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# Comprehensive monitoring of electrical machine parameters using an integrated fibre Bragg grating-based sensor system

M. Fabian, D. Hind, C. Gerada, T. Sun, and K.T.V. Grattan

***Abstract*—In this paper a multi-parameter, multi-sensor system for comprehensive electrical machine condition monitoring has been developed and the results of an evaluation reported. The FBG-based system developed allows for the simultaneous monitoring of key parameters including machine vibration, rotor speed, torque, spin direction, temperature distribution along the stator windings and on the rotor surface as well as the stator wave frequency. This all-optical sensing solution has been designed to be compatible with being fitted in the tight confines of an electric motor and uses the optical nature of the measurement and the insulating nature of the sensor material to avoid problems of electrical interference. The system reduces the component count over conventional sensor systems, i.e., all sensing elements are contained within the machine and operated by a single sensing interrogation unit, thereby reducing cost and allowing for a convenient interface for the user. The design of the system is presented, as are results on the testing and evaluation of the device the sensing system has been successfully integrated into and tested on a permanent magnet motor prototype.**

***Index Terms*—Fibre Bragg gratings, multi-parameter monitoring, temperature profiling, torque, rotor speed, vibration**

## I. INTRODUCTION

THE proliferation of the 'more electric' concept in many areas of engineering is bringing about an increase in demand on greater reliability, increased power density and higher manufacturing efficiency of rotating electrical machines. To address this ever-growing demand for new and more 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 required by owners of the equipment or the 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. To do this effectively requires the use of sensors, indeed sensor systems, well suited to the demanding environment of the electrical machines in which they are to be placed. Conventional sensors are problematic in such environments, due to the limitations of space and the need to feed cables out from a rotating machine, as well as difficulties that may occur due to electromagnetic interference and short circuits. Further to this, due to the relatively large size of insulated conventional sensors, the resulting sensor system created from the use of a number of such sensors could potentially occupy a spatial envelope larger than the drive itself. New and better tailored solutions are needed and 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 an approach takes full advantage of the fibre sensors' reduced spatial envelope and immunity to electromagnetic interference, critically important for this particular application.

One of the first efforts made in the direction of introducing an optical fibre sensor development for motor and drive applications was to exploit Rayleigh backscattering in conjunction with a fibre having its outer cladding modified at intervals to create a quasi-distributed temperature measurement system using an optical time domain reflectometry (OTDR) approach [1]. Since then different optical sensing techniques have been applied to monitoring a number of key motor parameters: end-winding vibratory behaviour [2], stator housing vibration [3], thermal effects [4-7] and torque [8,9], for instance. In a previous report, the authors introduced a successful stator wave and rotor speed tracking system based on Fibre Bragg Grating-based (FBG) sensors [10].

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This work builds on the above and the prior work by the authors [11] with the aim to address all the above-mentioned parameters to create a multi-parameter sensor system which additionally allows for monitoring in real-time. This has been done by using an array of specifically located FBG-based sensor devices, responding to a single sensing interrogation unit: in that way simply and cost-effectively eliminating the need for individual sensor systems for each parameter and therefore significantly reducing the complexity of electrical machine condition monitoring, with no compromise on functionality. The 'all-in-one' sensor system thus designed and developed was tested in an important 'real world' application: on a permanent magnet-based alternating current (PMAC) machine prototype where the rotor's rare earth magnet temperatures are of particular interest as overheating causes demagnetization and therefore machine failure. In that way, the multi-parameter outputs from the incorporated sensor system can be used for effective performance monitoring and signalling of incipient failure. A key feature of the system is that it can be used while the motor is in operation due to the optical nature of the sensor 'read out', in a way that does not interfere with the operation of the motor.

The principles of operation and the design of the sensor layout is discussed next, followed by the results of a series of tests carried out, after which conclusions on performance and capability are drawn.

## II. PRINCIPLE OF OPERATION AND SENSOR LAYOUT

In this investigation, FBG-based sensors were designed and used to measure the different above-mentioned parameters which are of critical importance to the performance of the electrical machine. To do so an FBG-based approach is used for all the parameters monitored; here the 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 [12] and are exploited in this research. The FBGs used in this study were manufactured 'in-house' using the phase mask technique. Photosensitive fibre (Fibercore SM1500) was chosen and it was illuminated using an ATLEX 300-SI laser at 248 nm, after which the gratings were annealed at 180˚C for approximately four hours to stabilize their performance. The reflectivity of the FBGs is ~25%, with a full-width half-maximum of ~300pm.

In order to evaluate the 'all-in-one' sensing concept which forms the basis of the sensor system, a PMAC machine was instrumented with a total of 48 FBGs, which formed different sensors which were placed at known, specific locations within the motor to allow key parameters at those locations to be monitored.

In the multi-parameter approach used, the principle exploited to measure vibrations, the rotor speed and, the stator wave frequency and the spinning direction were based on the spatial modulation of the air-gap flux in the stator core of the electrical machine [10]. The resulting stator tooth displacement could be measured in the form of strain by placing an FBG between adjacent stator teeth, as is schematically depicted in Fig. 1(a). In this investigation 12 FBGs were circumferentially mounted between every stator tooth pair (Fig. 1(b)). Since the machine is fully enclosed, the FBGs do not require any further packaging or protection, and were left bare. The signals received at the sensor interrogation system from any two of those FBGs can be used to determine the rotor's spinning direction, as will be discussed in Section III. The stator bore was instrumented with twelve sensors for redundancy reasons to allow for any problems that may occur with the measurement using any particular pair of sensors, given the ease with which FBG-based sensors can be written in the optical fibre used.

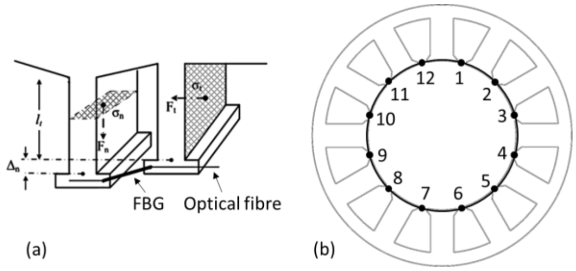

Fig. 1. (a) Schematic illustration of an FBG positioned between two stator teeth in an electrical machine used to detect tooth displacement. (b) Locations of the 12 circumferentially mounted FBGs used to measure stator vibrations and teeth elongations.

The stator windings were then instrumented with 24 FBG-based sensors to monitor the temperature distribution of the windings. The FBGs were distributed along the stator slots (two per slot) using two fibres, installed so that each meandered between every other stator slot, as is shown schematically in Fig. 2. Taking a view from the non-drive end (NDE) of the machine (as seen from Fig. 2(a)), the fibres were routed from the start point (S) toward the drive end (DE), looped around (broken line) skipping on stator slot to avoid very small bending radii, routed back to the non-drive end, looped around (solid line) and so on. The crosses and circles indicate the routing direction, i.e., a cross means 'away from the NDE' and a circle means 'toward the NDE'. The sensor locations are highlighted by white arrows in Fig. 2(b).

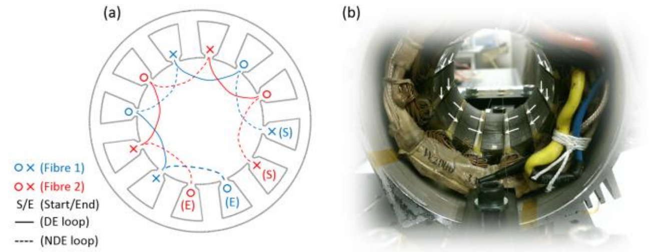

Fig. 2. (a) Fibre routing along the stator slots as seen from the machine's non-drive end (NDE). (b) Photograph of instrumented stator with two FBGs per stator slot (white arrows) for end winding temperature monitoring.

The method employed to measure torque was based on a differential wavelength approach where two FBGs were attached to the rotor shaft at an angle of ±45° with respect to the spinning axis [8,9]. In this configuration, the difference between the two FBG reflection peak wavelengths was used as a measure for torque, whereas the measurement at their mid-point was an indicator for the temperature at that location (Fig. 3).

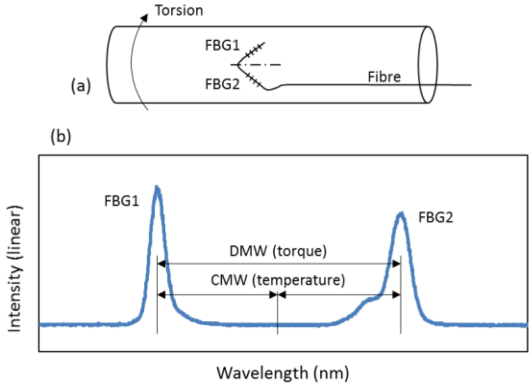

Fig. 3. (a) Torque measurement principle, i.e., two FBGs mounted on the rotor shaft surface at an angle of ±45° with respect to the shaft axis. (b) Exemplary reflection peaks of the two FBGs in (a). The differential mode wavelength (DMW, midpoint) relates to torque whereas the common mode wavelength (CMW, mid-point) changes with temperature.

The rotor was then instrumented with 12 FBGs on one fibre (Fig. 4), two of which are used to measure torque (as highlighted above) and the other ten to measure the magnet temperatures (using one FBG per magnet). The rotor sensors were interrogated through the use of a fibre-optic rotary joint (Princetel MJX series) attached to the non-drive end of the motor (Fig. 5) which allows for continuous conditioning monitoring while the rotor is spinning. This aspect is particularly valuable.

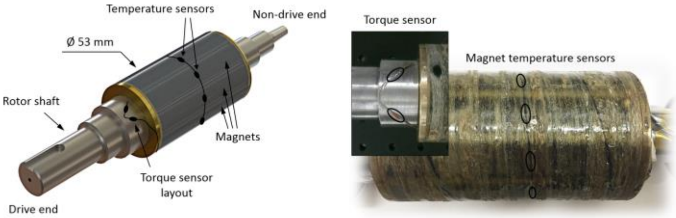

Fig. 4. Rotor layout. Twelve FBGs on one fibre were used to measure torque and the magnet temperatures.

All the FBGs used were fixed bare onto the respective surfaces using a two-component, high-temperature impregnation resin (Elantas Epoxylite® 235SG). This was done as the fibre would be protected when installed within the motor housing.

## III. Results and Discussion

The fully instrumented PMAC motor, with the sensors configured as discussed above, is shown in Fig. 5. All the sensors are confined *within the machine* with the only external component required being the rotary joint to allow the sensor system readout. The motor was subsequently evaluated on a full-scale test bench (Fig. 6) to assess the performance of the instrumented system.

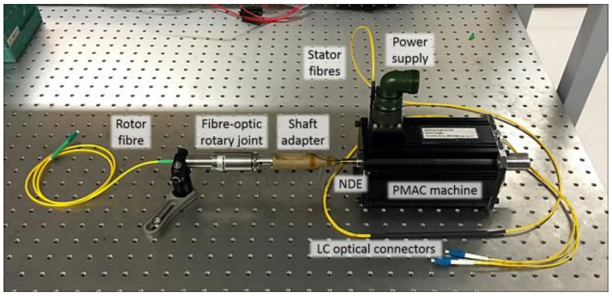

Fig. 5. Instrumented 2 kW, 2000 rpm PMAC machine showing the key components of the system.

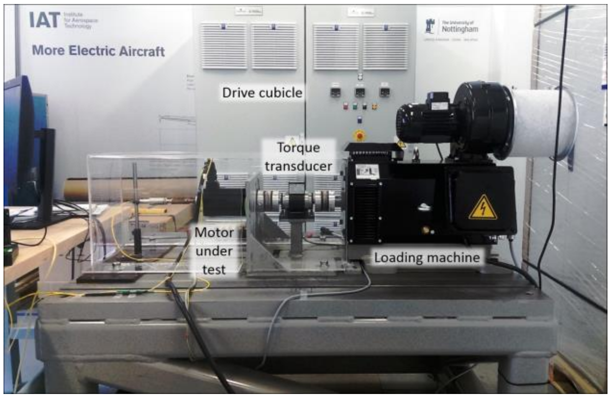

Fig. 6. Full-scale motor test bench installed at the Aerospace Technology Centre, University of Nottingham, UK.

An important feature of the sensor system is that the dynamic Bragg wavelength shifts of *all 48* FBGs were captured simultaneously using a Micron Optics SM130 sensing interrogator unit, at a high sampling rate, suited to the rotation conditions of the motor, of 2000 Hz. The DC components of the transient signals were used for thermal analysis (and torque) monitoring, whereas the AC components were used to determine the dynamic parameters, i.e., rotor speed, vibration, and spinning direction. In that way data on multiple parameters could be obtained simultaneously.

Fig. 7 shows the frequency response of one of the circumferentially mounted FBG-based sensors with the machine spinning at 16.7 Hz, under no load. For the chosen FFT window length of one second, the frequency resolution is one hertz. The first spectral feature recorded at 16.7 Hz represents the rotor speed (the mechanical frequency) and the main feature at 167 Hz corresponds to the stator wave frequency (the electrical frequency). Either of the two can be used to extract the rotor speed and convert it to the industry-standard rotations per minute (rpm). Other vibrational information, as evident from Fig. 7, gives machine developers and engineers important insights into the vibratory behaviour of a machine’s design, when driven at different loads. Since vibrations are also an early indicator for impending machine failure, the constant monitoring of vibrations is of significant importance for environments where increased reliability is required.

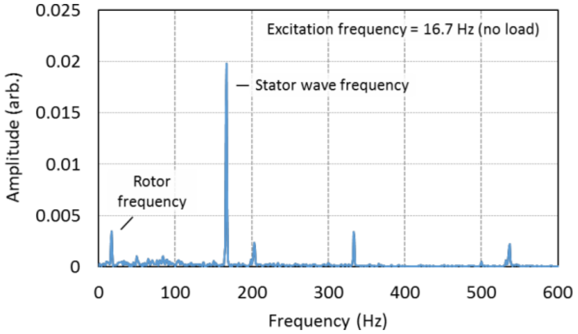

Fig. 7. Frequency response of one of the circumferentially mounted FBGs in the case of a spinning rotor under no load.

Fig. 8 shows the rotor speed information obtained from the FBG sensor data, monitored against an externally mounted reference sensor (Magtrol TMHS 311/111) – here the rotor speed was varied between 0 rpm and approximately 550 rpm. It is clear from Fig. 8 that the information obtained from the use of the FBG approach very closely matches the reference sensor signal – but at a much-improved signal-to-noise ratio. Thus, through this system effective data on this key parameter can be obtained using a sensor system integrated into the motor itself.

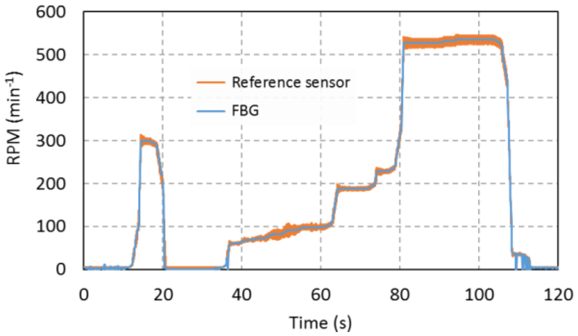

Fig. 8. Rotor speed transients vs time obtained from the FBG sensor and from a reference sensor.

Fig. 9 shows the dynamic responses of three of the circumferentially mounted FBG-based sensors, highlighting the phase shift between them for both the positive and the negative spinning direction. It is clear from Fig. 9 that the phase shifts in the two plots are reversed, as would be expected. The phase shift between any two of those FBGs then can be used to determine the spinning direction of the rotor, a positive phase shift indicating rotation in one direction and a negative phase shift rotation in the other direction.

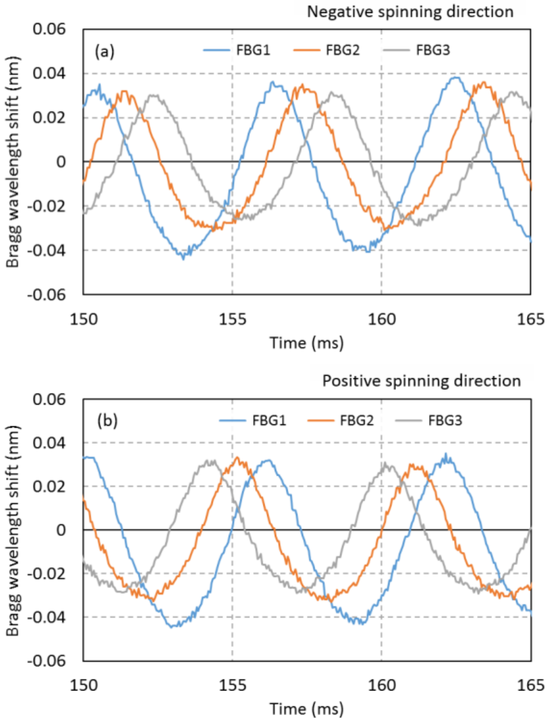

Fig. 9. Examples of phase shifts of three of the circumferentially mounted FBGs for both the negative (a) and the positive (b) spinning direction.

Fig. 10 shows further data obtained from the sensor system in the torque calibration curve, i.e., differential mode wavelength (FBG peak distance) versus torque with a linear relationship between the two parameters. 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 by using the torque-independent mid-point wavelength as an indicator of the temperature.

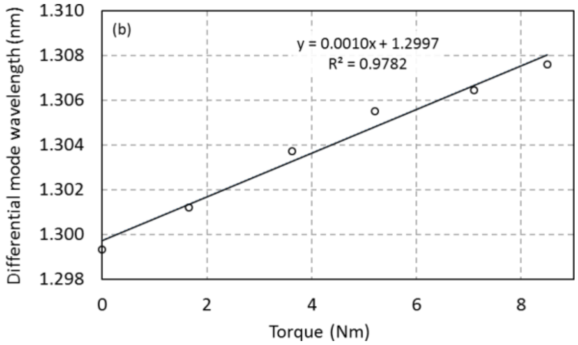

Fig. 10. Torque calibration curve of the PMAC machine under test.

The thermal profiling of the stator windings (using 24 FBGs), rotor magnets (using 10 FBGs) and rotor shaft (using 2 FBGs) is illustrated in Fig. 11. The Machine was driven at incremental loads of up to 8.5Nm for approximately 25 minutes, to generate a ‘rapid’ temperature increase, before the load was reduced to zero to monitor the cooling process. Developing a more detailed understanding of the thermal behaviour (with regard to the machine design) is beyond the scope of this investigation, which is a feasibility study (and will be published elsewhere).

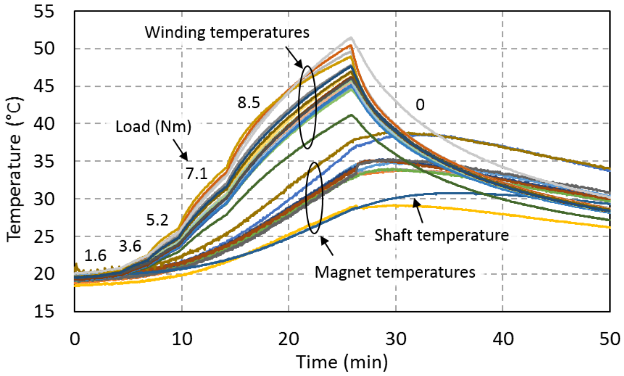

Fig. 11. Thermal profiling of the rotor (12 FBGs) and the stator windings (24 FBGs) under increased load conditions.

In order conveniently to illustrate the thermal profiling, the FBG sensor locations were mapped onto 3-D surface models of both rotor and stator (as can be seen from Fig. 12). This way, hot-spot visual identification is made possible. For the purpose of validating the mapping algorithm, the sensor data in Fig. 11 were simulated to achieve large temperature gradients across the surface which, in practise, only occurs in case of a machine fault – an important monitoring consideration.

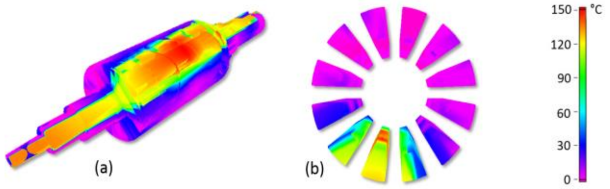

Fig. 12. Thermal profiling of the rotor (a) and the stator windings (b) by means of 3-D sensor mapping. The data in the plot is simulated to highlight possible hot-spot detection.

Taking the data from the above together, the proposed all-in-one sensor system can be seen to offer 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 aircraft or in power stations. The increasing emphasis on electrical vehicles provides another situation where such sensor systems could be used effectively.

## IV. CONCLUSIONS

A multi-parameter, multi-sensor system for comprehensive electrical machine condition monitoring has been developed and the results of an evaluation carried out have been reported. The FBG-based system developed has allowed for the simultaneous monitoring of key parameters including machine vibration, rotor speed, torque, spinning direction, temperature distribution along the stator windings and on the rotor surface as well as the stator wave frequency. Thus, 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.

This all-optical sensing solution has been designed to be compatible with being fitted in the tight confines of an electric motor and uses the optical nature of the measurement and the insulating nature of the sensor material to avoid problems of electrical interference. The 'all-in-one' sensor system discussed has the potential to replace conventional systems that require a separate sensor/system for each parameter to be monitored. In this way, this single optical fibre-based design 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 – this contrasts with the situation seen with the use of conventional sensors. Given the relatively high cost of optical sensing interrogation systems, the proposed sensor system is currently aimed at prototype diagnostics and evaluation (all presented data here are from a PMAC machine prototype), high-reliability applications where comprehensive machine monitoring is critical (e.g. electric motors on aircraft) as well as installations were the machine itself or the implicated cost of sudden failure would be vastly more expensive than the sensor system (e.g. large power generators in power plants or wind turbines).

Future work to develop this scheme further will focus on the implementation of an active feedback control system using the sensor data to control the speed of an electrical machine, operating under different load conditions for example. Given that FBG-based sensor systems can be operated effectively at significantly elevated temperatures [13,14], the system has potential to be used where higher temperatures are experienced, using an appropriate design of FBG-based optical fibre.

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She is currently the Director of the Research Centre of Sensors and Instrumentation and is leading a research team focused on developing a range of optical fibre sensors for a variety of industrial applications, including structural condition monitoring, early fire detection, homeland security, process monitoring, food quality and environmental monitoring. She has been working closely with partners across disciplines from academia and industry, both in the UK and overseas.

Prof. Sun is a member of the Institute of Physics and a Fellow of the Institution of Engineering and Technology and a Chartered Physicist and a Chartered Engineer in the United Kingdom. She has authored or co-authored some 230 scientific and technical papers.

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His research interests have expanded to include the use of fibre optic and optical systems in the measurement of a range of physical and chemical parameters for industrial applications. He obtained a DSc from City University in 1992 for his work in sensor systems was President of the Institute of Measurement and Control during the year 2000. He was awarded the Callendar Medal and the Honeywell Prize of the Institute of Measurement and Control and was Dean of the School of Engineering & Mathematical Sciences and the School of Informatics at City University from 2008-12. He was appointed Dean of the City Graduate School in 2012.

He was elected a Fellow of the Royal Academy of Engineering in 2008. He is the author of over seven hundred publications in major international journals and conferences and is the co-editor of a five volume topical series on Optical Fibre Sensor Technology.