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A magnetostrictive-fiber Bragg grating sensor for induction motor health monitoring

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ABSTRACT

AC induction motors are the most common motors used in industrial motion. They are widely used in industrial applications for its simplicity, rugged design, low-cost, low maintenance and direct connection to an AC power source. One of the faults occurring in induction motor is the rotor bar breakage that may rapidly spread to a functional failure with catastrophic consequences. Despite the low cost of an induction motor, production losses due to a functional failure in the motor may be greater than the cost of the motor itself. Therefore, the cost advantages that can be achieved with predictive maintenance justify research in monitoring techniques that can indicate the evolution of the conditions before a failure occurs. In this paper, we demonstrate a magnetic sensor based on fiber Bragg grating (FBG) and magnetostrictive composite made of Terfenol-D particulates immersed in epoxy resin matrix applied to induction motor to detect rotor broken bars. To the best of our knowledge, this work demonstrates by the first time an FBG based magnetic sensor applied to monitor an induction motor with the capability to distinguish defective bars, whereas at the same time, conventional technique of current signature at low loading levels failed to indicate the motor severity. The obtained results indicate that the Terfenol-D based sensor can be used for purposes of monitoring broken rotor bars in high voltage induction motors, even when the motor is installed in a dangerous atmosphere, due to the insulation provided by the optical fiber sensor.

1. Introduction

Induction motors are the most common motors used in industrial motion. They are widely used in industrial applications for its simplicity, rugged design, low-cost, low maintenance and direct connection to an AC power source. Additionally, as there is no electrical connection between the moving parts (rotor) and the stationary part (stator) there are no sparks produced, which poses an advantage when working in presence of liquid combustibles or explosive gases. Therefore, this kind of motor is widely used in the Oil and Gas Industry.

In a study from Williamson [1] he concluded that in developed countries, at least 60% of the total electrical energy consumed by the industry accounts for the energy consumed by induction motors.

A fault in the rotor of an induction motor represents only 10% of total failures that can occur [2], but despite of this lower contribution, a rotor bar breakage may rapidly spread to a functional failure with catastrophic consequences.

Rotor failures may be caused by defects in the manufacturing process or improper use. During startup, currents at the industrial frequency, around five to seven times the nominal current, are induced in the rotor bars. The bar breakage usually occurs due to a continued repetition of a fatigue process and also because of the skin effect during the startup that, due to the Joule effect, heats unequally the bar causing it to twist. With the centrifugal force, a broken bar may exit the slot or throw into the air gap broken pieces, damaging the stator core and winding.

Low voltage induction motors go up to 150 kW in industry and are usually connected to 440 V. Medium voltages from 2.3 kV to 4 kV are used for motors with power ratings up to 2.5 MW, and 13.2 kV is used for 2.5 MW motors and above. In the oil and gas industry, these motors drive pumps and compressors, usually in places with explosive atmosphere.

Medium voltage induction motors are simple, reliable and economical, but their cost rise exponentially as they increase in size. Despite its low cost compared to the driven equipment (pumps and compressors), production losses due to a functional failure in the motor may be greater than the cost of the motor itself. The worse concern to the Oil & Gas industry is when the system is not redundant, must run continuously for years and a motor replacement is not locally available. In addition, because large machines are tailor-made, often the repair

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can take several weeks and, if a replacement is necessary, it can take several months to get the system operating again.

The cost advantages that can be achieved with predictive maintenance justify research in monitoring techniques that can indicate the evolution of the conditions before a failure occurs. Condition health monitoring enables the programming of an intervention when needed and non-intervention when not needed. Therefore, any technique that allows the interpretation of a defect in evolution should be simple, straightforward, reliable, and its implementation should be feasible and cost effective.

Conventional methods to diagnose rotor faults and bar rupture can be divided between two basic approaches: current monitoring and magnetic flux monitoring.

Current monitoring is based on the motor current signature analysis using the fast Fourier transform (FFT) and other mathematical techniques. This is obtained by attaching a current sensors at each of the motor three-phase terminals, as in the work of Siddiqui and Giri [3] and performing a wavelet transform or as in the work of Saidi et al. [4] by spectral analysis.

Magnetic flux monitoring obtained by the use of Hall sensors is considered to be one of the most reliable electric technique for condition monitoring. Saad and Mirzaeva [5] monitored the main air gap flux with the help of a calibrated Hall Effect flux sensor, which is claimed by the authors to the best technique to measure the main air gap magnetic flux. In the case of broken rotor bar fault, they only simulated results that shown prospective for detecting this type of fault.

A relatively recent work of Mortazavizadeh and Mousavi [6] present a review on condition monitoring and diagnostic techniques for induction motors, describing many techniques, but all related to broken rotor bars based on current or magnetic flow measurement and analysis.

Considering a field application, particularly in an offshore oil platform, where every size of induction motors rein in an extremely harsh environment, we ponder whether complex digital signal processing or low noise instrumentation circuits are the best choice considering the local environment condition of high EMI allied to explosive atmosphere. For this reason, we propose a more robust technique to monitor the air gap magnetic flow.

In this paper, we demonstrate a magnetic sensor based on fiber Bragg grating (FBG) technique applied to induction motor in order to detect and localize rotor broken bars. We then decided for a magnetostrictive composite made of Terfenol-D particulates immersed in epoxy resin matrix. This is particularly interesting to be used in the field because they present high resistivity and therefore low eddy currents circulation and suitable for high frequencies.

2. Fiber Bragg grating and magnetostriction fundamentals

Fiber Bragg gratings are reflective structures inscribed in the core of optical fibers consisting in modulation of its refractive index (RI). The central wavelength of the reflected light, a small portion of the input spectrum, is called Bragg wavelength (λ_B) of the grating and varies according to

$$\lambda_B = 2n_{eff}\Lambda \tag{1}$$

where n_{eff} is the effective RI at the FBG location and Λ is the periodicity of the grating.

By taking the partial derivatives of the Bragg wavelength with respect to temperature and displacement in Eq. (1), it is possible to obtain the relationship between the Bragg wavelength with temperature and strain [7]:

$$\frac{\Delta\lambda_B}{\lambda_B} = (1-\rho_e)\varepsilon_{FBG} + (\alpha_{FBG} + \eta)\Delta T \tag{2}$$

In this last equation $\Delta\lambda_B$ is the Bragg wavelength shift, λ_B is the Bragg central wavelength, ρ_e is the photo-elastic coefficient, ε_{FBG} is the strain applied to the FBG, ΔT is the temperature variation, α_{FBG} is the silica thermal expansion coefficient and η is thermo-optic coefficient.

Therefore, an FBG is, basically, sensitive to temperature and strain; however, in order to make it sensitive to magnetic flux we simply attach it to a magnetostrictive material, as nickel for instance. When the magnetic field extends the material, the FBG will strain accordingly and a measurement of the strain, and therefore of the magnetic field can be obtained.

We have recently developed a magnetic flux sensor based on a giant magnetostrictive material (GMM) as primary sensor [8] for current monitoring. In fact, many other studies have demonstrated the excellent properties of GMM for current measurement systems based on FBGs, such the work of Cremonezi et al. [9], Nazaré and Werneck [10] and Silva et al. [11].

Indeed, the application of GMM for magnetic field or current measurement is not new. Mora et al. [12] described one of the first works of magnetic field and DC current measurement with FBG. In their work, a magnetostrictive material is in thermal equilibrium with another alloy with the same thermal expansion coefficient. By bonding an FBG in each material, one FBG can measure the magnetic field whereas the other FBG allows a reference for temperature compensation.

Another system for measuring AC currents was proposed by Hong et al. [13] in which a Terfenol-D rod with an FBG bonded to it is inserted inside a magnetic coil. The amplitude modulated output signal from the FBG interrogation system was shown to be proportional to the current inside the coil.

As it will be shown in the next section, the magnetostrictive deformation occurs symmetrically for positive or negative magnetic field. In another words, the material changes its length in the same direction whatever the magnetic field polarity. For circumvent this effect, Satpathi et al. [14] proposed a DC magnetic polarization in order to bias the Terfenol-D rod, hence making it possible to submit the sensor head to an AC magnetic field and obtaining, as a response, an equivalent FBG central wavelength displacement.

All ferromagnetic materials present magnetostriction, a property in which the material is strained when submitted to a magnetic field. Some ferromagnetic materials present small magnetostrictive effect, such as silicon-steel and ferrite. Other materials present higher magnetostrictive effect such as cobalt and nickel, and some other materials, in form of alloys, present an even higher effect such as Metglas ($Fe_{81}Si_{3.5}B_{13.5}C_2$) and Terfenol-D ($Tb_xDy_{1-x}Fe_2$), developed in the 1970s by the US Naval Ordnance Laboratory. In this work it was used Terfenol-D because it is the largest known magnetostrictive material.

The first step in the sensor production started with the FBG calibration. The technique consists in applying several known weights to the FBG and at the same time record the Bragg wavelength displacement. Then, one plots the Bragg wavelength against the respective strain, and trace a regression curve obtaining $R^2 = 0.999995$ in the following equation:

$$\lambda_B = 1151.4\frac{pm}{\mu\varepsilon}\varepsilon + 1536.2\,pm \tag{3}$$

where λ_B was measured in picometers and ε in microstrain. Now, from (2) and considering a constant temperature environment we arrive to:

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

where λ_B is the central Bragg wavelength at ambient temperature (25 °C), equal to 1536.2 nm. Then, the calibrated photoelastic constant ρ_e can be calculated from:

$$\rho_e = 1-\frac{1151.4}{1536.2} = 0.250 \tag{5}$$

Thus, the strain as a function of the Bragg wavelength shift is: