve the detection accuracy. To measure the thermal response of a 11 kV/415 V 400 kVA transformer, the FBG sensor was placed at the hot spot, and the reference sensor was directly placed in the ambient environment. However, the sensitivity \((0.2 \text{ pm/°C})\) is still not satisfied.

Long-time stability of the fibre and the FBGs are critical for field applications. J. Teunissen et al. [104] investigated the long-term stability of FBG in transformer oil. The result...
demonstrated that the mechanical strength and the refractive index of the optical fibre do not decrease in high temperature oil. Moreover, with an immersed optical fibre, the breakdown voltage under AC stress decreased about 8%. Besides, the breakdown voltage is not affected by temperature variation.

WDM is a well-known technique for realizing quasi-distributed measurements by FBG sensors. In Reference [105], a fibre-optic temperature monitoring system was established with an array of over four FBGs on a single fibre. In order to improve the measurement accuracy, temperature referenced FBGs and a Gaussian curve-fitting algorithm were adopted. The obtained temperature resolution was 0.6°C and the linearity error was less than 0.4%. The improved FBG sensing system was applied to a 3000 kVA transformer in field. The results indicated that compared to conventional thermocouples, FBG sensors have less random noise and are more immune to electromagnetic interference.

Different from the WDM technique, Reference [106] adopted space division multiplexing to realize the multiplexing of FBG sensors. A narrowband laser source was used to illuminate the uniform FBG sensing network with 12 sensors in a star-topology. The multi-point FBG sensing network was integrated into a 345 kV/3 kV, 20 MVA power transformer and continuously monitored the winding's hot spot temperature. The sensing unit had an accuracy of ±1°C and a resolution of 0.1°C over the temperature range from −25°C to +250°C. The sensor channels can be switched reciprocally at a frequency of 50 Hz to implement TDM.

Optimizing applications is important to improve the sensing methods from prototype to product. X. Zhang et al. [107] installed 14 FBG temperature sensors in the top oil, iron core, windings, and bottom oil of a 110 kV power transformer. The sensors had a temperature range from −20°C to 300°C and had a sensitivity of 10 pm/°C. In order to verify the practicality in a long-term operation, the monitoring system was put in operation for 10 months. Compared with the traditional sensors, it presented a better accuracy and a sufficient reliability as well.

In order to find out a new installation method to monitor the winding temperature more directly, J.G. Deng et al. [108, 109] embedded a FBG sensor into a magnet wire with a specially designed slot (shown in Figure 10), and fabricated a 35 kV 4000 kW transformer prototype. Two hundred and eighteen FBG sensors, which were arranged on 14 optical fibres, were successfully placed in windings, core, struts, and oil dome. The sensors fulfilled the temperature measurement requirements of 0~200°C, with a sensitivity of about 10 pm/°C, and the accuracy could reach ±0.5°C. The fibre was embedded into the slotted flat copper wire to prevent the sensor from being affected and destroyed by the winding stress.

Similar to the fluorescent fibre sensors, FBG sensors can only be used for single-point or quasi-distributed temperature monitoring, which makes it hard to achieve true distributed monitoring over a certain span range. Since FBGs can be arranged in series along a fibre, the FBG sensors are more flexible in multiplexing than the fluorescent fibre sensors. It is easier to achieve quasi-distributed temperature monitoring.

5.3 Distributed optical fibre temperature sensing

The fibres used in distributed fibre-optic temperature sensing systems are both transmission element and sensing element. This sensing technique provides a continuous profile of temperature distribution along the sensing fibre [110–112]. The main measuring principles are based on optical time-domain reflectometer (OTDR) and optical frequency-domain reflectometer (OFDR). Among them, distributed sensing Raman optical time-domain reflectometer (ROTDR) is a relatively mature technology [113]. Distributed fibre-optic temperature sensing systems are quite applicable to provide a real temperature distribution along the transformer windings.

D. Yu et al. [114] selected Raman temperature sensing technique to study the temperature distribution of a 110 kV transformer. The temperature spatial resolution was 4 m and the range of measurement was 0 to 150°C. In terms of the installation of sensing optical fibre, Y. Liu et al. [115] designed a winding wire with fibre embedded in. The ethylene-tetra-fluoro-ethylene jacket was used to protect the fibre. It had been proven to effectively slow down the ageing rate of the fibre coating in transformer oil and high temperature environments. Based on the new designed wire and ROTDR, the distributed temperature measurement for power transformer windings was achieved. The system can detect abnormal temperature rise in windings. The system's measuring range was from −190°C to 700°C, the accuracy was ±2°C, the resolution was better than 0.5°C, the spatial resolution was 0.4 m to 0.8 m, and the measuring distance was up to 2000 m.

Considering the length of the winding wire, A. Boiarski et al. [116] chose Rayleigh elad-scattering approach, which has a greater spatial resolution than ROTDR. Laboratory tests indicated that the spatial resolution was better than 10 cm. The system could measure temperatures over a range from 0 to 150°C with an accuracy of ±5°C, and the sensing length was set about 100 m. The system was also used for switchgear hot spot detection, rotor temperature detections.

Brillouin optical time-domain reflectometer (BOTDR) started later than Raman and Rayleigh based OTDR. But
theoretically it performs better in both spatial resolution and time resolution. Recent research [117] adopted the Brillouin–Raman joint measuring method to obtain the temperature distribution and the deformation of the transformer windings simultaneously in a distributed manner. The winding model and the measurement system are shown in Figure 11. A SMF and a multi-mode fibre (MMF) were placed in a grooved electromagnetic wire to form a composite wire. The SMF was used for strain-sensing and the MMF was used for temperature-sensing. The temperature precision was ±2°C in the range of 20~90°C. The temperature sensing length was set as 100m and the spatial resolution of the system was 2 m.

One of the advantages of BOTDR is that the light source only needs to be incident from one end. However, due to the very weak Brillouin scattering, the measurement accuracy and the measurement range are limited. In addition, as shown in Figure 12, Brillouin optical time-domain analysis (BOTDA) requires two optical paths for greater signal power and dynamic range [118], which brings higher cost to the sensing system.

J. Li [119] introduced BOTDA to realize the distributed fibre-optic online transformer winding deformation and temperature monitoring. They buried the sensing fibre into a transformer winding with a curved shape. This realized simultaneous measurement of temperature and strain for transformer windings. The temperature measurement range was from 0 to 150°C with a temperature resolution of 0.08°C. Since the spatial resolution is positively correlated with the light pulse width, the spatial resolution reached 0.5 m when the pulse width was 5 ns. In the experiments, using 1.5 ns wide pulses instead, the spatial resolution reached 15 cm.

Rayleigh backscattering can also be detected by OFDR via its frequency-domain information, as shown in Figure 13. P. Lu et al. [120] showed an OFDR system using a Luna OBR 4600 optical backscatter reflectometer to monitor the distributed real-time temperature rise of a compact transformer core. The sensing system accurately monitored the non-uniform internal temperature distribution of the transformer. The temperature resolution was demonstrated to be better than 4°C, and the spatial resolution was 5 mm over a distance more than 6.5 m for an 85.5 nm laser sweep range. The spatial resolution is apparently better than that of OTDR.

### 5.4 Advantages and disadvantages

In this Section, three types of optical sensing methods for temperature monitoring of power transformers are reviewed and summarized in Table 4.

Fluorescent fibre sensing is a mature and commercially available transformer temperature detection method, but the sensor probes are expensive. And it is not convenient for multiplexing. The FBG-based temperature sensors have the special merit of wavelength demodulation, which provides prominent anti-interference ability and low requirements on laser source. Furthermore, they can be connected in series to achieve multi-point temperature sensing.

Compared with the above discrete sensors, the distributed fibre-optic temperature sensing system has irreplaceable advantages. It uses a single optical fibre as a sensing element and a communication element and is capable of monitoring temperature distribution in space rather than point-like.

However, taking the installation in windings as an example, there is no yet a method that has been proven to have sufficient long-term operational reliability. In addition, although the sensing fibre is cheap, the price of the laser source and demodulation system is still high. So currently, it is mostly used as an aid in verifying thermal models during transformer development and theoretical verification, rather than an extensive tool of online monitoring.

**Figure 12** Schematic diagram for the fibre optic BOTDA sensor operation. BOTDA, Brillouin optical time-domain analysis; CW, Continuous wave; PD, photodetector

**Figure 11** (a) The optical fibre winding composite model and (b) measurement system [117]. BOTDR, Brillouin optical time-domain reflectometer; ROTDR, Raman optical time-domain reflectometer
6 | THE OTHER KEY PARAMETERS

6.1 | Winding deformation monitoring

Lightning events or short-circuits generate large current, inducing winding mechanically deformed to transformers [121]. There are two types of optical sensing methods to detect the transformer winding deformation. One is the vibration or pressure sensors based on FBG, and the other is distributed optical fibre sensors.

P. Kung et al. [122, 123] proposed a thin fibre-optic sensor for direct winding vibration measurements. The principle of the sensor is Fabry-Perot interferometer. The sensor was used to measure the magnetic force interactions and vibrations inside the transformer, and its bandwidth is 20 to 1000 Hz.

Take the advantage of multi-point measurement, FBG are suitable for winding deformation monitoring. Y. Liu et al. [124] proposed a FBG pressure sensor for axial force measurement of transformer windings. The sensor was designed with the structure of bending plate beam. Calibration experiment indicated that the sensitivity of the sensor was 0.133 pm/kPa and the repeatability error was 2.7% full scale.

The multiplexing capability of FBGs is still limited. Only 10 to 20 sensors can be connected in one single fibre, since clearance distances need to be guaranteed there are no overlaps between the sensors' wavelength peaks. Compared with FBG, a more attractive method is optical fibre distribution sensing. Y.P. Liu et al. [117] presented a transformer winding strain detection method based on Brillouin measuring method. An optic-fibre winding composite model was designed, and a local deformation test was carried out on the winding model. The test results showed that the distributed optic-fibre could transmit wire strain efficiently. They obtained the strain distribution curves of the transformer winding model. The accuracy of the system was 50 μe. Then, Y. Liu et al. [125] further investigated the diagnostic method with the measured strain based on Brillouin distributed fibre-optic sensing system. Firstly, the deformation of the winding in the process of transformer operation was simulated, and the corresponding Brillouin frequency shift was collected. Then, S-transform was used to perform the time-frequency analysis of the strain signal, and the transformed time-frequency feature was extracted as the input to the neural network. An extreme

![Figure 13](image.png)

**Figure 13** Schematic diagram of the configuration of the OFDR system. OFDR, optical frequency-domain reflectometer; PD, photodetector

### Table 4 Comparison of performance indicators for different temperature sensing methods

| Sensing technique | Number of sensors | Sensitivity (pm/°C) | Resolution (°C) | Accuracy (°C) | Scope of application (°C) | Ref. |
|-------------------|-------------------|---------------------|----------------|--------------|--------------------------|------|
| Fluorescent fibre sensing | - | - | 0.1 | ±2 | -40~260 | [95] |
| | 8 | - | - | ±1.5 | 3~105 | [96] |
| | ≥4 | - | - | ±2 | -150~400 | [97] |
| | 4~16 | - | - | ±2 | -30~200 | [98] |
| | 32 | - | - | ±0.3 | -50~240 | [99] |
| FBG sensing | 1 | 0.2 | - | <±3 | 0~100 | [103] |
| | 4, 10 | - | 0.6 | <0.4 (%) | 25~70 | [105] |
| | 12 | - | 0.1 | ±1 | -25~250 | [106] |
| | 14 | 10 | - | - | -20~300 | [107] |
| | 218 | 10 | - | ±0.5 | 0~200 | [108,109] |

| Sensing technique | Technical method | Sensing distance (m) | Spatial resolution (m) | Temperature accuracy/ resolution (°C) | Scope of application (°C) | Ref. |
|-------------------|-------------------|---------------------|----------------------|--------------------------|--------------------------|------|
| Distributed sensing | Rayleigh-OTDR | 100 | 0.1 | ±5/-- | 0~150 | [116] |
| | ROTDR | 2000 | 0.4~0.8 | ±2/0.5 | -190~700 | [115] |
| | Brillouin & Raman-OTDR | 100 | 2 | ±2/≤0.5 | 20~90 | [117] |
| | BOTDA | - | 0.5 | --/0.08 | 0~150 | [119] |
| OFDR | ≥6.5 | 0.05 | <4 | - | - | [120] |

Abbreviations, BOTDA, Brillouin optical time-domain analysis; FBG, fibre Bragg grating; OTDR, optical time-domain reflectometer; OFDR, optical frequency-domain reflectometer; ROTDR, Raman optical time-domain reflectometer.
learning machine was used for training identification. Results showed that the method could effectively identify the common winding deformation form, and that the recognition effect was better.

The distributed fibre-optic sensing system [117, 123, 125] has the advantage of high spatial resolution, wider monitoring range. Thus, the distributed fibre-optic sensing system is suitable for new power transformers. The pressure or vibration sensors [122, 124] can be used for old transformers as they are installed on the outer surface of the transformer tank. Besides that, the simpler structure and lower demand decrease the system cost for commercial applications.

6.2 Vibration

Vibrations of the power transformers are induced by magnetostriction or cooling system. The vibrations can reduce the reliability of the power transformer windings. Usually, the vibrations were measured on the outer surface of transformer tank during transformer diagnostic tests. With the help of optical sensors, the iron core vibration can be detected directly by putting sensors inside the transformer tank.

J A García-Souto et al. [126] proposed a fibre-optic interferometric sensor to measure the vibration of the magnetic core inside an oil-filled power transformer, as shown in Figure 14. Optical fibre in contact with the vibrating surface was used as an intrinsic transducer, and the transducer size was a few mm in length. The experiments indicated that the sensitivity of the sensor was 6.71 rad/μm. They carried out measurements inside a medium in-service power transformer. The same group further improved the interferometric sensor’s sensitivity to 64 rad/μm by using a longer sensing fibre [127, 128]. They also provided a demodulation system to detect the high frequency signals.

FBG is another method to achieve vibration measurement in power transformer. In Reference [129], the dynamic strain forces were measured by using an FBG on the iron core. The measurement results showed that the accuracy of the FBG sensor was better than that of the conventional piezoelectric sensor glued to the transformer tank. The strain measurement using FBG can be used to determine unbalanced voltage, short-circuit current, overloading due to the formation of vibration when the transformer is unbalanced.

The interferometric and FBG-based fibre-optic sensor for vibrations [126–129] mentioned in this Section may be fragile for field applications. Further study should be focused on their reliability. Besides that, load tap changers (LTC) on transformers are a constant source of problems for most owners. Failures in LTC are frequently dominated by faults that are mechanical in nature. These typically include failures of springs, bearings, shafts, and drive mechanisms. However, a few optical sensors have been developed to monitor the LTC vibration. In the future, vibration sensors will be a good choice for the LTC monitoring.

6.3 Moisture

Excessive moisture is detrimental to transformer operation. It affects the dielectric insulation life, as it is a major cause of many failures including PD, dielectric breakdown, and deterioration of insulation [11, 130]. As the diffusion speed of moisture in the oil-paper insulation is very slow, better methods to determine water content are desirable to improve the reliability of power transformers. Because optical sensors can be put directly into the oil-paper insulation, optical moisture sensors based on FBG or evanescent-wave were developed to obtain the water concentration earlier.

M. Ansari et al. [131, 132] performed an investigation to measure water content in transformer insulation by coating a moisture sensitive polyimide layer on FBG. Sensor response was calibrated and compared to a commercial capacitative moisture measurement instrument, and it was found that the sensor could detect moisture as low as 1% relative humidity. However, the sensitivity of the sensor was not satisfied which was only 0.9 pm/1% relative humidity.

The sensitivity of the moisture sensor can be improved by using another moisture sensitive material, such as methyl methacrylate [133] The wavelength changes to moisture content reached 29 pm/ppm was demonstrated, indicating detectable water content is better than 0.05 ppm.
Besides FBG, evanescent-wave sensor is another potential method for power transformer moisture monitoring [134]. An optic-fibre moisture sensor was prepared by coating Polyvinyl Acetate film with a thickness of 30 μm on a 1 mm polymer fibre. Light transmitted intensity was detected to monitor the moisture in the power transformer. The experiments indicated that less than 5% moisture can be measured with the proposed sensor.

By modifying the optical fibre structure to D-shape, S.F.A.Z. Yusoff et al. [135] significantly decreased the detection limit of evanescent-wave moisture sensor. The D-shaped optical fibre sensor was coated with a 25 nm platinum thin layer. A simulation-based investigation using COMSOL Multiphysics was also carried out to understand the relationship between analytic materials at different refractive index. Calibration results indicated that the sensor was fast responsive and sensitive. Oil sample with a low concentration of water (15 ppm) can be detected.

The disadvantage of the FBG humidity sensor investigated by W. Zhang et al. [133] is that the response time is not as good as evanescent-wave sensor. Also, the temperature effect needs to be eliminated. In addition, as the material used in the sensor is an organic compound, the performance under moisture loading and unloading cycles should be improved. On the other side, the evanescent-wave moisture sensors [134, 135] have the advantages of fast response and high sensitivity. The sensor performance under different oil flows and pressures should be investigated to improve the reliability of the moisture sensor.

7 | TECHNICAL CHALLENGES AND FUTURE RESEARCH

Optical sensing techniques provide numerous opportunities in power transformer monitoring. At the same time, the optical sensing technique is a new concept for electrical researchers and engineers. As such, there are still many knowledge gaps from laboratory research to field applications. The potential applications of fibre-optic sensing technologies used for transformers are shown in Figure 15.

One of the applications of optic-fibre sensing is for the detection of PD in power transformers. Despite the significant efforts have been devoted, there are still missing areas in which future investigation should be addressed. Current fibre-optic sensing techniques are hard to achieve high sensitivity and multiple sensing simultaneously. In addition, major works done in the laboratories under small and simplified models are far from the actual field conditions. Therefore, the stability studies of the fibre-optic ultrasonic sensing system in actual transformer should be focused on. Application methods of fibre-optic distributed sensing should be investigated before installing the optical fibre into the actual power transformer, because of the huge interference caused by the oil flow and heating inside the transformer. Furthermore, ultrasonic sensors usually require long-term operation in a transformer environment, the material ageing of optical sensors is another important issue should be considered. Additional efforts are required to improve materials in terms of the working lifetime and the tolerance in harsh working environments.

For gas sensing applications, improvements on the performance of optical sensors are important directions for future research. Moreover, environmental factors, such as oil temperature and pressure, play an important role in sensing system. For quantitative measurements, the relationship between sensor performance and dissolved gas concentration together with environmental parameters should be studied. Furthermore, the new type fibre can improve the performance of sensors based on the its unique structure. For instance, the optical pathlength could get shortened significantly by using the hollow core photonic crystal fibre [54, 136]. And some new trends in optical sensing should be taken into consideration, for example cavity-enhanced techniques and fibre loop ring-down techniques and so forth.

In terms of temperature sensing, sensors and instruments have been well established. Compared with the FBG and fluorescent fibre, distributed optical sensing has attracted more interest due to its high spatial resolution. It creates a great opportunity to enhance the observation of temperature distribution in power transformers. To improve the existing temperature measurement methods, one of the major challenges is to improve the installation reliability to ensure the distributed optical sensing performance.

For winding deformation monitoring, the distributed fibre-optic sensing system has the advantages of higher spatial resolution and wider monitoring range. The method to install the fibre-optic into the winding should be enhanced to prevent the breakage of fibre during the winding deformation. Despite the significant advancement in the last few years, the relationship between the 3D shape of the winding and the strain measured by the optical system has not been well understood. Acoustic sensor mounted

![FIGURE 15 Application of fibre-optic technologies for LPTs, LPTs, large power transformers](image-url)
outside the power transformer tank is another potential method of the winding deformation monitoring. The sensitivity should be further improved since the high attenuation of the acoustic signal in the complex structure of LPTs.

The method of vibration sensing on the iron core are well established as discussed in this paper. The challenge is how to simplify and miniaturize the system to decrease the cost. Besides, the LTC vibration is more important for monitoring since it has been a constant source of mechanical problems. The development of small and reliable vibration optical sensor suitable for the LTC is challenging.

The study of the moisture sensors for power transformer is far behind the other types of sensors. The design of the humidity sensors in various industries such as food processing and storage, agricultural, biomedical, chemical, structural health monitoring, ecological should be referred to. The temperature effect must be eliminated during the measurement. Besides that, the performance under moisture loading and unloading cycles should also be improved. The moisture sensing materials should be updated or validated in term of the reliability of the material.

8 | CONCLUSION

Recently, many novel developments in optical sensors for power transformer monitoring have been reported. Here, we critically reviewed various different measurement methods and summarized the recent research progress in the optical sensors for power transformers. We believe that more reliable and functional optical sensors remain to be developed. Here, we highlighted the existing challenges and future direction of optical sensors research.

i. It is important to build a knowledge bridge overcoming the barriers between optical sensing and transformer industry applications. For example, multidisciplinary teams including experts in power industry, chemical, physical, optical or electronic industry should be organized.

ii. The cost of the monitoring system is crucial for an entire electric grid system. The newly developed techniques with high detection sensitivity should be matched the design principles with lower cost, simpler structure, cheaper demodulation and multiplexing. This is an important factor that should be considered for practical applications.

iii. It should be noted that reliability is the most important thing in power industry. Optical sensors should be further investigated to improve their reliability, especially when the sensors are mounted inside the power transformer tank with complex chemical environments.

We anticipate that this review will inspire improvements in optical sensor development, especially for emerging optical sensors with reliable in situ diagnostic approaches.

ACKNOWLEDGEMENTS

This work was supported in part by National Natural Science Foundation of China (51677070 and 51807088), State Key Laboratory of Alternate Electrical Power System with Renewable Energy Sources (LAPS19010), Beijing Natural Science Foundation (3182036), Young Elite Scientists Sponsorship Program by CAST (YESS20160004), Fok Ying-Tong Education Foundation for Young Teachers in the Higher Education Institutions of China (161053), project of China Scholarship Council (CSC), and the Fundamental Research Funds for the Central Universities (2019MS006).

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How to cite this article: Ma G, Wang Y, Qin W, et al. Optical sensors for power transformer monitoring: A review. High Voltage. 2021;6:367–386. https://doi.org/10.1049/hve2.12021