FBG-T Sensor for Non-intrusive Broken Rotor Fault Severity Detection in Induction Machines

Belema P. Alalibo
School of Engineering & Applied Sciences, Aston University, Birmingham, UK
alalibob@aston.ac.uk

Wen-ping Cao
School of Engineering & Applied Sciences, Aston University, Birmingham, UK
w.p.cao@aston.ac.uk

Bing Ji
School of Engineering, University of Leicester, Leicester, UK
bing.ji@le.ac.uk

A. Gbadebo
SPI Lasers, Rugby, UK
adenowo.gbadebo@lexican.com.ng

K. Zhou
Aston Institute of Photonics Technologies, Aston University, Birmingham, UK
k.zhou@aston.ac.uk

ABSTRACT

Fiber bragg gratings (FBG) as optical sensors continue to gain increasing relevance in sensing and instrumentation owing to their numerous advantages including immunity to electromagnetic interference (EMI). This paper experiments on the use of a giant magnetostrictive material, Terfenol-D bonded to an FBG hereafter called FBG-T to detect external flux from electrical machines in a non-invasive manner. A DC motor and two identically rated three phase induction motors, FBG-T were used for rotor cage damage detection in this work. Further damage to the faulty rotor was carried out to observe if the FBG-T would distinguish severity in machine fault condition. Results show that the more severely faulted machine experienced the most Braggshift of about 20pm more than the healthy machine at 5Hz, compared to the less severely faulted machine which showed about 15pm more than the healthy machine. Another striking observation was the consistency in the distinct and deviant path followed by both faulty motor conditions when compared to the healthy motor. The more severe the rotor damage fault was, the larger the divergence from the healthy motor signature. The results do show that the faulty machine with the broken rotor consistently recorded more Braggshifts than the healthy motor at all frequencies. This resulted in a distinct and aberrant sensing profile which detects the fault in a non-intrusive manner. In addition to observed bragg shifts, divergence levels in grating profile from the healthy reference condition was used to succinctly detect the fault severity in the induction motor condition. This is hugely significant because of the non-intrusive nature of the technique given the ease-of-breakage and the challenges faced when FBG installed in machine stator slots are to be replaced. This technique easily overcomes the inevitable requirements of the offline FBG replacement and its associated economic costs including downtime.

Keywords

external flux, terfenol-D, non-invasive, severity, divergence, condition monitoring, FBG, induction motor, fault.

1. INTRODUCTION

GLOBAL carbon emissions reduction would require a colossal dependence on the use of electric machines where practicably possible such as in electric transport (cars, rails, ships, etc.). This undoubtedly means that electric machines must be reliable and rugged to meet the expected technological and environmental challenges alike. Real time condition monitoring and early fault detection of these electrical machines is thus more crucial than ever if an almost bump-less transition to net zero-based earth is to be realised. This is also important in terms of boosting man's confidence in the reliability and user-friendliness of these electric machines. Common techniques available for real time condition monitoring of machines include vibration spectral analysis (VSA), motor current spectral analysis (MCSA), Magnetic flux spectral analysis (MFSA), temperature and thermographic analysis (TA). Parameters sensed and constantly monitored depending on which technique is implemented include electric current, vibration, magnetic flux and temperature. Optical fibre sensors are now being increasingly used too especially in electrical engineering field. The use of optical fibre sensors is mainly due to the numerous merits it offers including its immunity to EMI. Fibre Bragg Gratings (FBG) are the commonest optical sensor used in electrical machine condition monitoring and fault detection hitherto. Based on works from [1-6] there are recent suggestions that FBG does possess encouraging potential for sensing applications in non-permanent magnet machines especially, induction machine and hydro generators. Applications in power electronics modules, multipoint voltage sensing and machine mechanical parameter monitoring such as bearings [7-12] have also been reported. FBG sensing is based on the variation of the refractive indices of the fibre core and cladding due to variations in some sensed parameter. This causes the light's centre wavelength to shift in a proportionate amount to the sensed parameter, the shift is called Bragg shift. FBG sensing is very commonly used for vibration and temperature sensing because of its reliability and sensitivity to both parameters with changing refractive indices. However, this advantage which makes it easy for FBG to sense either parameter also makes it difficult to distinguish between them, hence the issue of cross-sensitivity remains and usually needs to be compensated for depending on the accuracy required in the sensing application. In [13], ABB highlighted several merits of optical sensors; amongst which its immunity to electromagnetic interference (EMI) and multiplexing apability stand out. Experiments are being conducted on the use of FBG for monitoring machines' vibration (as strain) and temperature, due to thermo-optic effect [15-17]. [18, 19] reported the sensing of other parameters such as torque, magnetic flux, direction of rotation in their work on multi-parameter sensing which uses FBG multiplexing and sensing capabilities. Specific fault detection applications in the areas of hot spot monitoring, broken rotor bar (BRB) and winding faults are being investigated. For non-strain and/or non-temperature sensing, a transducer may be required to be bonded onto the FBG in order to function as a transducer/sensor unit. This is the case with magnetic flux sensing where FBG on its own cannot sense electromagnetic fields.

To expand the use of FBGs as sensors in order to maximise their benefits often depend on the number and quality of bonding [21, 22]. FBGs rely on adhesives as the medium of transfer for any sensed parameter between the machine and the grating [22]. Differential optical power (DOP) offers a complementary metric for feature extraction when using FBG optical sensor [22] but this is largely dependent on the availability of a tightly-controlled environment where external factors will not interfere with the optical power. Thus, considering the requirement of harsh but clean environmental conditions required for operating electric machines, DOP would not be used here as a complementary signature.

Two main ways to use optical fibre sensors to sense magnetic fields: the use of FBG with a transducer or uses left and right circularly polarised lights to sense magnetic field strength (called the Faraday's magneto-optic effect). The latter method is rarely use possibly because of the number of components required. Only ABB has commercially implemented the latter sensing principle hitherto. With FBG mostly used, the bonding of the sensor to some transducer is inevitable for magnetic field sensing. However each bonding point is still a potential point of failure and as such should be minimised or avoided where practicable, when utilising FBG as sensors in electric machines. In order to reduce the number of bonding points, the need for a non-intrusive condition monitoring of electric machines is necessary. As the number of bonding points increase, the level of attenuation should be closely monitored up to an optimum number to ensure signal-to-noise ratio (SNR) is still high enough for accurate sensing [22]. [2] reported applications where FBG based in-situ flux sensing implemented invasively may be impractical for large scale use. One reason is the nature of conventional radial flux design motor geometries which, in combination with the anisotropical behaviour of GMMs, impose significant space constraints for application of FBG/GMM based in-situ flux sensing [3]. However, electric machine external flux (EMEF) allows for the non-intrusive option in machine condition monitoring and has been advocated for recently by [23]. EMEF is the magnetic flux leaking out of the machine cast frame or yoke. It can be detected and set as the indicator to distinguish between faulty and healthy machines [24]. EMEF combined with FBG allows for non-intrusive monitoring whilst employing the simple Bragg shift optical option. Since terfenol-D has inherent high sensitivity it does not require a very strong field to cause a strain on FBG. Conversely, a very strong magnetic field could potentially saturate the terfenol-D as they only require a small to intermediate magnetic flux to expand or contract. Magnetostriction from terfenol-D is usually so small that highly sensitive and very small-length-measuring devices are required. This makes optics a worthy option to complement detection of nano- and pico-scaled distance movements, which are observed as Braggshifts in FBG spectral profiles.

2. FBG with Terfenol-D (FBG-T) Sensing

FBG sensing is fundamentally based on wavelength shifts also known as 'Bragg shifts'. The principle is such that when light is transmitted through the core of an optical fibre cable, it gets reflected once it strikes the sensing part of the cable called 'Fibre Bragg gratings' or FBG which are inscribed within the fibre to deliberately introduce changes to the refractive index of the fibre core [25]. This phenomenon causes the FBG to have a unique spectrum with a nominal centre wavelength called 'Bragg wavelength'. When the light comes in contact with some external influence, typically strain or temperature, the Bragg wavelength would shift proportionate to on the strength of the external influence being sensed resulting in Bragg shifts. The relationship between the Bragg wavelength (λ_B), the periodicity of the grating (Λ) and the effective refractive index of the fibre determined by the average of the refractive index of the fibre core and the refractive index of the fibre cladding n_{eff} is given by

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

Most external influences sensed by FBG optical sensors vary in nature but are usually transduced into either strain or temperature in order to utilise the FBG for sensing. These are respectively known as photo-elastic (strain) and thermo-optic (temperature) effects. Thus, these two effects are the two known factors that directly cause Bragg shifts in FBG sensing techniques. Other forms of FBG sensing typically require some form of bonding in order to proportionately transfer any external influence being transduced into strain and/or temperature to the optical sensor. As explained in [22], when an FBG bonded to some host structure is subjected to either a mechanical and/or a thermal agitation; this manifests as strain on the gratings resulting in shift in wavelength. The amount of shift corresponds to how much strain such agitation causes. An immanent problem with FBG sensing is its cross sensitivity between strain and temperature which, if not compensated for, could affect sensor reliability and accuracy [26]. In reality, it is difficult to ideally separate the impact of kinetic or vibrational impact from thermal impact as both phenomena intrinsically affect each other from molecular physics theories. The relationship between strain and temperature is given by:

$$\frac{\Delta\lambda_B}{\lambda_B} = (1 - \rho_e)\varepsilon_z + (\alpha + n)\Delta T \tag{2}$$

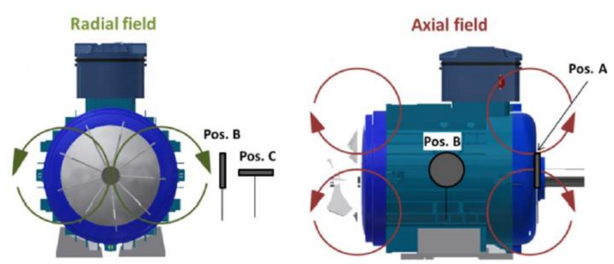
where ρ_e is photo-elastic coefficient; ε_z is the longitudinal strain of the grating; $\boldsymbol{\alpha}$ is thermal expansion of optical fibre material; and n is thermo-optic coefficient.

Non-intrusive condition monitoring is preferred with the FBG avoiding contact with the electric machine to reduce impact of any vibration which may be within acceptable limits for machine operations. In order to use the EMEF, the FBG has to be bonded to some transducer, in this case, Terfenol-D owing to the immune nature of optical fibre sensors to electromagnetic fields. The Terfenol-D being a giant magnetostrictive material would transduce the magnetic flux into strain which is then transferred on to the FBG sensor resulting in Bragg shifts. The composite sensor, called FBG-T thus, is able to detect magnetic flux, to which hitherto, the FBG will be immune to.

The sensing principle of the composite sensor is thus, based on magnetostriction. Developed in the 1970s by the US Naval Ordnance Laboratory, terfenol-D ($Tb_xD_{1-x}Fe_y,\ where\ yy \approx 2.0\ and\ x \approx 0.3$) boasts as one of the alloys which exhibit the largest known levels of magnetostrictive expansion or contraction at room temperature. It is currently commercially available in a variety of different forms, including thin slices, powder composites and monolith solid samples [2], [28]. Terfenol-D transduces magnetic flux into strain as change in length due to realignment of its internal atomic particles. This strain is then transferred via bonding on to the gratings which in turn cause Bragg shifts proportional to the strain sensed from the Terfenol-D. In other words, as EMEF emerges out of the machine yoke, then comes in contact with the Terfenol-D to which the FBG is bonded. Terfenol-D alters its length in response to the EMEF causing a strain of the gratings on the fibre; which then causes shifts in wavelength proportionate to the strain transduced by the terfenol-D alloy. Bragg shifts are recorded and analysed as changes in FBG spectral profile on an optical spectrum analyser. FBG-T thus combines the FBG inherent strain sensing feature with high magnetostriction properties of Terfenol-D material [27-29]. With the use of EMEF, FBG-T measurements are not affected by cross sensitivity provided the external temperature where the sensor is used is regulated or the sensor is packaged in a well-insulated thermally-resistant environment which is easy to achieve. However, Terfenol-D exhibits some characteristics that are worthy of note if results from their use are to be meaningful. Magnetostrictve transduction of terfenol-D shows unipolar characteristics regardless of the magnetic field direction they come in contact with [30]. This means they may contract or expand when exposed to positive and negative magnetic flux lines. Thus during calibration their behavioural response to the given magnetic field must be fathomed prior to their installation. In other words, their use as FBG-T sensors has to be carefully studied initially and reference features defined prior to in-service condition monitoring and feature extraction purposes. Once their behaviour in the specific application of use is known, then aberration from initially observed behaviour can be used as fault signature. Also, Terfenol-D strain response to magnetic flux is highly non-linear and does not only depend on the magnetic field strength, but also on its pre-stress level i.e. the state of orientation of its atomic structure just before it senses the magnetic field [31]. Measurements taken within short intervals thus, may be variable even when procedures are repeated, depending on the pre-stress orientation of atoms within the Terfenol-D alloy. A major factor that makes FBG-T well suited for non-intrusive EMEF sensing is that Terfenol-D's change in length is said to be generally approximately proportional to the *square* of the magnetic field it is subjected to. This means only a reasonable amount of flux is required for FBG-T sensing which makes the EMEF an excellent source of non-invasive feature extraction. This non-intrusive option takes better advantage of the use of FBG as optical sensors by minimising the number of bonding points required per application as well as significantly mitigate the in-borne cross sensitivity issue due to machine vibration. It is worth mentioning that main air gap flux has been used in [31] where, though physically intrusive, the underpinning sensing principle of directly exposing the composite sensor to magnetic excitation from a permanent magnet synchronous machine, was followed.

3. GMR versus FBG-T Stray Flux Sensing Techniques

The use of giant magnetostrictive materials (GMM) have proved extremely useful for condition monitoring owing to their high sensitivity and resolution especially in sensing even very small magnetic fields [32, 33]. Common sensors built with GMM are based on giant magnetoresistive (GMR) sensing which is in turn based on the change in electrical resistance depending on whether the magnetization of adjacent ferromagnetic layers are in parallel or an antiparallel alignment [32]. GMR effect has been used in several applications such as non-destructive testing, inspection of cracks in metal plate structures, bearings, rails and even in biosensing [33]. GMR sensing has also been utilised for stray flux sensing in [24, 34-35] for fault detection in machines. However, when compared to FBG-T stray flux sensing, two main advantages of the latter over GMR stand out. First, GMR effect is such that the output resistive signal is linearly proportional to the stray field [36] whereas for FBG-T, the magnetostrictive effect of terfenol-D is proportional to the square of the stray field. This translates into even higher sensitivity for FBG-T compared to GMR sensors. Secondly, resistance is translates into heat (I2R) which means during signal processing some of the output will be lost as heat compared to FBG-T which avoids transducing its output to resistance, thus will not have this issue. The output of GMR (resistance) during signal processing remains susceptible to electromagnetic interference (EMI) since current is affected by EMI. In other words, GMR has first and second order susceptibility to EMI during its entire transduction process whereas FBG-T boasts of only a first order susceptibility since its secondary sensing is utterly immune to EMI. However, both GMR and FBG-T require signal processing instruments to retrieve sensed information; and both sensors are excellent performers in low magnetic field applications hence are suitable for stray flux condition monitoring of electrical machines. Both GMR and FBG-T sensors can be positioned either radially or axially depending on application and how the magnetic flux is expected to cut across or through the sensor [37] as shown in Fig.2. An important caveat in the use of FBG-T for condition monitoring is that the sensor should be positioned in approximately same location for both healthy and faulty machines for



a).

b).

Fig.2: a) GMR and FBG-T possible sensor positions [33] b). Set up showing GMR stray flux sensing in radial sensor position [24]

TABLE I

DC MOTOR AVERAGE MEASUREMENTS

Voltage (V)	Current (A)	RMS Flux density (mT)	Temperature (°C)
11.59	5.175	0.3803	23.7
8.7	4.238	0.2674	22.6
7	3.687	0.2344	21.8
5.5	3.127	0.1806	21.1
4	2.558	0.1145	20.9

accurate reference and/or calibration. One major hurdle overcome by this non-invasive FBG-T method in comparison to other FBG sensing techniques is that there is a reduced requirement for the protection of the optical fibre due to its brittleness when installed external to the machine.

4. Experimental Set Up For FBG-T EMEF Sensing

This experiment uses three electric machines viz: a 12V DC motor, and two identical 2.2kW three phase AC induction motors (IMs) driven by a variable frequency drive (VFD). The FBG was bonded onto the terfenol-D using a high viscosity, ethyl-based instant adhesive, Loctite 416, to realise the composite FBG-T optical sensor. Loctite 416 was used as the adhesive because of its suitability for metals and alloys and it has a flash point of 80-93^{o}C which is rarely reached in environments were most industrial machines operate. On the contrary, intrusive FBG methods would require suitable adhesives with much higher flash points since machines' internal operating temperature is usually much higher and varies with loading. This is to avoid weakening of the bonding due to reduced viscosity which will in turn affect sensor performance

The FBG-T is then inserted into a clear acrylic tube which is insensitive to magnetic flux. This was confirmed using a fluxmeter. The FBG-T-in-tube sensor was then positioned axially at the drive

(DE) so that the axial flux can cut maximally through the terfenol-D alloy (see Pos.A in Fig.2a). [37] did highlight two modes of EMEF: radial and axial stray fluxes and the sensor position determines which of the modes is more effective for feature extraction. The decision to locate the FBG-T sensor at the DE of the machine yoke was to ensure the sensor was in close proximity with the main air gap, thus further reduce any magnetic leakage present. Terfenol-D rods manufactured by TdVib LLC, USA, each of cylindrical geometry, 6mm in diameter and 26mm in length were used in this work. Table 1 shows measurements taken when FBG-T sensor was installed on the DC motor. Instantaneous measurements of temperature and magnetic flux density were taken every 10 minutes with their root mean square (RMS) and average temperature per voltage level hown respectively. Temperature was measured mainly because of the non-linear and thermal behaviour of Terfenol-D. As observed, room temperature was largely constant with negligible variations especially during the nights. Experimental set up of the FBG-T DC Motor condition monitoring is as shown in Fig. 3a. The FBG-T sensor is then connected to a dual function Hewlett Packard (HP) optical spectrum analyser (OSA) which

TABLE 2

AC INDUCTION MOTOR AVERAGE MEASUREMENTS

RMS Flux density (mT) – healthy IM	RMS Flux density (mT) – faulty IM	Frequency (Hz)	Temperature (°C)
0.0729	0.0581	10	19.6
0.1624	0.1536	20	19.4
0.2142	0.1969	30	18.9
0.2382	0.2342	40	19.9
0.2534	0.2474	50	19.0

comes with a broadband light source. A National Instrument GPIB-USB-HS adapter was used to acquire numerical data from the OSA via a LabView graphical user interface (GUI) on a Windows 7 computer. Data are then exported into MATLAB environment for further analysis and interpretation.

Two identical AC three phase induction motors, with the same specification and manufactured by the same manufacturer, WEG Industries were also experimented using FBG-T (Fig.3b). Both machines have two different health conditions: one machine was healthy, the other faulty. FBG-T sensor was inserted in the acrylic tube and positioned at the drive end of the induction motors (IMs), each in turn. Each induction motor was connected to a variable frequency drive (VFD) and then used to drive a DC motor. [38] created finite element model of a healthy and a faulty IM with broken rotor bar

a).

b).

Fig.3 Laboratory set up for non-intrusive FBG-T induction machine sensing a).DC machine b). Healthy and Faulty induction machines

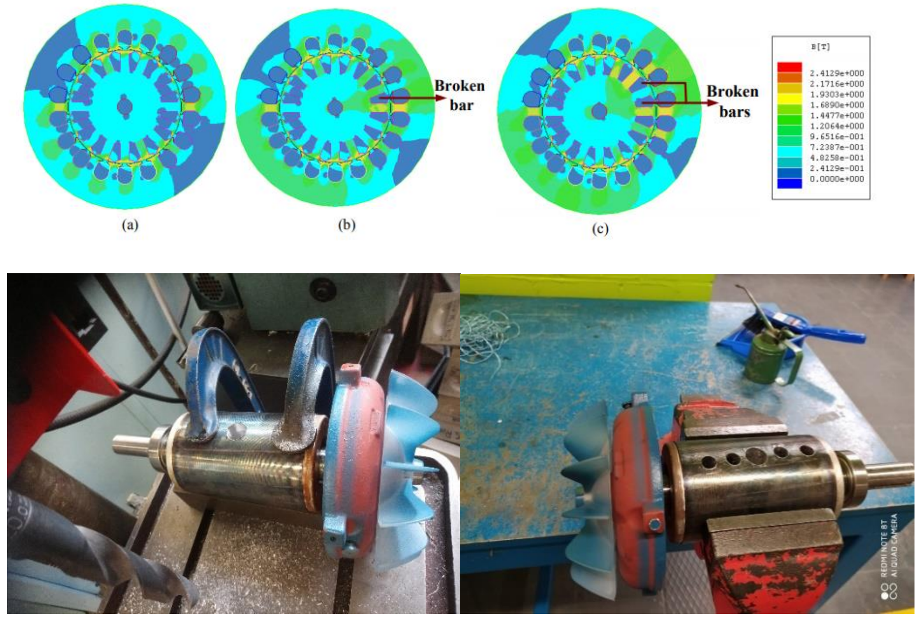


Fig.4. FE model of flux density distribution: a) healthy rotor cage b) one-broken bar fault c). continuous two broken bars [37] d)less severely damaged IM rotor e) more severely damaged rotor condition

identical to the one used is shown in fig.4a-c showing the associated magnetic flux density distribution. To distinguish between fault severities, the faulty motor was initially defected by boring a hole on its laminated rotor cage (Fig.4d). The motor was then reassembled and setup as in Fig 3b and tested with the FBG-T sensor alongside the healthy one. Measurements obtained for both induction motors at different frequencies are depicted in table 2. After measurements were taken, the IM was then disassembled and more holes bored on the laminated rotor cage to emulate a more severe faulty condition (Fig.4e). The faulty IM was again reassembled and setup as in Fig. 3b and tested with the FBG-T sensor with measurements taken during the tests under similar conditions as before.

5. Results and Discussion

When the variation of the magnetic flux density with maximum observable Braggshift was plotted for the DC motor, there was a near-linear trend. An identical observation was made with the variation of magnetic flux density with time for the same DC motor (Fig.5). This means that the magnitiude of the flux density cutting through the FBG-T sensor is directly related the amount of strain transferred to the sensor which translates into optical Braggshift. An important deduction from this observation is that the adhesive bonding has no significant effect on the FBG-T sensing performance. This is significant in itself because the use of FBG-T sensor relies largely on the effectiveness of the bonding between the terenol-D and the FBG. Fig.6 shows the spectral profile of a typical FBG and the Braggshift phenomenon i.e. how the FBG-T profile physically shifts in response to the

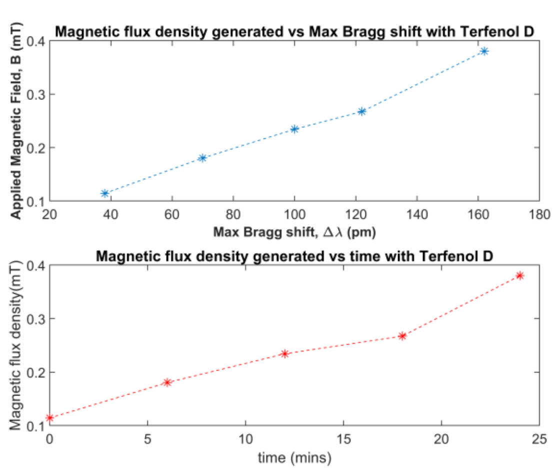


Fig.5. FBG-T wavelength changes as the external stray flux changes with frequency for a DC motor

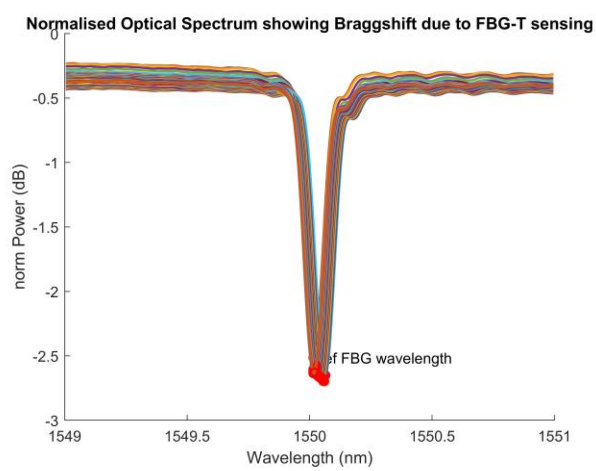


Fig.6. FBG-T spectrum showing Braggshift sensing principle using external flux from a healthy induction motor

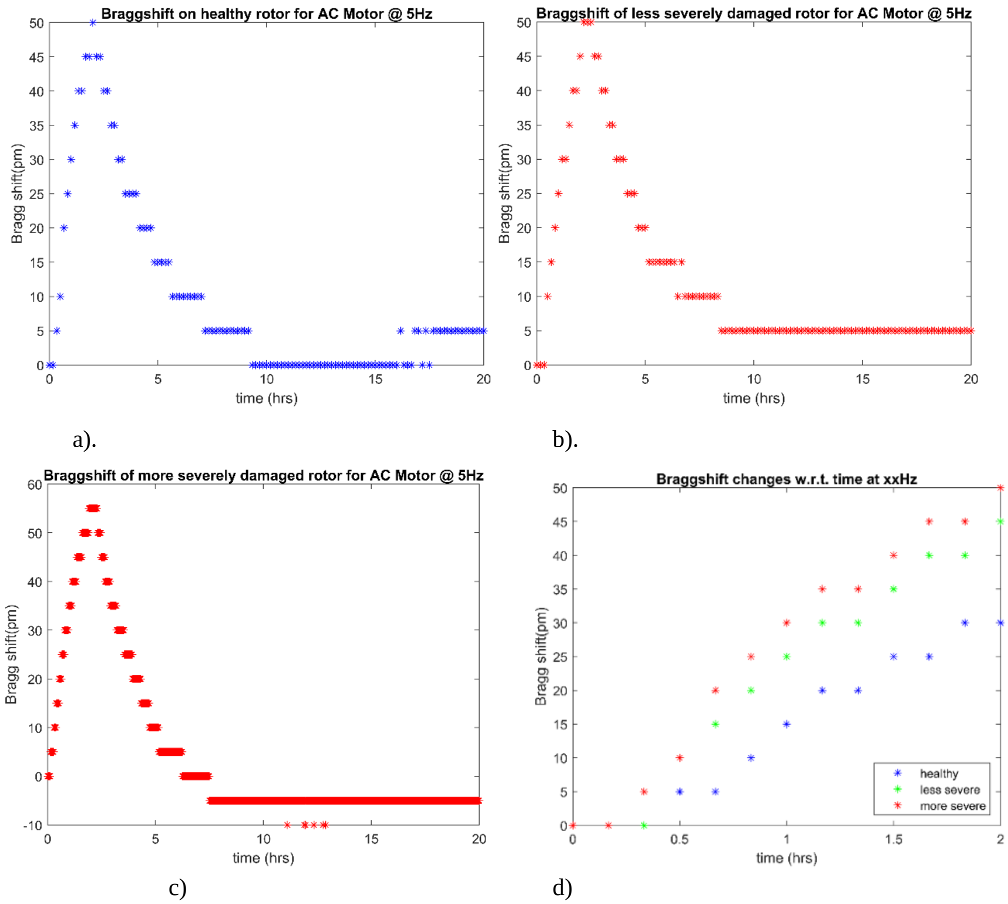


Fig.7. FBG-T change in wavelength with time for: a).healthy AC motor@5Hz b).less severe faulty AC motor@5Hz c). more severe faulty AC motor@5Hz d) Braggshift changes with respect to time for healthy, less severe and more severely faulted induction machine conditions@5Hz

sensed parameter in this case, the external magnetic flux or EMEF. of terfenol-D. The Braggshift was observed to occur provided the motor stayed on and once the motor is turned off, the profile then begins a return hysteresis path back to its original wavelength. The hysteresis observed was tolerable in the order of picometre (pm) which is a huge advantage for the sensor in terms of resolution. FBG-T measures in the picometre range thus can be used even for small magnetic flux such as the EMEF. More significantly is the fact that because the reference for each measurement is unique, the hysteresis does not affect the Braggshift caused by the EMEF. The implication of the hysteresis is simply that the reference will vary for each measurement hence should be taken each time before a new measurement is performed. For the IM, a similar response was observed as in the DC motor case where the variation of maximum Braggshift with time was near linear with the IMs switched on and driven by the VFD for about two hours (Fig.7a-c). The FBG-T spectrum was observed to shift until it settled at a specific wavelength. The EMEF variation at different frequencies produced these maximum Braggshifts, thus corroborating the direct proportionality between the EMEF and the maximum Braggshifts observed. This also means that the bonding has not adversely affected the FBG-T sensing just as before. While the observation confirms that the larger the Braggshift, the longer it will take the FBG-T sensor to reach such shift; it unarguably shows that the terfenol-D behaviour is impressed onto FBG sensor. This then means that provided the magnetic field strength is just enough to causes an observable magnetostriction and the bonding is effective enough, accurate and simple non-invasive condition monitoring can be realised.

After two hours, the IMs were turned off to observe the behavioural response of the FBG-T sensor. It was observed that in. the FBG-T tends to move further before it commences its reverse path to return to its initial reference wavelength just before the motor was turned on. Given the impact of the sudden loss of magnetic field excitation of the terfenol-D internal particles, they would have been possibly forced to realign into new natural positions which are not subject to any external field influence. During such realignment, further strain is sensed by the FBG-T due to the permeability of the terfenol-D alloy, resulting in further transient wavelength shifts just immediately after the loss of excitation (when the motor is turned off). After the passage of this transient occurrence, the magnetostrictive particles are then naturally forced to return back to their initial inertial state. The final wavelength after 18 hours per frequency trial was observed to be different and inconsistent due to hysteresis (Fig.7a-c). Pre-stress level of the magnetostrictive particles was another factor that was observed to influence the response time of the FBG-T sensor.

Measurements taken after a weekend tend to respond more slowly than the ones taken the next day but as mentioned earlier, this has not impacted on the maximum observable Braggshift, but only on the response time. For the healthy IM run at 5Hz for two hours and then turned off for 18hours, it was observed that the FBG-T sensor did return to its original wavelength after 10 hours and remained there for another 5 hours before then shifting to a new final wavelength which was 5pm more than its reference wavelength (Fig.7a). This was not the case for the less severely damaged motor where the FBG-T sensor did not return to its original wavelength but settled at a new wavelength of about original wavelength plus 5pm (Fig.7b). The more severely damaged motor after 18 hours of being turned off did briefly return to its initial wavelength but largely settled at a new wavelength like the less severely damaged condition. The new wavelength was also about 5pm more than the initial sensor wavelength (Fig.7c). As earlier mentioned, the picometre range for shifts and nanometer wavelength range may appear insignificant for this application; however, in other applications such as in electrical protection systems such sensing ranges could be significant for parameter detection and variation analysis. This is a huge advantage of fibre-optic sensors. No observable evidence of a correlation between the actual motor condition and the FBG-T's final wavelength. This hysteresis behaviour is seen as a corroboration of the widely agreed characteristic of terfenol-D which is inherent in the FBG-T sensor. However, the actual machine condition and its severity was observed to directly impact on the Braggshift as experimental results show. In Fig. 7d a normalisation of all three machine conditions was performed to observe the variation of Braggshift with time. It was evident that the FBG-T experienced different amount of wavelength shifts under all three conditions. Both faulty conditions were observed to have higher Braggshift and distinct aberrance from the health condition. The less severe faulty machine experienced about 15pm more shift than the healthy machine whilst the more severe faulty condition experienced about 20pm more shift than the healthy condition. The deviant paths followed by both faulty machines also distinctly show that the more severely faulted machine is further deviated from the healthy state compared to the less severely faulted case. This is hugely significant in that the FBG-T sensor is capable of distinctly identifies and classifies fault severity in addition to its sensing capability. Another interesting observation was the similarities in the step-wise Braggshifts that were observed under all three conditions. Although the path for each condition was clearly distinct, one could see from Fig.7d that the sensor was consistent in taking 5pm Braggshifts steps when creating the unique paths for each machine condition. This means better understanding of the sensor behaviour can better improve the characterization of the FBG-T sensor. While the non-linear profile depicts the hysteresis behaviour of the terfenol-D transducer, it means that this composite FBG-T sensor can produce reliable signatures for a given machine operating condition as well as classify any severity. The transduction of magnetic flux to strain and then optical wavelength shifts is not affected by the source of such a flux; whether it is the sensed from the main air gap or simply a stray non-invasive magnetic field.

6. Conclusion

This work has used an optical sensor FBG-T to measure the stray flux from electric machines and detect faulty conditions. It has also been used to distinguish between fault severities signatures in a non-intrusive condition monitoring set up. A DC motor was used to initially confirm that observable signatures can be observed by exposing the FBG-T to external magnetic field and measuring the spectrum using an optical spectrum analyser. Identical three phase 2.2kW induction machines were run under three conditions viz: healthy, less severe and more severe using a variable frequency drive (VFD). Even with the highly inherent non-linear characteristic of terfenol-D, there was consistency in the direct proportionality relationship observed when variation of the measured EMEF with maximum Bragg shift was compared with the time required to attain such wavelength shifts under all machine's conditions. Each of the observed patterns was significantly distinct when healthy and faulty conditions were juxtaposed; which is a promising and reliable feature extraction requirement for condition monitoring and fault detection techniques. In fact, the FBG-T sensor was able to distinguish between the less severely faulted motor condition and the more severely faulted condition which is a very promising supplementary sensor feature. Similarity in the FBG-T sensor behaviour when observed for over 20 hours under each machine condition proved that electric machine external flux (EMEF) is sufficient to reliably carryout non-intrusive condition monitoring. Undesired situations avoided by the use of this non-intrusive solution include: taking machine offline (out of service), machine disassembly and reassembly. However, the use of one terfenol-D per sensor limits the sensing to a point-based rather than a distributed sensing. With the current lack of standard on optimal GMR sensor positioning, the FBG-T used in this work offers a significant potential for non-invasive condition monitoring and fault severity detection of electrical machines.

REFERENCES

[1] A. Mohammed and S. Djurović, "Multiplexing FBG Thermal Sensing for Uniform/Uneven Thermal Variation Monitoring in In-service Electric Machines," *2019 IEEE 12th International Symposium on Diagnostics for Electrical Machines, Power Electronics and Drives (SDEMPED), Toulouse, France, 2019*, pp. 316-322.

[2] A. Mohammed et al., "Distributed Thermal Monitoring of Wind Turbine Power Electronic Modules Using FBG Sensing Technology," in *IEEE Sensors Journal*, 2020.

[3] A. Mohammed, J. I. Melecio and S. Djurović, "Electrical Machine Permanent Magnets Health Monitoring and Diagnosis Using an Air gap Magnetic Sensor," *IEEE Sensors Journal*, January 2020, pp. 99.

[4] A. Mohammed, J. I. Melecio and S. Djurović, "Stator Winding Fault Thermal Signature Monitoring and Analysis by In Situ FBG Sensors," in *IEEE Transactions on Industrial Electronics*, vol. 66, no. 10, pp. 8082-8092, Oct. 2019.

[5] ABB, "FOCS applications and benefits," 2014. [Online]. Available: http://new.abb.com/power-electronics/focs/applications-and-benefits. [Accessed: 23-Nov-2017].

[6] Ambrosino, S. Campopiano, A. Cutolo and A. Cusano, "Sensitivity Tuning in Terfenol-D Based Fiber Bragg Grating Magnetic Sensors," in *IEEE Sensors Journal*, vol. 8, no. 9, pp. 1519-1520, Sept. 2008.

[7] B. Mu et al., "Fiber Bragg Grating-Based Oil-Film Pressure Measurement in Journal Bearings," in *IEEE Transactions on Instrumentation and Measurement*, vol. 68, no. 5, pp. 1575-1581, May 2019.

[8] B. P. Alalibo, W.-P. Cao, A. Gbadebo, L. Aarniovuori, and K. Cai, "Investigation of the Effect of Bonding Points on Metal Surface-Mounted FBG Sensors for Electric Machines," *Progress In Electromagnetics Research C*, vol. 97, 255-265, 2019.

[9] Bieler, Geraldo, and Marcelo M. Werneck. "A magnetostrictive-fiber Bragg grating sensor for induction motor health monitoring." *Measurement* 122 (2018): 117-127.

[10] C. Jiang, S. Li and T. G. Habetler, "A review of condition monitoring of induction motors based on stray flux," *2017 IEEE Energy Conversion Congress and Exposition (ECCE)*, Cincinnati, OH, 2017, pp. 5424-5430.

[11] D. Davino, C. Visone, C. Ambrosino, S. Campopiano, A. Cusano and A. Cutolo, "Compensation of hysteresis in magnetic field sensors employing Fiber Bragg Grating and magneto-elastic materials", *Sensors and Acutators A*, vol. 147, pp. 127-136, 2008.

[12] D. Hind et al, “Use of optical fibres for multi-parameter monitoring in electrical AC machines,” in *2017 IEEE 11th International Symposium on Diagnostics for Electrical Machines, Power Electronics and Drives (SDEMPED)*, 2017, pp. 208–212.

[13] Fracarolli, João PV, et al. "Development and field trial of a FBG-based magnetic sensor for large hydrogenerators." *Fiber Optic Sensors and Applications XIII*. Vol. 9852. International Society for Optics and Photonics, 2016.

[14] G. Engdahl, Ed., Handbook of Giant Magnetostrictive Materials. New York: Academic, 2000.

[15] J. Antonino-Daviu, I. Zamudio-Ramírez, R. A. Osornio-Ríos, V. Fuster-Roig, R. de Jesús Romero-Troncoso and L. D. Dunai, "Stray Flux Analysis for the Detection of Rotor Failures in Wound Rotor Induction Motors," *IECON 2019 - 45th Annual Conference of the IEEE Industrial Electronics Society*, Lisbon, Portugal, 2019, pp. 3704-3709.

[16] J. D. Lopez et al., "Fiber-Optic Current Sensor Based on FBG and Optimized Magnetostrictive Composite," in *IEEE Photonics Technology Letters*, vol. 31, no. 24, pp. 1987-1990, 15 Dec.15, 2019.

[17] J. D. Lopez et al., "Fiber-Optic Current Sensor Based on FBG and Terfenol-D With Magnetic Flux Concentration for Enhanced Sensitivity and Linearity," in *IEEE Sensors Journal*, vol. 20, no. 7, pp. 3572-3578, 1 April1, 2020

[18] J. D. Pelegrin, U. J. Dreyer, C. Martelli and J. C. C. D. Silva, "Optical Fiber Sensor Encapsulated in Carbon Fiber Reinforced Polymer for Fault Detection in Rotating Electrical Machines," in *IEEE Sensors Journal,* May 2020.

[19] J. I. Melecio, A. Mohammed and S. Djurović, "Characterisation of FBG based Magnetic Field Sensor Response Sensitivity to Excitation Orientation for Rotating Electric Machine Applications," *2019 8th Mediterranean Conference on Embedded Computing (MECO)*, Budva, Montenegro, 2019, pp. 1-5. C.

[20] J. P. Bazzo, T. Lukasievicz, M. Vogt, V. De Oliveira, H. J. Kalinowski, and J. C. C. Da Silva, "Monitoring the junction temperature of an IGBT through direct measurement using a fiber Bragg grating," in *21st International Conference on Optical Fiber Sensors,* 2011, vol. 7753: International Society for Optics and Photonics, p. 77538Q.

[21] J.-l. Zhang, H. You, J. He, X.-j. Xin, and F. Tian, "A fiber bragg grating sensing system for monitoring IGBT temperature distribution and thermal conduction state of upper surface silicone," in *Optical Sensing and Imaging Technologies and Applications*, 2018, vol. 10846: International Society for Optics and Photonics, p. 1084616.

[22] K. B. Li et al., "Magnetization reversal and stray field of periodically magnetic dots detected by both MFM and GMR read head," *2005 IEEE International Magnetics Conference (INTERMAG)*, Nagoya, 2005, pp. 703-704.

[23] K. N. Gyftakis and A. J. Marques Cardoso, "Reliable Detection of Stator Inter-Turn Faults of Very Low Severity Level in Induction Motors," in *IEEE Transactions on Industrial Electronics*, May 2020.

[24] Lazoc Sensing Technology, “Fiber Bragg Grating Sensor (FBG)” Technical Information, September 2020,. Available: http://www.lazoc.jp/english/technical/principle/000309.html

[25] Liu, Z. (2018). *Stray Magnetic Field Based Health Monitoring of Electrical Machines* [Doctoral dissertation, Newcastle University, United Kingdom]. Available at: https://theses.ncl.ac.uk/jspui/bitstream/10443/4105/1/Lui%2C%20Z%2C%202018.pdf.

[26] M. Brela, N. Kassim and J. Franke, "Characterization of magnetic actuators by measuring of magnetic stray fields with GMR-sensors," *2013 3rd International Electric Drives Production Conference (EDPC)*, Nuremberg, 2013, pp. 1-7

[27] M. Fabian, D. Hind, C. Gerada, T. Sun, and K.T.V Grattan, “Multi-parameter monitoring of electrical machines using integrated fibre Bragg gratings,” *25th Optical Fiber Sensors Conference*, vol. 44, pp. 1–4, 2017.

[28] M. Regina et al, “A Guide to Fiber Bragg Grating Sensors,” in *Current Trends in Short- and Long-period Fiber Gratings*, InTech, 2013.

[29] M.A. Ismail, N.Tamchek, M. R. A. Hassan, K.D. Dambul , J. Selvaraj, N. A. R.R. Sandoghchi and F. R. M. Adikan , "A fiber Bragg grating—bimetal temperature sensor for solar panel inverters," *Sensors*, vol. 11, no. 9, pp. 8665-8673, 2011.

[30] Mohammed A and Durović S. “Design, Instrumentation and Usage Protocols for Distributed In Situ Thermal Hot Spots Monitoring in Electric Coils using FBG Sensor Multiplexing.” *Journal of Visualized Experiments: Jove.* March 2020 (157).

[31] Motwani, P., Perogamvros, N., Taylor, S., Sonebi, M., Laskar, A. and Murphy, A., ’ Experimental Investigation of Strain Sensitivity for Surface Bonded Fibre Optic Sensors,’ *Sensors and Actuators A: Physical*, Elsevier, p.111833, vol. 303, March 2020.

[32] P. Zhang, N. Thiyagarajah and S. Bae, "Magnetically Labeled GMR Biosensor With a Single Immobilized Ferrimagnetic Particle Agent for the Detection of Extremely Low Concentration of Biomolecules," in *IEEE Sensors Journal*, vol. 11, no. 9, pp. 1927-1934, Sept. 2011.

[33] Ping-an Liu, Mingming Huo, Yi Yin, Dongbin Zhang, Wei Yan, Ruizhan Zhai, Yong Wang, "Fiber Bragg grating sensor for motor transient torque measurement," *Proc. SPIE 11068, Second Symposium on Novel Technology of X-Ray Imaging*, 1106826 (10 May 2019)

[34] Terfenol-D, “Physical Properties”, http://tdvib.com/terfenol-d/, 2019.

[35] Y. He, Q. Yang, S. Sun, M. Luo, R. Liu and G. Peng, " A multi-point voltage sensing system based on PZT and FBG," in *International Journal of Electrical Power & Energy Systems,* vol.117, May 2020.

[36] Y. Wang, A. Mohammed, N. Sarma and S. Djurović, "Double Fed Induction Generator Shaft Misalignment Monitoring by FBG Frame Strain Sensing," in *IEEE Sensors Journal*, 2020 doi: 10.1109/JSEN.2020.2984309.

[37] Zheng Liu, W. Cao, P. Huang, G. Tian and J. L. Kirtley, "Non-invasive winding fault detection for induction machines based on stray flux magnetic sensors," *2016 IEEE Power and Energy Society General Meeting (PESGM)*, Boston, MA, 2016, pp. 1-6