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A Brief Review on Optical Fiber Sensing for the Power Grid

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Abstract

In this work, a brief review on the application of fiber optic sensors on power grid apparatus is presented. Power transformers, which are the nodes between electrical transmission lines, are the most expensive, critical and one of the central units of this network. The failure of electrical machines compromises the whole grid leading to power outages and income losses. Thus, constant monitoring of structural health and operating conditions of core infrastructures is sought. With different types of sensors either on the market or in the literature, it is possible to measure physical parameters that make this equipment more reliable.

Author Keywords. Smart Grid, Power Transformer, Transmission Line, Optical Fiber Sensor, Fabry-Perot, Bragg Grating, Distributed Sensing, Health Monitoring.

Type: Research Article

1. Introduction

Optical fiber sensing is a well-established technology, having a special interest in applications for harsh environments. Fiber sensors have advantages over conventional ones since they can be multiplexed, are lightweight yet robust, and are immune to electromagnetic interferences. Due to the multifunctionality of fiber sensor techniques, the same kind of fiber optic sensors can be applied to different structures and to access different physical and chemical measurands such as strain, pressure, force, acceleration, vibrations, electric and magnetic fields, temperature, humidity, and gas composition analysis (Rajan 2015). The power transformers need to be monitored to keep fully functional throughout their lifetime. The parameters which are important to monitor includes: partial discharge; temperature, dissolved gas (hydrogen), strain (clamping force) and vibration (vibro-acoustic behavior) (N'Cho and Fofana 2020). Extended reviews for optical sensing in the electrical machinery have been presented, in particular the use of FBGs for partial discharge detection (Meitei, Borah, and Chatterjee 2021), power transformer monitoring (Ma et al. 2021), health monitoring (Chai et al. 2019).

In this brief review, it is provided a general vision of the state of the art for recent developments in optical fiber sensing for the power grid systems.

2. Optical Fiber Sensors

The implementation of fiber optic sensors, classified as interferometric, fiber Bragg grattings (FBG), and distributed sensing allow the *in-situ* measurement of the main stress sources such as electrical, thermal, and mechanical. Interferometric sensors are usual applied for acoustic sensing, being capable of detecting partial discharges and structural vibrations. Special fibers are the most used for electrical current measurements (Wang et al. 2016). The FBG technology is already well established in the industry for different engineering applications. In this area, they are mainly used to access structural strain, temperature, and acceleration. Distributed sensors are mainly developed for sensing temperature, detecting hotspots inside the transformer and monitoring transmission lines. A summary of the optical sensors and their application in the power grid (See Figure 1).

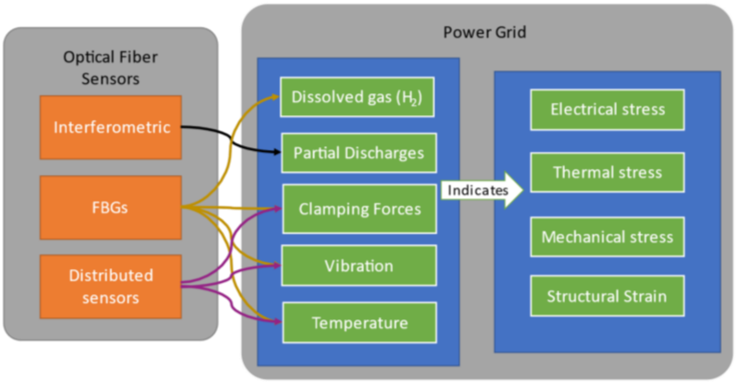

Figure 1: Application of optical Fiber sensors for the main sources of equipment failure in the power

2.1. Interferometric sensors

Interferometric sensors (IS) are based on the superposition of two or more beams. Depending on the interferometer topology they can be divided into four different categories as follows: Fabry-Perot interferometers (FPI); Mach-Zehnder interferometers (MZI); Michelson interferometer (MI); and Sagnac interferometers (SI). In an FPI, see Figure 2, a sensing zone is formed in a cavity between two reflective surfaces, the superposition of the multiple beam reflections caused by the cavity form the interference pattern. The FPI pattern depends on the reflectivity of the surfaces and the optical length of the cavity and can be tuned to have different sensing characteristics (Rodrigues et al. 2021). Both MZI and MI sensors are comprised of a reference arm and a sensing arm. A propagating beam is divided among the two arms, while the reference arm keeps unaltered by external factors, the sensing arm is affected by them. An optical path difference is introduced in the sensing arm and gives rise to the interference pattern. In the MZI interferometer, the beam recombination happens in a transmission configuration while in the MI interferometer this happens in a reflection configuration, where each beam is reflected in a mirror. The IS has a fiber loop topology, a beam is coupled into two counter-propagating directions in the loop and recombined in the same coupler.

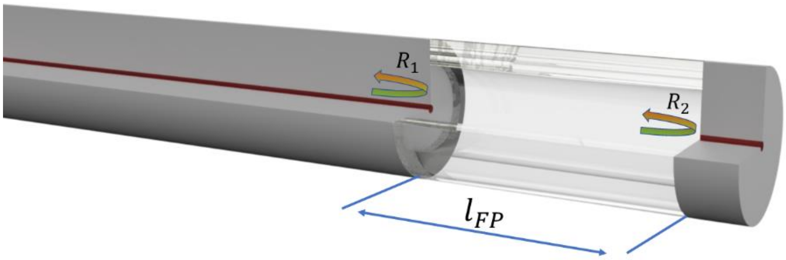

Figure 2: Structure of a Fabry Perot cavity

Among the FP based devices for partial discharge monitoring that have been proposed, an array with a 2x2 configuration was also proposed in order to spatially locate the discharge inside a 35 kV power transformer (Gao et al. 2018). A similar array, with three FPs, was recently proposed to reduce false-positive events and improve sensitivity (Zhang et al. 2022). Recently, an extrinsic FP sensor fabricated with a quartz tube and a nickel diaphragm was developed. The influence of the diaphragm diameter and thickness was studied (Lei et al. 2020).

2.2. Fiber Bragg sensors

The working principle of a Bragg grating, depicted in Figure 3, consists of the temporary or permanent modulation of the fiber index of refraction, which produce a spectrally narrow reflection at a specific wavelength called Bragg reflection determined by the spatial period of the index modulation. Multiplexing FBGs is possible due to the narrow reflection which allows the simultaneous interrogation of a single line with multiple FBGs along the fiber. Quasi-distributed sensing is attainable by multiplexing FBGs.

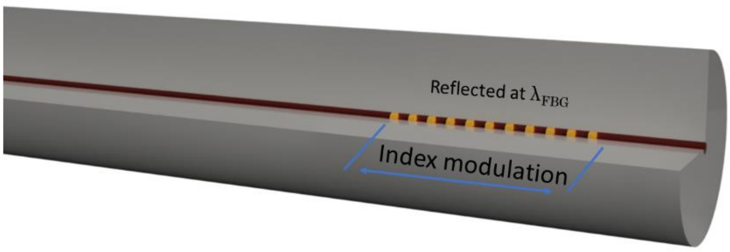

Figure 3: Structure of a Bragg grating inscribed in optical fiber

Different applications using FBGs have been proposed for the power grid systems. A sensor using a side polished FBG was developed for measuring dissolved hydrogen in power transformers oil reporting a sensitivity as high as 0.477 (pm/(µL/L)), which is about 11.4 times higher than other FGB hydrogen sensors (Jiang et al. 2015). Using tilted FBGs in depressed cladding fiber-enhanced transverse strain response, thus accelerometers suited to measure weak vibrations, in the range 0.2–6.5 m/s^2, with a flat response of 0.8-1.1 V/(m/s^2) at low frequencies up to around 120 Hz, were proposed for monitoring transmission lines (Cai et al. 2017) and transmission towers (Nan et al. 2020). A temperature-compensated force sensing device using several packages of three FBGs each was proposed for monitoring electrified railway pantographs (Chen et al. 2017). The temperature compensation is achieved by comparing each FBG response to temperature inside each patch. A smart bolt using an integrated FBG was developed to control transmission lines by monitoring the bolt looseness and simultaneously accessing the galloping behavior of the line at low frequencies up to 2 Hz (Duan et al. 2020).

2.3. Distributed sensors

Distributed sensors rely on the fiber itself for sensing physical quantities. The optical fiber interacts with the surrounding environment and changes the propagating signal (Galindez-Jamioy and López-Higuera 2012). This technique Interrogating these sensors requires the use of an Optical Time Domain Reflectometer (OTDR) of optical frequency domain reflectometer (OFDR). The internal temperature of the power transformer has been recently implemented by using an optical backscatter sensor (Wright et al. 2019) and an OFDR (Badar et al. 2020, 2021). A reference-free temperature sensor for power lines has also been reported by Datta et al. (2020) using distributed anti-Stokes Raman thermometry in a loop configuration. Transformer winding temperature was monitored with less than 1 m positioning accuracy using a Raman OTDR (Liu et al. 2019).

3. Overview

The electricity demand in the efforts to reduce pollution and create a more sustainable world, requires a more efficient energy production and consumption and taking advantage of the current electrical systems. To guarantee this, the smart and integrated monitoring of the transmission line and power transformers is currently being studied. Optical sensors are in fact highly attractive for this purpose. Several interferometers, FBGs, and distributed sensors have already been proposed. Currently, the successful use of optical sensors for temperature monitoring in power transformers has shown a strong interest by electrical utilities and power products manufactures. It is expected that we observe, in the near future, a more widespread use of other sensors incorporated inside the power transformers, measuring either electrical discharges, changes in the properties of mineral oil or measuring the vibration changes caused by internal or external faults.

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