The 28th Iranian Conference on
Optics and Photonics (ICOP 2022),
and the 14th Iranian Conference on
Photonics Engineering and
Technology (ICPET 2022).
Shahid Chamran
University of Ahvaz,
Khuzestan, Iran,
Feb. 1-3, 2022

شبیه سازی و تحلیلِ حسگریِ توزیع شده‌ی تخلیه جزئی در روغن ترانسفورمر قدرت، با استفاده از توری‌های براگ تار نوری شیفت فازیافته‌ی اپودایز شده

وحید طالبی، هادی صوفی

دانشگاه تبریز، دانشکده مهندسی برق و کامپیوتر

vahid.talebi98@ms.tabrizu.ac.ir , h.soofi@tabrizu.ac.ir

چکیده- در این پژوهش، یک سامانه‌ی حسگری تخلیه جزئی توزیع شده برپایه حسگرِ تار نوری و با استفاده از توری‌هایِ براگِ تارِنوریِ شیفت فازیافته‌ی اپودایز شده جهت تشخیص شکست روغن ترانسفورمر پیشنهاد شده و مورد ارزیابی قرار می‌گیرد. اعمال شیفت فاز در توری براگ تار نوری حساسیت سنسور را به طور قابل ملاحظه ای افزایش می‌دهد. همچنین با اعمال اپودایز در توری براگ، گلبرگ‌های جانبی طیف تا ۱۰۰٪ از بین رفته که نه تنها باعث تشخیص دقیق تخلیه‌های جزئی می‌شود بلکه یک درجه آزادی دیگری نیز ارائه می‌دهد که با استفاده از آن می‌توان بازه تشخیص دامنه امواج آکوستیکی و تنش حاصل از تخلیه جزئی را افزایش داد.

کلید واژه: توری براگ اپودایز شده، تخلیه جزئی، روغن ترانسفورمر، سنسورتارنوری، سنسور نوری توزیع شده

Simulation and Analysis of Distributed Partial Discharge Sensing in Power Transformer Oil, Employing Apodized Phase Shifted FBG

Vahid Talebi, Hadi Soofi

Faculty of Electrical and Computer engineering, University of Tabriz, Tabriz, Iran

vahid.talebi98@ms.tabrizu.ac.ir , h.soofi@tabrizu.ac.ir

Abstract - In this research, a distributed partial discharge detection system based on optical fiber sensing, and employing Apodized π-Phase Shifted Fiber Bragg Grating (FBG) sensors is proposed and analyzed, in order to detect power transformer oil breakdown. It is shown that applying phase shift on FBG can extremely enhance its sensitivity. In addition, by applying a Gaussian apodizaion on the FBG, we obtain almost 100% sidelobe suppression in its spectrum, which not merely does result in accurate detection but also gives us another degree of freedom to manipulate the line width of the sensor to the desired value.

Keywords: Apodized FBG, Distributed Sensing, Optical Fiber Sensor, Partial Discharge, Transformer Oil

1. Introduction

Electrical breakdown of the power transformer oil, due to the high voltage the oil is subjected to, can cause huge damages to the power system. One approach to anticipate and prevent the oil breakdown is to continually monitor the quality of the transformer oil by employing optical [1] or chemical [2] methods. Optical quality monitoring mainly involves analyzing the refractive index of the oil, and in the chemical method, the types and amounts of the chemical compounds, as well as gases, are analyzed through, for instance, Dissolved Gas Analysis (DGA) [2]. However, these methods are surveying the aging of power transformer insulation, and they are neither capable of detecting the exact breakdown points nor suitable for online monitoring.

Partial discharge (PD) as the local electrical discharge in the power transformer oil is an early indication of severe oil quality reduction and dielectric breakdown. Energies emitted by PD, propagate as an expansion and retraction acoustic pressure wave, applying stress and strain to the transformer inner walls and coils [3]. Hence, recently, detection of power transformer oil breakdown based on PD detection and sensing PD-induced strain has caught a great deal of interest. In this regard, interferometric sensors, such as Mach–Zehnder or Fabry–Perot have been widely investigated [4], for instance, by using a silica diaphragm at the sensing head. However, multiplexing interferometric sensors in a single fiber are quite difficult, and they are not small enough to be implemented inside the transformer.

In the past two decades, Fiber Bragg Grating (FBG) sensors have been widely used in stress, strain, and vibration [5], temperature [6], gas sensing [7], and structural health monitoring [8]. Similarly, a few research projects proposed FBG sensors for PD detection [9]. However, in some of these works, a mandrel has been employed to amplify the acoustic waves, which may cause problems in the case of installing the sensor inside the transformer. In addition, applying a phase shift on the FBG has been investigated in order to obtain higher sensitivity [10]. It is shown that the Phase Shifted FBG (PSFBG) offers appreciable sensitivity, due to the strong resonances at frequencies within their optical band-gap. Although using PSFBG removed the need for the mandrel, the simple PSFBG deteriorates the performance of the sensor, due to their low Side Lobe Suppression Ratio (SLSR). In addition, the detection range in PSFBGs is limited to ultra-small amounts of strains [11].

In this paper we propose a distributed sensing of PDs in transformer oil, using several numbers of Apodized π-Phase Shifted Fiber Bragg Gratings (AP-PSFBG), depending on the size of the power transformer. We analyze AP-PSFBG response to the small amounts of stresses and strains induced by PD, and the results justify that using a Gaussian apodization on PSFBG not solely improves performance but also broadens detection bandwidth. Admittedly, apodizaion curbs almost 100% of side lobes, which is highly desirable in distributed sensing. Furthermore, it is shown that by modifying the apodization factor, it is possible to tune the line width of the sensor to detect larger amplitudes of PD-induced acoustic waves, and the dynamic range for strain detection is as high as 4.5 μStrain.

2. Theory and Background

For our non-uniform grating structure, the Transfer Matrix Method (TMM) is utilized to calculate its spectral response. Here, we employ Python programming in order to solve the coupled-mode equations and obtain FBG spectral response. Afterward, the captured PD-induced strain profile is applied to AP-PSFBG in order to observe the corresponding wavelength shift and reflection intensity variation. A complete description of TMM can be found in the literature [11].
The refractive index modulation along the fiber axis is defined as (1). Here, n_{eff} is the average refractive index of the fiber core, and $R_n(z)$ is the modulation of the refractive index, defined as (2), where $A(z)$ is the apodization function, Λ_0 is the grating period, υ denotes fringe visibility and Δn is the refractive index contrast.

$$n(z) = n_{eff} R_n(z) \tag{1}$$

$$R_n(z) = A(z)\Delta n[1 + \upsilon \cos(\frac{2\pi}{\Lambda_0} z)] \tag{2}$$

As can be perceived from equation (2), the refractive index modulation of $R_n(z)$ depends on the apodization function ($A(z)$). The Gaussian apodization function is defined as (3), where m is the apodization factor and L is the grating length [11].

$$A(z) = \exp[-m(\frac{z - L/2}{L})^2] \tag{3}$$

Fig. 1 shows the different Gaussian apodization profiles which are applied on a phase-shifted FBG, and the corresponding reflection spectrum. It is clear that by decreasing m, the FBG profile gets closer to the uniform profile, which results in high sidelobes ratio. In all simulations, the length of FBG is considered to be 10 mm and $\Delta n=4\times10^{-4}$. The Bragg wavelength displacement due to strain along the fiber is described by (4). Here, z is the longitudinal direction of the fiber, ρ_e is the photo-elastic coefficient of the fiber, $\varepsilon_{FBG}(z)$ is strain variation along the fiber and $\Delta\lambda_B$ is the shift in the Bragg wavelength [5].

$$\frac{\Delta\lambda_B}{\lambda_B}=(1-\rho_e)\varepsilon_{FBG}(z) \qquad (4)$$

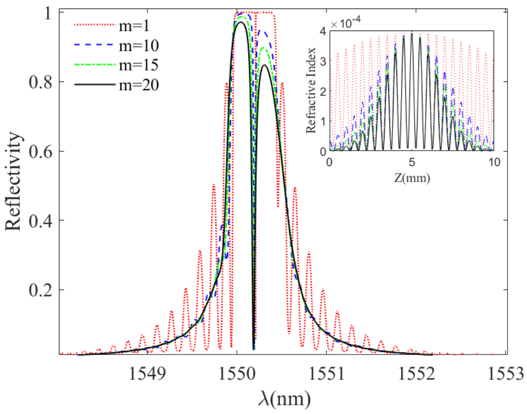

Fig. 1: The reflection spectrum for different apodization factors, and Gaussian apodized FBG refractive index modulation for different amounts of apodization factors.

The three most important characteristics of FBG sensors for three different kinds of FBGs are compared in Table I. It is seen that the line-width of FBG after applying phase shift is almost 16 times less than uniform FBG, and this is the indication of their extreme sensitivity. Similarly, by applying Gaussian apodization with m=20, the linewidth is even decreased further.

Table I. Different FBG sensors' characteristic.

Type of sensor	Uniform FBG	PS-FBG	AP-PSFBG
Line width	506.9 pm	32.4 pm	27.8 pm
Reflectivity	100%	94.8%	93.1%
Side lobe ratio	High	High	0

3. Results and Discussions

Fig. 2 depicts strain sensing using PSFBG and AP-PSFBG. A narrowband laser can be employed to illuminate an optical fiber including the FBG sensor, and the light intensity reflected back from FBG can be captured through an optical circulator. Hence, a gradual increase in strain will result in a steady increase in reflection intensity. As can be seen, the maximum amount of stress that can be measured by PSFBG depends on its linewidth. For instance, the maximum strain that can be measured by PSFBG is less than 2.5µStrain, while this value rises to more than 4.5µStrain in AP-PSFBG (with m=40). To this end, the proposed PD detection system is based on AP-PSFBG which is demonstrated in Fig. 3

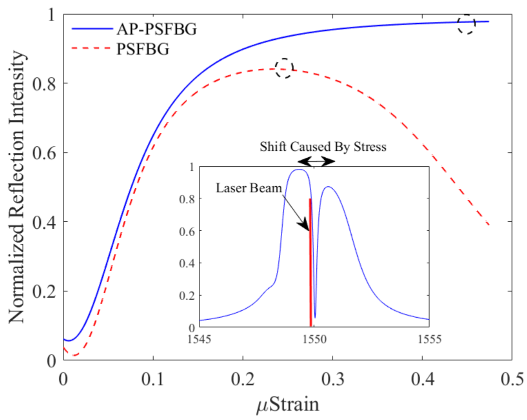

Fig. 2: Strain sensing comparison by PSFBG and AP-PSFBG. The dashed circle in each case shows the maximum amount of strain that can be measured.

As depicted in Fig. 3, a single-mode optical fiber including several numbers of AP-PSFBGs is illuminated by a multi-wavelength tuneable laser, in order to achieve distributed sensing. In addition, a signal separation unit is employed to separate the low-frequency signals, due to the temperature variation, and high-frequency signals owing to the acoustic pressure waves. Finally, these signals are analyzed in the control unit, where the low-frequency signals are used to tune the laser, in order to compensate temperature variation effect, and the high-frequency signals served as the indication of PD occurrence. A similar interrogation system is proposed in [10].

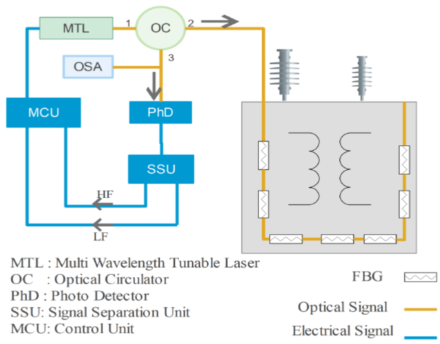

Fig. 3: Schematic diagram of PD detection system.

An exhaustive experimental and theoretical investigation of acoustic pressure waves, resulted from PD occurrence can be found in the literature [12]. Fig. 4 demonstrates the acoustic wave profile and the associated captured optical signal on one of FBGs. Here, the black curve indicates the PD-induced acoustic wave which applies strain on the fiber, and the dotted red curve is the resulting reflection intensity variation, which is the indication of PD occurrence and oil breakdown. In addition, the inset curve on this figure shows the spectrum of distributed strain sensing. Here, an arbitrary strain profile, starting from a peak value and diminishing to zero is applied to the system, containing four APSFBG. As can be seen, the wavelength shift is larger for the FBG that experiences higher strain, and as the strain reduces, the wavelength shift declines as well.

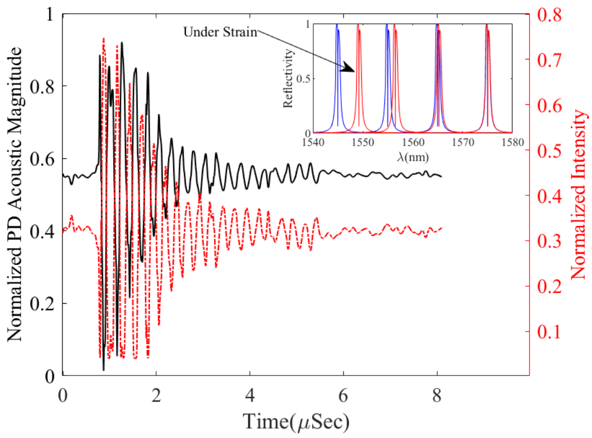

Fig. 4: Applied PD Pressure wave to Apodized PSFBG and the corresponding reflection intensity variation.

3. Conclusion

In this paper, a distributed sensing method for the detection of partial discharge in power transformer oil is proposed. It is seen that PSFBGs can effectively detect the acoustic pressure wave emissions due to PD occurrence. In addition, we investigated applying different Gaussian apodizations on PSFBG and the simulation results confirmed that maximum SLSR of as high as 100% can be achieved. Moreover, the maximum amount of strain that could be detected increased from 2.5µStrain to 4.5µStrain. Interestingly, the proposed method is simple that can be mounted in a power transformer without any disturbance.

References

[1] Baharil I. Onn, Punithavathi Thirunavakkarasu, Yusser Al-Qazwini, Ahmad Fauzi Abas, N. Tamchek, and Ahmad Shukri Muhammad Noor, "Fiber bragg grating sensor for detecting ageing transformer oil," 2012 IEEE 3rd Int. Conf. on Photonics, Oct 1-3, pp. 110-113, 2012.

[2] M. Duval, "Dissolved gas analysis: It Can Save Your Transformer," IEEE Electr. Insul. Mag. vol. 5, no. 6, pp. 22-27, 1989

[3] R. Sarathi, Prathab D. Singh, and Michael Danikas, "Characterization of partial discharges in transformer oil insulation under AC and DC voltage using acoustic emission technique," J. Electr. Eng. vol. 58, no. 2, 91–97, 2007

[4] Mohd Muhridza Yaacob, Malik Abdulrazzaq Alsaedi, Jabbar Rashed, Adel M. Dakhil, and S.F Atyah,"Review on partial discharge detection techniques related to high voltage power equipment using different sensors,". Photonic Sens. Vol. 4, pp. 325–337, 2014.

[5] Farinaz Kouhrangiha, Mojtaba Kahrizi, and Khashayar Khorasani, "Structural health monitoring using Apodized Pi-Phase Shifted FBG: decoupling strain and temperature effects," 2019 IEEE Sensors Conf. Oct. 27-30, pp. 1-4, 2019.

[6] Venkatesh Chakravartula, Sampita Rakshit, Dhanalakshmi Samiappan, R. Kumar, and R. Narayanamoorthi, "Linear temperature distribution sensor using FBG in liquids-local heat transfer examination application," IEEE Sens. J, vol. 21, no. 15, pp. 16651-16658, 2021.

[7] MA Guoming, Chengrong Li, Rui-Duo Mu, Jun Jiang, and Ying-Ting Luo, "Fiber Bragg grating sensor for hydrogen detection in power transformers," IEEE Trans. Dielectr. Electr. Insul., vol. 21, no. 1, pp. 380-385, 2014.

[8] S. Jinachandran and G Rajan, "Fiber Bragg grating based acoustic emission measurement system for structural health monitoring Applications," Materials, vol.14, no.4, pp.897-??, 2021.

[9] Mohsen Ghorat, Gevork Gharehpetian. Hamid Latifi, M Akhavanhejazi, and M Bagheri, "High-resolution FBG-based Fiber-optic sensor with temperature compensation for PD Monitoring," Sensors vol. 19, no.23, pp.5285-??, 2019.

[10] MA Guoming, Zhou Hongyang, Cheng Shi, Ya-bo Li, Zhang Qiang, Chengrong Li, and Qing Zheng, "Distributed partial discharge detection in a power transformer based on phase-shifted FBG," IEEE Sens. J. vol. 18, no. 7, pp. 2788-2795, 2018

[11] Raman Kashyap, *Fiber Bragg Gratings*, Academic Press, San Diego & London, pp. 195-221, 1999.

[12] Gu FengChang, Chen HungCheng, Chao MengHung, "Application of Improved Hilbert–Huang Transform to Partial Discharge Defect Model Recognition of Power Cables," J. Appl. Sci. , Vol.*7,* no.10, pp. 1021-??, 2017