The Journal of Engineering

The 9th International Conference on Power Electronics, Machines and Drives (PEMD 2018)

Bi-Signature optical spectroscopy for online fault detection in electrical machines

eISSN 2051-3305
Received on 21st June 2018
Accepted on 27th July 2018
E-First on 14th May 2019
doi: 10.1049/joe.2018.8062
www.ietdl.org

Belema P. Alalibo[1] ✉, Wenping Cao[1], Zheng Liu[1]
[1]School of Engineering and Applied Science, Aston University, Birmingham, UK
✉ *E-mail: alalibob@aston.ac.uk*

Abstract: A novel bi-signature optical spectroscopy for fault detection in electrical machines is presented. The combined use of long period grating (LPG) and two fibre Bragg gratings (FBG1 and FBG2) is implemented to discriminate between vibration and temperature sensitivity in the detection of machine faults. With LPG having higher sensitivity to temperature compared to both FBGs, machine faults are detected through spectral analysis of both signatures; and the optimal detection signature for each fault is consequently analysed. This novel technique utilises the principle of a shift in the wavelengths of the gratings to determine the kind of fault present in an electrical machine as the signature spectroscopy reveals varying amount of Bragg wavelength shifts for various fault types. The use of FBG sensing for fault detection in electrical machines has the potential of revolutionising non-intrusive real-time condition monitoring of future industrial machines with high reliability due to zero electromagnetic interference (EMI) as well as significant low cost of fibre-optic sensors.

1 Introduction

Electric machines play pivotal roles in both domestic and industrial operations such as in refrigerators, washing machines, escalators, lifts, trains aeroplanes, and cars as well as in power plants, petro-chemical and manufacturing plants, transport sector among others. As [1] asserts, electric motors are everywhere and efficient. Electric motor-driven systems consume about half of all global electricity accounting for about $565 billion each year for electricity costs and roughly 6040 metric ton of CO_2 emissions [1]. Despite the very important role these electric machines play in our day to day existence, one of the biggest challenges in many industrial operations which has persisted is the susceptibility of these machines to unexpected breakdown due to the harsh and highly stressed environments [2] under which they are operated in order to provide the goods and services humans need.

ABB an electrical manufacturing giant corroborates that condition-based maintenance strategy allows drastic reduction in the cost associated with maintenance, thereby minimising the occurrence of serious faults due to early fault detection as well as optimising the management of the available economic resources [3]. The key feature of online condition monitoring for machines is the early fault detection which requires continuous monitoring of some signature(s) obtained from the machine while running. Several fault signature extraction techniques exist in literature. These are mainly defined by the machine parameter being analysed in order to detect aberrations. Machine parameters mostly used include motor current, vibration, magnetic flux, and temperature.

The mostly used signature extraction techniques can be categorised into: motor current spectral analysis (MCSA), vibration spectral analysis (VSA), flux spectral analysis (FSA), temperature and thermographic analysis (TA). While there remains a widely agreed notion on the most commonly used technique, there is still the lingering resolution on the most reliable and best technique. This is due to the limitations evinced by each technique, one of which remains the inability of one single technique or signature to detect all common faults in a machine. Recently, the use of fibre-optic sensing has gained a lot of research interest especially in the area of structural condition monitoring. Its implementation in the area of machine fault detection is still nascent in terms of research and undoubtedly boasts of huge potential in achieving a multi-signature extraction and multiple fault identification.

2 Some limitations of existing fault detection techniques

Two general limitations for most of the literature reviewed that utilised the MCSA are that the sensors used for the current signal extraction are susceptible to electromagnetic interference (EMI) and the fact that only one fault type was usually investigated which conceals the further research issue of fault discrimination that is yet to be adequately addressed. Fault discrimination issue arises because research has shown that different faults when analysed within the same machine produce similar spectral response, thus makes it difficult to identify the fault type, and in turn its severity. One of the reasons for the common use of VSA is its capability in detecting the widest range of mechanical faults [4]. Most research work utilising the VSA focussed on detection of a single fault which in reality is not possible as one or multiple machine faults can occur at any time, and the nature of the faults to occur, whether electrical or mechanical, cannot be presumed. In addition, the transducers utilised for vibration signature extraction are also susceptible to EMI. Hence, the need for a robust and comprehensive technique is capable of detecting any likely machine fault regardless of its nature even in multiple fault occurrence.

From reviewed literature, there are no complex signal processing techniques for the air gap flux spectral analysis, but the influence of EMI on the flux sensors as well as its impact on fault detection has not been sufficiently investigated. Also, the use of air gap flux for multiple fault detection has not been sufficiently researched, which evades the issue of similar spectral response and discrimination. It is the submission of proponents of the use of stray flux for fault detection that because it is a non-invasive or non-intrusive technique, it does not require alterations to the machine, hence it can be very easily implemented in both new and already commissioned machines. However, stray flux sensing is more susceptible to EMI as well as environmental factors implying a low signal-to-noise ratio despite already being attenuated by the machine cast frame. The reliability of the use of stray flux is yet to be widely accepted and in a typical industrial environment with several machines in close proximity, the use of stray flux may be unrealistic.

Three approaches to temperature monitoring as described by [5] are: local point temperature measurements using surface or embedded temperature detectors; thermal imaging or thermography; and distributed temperature measurements. In [6] opinion, temperature monitoring method does not directly detect the fault or its cause, but rather provides an indication of a looming fault. In terms of fault detection, many machine faults such as winding short circuit, bearing defects, de-magnetisation result in temperature increase which often leads to the issue of fault discrimination. A more viable option which is increasingly being implemented either as stand-alone or as a complementary technique with other detection techniques is the infrared (IR) thermography. Two common drawbacks for all these research works using IR thermography are the dependence of the technique on the thermographer's experience in setting up the thresholds prior to using the camera; and the fact that for each machine being monitored, a specific IR camera has to be assigned. In other words, for a typical industrial site with hundreds of machines, it is difficult to imagine how these hundreds of IR cameras will be set up with space requirements, cost ineffectiveness, and interference issues as IR works with line-of-sight (LOS) principle. Reliance on thermographer's experience introduces a source of possible human error in judgement and it will be difficult to standardise such technique, hence difficulty in regulating its implementation.

Most reviewed literature which implemented multi-signature extraction techniques were limited to two signatures in a complementary manner such that one signature was more mechanically biased, while the other was either more electrically biased or more magnetically biased. For example, MCSA and stray flux were both simultaneously extracted for broken rotor bar detection in [7]; and for eccentricity detection in [8]. In another pairing, MCSA and vibration were utilised by [9–12] to detect bowed rotor fault, inter-turn short-circuit fault, dynamic eccentricity, and bearing faults. Also, the use of flux and vibration was explored for the detection of short-circuit and phase unbalance faults [13–15]. The identified limitations of such research works are the use of extra sensors due to the extraction of two signatures, and the sensors are all susceptible to EMI as they are conventional sensors.

3 Principle of LPG and FBG fault detection

Until recently, the use of fibre optics has been mainly for network communications purposes especially over long distances. At the beginning of the fibre-optic era, optical fibre and its associated devices were very expensive affordable only by telecommunications companies to replace the old saturated copper telephone network [16]. Nowadays, optoelectronic components are cheaper which has contributed to the use of fibre optics in many sensing and health monitoring applications including structural health monitoring as well as biomedical optics. Recently, fibre-optic sensing (FOS) is being extended to the electrical power industry where it is used on transmission buses and electrical machines. The numerous advantages of using fibre-optic sensing according the industrial giant, ABB [17] include: high accuracy, high bandwidth, wide temperature range, full digital processing, uni- or bi-directional measurements possible, easy to install and does not require re-calibration, small size and weight, no magnetic overload issue, or magnetic centring necessary, immune to EMI, electronics fully insulated from bus bars, hence it is possible to place them very close or even over high-potential conductors without necessarily requiring electrical power at the sensor location [16]. This makes them also suitable for use in hazardous environments which usually require intrinsically safe instrumentation. Other advantages include: low power consumption, chemically inert even against corrosion, work over long distances, several sensors can be multiplexed on the same fibre.

One of the most commonly used optical fibres for strain and temperature measurements is the fibre Bragg grating (FBG) technology due to its ease of manufacture as well as its relatively strong signal reflectivity [16] upon which its sensing principle depends. The term Bragg grating was first used after this law was applied to periodical structures inscribed inside the core of a conventional telecom fibre to vary its refractive index [16]. When the light is guided along the fibre core comes in contact with the inscription of the gratings, it is weakly reflected by each grating plane by Fresnel effect; and the reflected light from each grating plane then recombines with other reflections in the backward direction in either a constructive or destructive interference pattern depending on whether the wavelength of the incoming light satisfies Bragg's law given by [16]:

$$2d\sin\theta = \eta\lambda \quad (1)$$

With the light's incident angle $\theta = 90°$ and d, the distance between peaks of the interference pattern, then for vacuum with refractive index, $\eta = 1$; $\lambda = 2d$ is the approximate wavelength of the reflection peak which means the fibre reflects part of the incoming spectrum [16]. For silica material used to make optical fibre, the distance travelled by light, d is affected by the material's refractive index, η, thus (1) can be adapted for silica as:

$$2\eta_{\text{eff}}\Lambda = \lambda_{\text{B}} \quad (2)$$

where λ_{B} is the Bragg wavelength, η_{eff} is the effective refractive index of the fibre and Λ is the periodicity of the grating [16]. The η_{eff} is determined by the average of the refractive index of the fibre core and the refractive index of the fibre cladding. From (2), it is possible to change the Bragg wavelength also known as 'Bragg Shift' by either varying the fibre's effective refractive index or the grating periodicity or both. This is the fundamental principle of the FBG sensing. According to [16], by designing the proper interface, desired measurement can be made to impose some external force or disturbance on the grating which will result in a Bragg shift proportional to the perturbation applied. This makes the FBG useful as a sensor in a wide range of parameter measurements including temperature, vibration, pressure, and displacement.

Longitudinal deformation and temperature variation are two forms of perturbations that have been observed to change both η_{eff} and Λ [16]. Longitudinal deformation and temperature result in photo-elastic and thermo-optic effects, respectively, where the change in the optical behaviour of the gratings due to their effective refractive index (η_{eff}) is proportional to the amount of strain and temperature difference applied to the fibre, respectively. Longitudinal deformation and temperature also result in increase in the grating pitch and thermal expansion, respectively, which affect the periodicity of the fibre gratings (Λ). The effect of temperature can be incorporated into (2) as [16]:

$$\frac{\Delta\lambda_{\text{B}}}{\Delta T} = 2\eta_{\text{eff}}\frac{\partial\Lambda}{\partial T} + 2\Lambda\frac{\partial\eta_{\text{eff}}}{\partial T} \quad (3)$$

If we substitute (2) into (3) for both expressions on the right hand side of (3) and rearranging we get:

$$\frac{\Delta\lambda_{\text{B}}}{\lambda_{\text{B}}} = \frac{1}{\Lambda}\frac{\partial\Lambda}{\partial L}\Delta T + \frac{1}{\eta_{\text{eff}}}\frac{\partial\eta_{\text{eff}}}{\partial L}\Delta T \quad (4)$$

which can be rewritten simply as

$$\frac{\Delta\lambda_{\text{B}}}{\lambda_{\text{B}}} = (\alpha + \eta)\Delta T \quad (5)$$

The first term represents the thermal expansion of silica (α) while the second term represents the thermo-optic coefficient (η).

Similarly, the effect of longitudinal deformation or simply referred to as strain can be incorporated into (2) as [16]:

$$\frac{\Delta\lambda_{\text{B}}}{\Delta L} = 2\eta_{\text{eff}}\frac{\partial\Lambda}{\partial L} + 2\Lambda\frac{\partial\eta_{\text{eff}}}{\partial L} \quad (6)$$

If we substitute (2) into (6) for both expressions on the right hand side of (6) and rearranging we get:

$$\frac{\Delta\lambda_{\text{B}}}{\lambda_{\text{B}}} = \frac{1}{\Lambda}\frac{\partial\Lambda}{\partial L}\Delta L + \frac{1}{\eta_{\text{eff}}}\frac{\partial\eta_{\text{eff}}}{\partial L}\Delta L \quad (7)$$

a

b

Fig. 1 *Before and after broken rotor fault on a squirrel cage rotor*
(a) Healthy rotor, ***(b)*** Broken rotor [18]

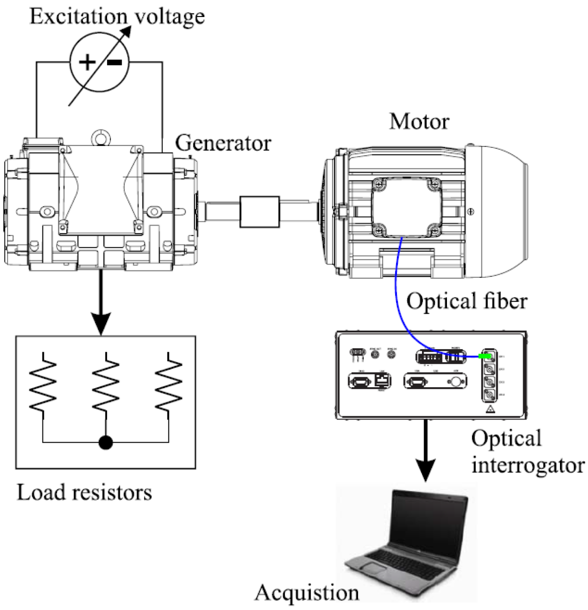

Fig. 2 *Experimental set up for feature extraction in an induction machine using FBG sensing technique*

The first term on the right hand side of (7) represent the strain of the grating period due to fibre extension while the second term is the photo-elastic coefficient (ρ_e) due to change in refractive index with strain. In optical fibre, both terms produce opposite effects when strain is applied to the fibre such that while the distance between gratings tends to increase, thus increasing the Bragg wavelength, the photo-elastic effect results in a decrease in the effective refractive index due to decrease in the density of the fibre (from cladding to core), thus decreasing the Bragg wavelength [16]. Hence in simplifying (7), second term carried a negative sign as follows:

$$\frac{\Delta\lambda_B}{\lambda_B} = (1 - \rho_e)\varepsilon_Z \quad (8)$$

where εz is the longitudinal strain of the grating.

Therefore, the sensitivity of FBG to strain and temperature can be represented by combining (5) and (8) as follows:

$$\frac{\Delta\lambda_B}{\lambda_B} = (1 - \rho_e)\varepsilon_Z + (\alpha + \eta)\Delta T \quad (9)$$

Theoretically, for the F-SM1500-4.2/125 single mode all glass highly bend insensitive and photosensitive fibre used in this research @1550 nm wavelength will have:

$$\rho_e = 0.22,\ \alpha = 0.55 \times 10^{-6}/^\circ\mathrm{C},\ \text{and}\ \eta = 8.6 \times 10^{-6}/^\circ\mathrm{C}$$

Thus, sensitivities of the FBG fabricated on this fibre for temperature and strain will be:

$$\frac{\Delta\lambda_B}{\Delta T} = 14.10\,\mathrm{pm}/^\circ\mathrm{C};\ \text{and}\ \frac{\Delta\lambda_B}{\Delta\varepsilon} = 1.209\,\mathrm{pm}/\mu\varepsilon$$

4 Broken rotor bar experiment

Fig. 1 shows a healthy and a broken squirrel cage rotor, which is the mechanical fault being considered here.

Using a similar set up as in Fig. 2, two machines, 30 kW induction motor as generator and 15 kW permanent magnet type as motor, will be utilised during the experiment. Due to earlier deduction of the dependence of FBG sensing and feature extraction on both strain and temperature, there exists a phenomenon known as cross-sensitivity. This phenomenon occurs always and to the best of the authors' knowledge, no work related to machine fault detection using FBG has attempted to separate the effects of strain and temperature in order to improve the reliability of the extracted fault signature. Results presented in the Fig. 3 illustrate spectral performance from using different FBGs to detect both broken rotor bar and dynamic eccentricity as experimented by [19, 20] using a 3-hp 4 pole motor, 220 V Δ-connected. The HBM interrogator has four input channels capable of interrogating several multiplexed sensors on a single fibre [19].

5 Future work and conclusion

To further improve the reliability of the results above, experiments will be carried out based on the sensitivities of the FBG fabricated (14.10 pm/°C and 1.209 pm/με) but in addition LPG will be spliced

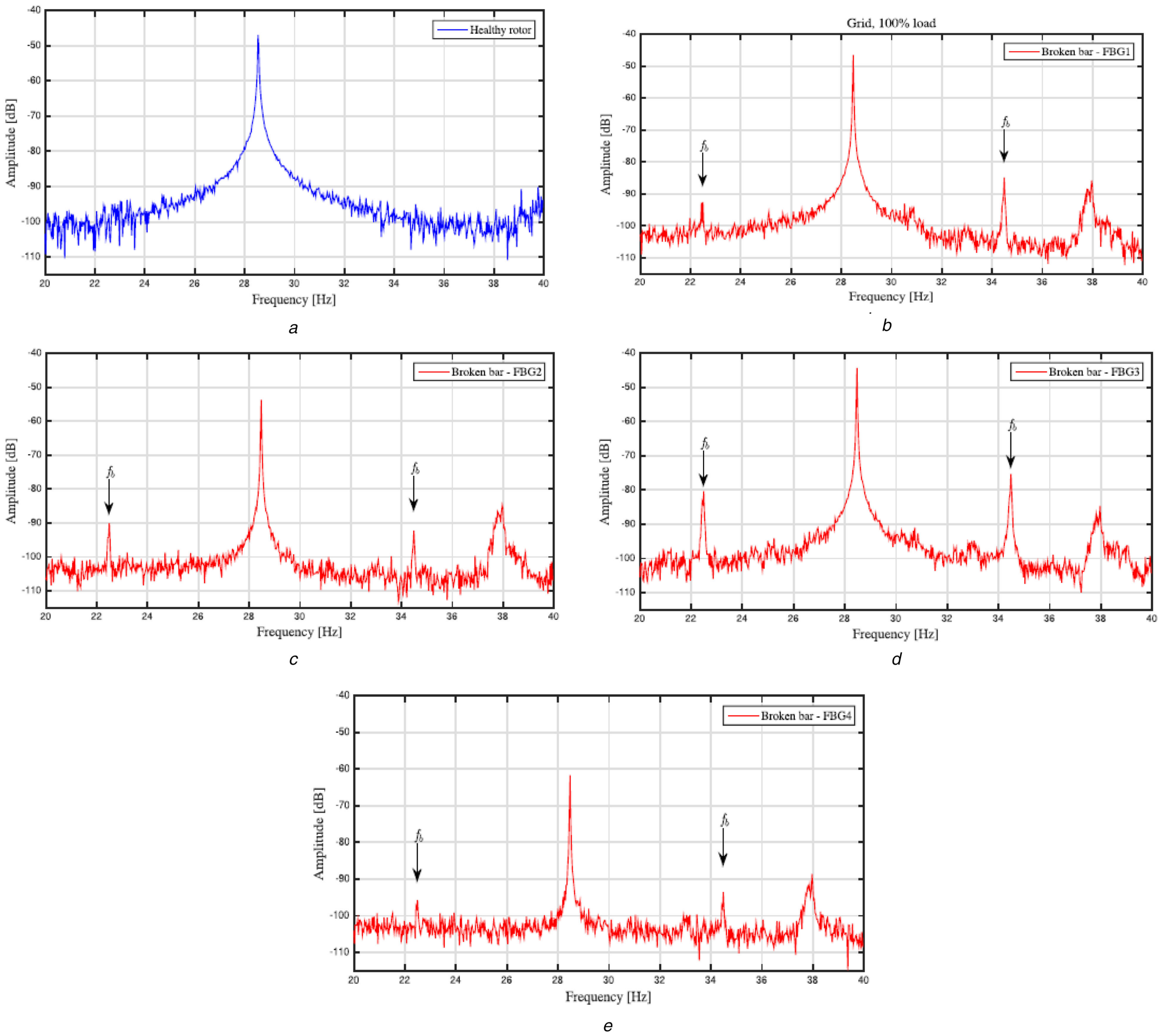

Fig. 3 *FBG Spectral output for broken rotor bar detection*
(a) Healthy rotor; ***(b)–(e)*** Broken rotor bar for FBG 1-4 [19]

to the FBG to address the cross-sensitivity issue and results will be reported in subsequent publications. Also, other machine faults such as winding faults and bearing failures will be reported after further experiments.

This paper looks to address the impact of cross-sensitivity between strain (vibration) and temperature during fault signature extraction using FBGs. This impact has been analysed to show that the use of FBG for sensing is dependent on both parameters and hence, the need for improving the reliability of the FBG technique through the combined use of LPG and FBG. Further experimental work is being carried out and will be reported in subsequent publications.

6 References

[1] Gallinat, C.S., Weyl, D.K.: 'Motors are everywhere and efficient – but they can be even better', CLEANENERGY MINISTERIAL, 2014. Available at http://www.cleanenergyministerial.org/Blog/motors-are-everywhere-and-efficient-but-they-can-be-even-better-414

[2] Zhang, P.J., Du, Y., Habetler, T.G., *et al.*: 'A survey of condition monitoring and protection methods for medium-voltage induction motors', *IEEE Trans. Ind. Appl.*, 2011, **47**, (1), pp. 34–46

[3] ABB: '4 types of maintenance strategy, which one to chose?', 2017. Available at http://new.abb.com/medium-voltage/service/maintenance/feature-articles/4-types-of-maintenance-strategy-which-one-to-choose

[4] Plante, T., Stanley, L., Nejadpak, A., *et al.*: 'Rotating machine fault detection using principal component analysis of vibration signal', 2016

[5] Yang, W., Tavner, P.J., Wilkinson, M.: 'Wind turbine condition monitoring and fault diagnosis using both mechanical and electrical signatures'. 2008 IEEE/ASME Int. Conf. Advanced Intelligent Mechatronics, Xi'an, China, 2008, pp. 1296–1301

[6] Tonks, O., Wang, Q.: 'The detection of wind turbine shaft misalignment using temperature monitoring', *CIRP J. Manuf. Sci. Technol.*, 2017, **17**, pp. 71–79

[7] Chernyavska, I., Vitek, O.: 'Analysis of broken rotor bar fault in a squirrel-cage induction motor by means of stator current and stray flux measurement'. Proc. – 2016 IEEE Int. Power Electron. Motion Control Conf. PEMC 2016, 2016, pp. 532–537

[8] Ishkova, I., Vitek, O.: 'Analysis of induction motor faults by means of monitoring the current and magnetic flux density spectrums'. 2016 Int. Symp. Power Electron. Electr. Drives, Autom. Motion, SPEEDAM 2016, no. 2, Anacapri, Italy, 2016, pp. 611–616

[9] Garcia-Perez, A., Romero-Troncoso, R.D.J., Cabal-Yepez, E., *et al.*: 'The application of high-resolution spectral analysis for identifying multiple combined faults in induction motors', *IEEE Trans. Ind. Electron.*, 2011, **58**, (5), pp. 2002–2010

[] Uddin, M.N., Rahman, M.: 'Online current and vibration signal monitoring based fault detection of bowed rotor induction motor'. IEEE Energy

Conversion Congress and Exposition (ECCE), Montreal, QC, Canada, 2015, pp. 2988–2994

[11] Li, Y., Liang, Y.: 'The correlation analysis of PM inter-turn fault based on stator current and vibration signal'. 2015 IEEE Int. Conf. Mechatronics Autom. ICMA 2015, Beijing, China, 2015, pp. 1733–1737

[12] Sobra, J., Belahcen, A., Vaimann, T.: 'Vibration and stator current spectral analysis of induction machine operating under dynamic eccentricity'. 2015 Int. Conf. Electr. Drives Power Electron. EDPE 2015 – Proc., The High Tatras, Slovakia, 2015, pp. 285–290

[13] Lamim Filho, P.C.M., Pederiva, R., Brito, J.N.: 'Detection of stator winding faults in induction machines using flux and vibration analysis', *Mech. Syst. Signal Process.*, 2014, **42**, (1–2), pp. 377–387

[14] Babić, B.M., Milić, S.D., Rakić, AŽ: 'Fault detection algorithm used in a magnetic monitoring system of the hydrogenerator', *IET Electr. Power Appl.*, 2017, **11**, (1), pp. 63–71

[15] Cuevas, M., Romary, R., Lecointe, J.P., *et al.*: 'Non-invasive detection of rotor short-circuit fault in synchronous machines by analysis of stray magnetic field and frame vibrations', *IEEE Trans. Magn.*, 2016, **52**, (7), pp. 2–5

[16] Werneck, M.M., Allil, R.C.S.B., Ribeiro, B.A., *et al.*: 'A guide to fiber Bragg grating sensors', in: '*Current trends in short- and long-period fiber gratings*' (InTechOpen, London, UK, 2013), pp. 1–7

[17] ABB: 'FOCS applications and benefits', 2014. Available at http://new.abb.com/power-electronics/focs/applications-and-benefits, accessed 23 November 2017

[18] Xie, Y., Gu, C., Cao, W.: 'Study of broken bars in three-phase squirrel-cage induction motors at standstill', *Int. Trans. Electr. Energy Syst.*, 2013, **23**, (7), pp. 1124–1138

[19] Sousa, K.M., Brutkowski Vieira da Costa, I., Maciel, E.S., *et al.*: 'Broken bar fault detection in induction motor by using optical fiber strain sensors', *IEEE Sens. J.*, 2017, **17**, (12), pp. 3669–3676

[20] Sousa, K.M., Dreyer, U.J., Martelli, C., *et al.*: 'Dynamic eccentricity induced in induction motor detected by optical fiber Bragg grating strain sensors', *IEEE Sens. J.*, 2016, **16**, (12), pp. 4786–4792