Multi-parameter monitoring of electrical machines using integrated fibre Bragg gratings

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ABSTRACT

In this paper a sensor system for multi-parameter electrical machine condition monitoring is reported. The proposed FBG-based system allows for the simultaneous monitoring of machine vibration, rotor speed and position, torque, spinning direction, temperature distribution along the stator windings and on the rotor surface as well as the stator wave frequency. This all-optical sensing solution reduces the component count of conventional sensor systems, i.e., all 48 sensing elements are contained within the machine operated by a single sensing interrogation unit. In this work, the sensing system has been successfully integrated into and tested on a permanent magnet motor prototype.

Keywords: Fibre Bragg gratings, multi-parameter monitoring, temperature profiling, torque, rotor speed, vibration

1. INTRODUCTION

The proliferation of the ‘more electric’ concept in many areas of engineering is bringing about an increase in demand on reliability, power density and manufacturing efficiency of rotating electrical machines. To address this ever growing demand for new and reliable designs, electrical machines are increasingly required to be monitored in real-time with the data obtained being used for both model validation and prototype diagnostics. The latter helps to identify potential modes of failure and thus ensures the drive’s reliability, as requested by machine owners or end users. If a conventional approach were to be adopted to achieve such multipoint, multi-parameter measurements, it would involve a drastic increase of component count thus reducing the overall reliability of the system in question. Further to this, due to the relatively large size of insulated conventional sensors, the resulting system will potentially occupy a spatial envelope larger than the drive itself. This work thus aims to address the above challenges, by replacing such conventional sensors with an integrated optical fibre-based, quasi-distributed, sensing system in electrical machines for real-time monitoring. Such a novel approach takes full advantage of the fibre sensors’ reduced spatial envelope and immunity to electromagnetic interference.

One of the first efforts made in the direction of introducing an optical fibre sensor for motor and drive applications was to exploit Rayleigh backscattering in conjunction with a fibre having its outer cladding modified at intervals for a quasi-distributed temperature measurement system using an optical time domain reflectometry (OTDR)[1]. Since then different optical sensing techniques were applied to monitor end-winding vibratory behaviour[2], stator housing vibration[3], thermal effects[4] and torque[5], for instance. In a previous report, the authors introduced a stator wave and rotor speed tracking system based on fibre Bragg grating (FBG) sensors[6].

This report aims for all the above mentioned parameters, and more, to be monitored in real-time using an array of specifically located FBGs operated by a single sensing interrogation unit thus eliminating the need for individual sensor systems for each parameter and therefore significantly reducing the complexity of electrical machine condition monitoring. The developed all-in-one sensor system was tested on a permanent magnet AC (PMAC) machine prototype where the rotor’s rare earth magnet temperatures are of particular interest as overheating causes demagnetization and therefore machine failure.

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2. PRINCIPLE OF OPERATION

An FBG formed within a fibre behaves like a 'notch filter' (in transmission), which reflects light at a wavelength termed the Bragg wavelength that satisfies the so-called Bragg condition whose effects on temperature and strain have been widely reported[7]. The principle exploited to measure vibrations, the rotor speed and its position, the stator wave frequency and the spinning direction is based on the spatial modulation of the air-gap flux in the stator core of an electrical machine. The resulting stator teeth displacement can be measured in the form of strain using FBGs as previously reported by the authors[6]. The method employed to measure torque is based on a differential wavelength approach where two FBGs are attached to the rotor shaft at an angle of ±45° with respect to the spinning axis[5]. In this configuration, the difference between the two FBG reflection peak wavelengths is a measure for torque whereas their mid-point is an indicator for the temperature at that location. The dynamic Bragg wavelength shifts of all 48 FBGs were captured simultaneously using a Micron Optics SM130 sensing interrogator unit, at a sampling rate of 2000 Hz. The DC components of the transient signals were used for thermal analysis (and torque) whereas the AC components were used to determine stator vibrations and phase shifts necessary extract the dynamic parameters.

3. SENSOR LAYOUT

In order to evaluate the all-in-one sensing concept a PMAC machine was instrumented with a total of 48 FBGs at specific locations within the motor. Two fibres of 12 FBGs each were routed along the stator windings for thermal profiling, two FBGs in each stator slot as shown in figures 1(a) and 1(b). The fibres were looped around several times at either end of the stator core. A third fibre of 12 FBGs was circumferentially mounted on the stator core with each FBG placed in between adjacent stator teeth (figure 1(c)) to measure vibrations, the rotor speed and its position, the stator wave frequency and the spinning direction.

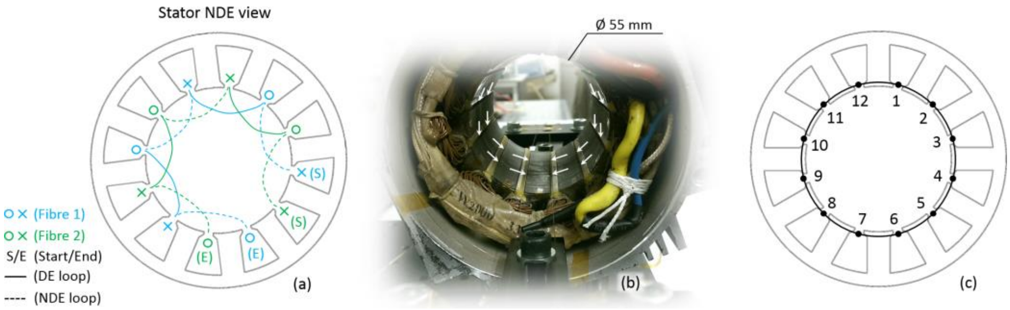

Figure 1. Schematic (a) and photograph (b) of the distribution of 24 FBGs along the stator windings for their thermal profiling. (c) Schematic of the 12 circumferentially mounted FBGs used to measure stator vibrations that result in a number of parameters possible to be extracted.

The remaining 12 FBGs were distributed across the rotor surface, one on each of the ten magnets, again for thermal profiling, and the other two on the rotor shaft for simultaneous torque and temperature monitoring. This is illustrated in figure 2. The rotor fibre was interrogated by means of a fibre-optic rotary joint which allows for the continuous monitoring of the rotor condition while spinning.

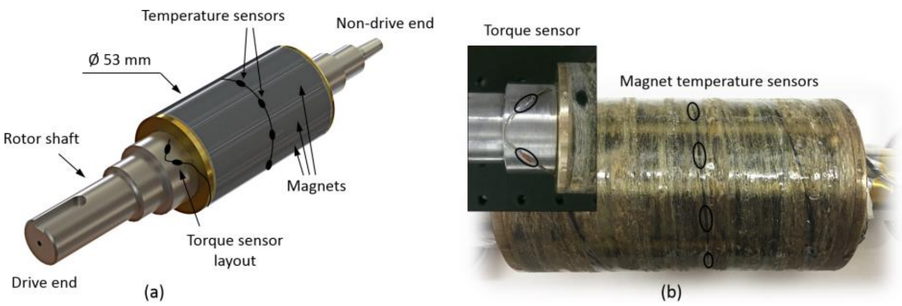

Figure 2. Schematic (a) and photograph (b) of the instrumented PMAC rotor. One fibre of 12 FBGs is attached to the rotor, one to each of the 10 rotor magnets and 2 FBGs on the rotor shaft for torque measurement.

4. RESULTS AND DISCUSSION

Figure 3(a) shows the frequency response of one of the circumferentially mounted FBGs with the machine spinning at 16.7 Hz excitation. The first spectral feature at 16.7 Hz represents the rotor speed and the second (main) feature at 167 Hz corresponds to the stator wave frequency. Either of the two can be used to extract the rotor speed and convert it to rotations per minute (rpm). Other vibrational information, as evident from figure 3(a), gives machine developers and engineers an important insight into the vibratory behaviour of a machine’s design. Since vibrations are also an early indicator for impending machine failure, the constant monitoring of vibrations is of high importance in increased reliability environments.

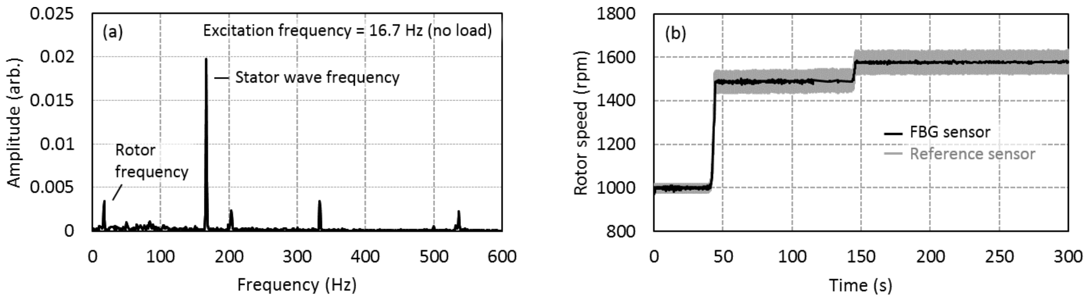

Figure 3. (a) Frequency response of one of the circumferentially mounted FBGs in the case of a spinning rotor under no load. (b) Rotor speed vs time obtained from the FBG sensor and from a reference sensor.

Figure 3(b) shows the rotor speed obtained from the FBG data against a reference sensor with the rotor speed being varied between 1,000 and 1,600 rpm. It is clear from figure 3(b) that the FBG approach very closely matched the reference sensor signal at a much-improved signal-to-noise ratio. Figure 4(a) shows the dynamic responses of four of the circumferentially mounted FBGs highlighting the phase shift between them. This phase shift can be used to track the rotor position with regard to a reference point, i.e., acting like a conventional encoder. The phase shift between any two of those FBGs can also be used to determine the spinning direction of rotor, a positive phase shift indicating rotation in one direction and a negative phase shift rotation in the other direction.

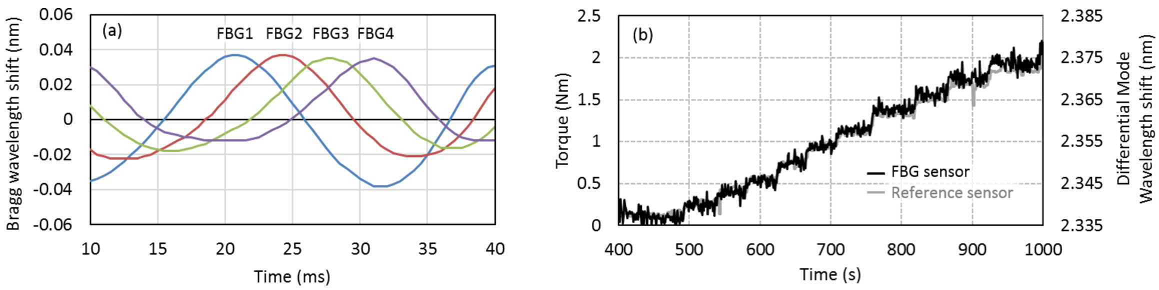

Figure 4. (a) Exemplary phase shifts of the four of the circumferentially mounted FBGs. (b) Differential mode wavelength shift of the FBG torque sensor compared with the data of a reference torque transducer.

Figure 4(b) shows the differential mode wavelength shift (the distance between the two FBG reflection peaks) of the torque sensor layout at varied levels of torque up to 2 Nm. Again, a very close correlation between the FBG approach and the reference sensor has been achieved with a linear torque – wavelength shift relationship (21.5 pm/Nm). In practise it is challenging to realise an angle of exactly 90° between the two FBGs meaning that the differential mode wavelength will experience some sort of temperature dependence. However, this is easily compensated for using the torque-independent mid-point wavelength as an indicator for the temperature.

The thermal profiling of the stator windings and rotor magnets is illustrated in figure 5 where the FBG sensor locations were mapped onto 3-D surface models of both rotor and stator. This way, visual hot-spot identification is made possible.

For the purpose of validating the mapping algorithm, the sensor data in figure 5 was simulated to achieve large temperature gradients across the surface which, in practise, only occurs in faulty machines.

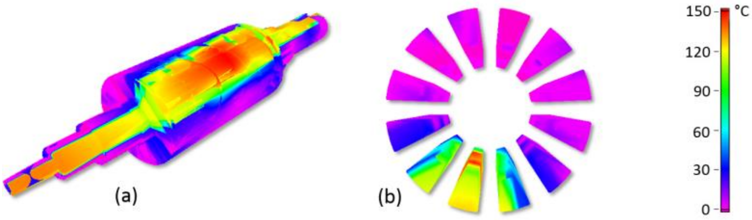

Figure 5. Thermal profiling of the rotor (a) and the stator windings (b) by means of 3-D sensor mapping. The data in the plot is simulated to highlight possible hot-spot detection.

The proposed all-in-one sensor system offers comprehensive real-time condition monitoring of electrical machines for prototype diagnostics or in safety critical environments where early fault indication is of high importance such as on aircrafts or in power stations.

5. CONCLUSIONS

It was shown that when placing a network of FBGs at certain locations within an electrical machine, comprehensive condition monitoring can be performed at a high level of accuracy. Multiple parameters can be extracted from the FBG data by using appropriate data processing and compensation algorithms. The proposed all-in-one sensor system has the potential to replace conventional systems that require a separate sensor/system for each parameter to be monitored. It reduces the component count and spatial envelope of a test environment as all sensing elements are confined within the machine with minimum external wiring/coupling as opposed to conventional sensors. Future work will focus on the implementation of an active feedback control system using the sensor data to control a machine's speed under different load conditions, for instance.

ACKNOWLEDGMENTS

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