Monitoring and Damping UMP Due to Eccentricity Fault in Induction Machines: A Review

Ahmad Salah and Youguang Guo
School of Electrical, Mechanical and Mechatronic Systems
University of Technology Sydney
Sydney, NSW 2007, Australia
Ahmad.a.salah@student.uts.edu.au
Youguang.Guo-1@uts.edu.au

David Dorrell
Howard College Campus
University of KwaZulu Natal
Durban 4041, South Africa
Dorrelld@ukzn.ac.za

***Abstract*— Three-phase induction machines are reliable and widely used in industrial plants. Efficient condition monitoring can diagnose the inception of fault mechanisms in induction motors thus avoiding failure and expensive repairs. Therefore, there is a strong need to develop a more efficient condition monitoring. The main target is to achieve a relatively low cost and/or non-invasive system which is still powerful in terms of monitoring for online detection of developing faults. In order to reduce the unbalanced magnetic pull (UMP) in case of an eccentric rotor, the eccentricity-generated additional airgap flux waves should be reduced. The present paper addresses rotor eccentricity faults and studies conventional monitoring techniques for induction motors. The radial forces in an induction motor are calculated. In addition, the characteristics of UMP in induction machines are stated.**

Keywords*— *condition monitoring; eccentric rotor; induction machines; unbalanced magnetic pull (UMP)

I. INTRODUCTION

The best definition of condition monitoring is the continuous evaluation of the health of the plant and associated electrical machines throughout their service life. The key is the ability to detect faults while they are still developing which is called incipient failure detection [1]. By implementing or applying a good condition monitoring method, it is possible to provide adequate warning of imminent failure. Thus, it is also possible to schedule future preventive maintenance and repair work [2]-[4].

Different methods for fault identification have been developed and used effectively to detect the machine faults at different stages using machine variables, such as current, voltage, speed, torque, noise and vibrations [5]-[10]. In most cases, faults produce one or more indicative signs, such as increased losses, excessive heating, torque pulsation, and unbalanced air-gap voltages and line currents. Current methods may involve several different types of analysis but often the underlying requirement is an understanding of the electromagnetic characteristics of the machine. In general, the motor faults are due to mechanical and electrical stresses [11]. Mechanical stresses occur with overloads and unforeseen load changes, which may cause bearing faults and broken rotor bars. Electrical stresses are directly or indirectly associated with the power supply, which may produce stator winding short circuits. Fault mechanisms for induction machines have been extensively studied. According to IEEE and EPRI reports [12]-[13], the occurrence of faults in induction machines are as

Table I. Summary of motor faults, percentage of failure, causes, and sensor signal used for faults detection.

Faults Classification	Major Components	Percentage IEEE	Percentage EPRI	Causes	Detections Methods
Electrical Faults	Rotor faults	8%	9%	Thermal- stresses Corrosion Poor manufacturing	Stator current Axial flux Vibration Torque, speed
	Stator faults	26%	36%	Over-heating Over-voltages Mechanical stresses	Axial flux Stator current
Mechanical Faults	Bearing faults	44%	41%	Contamination Improper installation and lubrication End of life	Stator current Vibration
	Other faults (mainly – eccentricity causing unbalanced magnetic pull)	22%	14%	Bent Rotor Bearing wear Misalignment	Stator current Vibration Axial flux

shown in Table I. Bearings are common elements of an electrical machine and Table I indicates that they are the single largest cause of machine failures. Eccentricity fault represents a considerable part of the three phase induction motor faults. What we have to keep in mind is that airgap eccentricity exists even in the healthy motor, but the permissible limit depends on the motor construction. It is considered that the permissible value of airgap eccentricity is 10% for a healthy motor.

Rotor eccentricity as a fault is discussed on the basis of its importance regarding condition monitoring of induction motors in the next section. According to [14]-[16], the radial forces in an induction motor due to eccentricity faults are stated and calculated in Sections two and three. In terms of eccentricity faults in induction machines then there are several detection methods as addressed in [17]-[19], and they will be discussed in Section four.

II. AIR GAP ECCENTRICITY FAULT

An unequal airgap between the stator and rotor results in eccentricity of the rotor in an induction motor [16]-[22], and the imbalance produces electromagnetic forces between the stator and rotor. This electromagnetic force depends on the movement of rotor axis away from stator axis, and the motion of eccentric rotor in terms of its angular velocity. There are also considerable effects due to winding arrangement, loading and slotting. This force acts between rotor and stator in an irregular manner and pulls the rotor out of alignment, and this is known as unbalanced magnetic pull (UMP). Further increase in the UMP may cause damage to the machine. Normally the eccentricity appears due to manufactu- ring tolerances. The inaccuracy of installation is another reason for increasing UMP, for example, when the bearings are incorrectly positioned or worn.

Assuming that the stator and rotor surfaces are perfectly circular then there are two main types of eccentricity: static and dynamic. Static eccentricity occurs when the axis of the rotor is at a constant distance from the centre of the stator, although the rotor still rotates about its own axis. However dynamic eccentricity occurs when the rotational axis of the shaft is not the true axis, although it still rotates on the stator axis. Obviously these conditions can exist together, and the eccentricity is not necessarily constant down the bore. Static eccentricity produces a steady pull on the rotor to one side while dynamic eccentricity produces a rotating force vector acting on the rotor and rotating with rotor velocity. Other vibrations can also be generated. Fig. 1 illustrates the different cases of eccentricity.

III. CALCULATION OF UMP

Many different approaches were developed for electromagnetic force calculation in induction machines with eccentric rotors. These can generally be organized into two main categories: analytical methods and numerical methods. Both analytical and numerical methods have their own benefits and drawbacks in studying induction machines as in Table II.

In order to calculate the UMP, a machine consisting of a pair of poles is considered as shown in Fig. 2. The rotor of the machine is set symmetrically within the stator bore. Rotor and stator are purely cylindrical, thus the length of air gap is uniform. The rotation of the rotor is on account of the formation of poles of opposite polarity on stator and rotor which exert a tangential force on the rotor. However, a much stronger magnetic force of attraction takes place between the stator and the rotor poles acting along a direction perpendicular to the rotor shaft axis. These forces therefore act radially. In a symmetrical machine the mmf per pole and the area per pole are the same for all the poles. Assume the flux density B is uniform in the airgap, and mmf required for the iron parts is negligible. The forces of attraction between stator and rotor poles in the top and bottom are equal and act in the opposite direction to each other as:

Table II. Comparing the Analytical and Numerical Methods.

	Analytical Methods	Numerical Methods
Prompt results	✓	
Simple interpretation	✓	
Evaluate accurately the effects of magnetic saturation		✓
Evaluate accurately the effects of circulating currents		✓
Evaluate accurately the effects of stator and rotor slotting		✓
Provide high degree of accuracy in the final solution		✓
Require computational power of computers and time consuming		✓

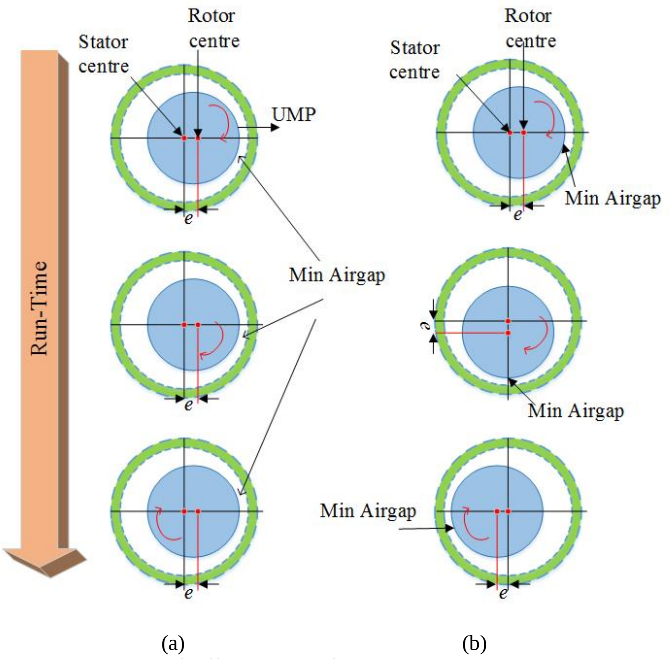

Fig. 1. Illustration of different cases of eccentricity. (a) Static eccentricity and (b) Dynamic eccentricity.

$$F_1 = \frac{1}{2}\frac{B^2}{\mu_0}A = \frac{1}{2}\mu_0\left(\frac{mmf}{g}\right)^2 A \tag{1}$$

$$F_2 = \frac{1}{2}\frac{B^2}{\mu_0}A = \frac{1}{2}\mu_0\left(\frac{mmf}{g}\right)^2 A \tag{2}$$

where A is the area per pole, and g is the length of the air gap.

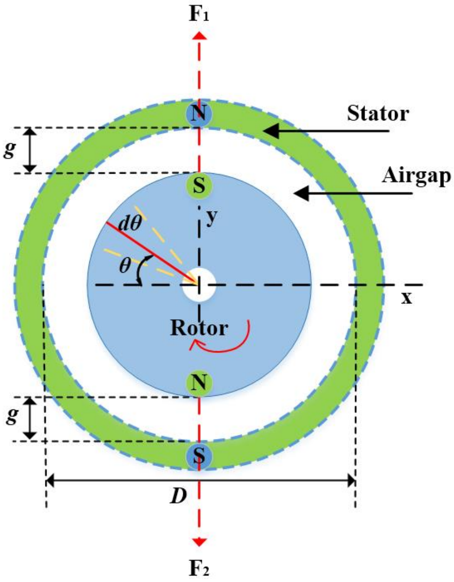

Fig. 2. Radial magnetic forces in symmetrical machine.

Forces are equal and hence their resultant is equal to zero. There is no resultant radial magnetic pull on the rotor. In the analysis given above, the flux density distribution has been assumed uniform in the airgap. In the real case the flux density distribution is sinusoidal, considering an elemental angle $d\theta$ at an angle θ from axis x, and D is the diameter of stator bore. The radial force acting on the elemental strip:

$$F = \frac{1}{2\mu_0}\left(B_m \sin\theta\right)^2 \frac{DL}{2} d\theta \tag{3}$$

and the vertical component of the force is:

$$F_v = \frac{DL}{4\mu_0} B_m{}^2 \left(\sin\theta\right)^3 d\theta \tag{4}$$

It is evident if ($g_1 > g_2$) as in Fig. 3, force F_2 is greater than F_1, and hence a resultant pull radial force acts on the rotor in the downward direction. It should be noticed that it is not only the abnormality of the airgap that causes UMP but also any other asymmetry in the airgap flux destiny destitution or winding would causes UMP. When the rotor of induction machine is not concentric with stator, the airgap is not uniform over periphery. The UMP would be produced which tends to draw the rotor over to the side where the airgap is smaller. This was showed earlier that the UMP is inversely proportional to square of the length of the airgap.

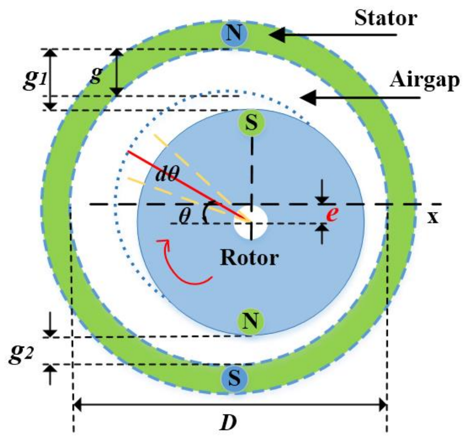

Fig. 3. Machine with rotor displaced vertically downwards.

Consider the case of a rotor when it is moved vertically downwards as shown in Fig. 3, where e is the displacement of the rotor along downward direction. The total UMP acting on the rotor:

$$F_{UMP} = P_m \frac{DL}{4\mu_0} B_m{}^2 \frac{e}{g} \int_0^{\theta} \left(\sin\theta\right)^2 d\theta \tag{5}$$

where P_m is fundamental pole-pair number of the machine.

The analysis given above assumes the case of static eccentricity; hence the stator and rotor axes remain parallel during the running time. When calculating UMP it has been assumed that the peak value of the flux density remains the same irrespective of the eccentricity which is not correct. Therefore, the UMP has been calculated for the worst case. As described in many studies, for a given airgap eccentricity and flux density, the UMP increases with rotor diameter and rotor length. According to [15], [22], and [23], if the rotor is not centered then permeance modulation of mmf takes place so that for a P_m, there will be not only a P_m pole pair magnetic flux but also $P_m\pm1$ pole pair magnetic flux waves. In other words, the eccentricity will produce additional flux waves of different pole number in the airgap. Once the terms for the additional airgap flux waves are obtained as in (6) then the UMP can be calculated. The additional flux waves are the second and third terms:

$$b(x,y,t) = \mathrm{Re}\sum_{n=-\infty}^{\infty}\begin{bmatrix} \bar{B}^{P_m} e^{j(\omega t - P_m k y)} + \\ \bar{B}^{P_m-1}(x) e^{j(\omega t - k(P_m-1)y)} + \\ \bar{B}^{P_m+1}(x) e^{j(\omega t - k(P_m+1)y)} \end{bmatrix} \tag{6}$$

where the field magnitudes are

$$\bar{B}^{P_m} = \frac{j\mu_0 \bar{J}_{st}}{kP_m g} \tag{7}$$

$$\text{and} \quad \bar{B}^{P_m\pm1}(x) = \frac{j\mu_0 \bar{J}_{st}}{kP_m g}\bar{\delta}(x) \tag{8}$$

where $\delta(x)$ is the absolute static airgap eccentricity and it is equal to (e/g), J_{st} is the current density, y is the circumferential distance around the air gap, ω is the angular velocity, and k is the inverse of the average air gap radius. At any particular point in the airgap the radial force can be calculated from the Maxwell stress. Reference [24] considered the effects of the tangential flux density component and assessed it to be low. The characteristics of UMP forces depend on the air-gap flux density, geometric design of the machine eccentricity level, and the loading condition. As shown in [25] and [26], if the flux density increases by 20% then the UMP will increase by 44% for a given eccentricity.

IV. Existing Condition Monitoring Techniques

This section is focused on the condition monitoring of the induction machine, illustrating how the eccentricity fault could be detected and evaluated. Several methods of electrical machine condition monitoring have evolved over time but the most distinct techniques are motor current monitoring, vibration monitoring, thermal monitoring, torque monitoring and flux monitoring.

A. Stator Current Monitoring

The popular method is to use line current monitoring where signature current sidebands are monitored [6], [25], [27], and [29]. It is the most economically attractive technology in induction motor, and it monitors the stator current of an induction motor in a non-invasive manner. Therefore, current monitoring is a sensorless detection method that can be implemented without any extra hardware to the machine. However, these are relevant to cage induction machines in terms of commercial system development. In renewable energy, particularly wind turbines, wound rotor induction generators are used and these do not produce the same sideband currents as shown in [28].

A clip-on current transformer can be used to measure the signal. It is not required to access to the machine; the current can be measured in the supply side without any disturbance to the operation of the motor [29]-[31]. Thomson [27] presented the classical rotor slot passing frequency flux and current components that are spaced at twice the supply frequency $2f$ apart (9), and (10) predicts the current signature pattern that is a function of airgap eccentricity. The current monitoring is also extensively used to detect broken rotor bars. On the other hand current monitoring techniques require a high degree of human expertise.

$$\begin{aligned} f_{rs} &= f\left\{\frac{R}{p_m}(1-s) \pm n_{ws}\right\} \\ f_{ec} &= f_{rs} \pm f_r \end{aligned} \tag{9}$$

$$f_{ec} = f\left(\frac{R}{p_m}(s-1) \pm n_{ws}\right) \pm n_d\left(f\,\frac{(1-s)}{p_m}\right) \tag{10}$$

where f_{rs} are the frequency components due to rotor slotting, n_{ws} the number of the rotor slots, n_{ws} =1,2,..integer corresponds to the fundamental component in mmf waveform, n_d=1,2,..airgap eccentricity index, and f_r rotor speed frequency. The eccentricity fault diagnosis can be done in real time by analyzing frequency components of stator current signals that was discussed in [6] and [27].

B. Thermal Monitoring

The thermal monitoring of induction machines is carried out either by measuring the local or bulk temperatures of the motor, or by parameter estimation. For example, when the stator faults happen, they generate heat in the shorted turns. The heat extends until it reaches a destructive stage. The stator temperature can also be estimated based on the stator resistance measurement as in [32] and [33]. The researchers developed a thermal model of synchronous motors, and then the thermal model was presented to focus on estimating the temperature of the motor and identify faults as shown in [34].

Rubbing can happen between the stator and rotor due to many of reasons, For example, when there is a misalignment or bearing failure, the rotor can cause puncture of the coil insulation of the stator laminations, resulting in grounding the coil [35]. This method is very useful in detecting bearing faults, because the increased bearing wear will increase the friction and temperature in the fault region.

Though thermal method can be classified as indirect method to evaluate some stator faults, it might be too slow to detect the incipient faults inside the motor.

C. Vibration Monitoring

Vibration signal analysis has been widely used in the fault detection of induction machines [36], [37], and [38]. Faults create harmonics with different frequencies and power levels in the vibration signal. Consequently the vibration signal is first sensed via a vibration sensor mounted on the stator frame, and then its spectrum is calculated using a Fourier transform or a fast Fourier transform (FFT). The main source of noise production in electrical machines is the UMP in the airgap, since the resultant mmf that was produced by air gap flux wave contains the effect of any rotor and stator asymmetries. The study in [9] verified that airgap eccentricity resulted in vibratory harmonics at frequencies of (f_m, f_{m2}, f_{m3}, *or* f_{m4}). The expensive cost of vibration sensors weakens the vibration monitoring technique, and the acquisition of the vibration signal requires a significant investment.

D. Flux Monitoring

A flux monitoring method can give reliable and accurate information for the condition of an electrical machine. Reflected harmonic spectra will appear if any change occurs in air gap, winding, voltage, or current. In [39] the authors studied the airgap flux as a function of static eccentricity. Any change in the airgap flux can indicate a developing fault and it can be reflected in the harmonic spectrum. In [40] and [41] designed search coils are placed under the stator winding wedges of the motor, and they are used for measuring the actual magnetic flux. A search coil around the rotor shaft can also be used in order to evaluate the axial flux components due to eccentricity [42], however, it is not easy to install the search coil in the correct position to ensure that a reliable signal is obtained. A search-coil was used as magnetic field sensor to measure the stray magnetic flux outside the motor in [43]. The main drawback of these methods is the implementation and installation.

A simple method in [28] and [44] using pole-specific search coils was introduced and theory was developed to illustrate that rotor eccentricity leads to the generation of airgap flux waves with pole-pairs that are $P_m \pm 1$. The method was tested using search coils in a four pole wound rotor machine and it was found to successfully indicate the presence of rotor eccentricity. The main challenge of flux monitoring is the small air gap in most induction motors; the installation of search coils may require design modifications that may not be easy to implement.

E. Airgap Torque Monitoring

The flux linkage and the currents of the induction machine produce the airgap torque. Faults create unbalanced state, and it will have influence on the air gap torque. Hsu [45] suggested a method for detecting defects such as cracked rotor bar and shored stator coils. Airgap torque can be measured while the motor is running. The zero frequency of the airgap harmonics distinguishes that the machine is normal. The forward stator rotating field produces a constant torque. The backward stator field interacting with the rotor field produces a harmonic torque. Its frequency is:

$$\text{Frequency} = \begin{bmatrix} \text{Stator field angular speed-} \\ \text{(Rotor field angular+} \\ \text{Rotor field observed from Rotor)} \end{bmatrix}$$

$$= -\omega_s - \left\{\omega_s\left(1-s\right) + s\omega_s\right\} = -2\omega_s \tag{11}$$

This means the double slip frequency torque indicates an unbalanced rotor cage. However, once the leakage reactances and magnetic paths of the three phases become asymmetrical, errors are induced and the calculation of air gap torque as in (11) is no longer accurate [46].

V. Reduction of UMP

In recent years the reduction of radial electromagnetic forces has been the objective of many works. According to [14] rotor eccentricity leads to the generation of airgap flux waves with pole-pairs that are $P_m \pm 1$. In order to damp the UMP in case of an eccentric rotor, the additional airgap flux waves $P_m \pm 1$ should be eliminated or reduced. Three approaches have been previously suggested to achieve this; the use of parallel paths for stator winding currents, the use of stator damper windings to reduce the side-band flux waves, and the use of equalizing windings on the stator [21] and [24].

The reduction of UMP in induction motors is achieved by using parallel connection of the stator coil groups in order to reduce the additional airgap flux density due to eccentricity [47]. Magnetic field harmonics due to the rotor eccentricity generate currents circulating in the parallel paths of the rotor and stator windings. These currents equalize the magnetic field distribution in the air gap, and hence reduce the resultant UMP. The results of the experiment in [48] showed that the parallel stator windings effectively attenuate the net eccentricity force by suppressing significantly the eccentricity harmonics related to the fundamental magnetic field. The studies in [49] and [50] investigated the electromagnetic force harmonies to determine a current slot combination for induction machines in order to reduce UMP. However, the stator winding contains normally fewer parallel paths. Thus the degree of the UMP reduction may depend on the position of the rotor axis displacement, causing the electromagnetic system of the motor to behave inconsistently. There is a difference between the cage rotor and wound rotor UMP. The cage rotor will have substantial differential which can add to the UMP while the wound-rotor machine will not have a parallel path structure like the cage that can damp ($P_m \pm 1$) flux waves generated by the eccentricity. Overall, it has been illustrated that the wound rotor machine has more UMP than the cage machine [14]. Similar results of reducing UMP using parallel connections are reported by Berman in [51]. His experimental findings have shown that using equalizing connections in the stator the UMP of an induction machine can be reduced by 25 times. The particular winding scheme has been called the bridge configured winding (BCW) scheme [52], and the currents flowing across this bridge are known as equalizing currents. It has shown the effect of equalizing currents (applied to the bridge) on the magnetic field coupled with rotor eccentricity.

A two pole induction machine was presented in [23], and it was built with four pole damper winding in stator. The test has shown that using the four-pole extra stator winding to damp the four pole flux reduced the total vibration significantly and stabilize the machine. The authors measured and predicted the unipolar flux in the machine. In [28] a method using pole-specific search coils was introduced and theory was developed. It was tested using search coils in a four pole wound rotor machine. Therefore it was developed to include the damper windings to reduce the UMP, particularly in a wound-rotor machine. Finally an impedance matrix was developed to predict the winding voltages as a function of eccentricity.

VI. Conclusion

This paper has presented a survey of the condition monitoring and the fault diagnoses in induction machines which are related to eccentricity fault. It summarizes the techniques that can be used to detect rotor eccentricity faults in the early stage. Furthermore it discusses the methods which have been proposed to damp UMP. The characteristics of UMP are addressed. The electromagnetic forces between the stator and the rotor can be calculated very quickly but certain aspects of an induction machine such as magnetic saturation, skew effect, effect of slots, and uneven distribution of field are difficult to be incorporated in the calculation. It is clear from the literature that stator current monitoring is by far the most preferred technique to diagnose faults.

More experimental testing and evaluation under real-life conditions and more researches in some specific condition monitoring and fault diagnosis areas are required in the future for the reliable condition monitoring and protection of induction machines. It is important also to compare how the

UMP is affected by the parallel paths in the stator side and the parallel paths in the rotor side.

ACKNOWLEDGMENT

The authors would like to sincerely thank Al-Hussein Bin Talal University for its financial support given through doctoral scholarship to the student Ahmad Salah.

REFERENCES

[1] P. Vas, *Parameter estimation, condition monitoring, and diagnosis of electrical machines*: Oxford University Press, USA, 1993.

[2] P. J. Tavner and J. Penman, *Condition monitoring of electrical machines,* vol. 1: Research Studies Pre, 1987.

[3] W. R. Finley and R. R. Burke, "Troubleshooting motor problems," *Industry Applications, IEEE Transactions on,* vol. 30, pp. 1383-1397, 1994.

[4] R. Belmans and K. Hameyer, "Different approaches to the preventive maintenance of induction motors," in *Proceedings of ICEM 1996*, 1996, pp. 423-428.

[5] H. Toliyat and S. Nandi, "Condition monitoring and fault diagnosis of electrical machines—A review," in *Proceedings of the IEEE-IAS 1999 Annual Meeting*, 1999, pp. 3-7.

[6] W. Thomson, D. Rankin, and D. Dorrell, "On-line current monitoring to diagnose airgap eccentricity in large three-phase induction motors-industrial case histories verify the predictions," *Energy Conversion, IEEE Transactions on,* vol. 14, pp. 1372-1378, 1999.

[7] M. El Hachemi Benbouzid, "A review of induction motors signature analysis as a medium for faults detection," *Industrial Electronics, IEEE Transactions on*, vol. 47, pp. 984-993, 2000.

[8] E. Wiedenbrug, G. Frey, and J. Wilson, "Impulse testing and turn insulation deterioration in electric motors," in *Pulp and Paper Industry Technical Conference, 2003. Conference Record of the 2003 Annual*, 2003, pp. 50-55.

[9] J. Cameron, W. Thomson, and A. Dow, "Vibration and current monitoring for detecting airgap eccentricity in large induction motors," in *IEE Proceedings B (Electric Power Applications)*, 1986, pp. 155-163.

[10] D. Basak, A. Tiwari, and S. Das, "Fault diagnosis and condition monitoring of electrical machines-A Review," in *Industrial Technology, 2006. ICIT 2006. IEEE International Conference on*, 2006, pp. 3061-3066.

[11] L. K. Singh and P. K. S. Komal, "Condition Monitoring of Induction Motor," 2015.

[12] M. Group, "Report of large motor reliability survey of industrial and commercial installations, Part II," *IEEE Trans. Ind. Appl*, vol. 21, pp. 865-872, 1985.

[13] EPRI, "Improved Motors for Utility Applications," *EPRI Final Report,* 1982.

[14] D. G. Dorrell, "Sources and characteristics of unbalanced magnetic pull in three-phase cage induction motors with axial-varying rotor eccentricity," *Industry Applications, IEEE Transactions on,* vol. 47, pp. 12-24, 2011.

[15] D. Dorrell and A. Smith, "Calculation and measurement of unbalanced magnetic pull in cage induction motors with eccentric rotors. Part 2: Experimental investigation," *IEE Proceedings-Electric Power Applications,* vol. 143, pp. 202-210, 1996.

[16] D. G. Dorrell, "*Calculation of unbalanced magnetic pull in cage induction machines*," Thesis, University of Cambridge, 1993.

[17] Y. Amirat, M. Benbouzid, B. Bensaker, and R. Wamkeue, "Condition monitoring and fault diagnosis in wind energy conversion systems: a review," in *IEEE IEMDC'07*, 2007, pp. 1434-1439.

[18] B. Lu, Y. Li, X. Wu, and Z. Yang, "A review of recent advances in wind turbine condition monitoring and fault diagnosis," in *Power Electronics and Machines in Wind Applications, 2009. PEMWA 2009. IEEE*, 2009, pp. 1-7.

[19] Y. Han and Y. Song, "Condition monitoring techniques for electrical equipment-a literature survey," *Power Delivery, IEEE Transactions on,* vol. 18, pp. 4-13, 2003.

[20] D. G. Dorrell and O. Kayani, "Measurement and calculation of unbalanced magnetic pull in wound rotor induction machine," *Magnetics, IEEE Transactions on,* vol. 50, pp. 1-4, 2014.

[21] M. Osama and T. Lipo, "A new induction machine model for analysis of eccentric rotor magnetic pull," in *Proc. of Symposium on Power Electronics, Electrical Drives, Advanced Electrical Motors, SPEEDAM'94Taormina*, 1994, pp. 173-177.

[22] D. G. Dorrell, W. T. Thomson, and S. Roach, "Analysis of airgap flux, current, and vibration signals as a function of the combination of static and dynamic airgap eccentricity in 3-phase induction motors," *Industry Applications, IEEE Transactions on,* vol. 33, pp. 24-34, 1997.

[23] A. Sinervo, A. Laiho, and A. Arkkio, "Low-frequency oscillation in rotor vibration of a two-pole induction machine with extrafour-pole stator winding," *Magnetics, IEEE Transactions on*, vol. 47, pp. 2292-2302, 2011.

[24] K. Binns and M. Dye, "Identification of principal factors causing unbalanced magnetic pull in cage induction motors," *Electrical Engineers, Proceedings of the Institution of,* vol. 120, pp. 349-354, 1973.

[25] W. T. Thomson and M. Fenger, "Current signature analysis to detect induction motor faults," *Industry Applications Magazine, IEEE*, vol. 7, pp. 26-34, 2001.

[26] W. T. Thomson, "On-line MCSA to diagnose shorted turns in low voltage stator windings of 3-phase induction motors prior to failure," in *Electric Machines and Drives Conference, 2001. IEMDC 2001. IEEE International*, 2001, pp. 891-898.

[27] W. T. Thomson and A. Barbour, "On-line current monitoring and application of a finite element method to predict the level of static airgap eccentricity in three-phase induction motors," *Energy Conversion, IEEE Transactions on*, vol. 13, pp. 347-357, 1998.

[28] D. G. Dorrell and A. Salah, "Detection of rotor eccentricity in wound rotor induction machines using pole-specific search coils," in *Magnetics Conference (INTERMAG), 2015 IEEE*, 2015, pp. 1-1.

[29] W. Thomson, "On-line current monitoring to detect electrical and mechanical faults in three-phase induction motor drives," in *Life Management of Power Plants, 1994., International Conference on*, 1994, pp. 66-73.

[30] G. Kliman and J. Stein, "Induction motor fault detection via passive current monitoring-A brief survey," in *Proc. 44th Meeting of the Mechanical Failures Prevention Group*, 1990, pp. 49-65.

[31] W. Thomson and D. Rankin, "Case histories of rotor winding fault diagnosis in induction motors," in *Proceedings of the 1987 International Conference on Condition Monitoring*, 1987, pp. 798-819.

[32] S.-B. Lee and T. G. Habetler, "An on-line stator winding resistance estimation technique for temperature monitoring of line-connected induction machines," in *Industry Applications Conference, 2001. Thirty-Sixth IAS Annual Meeting. Conference Record of the 2001 IEEE*, 2001, pp. 1564-1571.

[33] R. Beguenane and M. E. H. Benbouzid, "Induction motors thermal monitoring by means of rotor resistance identification," *Energy Conversion, IEEE Transactions on,* vol. 14, pp. 566-570, 1999.

[34] P. Milanfar and J. H. Lang, "Monitoring the thermal condition of permanent-magnet synchronous motors," *Aerospace and Electronic Systems, IEEE Transactions on,* vol. 32, pp. 1421-1429, 1996.

[35] A. Siddique, G. Yadava, and B. Singh, "A review of stator fault monitoring techniques of induction motors," *Energy Conversion, IEEE Transactions on,* vol. 20, pp. 106-114, 2005.

[36] D. Guo, F. Chu, and D. Chen, "The unbalanced magnetic pull and its effects on vibration in a three-phase generator with eccentric rotor," *Journal of Sound and vibration,* vol. 254, pp. 297-312, 2002.

[37] B. Li, M.-Y. Chow, Y. Tipsuwan, and J. C. Hung, "Neural-network-based motor rolling bearing fault diagnosis," *Industrial Electronics, IEEE Transactions on,* vol. 47, pp. 1060-1069, 2000.

[38] A. Belahcen, A. Arkkio, P. Klinge, J. Linjama, V. Voutilainen, and J. Westerlund, "Radial forces calculation in a synchronous generator for noise analysis," in *Proceeding of the Third Chinese International Conference on Electrical Machines,* 1999, pp. 199-122.

[39] H. Toliyat, M. Arefeen, and A. Parlos, "A method for dynamic simulation and detection of air-gap eccentricity in induction machines," in *Industry Applications Conference, 1995. Thirtieth IAS Annual Meeting, IAS'95., Conference Record of the 1995 IEEE*, 1995, pp. 629-636.

[40] D.-H. Hwang, K.-C. Lee, J.-H. Lee, Y.-J. Kim, K.-H. Choi, and J.-H. Lee, "A method for dynamic simulation and detection of air-gap eccentricity in induction motors," *2004 ICPE,* 2004, pp. 725-728, 2004.

[41] I. Ahmed, R. Supangat, J. Grieger, N. Ertugrul, and W. Soong, "A baseline study for on-line condition monitoring of induction machines," in *AUPEC 2004, Australasian Universities Power Engineering Conference, Brisbane*, 2004.

[42] J. Penman, M. Dey, A. Tait, and W. Bryan, "Condition monitoring of electrical drives," *IEE Proceedings B (Electric Power Applications)*, pp. 142-148, 1986.

[43] M. Rigoni, N. Sadowski, N. Batistela, J. Bastos, S. Nau, and A. Kost, "Detection and analysis of rotor faults in induction motors by the measurement of the stray magnetic flux," *Journal of Microwaves, Optoelectronics and Electromagnetic Applications*, vol. 11, pp. 68-80, 2012.

[44] D. G. Dorrell, A. Salah, and O. Kayani, "The detection and suppression of unbalanced magnetic pull in wound rotor induction motors using pole-specific search coils and auxiliary windings," *Magnetics, IEEE Transactions on,* 2015.

[45] J. S. Hsu, "Monitoring of defects in induction motors through air-gap torque observation," *Industry Applications, IEEE Transactions on,* vol. 31, pp. 1016-1021, 1995.

[46] J. Hsu, H. Woodson, and W. Weldon, "Possible errors in measurement of air-gap torque pulsations of induction motors," *Energy Conversion, IEEE Transactions on*, vol. 7, pp. 202-208, 1992.

[47] D. G. Dorrell, J. K. Shek, M. A. Mueller, and M.-F. Hsieh, "Damper windings in induction machines for reduction of unbalanced magnetic pull and bearing wear," Industry Applications, IEEE Transactions on, vol. 49, pp. 2206-2216, 2013.

[48] A. Burakov, *Modelling the unbalanced magnetic pull in eccentric-rotor electrical machines with parallel windings*: Helsinki University of Technology, 2007.

[49] B.-T. Kim, B.-I. Kwon, and S.-C. Park, "Reduction of electromagnetic force harmonics in asynchronous traction motor by adapting the rotor slot number," *Magnetics, IEEE Transactions* on, vol. 35, pp. 3742-3744, 1999.

[50] K. Huang, Z. Liu, H. Li, J. Yang, D. Turner, L. Jiang, *et al.*, "Reduction of electromagnetic noise in three-phase induction motors," *in Power System Technology, 2002. Proceedings. PowerCon 2002. International Conference* on, 2002, pp. 745-749.

[51] M. Berman, "On the reduction of magnetic pull in induction motors with off-centre rotor," *in Industry Applications Society Annual Meeting, 1993., Conference Record of the 1993 IEEE*, 1993, pp. 343-350.

[52] R. S. Konwar, K. Kalita, A. Banerjee, and W. K. S. Khoo, "Electromagnetic analysis of a bridge configured winding cage induction machine using finite element method," *Progress In Electromagnetics Research B*, vol. 48, pp. 347-373, 2013.