Monitoring and Damping Unbalanced Magnetic Pull Due to Eccentricity Fault in Induction Machines: A Review

Ahmad Salah[1], Youguang Guo[1], and David Dorrell[2]
[1]Faculty of Engineering & IT, University of Technology Sydney, Sydney, NSW 2007, Australia
[2] Howard College Campus, University of KwaZulu Natal, Durban 4041, South Africa
Ahmad.a.salah@student.uts.edu.au

***Abstract*--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 an 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. The presented paper addresses rotor eccentricity faults and studies conventional monitoring techniques for induction motors. 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 radial forces in an induction motor are calculated, and the characteristics of unbalanced magnetic pull are described.**

***Index Terms*--condition monitoring, eccentric rotor, induction machines, unbalanced magnetic pull (UMP).**

I. Introduction

The best definition of condition monitoring may be the continuous evaluation of the health of the 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 an efficient condition monitoring, it is possible to provide adequate warning of imminent failure. Thus, it is also possible to schedule future preventive maintenance and repair work [2], [3]. 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 [4]-[8]. 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. The motor faults are due to mechanical and electrical stresses [9]. According to IEEE and EPRI reports [10],[11] the occurrence of faults in induction machines are as 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. However, 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, e.g. 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 [12], [13], 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, there are several detection methods as addressed in [14],[15]; each method has its advantages and disadvantages. However, the main idea is that these methods are able to expose faults and to prevent the total damage and reduce unexpected shutdowns. These methods 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 [15]-[19], 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.

TABLE I
SUMMARY OF MOTOR FAULTS, PERCENTAGE OF FAILURE, CAUSES, AND SENSOR SIGNAL USED FOR FAULTS DETECTION

Major Components	Percentage (%) IEEE	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)	22	14	Bent rotor Bearing wear Misalignment	Stator current Vibration Axial flux

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. Other vibrations can also be generated. The eccentricity often appears due to manufacturing 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, 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 center 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. The distribution of the magnetic flux density between the stator and the rotor will be changed due to the eccentricity fault. When an airgap asymmetry appears, a resultant radial force is produced on the rotor and stator, acting at the minimum airgap. 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. Fig. 1 illustrates the different cases of eccentricity. The red areas in Fig. 1 represent the minimum airgap during the run-time.

III. Calculation of UMP

Many different approaches were developed for electromagnetic force calculation in induction machines with eccentric rotors. These can often 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.

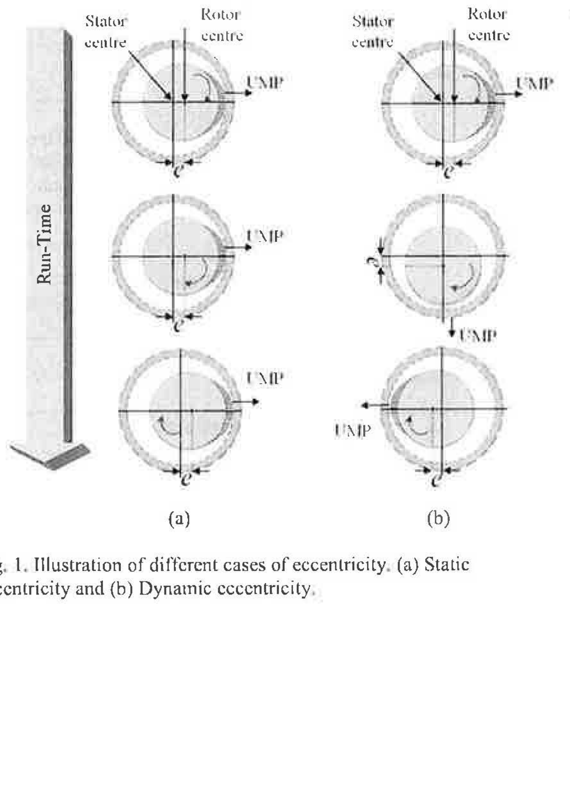

Fig. 1. Illustration of different cases of eccentricity. (a) Static eccentricity and (b) Dynamic eccentricity.

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		✓

A machine consisting of a pair of poles is considered to explain the UMP calculation process as shown in Fig. 2a. 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 magnetomotive force (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 below:

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

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

where A is the area per pole, and g is the length of the air gap, and P_m is fundamental pole-pair number.

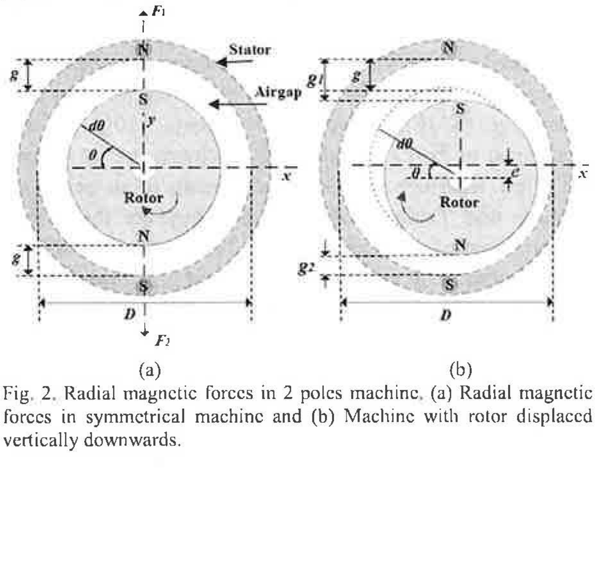

Fig. 2. Radial magnetic forces in 2 poles machine. (a) Radial magnetic forces in symmetrical machine and (b) Machine with rotor displaced vertically downwards.

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, D is the diameter of stator bore, and L is the length of machines core. The radial force acting on the elemental strip is:

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

and the vertical component of the force is:

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

It is evident that if ($g_1 > g_2$) as in Fig. 2b, 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 cause UMP. When the rotor of induction machine is not concentric with the 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 the square of the length of the airgap. Consider the case of a rotor when it is moved vertically downwards as shown in Fig. 2b, where (e) is the displacement of the rotor along downward direction. The total UMP acting on the rotor is

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

The analysis given above assumes the case of static eccentricity, and hence the stator and rotor axes remain parallel during the running time. In (5), 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 [13], [19], and [20], if the rotor is not centered, the 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 $P_m \pm 1$ pole pair magnetic flux waves. In other words, the eccentricity will produce additional flux waves of different pole number in the airgap. This aspect not only opens the door for better understanding of the electromagnetic radial forces in different sorts of the induction machine but also helps to diagnosis the machine vibration in industrial environment. Once the terms for the additional airgap flux waves are obtained as in (6) below, the UMP can be calculated. The additional flux waves are the second and third terms:

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

where B^{Pm} is the peak of the normal component of the main P_m pole pair airgap flux density wave as in (7) below:

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

$$\text{and} \quad \bar{B}^{P_m \pm 1}(x) = \frac{j\mu_0 \bar{J}_{st}}{kP_m g} \bar{\delta}(x) \quad (8)$$

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 [21] 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 [22], if the flux density increases by 20%, the UMP will increase by 44% for a given eccentricity.

IV. Existing Condition Monitoring Techniques

Several methods of electrical machine condition monitoring have evolved over time, but the most distinct techniques are motor current monitoring, thermal monitoring, vibration monitoring, flux monitoring, and torque monitoring. In all the techniques, the obtained signals from the machine are analyzed continuously, thus identifying any significant change which is the indicative of a developing fault.

A. *Stator Current Monitoring*

The popular method is to use line current monitoring where the signature current sidebands are monitored [5], [22], and [23]. 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, the current monitoring is a sensorless detection method that can be implemented without any extra hardware to the machine. However, it is relevant to cage induction machines in terms of commercial system development. In renewable energy, particularly wind turbines, wound rotor induction generators are used and they do not produce the same sideband currents as shown in [25], and [26].

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 [22], [27]. Thomson [23] presented the classical rotor slot passing frequency flux and current components that are spaced at twice the supply frequency $2f$ apart (9), and (10) below 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. There is another major challenge to use this method, as presented in [28] that the unstable load can produce a current harmonic at the frequencies defined by (10)

$$f_{rs} = f\left\{\frac{R}{p_m}(1-s) \pm n_{ws}\right\} \quad (9)$$

$$f_{ec} = f_{rs} \pm f_r$$

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

where f_{rs} are the frequency components due to rotor slotting, R is 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 frequency. The eccentricity fault diagnosis can be done in real time by analyzing frequency components of stator current signals that was discussed in [5] and [24]. For example, monitoring stator current and voltage which is based on the computer-aided monitoring of the stator current and voltage Park's Vectors [29] for detecting the airgap eccentricity.

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 [30]. 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 [31].

Rubbing can happen between the stator and rotor due to many reasons. For example, when there is a misalignment or bearing failure, the rotor can cause puncture in the coil insulation of the coil laminations, resulting in the coil grounding [32]. 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 machine [32]-[34]. 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 induction 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 [7] verified that airgap eccentricity resulted in vibratory harmonics at frequencies of (f_m, f_{m2}, f_{m3}, or f_{m4}). The imbalance of the rotor can also create rotating velocity vibration. Thus it will not be easy to detect the dynamic eccentricity individually by monitoring rotational velocity vibration.

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. Some reflected harmonic spectra will appear if any change occurs in airgap, winding, voltage, or current. In [35] the authors studied the airgap flux as a function of static eccentricity. The change in the airgap flux, can indicate a developing fault and it can be reflected in the harmonic spectrum. In [36] 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 [37], but 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 [38]. A simple method in [25], [26] 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±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 [39] 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 steady torque. The backward stator field interacting with the rotor field creates the oscillating torque. Its frequency is:

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

$$= -\omega_s - \{\omega_s(1-s) + s\omega_s\} = -2\omega_s \quad (11)$$

The double slip frequency torque indicates an unbalanced rotor. 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 [40].

V. Reduction of UMP

In recent years the reduction of radial electromagnetic forces has been the objective of many works. 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 equalizing windings on the stator [18], [21], the use of stator damper windings to reduce the side-band flux waves; and reconnection the stator coils groups to build the parallel paths from winding current.

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 [41] as shown in Fig. 3. The two parallel paths illustrate the equalizing connections in the induction machines and I_{q1} and I_{q2} represent the equalizing current. 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 [42] showed that the parallel stator windings effectively attenuate the net eccentricity force by suppressing significantly the eccentricity harmonics related to the fundamental magnetic field. 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 irregularly.

There is a difference between the cage rotor and wound rotor in the generated 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. It has been illustrated that the wound rotor machine has more UMP than the cage machine [12]. Similar results of reducing UMP using parallel connections are reported by Berman in [43]. The 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 [44], 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 [20], 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 [25]-[26] a method using pole-specific search coils was introduced and theory was developed. It was tested using $P_m \pm 1$ search coils in a four pole wound rotor machine as shown in Fig. 4. Therefore it was developed to include the damper windings to reduce the UMP, particularly in a wound-rotor machine.

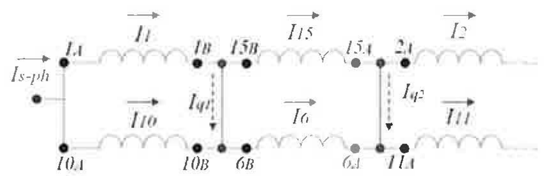

Fig. 3. Phase winding of a four-poles induction machine, with two parallel paths involving three series connected coils each. This figure covers the coil number 1, 2, 6, 10, 11, and 15.

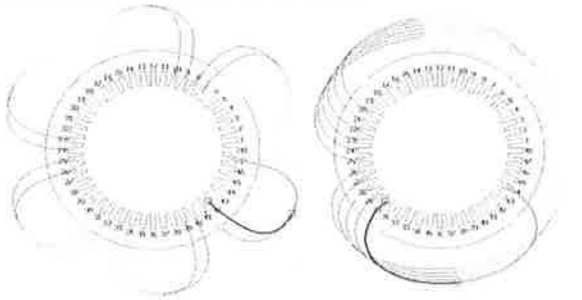

Fig. 4. Phase search windings: 6-pole search coils, 12 coils per phase, and 44 turns per coil and 2-pole search coils, 12 coils per phase, and 15 turns per coil – one phase of each shown.

VI. CONCLUSIONS

This paper has outlined a survey on the condition monitoring and the fault diagnoses in induction machines which are related to eccentricity fault. The paper summarized the techniques that can be used to detect rotor eccentricity faults in the early stage and the methods which have been proposed to damp UMP. The electromagnetic forces between the stator and the rotor vary 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. The researchers have begun to implement artificial neural networks (ANNs) or neuro-fuzzy system to speed and torque estimation. These new techniques including automated fault detection will improve the condition monitoring and faults detection in the future to be more accurate and faster.

More experimental testing and evaluation under real-life conditions are required in the future for the reliable condition monitoring. There is a strong need to develop researches in the area of eccentricity detection of closed-loop drive-fed motors. 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.

REFERENCES

[1] P. Vas, *Parameter Estimation, Condition Monitoring, and Diagnosis of Electrical Machines*, Oxford University Press, USA, 1993.

[2] W. R. Finley and R. R. Burke, "Troubleshooting motor problems," *IEEE Trans. Ind. Appl.*, vol. 30, no. 5, pp. 1383-1397, 1994.

[3] R. Belmans and K. Hameyer, "Different approaches to the preventive maintenance of induction motors," in *Proc. ICEM 1996*, 1996, vol. 2, no. 3, pp. 423-428.

[4] H. Toliyat and S. Nandi, "Condition monitoring and fault diagnosis of electrical machines—A review," in *Proc. IEEE-IAS 1999 Annu. Meeting*, vol. 1, 1999, pp. 3-7.

[5] 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,"

IEEE Trans. Energy Convers., vol. 14, no. 4, pp. 1372-1378, 1999.

[6] M. El Hachemi Benbouzid, "A review of induction motors signature analysis as a medium for faults detection," *IEEE Trans. Ind. Appl.*, vol. 47, no. 5 , pp. 984-993, 2000.

[7] J. Cameron, W. Thomson, and A. Dow, "Vibration and current monitoring for detecting airgap eccentricity in large induction motors," *Proc. IEEE B (Elect. Power Appl.)*, vol. 133, no. 3, pp. 155-163, 1986.

[8] D. Basak, A. Tiwari, and S. Das, "Fault diagnosis and condition monitoring of electrical machines-A Review," *Ind. Tech. ICIT 2006. IEEE Int. Conf.*, 2006, pp. 3061-3066.

[9] L. K. Singh and P. K. S. Komal, "Condition monitoring of induction motor," *Int. Journal of Engineering and Technical Research*, vol. 3, 2015.

[10] M. Group, "Report of large motor reliability survey of industrial and commercial installations, Part II," *IEEE Trans. Ind. Appl.*, vol. 21, no. 4, pp. 865-872, 1985.

[11] EPRI, "Improved motors for utility applications," *EPRI Final Report*, 1982.

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

[13] D. G. Dorrell and A. Smith, "Calculation and measurement of unbalanced magnetic pull in cage induction motors with eccentric rotors. Part 2: Experimental investigation," *IEEE Proc. Electric Power Appl.*, vol. 143, no. 3, pp. 202-210, 1996.

[14] 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 Appl., 2009. PEMWA 2009. IEEE*, 2009, pp. 1-7.

[15] Y. Han and Y. Song, "Condition monitoring techniques for electrical equipment-a literature survey," *IEEE Trans. Power Delivery*, vol. 18, no. 1, pp. 4-13, 2003.

[16] G. M. Joksimovic, "Dynamic simulation of cage induction machine with air gap eccentricity," *Proc. Inst. Elect. Eng.—Elect. Power Appl.*, vol. 152, no. 4, pp. 803–811, Jul. 2005.

[17] D. G. Dorrell and O. Kayani, "Measurement and calculation of unbalanced magnetic pull in wound rotor induction machine," *IEEE Ind. Appl. Mag.*, vol. 50, pp. 1-4, 2014.

[18] 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.

[19] 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," *IEEE Trans. Ind. Appl.*, vol. 33, no. 1, pp. 24-34, 1997.

[20] A. Sinervo, A. Laiho, and A. Arkkio, "Low-frequency oscillation in rotor vibration of a two-pole induction machine with extrafour-pole stator winding," *IEEE Ind. Appl. Mag.*, vol. 47, no. 9, pp. 2292-2302, 2011.

[21] K. Binns and M. Dye, "Identification of principal factors causing unbalanced magnetic pull in cage induction motors," *Proc. of the Institution of Electrical Engineers*, vol. 120, no. 9, pp. 349-354, 1973.

[22] W. T. Thomson and M. Fenger, "Current signature analysis to detect induction motor faults," *IEEE Trans. Ind. Appl.*, vol. 7, no. 4, pp. 26-34, 2001.

[23] 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 Conf., 2001. IEMDC 2001. IEEE Int.*, 2001, pp. 891-898.

[24] 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," *IEEE Trans. Energy Convers.*, vol. 13, no.4, pp. 347-357, 1998.

[25] D.G Dorrell, A. Salah, & Y. Guo, "The detection and suppression of unbalanced magnetic pull in wound rotor induction motors using pole-specific search coils and auxiliary windings," *IEEE Trans. Ind. Appl.*, vol. 53, no. 3, pp. 2066-2076, 2017.

[26] D. G. Dorrell and A. Salah, "Detection of rotor eccentricity in wound rotor induction machines using pole-specific search coils," *IEEE Mag.Conf. , 2015*, pp. 1-1.

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

[28] R. R. Obaid, T. G. Habetler, and D. J. Gritter, "A simplified technique for detecting mechanical faults using stator current in small induction motors," in *Conf. Rec. IEEE IAS Annu. Meeting*, 2000, vol. 1, pp. 479–483.

[29] A. J. M. Cardoso and E. S. Saraiva, "Computer-aided detection of airgap eccentricity in operating three-phase induction motors by Park's vector approach," *IEEE Trans. Ind. Appl.*, vol. 29, no. 5, pp. 897–901, Sep./Oct. 1993.

[30] R. Beguenane and M. E. H. Benbouzid, "Induction motors thermal monitoring by means of rotor resistance identification," *IEEE Trans. Energy Convers.*, vol. 14 , no. 3, pp. 566-570, 1999.

[31] P. Milanfar and J. H. Lang, "Monitoring the thermal condition of permanent-magnet synchronous motors," *IEEE Trans. Aerospace and Electronic Systems*, vol. 32, no. 4 , pp. 1421-1429, 1996.

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

[33] B. Li, M.-Y. Chow, Y. Tipsuwan, and J. C. Hung, "Neural-network-based motor rolling bearing fault diagnosis," *IEEE Trans. Ind. Electro.*, vol. 47, no. 5, pp. 1060-1069, Oct.2000.

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

[35] H. A. Toliyat, M. S. Arefeen, and A. G. Parlos, "A method for dynamic simulation of air-gap eccentricity in induction machines," *IEEE Trans. Ind. Appl.*, vol. 32, no. 4, pp. 910–918, Jul./Aug. 1996.

[36] 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.

[37] J. Penman, M. N. Dey, A. J. Tait, and W. E. Bryan, "Condition monitoring of electrical drives," *Proc. Inst. Elect. Eng.—Elect. Power Appl.*, vol. 133, no. 3, pp. 142–148, May 1986.

[38] 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 Appl.*, vol. 11, no.1, pp. 68-80, 2012.

[39] J. S. Hsu, "Monitoring of defects in induction motors through air-gap torque observation," *IEEE Trans. Ind. Appl.*, vol. 31, no. 5, pp. 1016-1021, 1995.

[40] J. Hsu, H. Woodson, and W. Weldon, "Possible errors in measurement of air-gap torque pulsations of induction motors," *IEEE Trans. Energy Convers.*, vol. 7, no. 1, pp. 202-208, 1992.

[41] 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," *IEEE Trans. Ind. Appl.*, vol. 49, no.5, pp. 2206-2216, 2013.

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

[43] M. Berman, "On the reduction of magnetic pull in induction motors with off-centre rotor," *IEEE Trans. Ind. Appl. Society Annu. Meeting, 1993., Conf. Record of the 1993 IEEE*, 1993, pp. 343-350.

[44] 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.