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BROKEN ROTOR BAR FAULT DETECTION IN LINE START-PERMANENT MAGNET SYNCHRONOUS MOTOR

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By

MOHAMMAD REZAZADEH MEHRJOU

This thesis Submitted to the School of Graduate Studies, Universiti Putra Malaysia, in Fulfillment of the Requirements for the Degree of Doctor of Philosophy

October 2016

DEDICATION

To my Parents: Ail and Iran
my Parents in law: Amrolah, Afsar
my lovely Wife, Firoozeh Danafar,
my caring Son: Radin, and
my Family

Abstract of thesis presented to the Senate of Universiti Putra Malaysia in fulfillment of the requirement for the degree of Doctor of Philosophy

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Chairman : Professor Norman Mariun, PhD, PEng
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High efficiency motors are being gradually exerted in many industrial applications because of their positive impacts on the environment by reducing energy consumption and CO_2 emission. In this regard, Line Start Permanent Magnet Synchronous Motors (LS-PMSMs) have been introduced to the market recently. Due to the unique configuration, LS-PMSMs are allowed to reach Super Premium Efficiency levels accompanied with high torque and power factor. However, since the use of LS-PMSMs in industry is in its infancy, no efficient scheme has been reported for faults detection in this type of motor. Online monitoring and setting of preventive maintenance programs in the industries is one of the important issues. Therefore, in order to classify different indices of motor under fault condition, the electrical behavior of LS-PMSMs motor under broken rotor bar should be considered and the electrical parameters should be characterized. The main aim of this research is to investigate the effects of broken rotor bar fault on LS-PMSMs performance, and also to find reliable fault-related feature for this fault. The proposed detection strategy for broken rotor bar in LS-PMSM is based on monitoring of startup current signal. In this regard, a simulation model and experimental setup for investigation of broken rotor bar in LS-PMSM is obtained. The current signal is used to extract the fault-related features using three different signal processing method. Finally, the ability of these features is validated for detection of broken rotor bar in LS-PMSM through statistical analysis. This study can be beneficial for the industry by using the online monitoring systems where the motor fault can be detected during its operation. Therefore, the proposed method can be used in the preventive maintenance programs.

This research indicates the importance of load effects on broken bar detection in LS-PMSMs. The current signal is collected at different load levels of starting torque within four steps, which increases from 0% to 65%. The experimental and simulation results substantiate that increasing the load, will also increase the starting time duration. The time duration of machine with one broken rotor bar also increases compared to healthy

condition. The value of starting torque drops in the presence of broken rotor bar fault. In the time domain analysis, three features, namely peak to peak, shape factor and impulse factor cannot distinguish faulty state of motor from healthy state based on upward or downward trend. Skewness also fails to detect broken bar when the starting torque is high. In time domain analysis using of envelop signal, four features, namely RMS, RSSQ, Energy and Variance cannot distinguish faulty state of motor from healthy state at low level load. The variance feature also fails to detect the fault based on upward or downward trend. When the starting torque is high, Kurtosis feature is not a suitable feature to detect broken rotor bar. In the time-frequency domain analysis, Log Energy Entropy feature has satisfactory performances for broken rotor bar detection compare to Shannon Entropy feature. The result also presents that the most effective sub-band frequency is Detail of level 7 that includes the frequency band ranges of [39.06-19.53]Hz. The simulation results were validated with an experimental work to confirm the effectiveness of proposed methods.

Abstrak tesis yang dikemukakan kepada Senat Universiti Putra Malaysia sebagai memenuhi keperluan untuk ijazah Doktor Falsafah

PENGESANAN KEROSAKAN BAR ROTOR PECAH DALAM MOTOR SEGERAK MAGNET KEKAL MULA TALIAN

Oleh

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Motor kecekapan tinggi sedang digunapakai secara berperingkat dalam pelbagai aplikasi industri kerana kesan positifnya terhadap alam sekitar dengan mengurangkan penggunaan tenaga dan pelepasan CO_2. Dengan itu, Motor Segerak Magnet Kekal Mula Talian (LS-PMSMs) telah diperkenalkan baru-baru ini. Oleh kerana konfigurasinya yang unik, LS-PMSMs membolehkan motor untuk mencapai tahap kecekapan super premium dengan disertai tork dan faktor kuasa yang tinggi. Walau bagaimanapun, sejak penggunaan LS-PMSMs dalam industri di peringkat awal, tidak ada lagi sistem cekap yang dilaporkan untuk mengesan kerosakan motor ini. Pemantauan dalam talian dan penetapan program penyelenggaraan pencegahan dalam industri adalah salah satu isu penting. Oleh itu, untuk mengelaskan indeks motor yang berbeza dalam keadaan rosak, tingkah laku elektrik motor LS-PMSMs di bawah bar rotor pecah perlu dipertimbangkan dan parameter elektrik harus dicirikan. Matlamat utama kajian ini adalah untuk mengkaji kesan kerosakan bar rotor pecah pada prestasi LS-PMSMs, dan untuk mencari ciri-ciri kaitan kerosakan ini. Strategi pengesanan untuk bar rotor pecah pada LS-PMSM dicadangkan di sini di mana ianya adalah berdasarkan pemantauan isyarat semasa permulaan. Dalam hal ini, model simulasi dan persediaan eksperimen untuk siasatan bar rotor pecah dalam LS-PMSM diperolehi. Isyarat semasa digunakan untuk mengekstrak ciri yang berkaitan dengan kerosakan menggunakan tiga kaedah pemprosesan isyarat yang berbeza. Akhir sekali, keupayaan ciri-ciri ini disahkan untuk mengesan bar rotor pecah dalam LS-PMS motor melalui analisis statistik. Kajian ini boleh memberi manfaat kepada industri dengan menggunakan sistem pemantauan dalam talian di mana kerosakan motor boleh dikesan semasa operasinya. Oleh itu, kaedah yang dicadangkan boleh digunakan dalam program-program penyelenggaraan pencegahan.

Kajian ini menunjukkan betapa pentingnya kesan beban pada pengesanan bar rotor pecah dalam LS-PMSMs. Isyarat semasa dikumpulkan dalam tahap beban yang berbeza pada tork yang bermula dalam empat langkah, yang meningkat dari 0% hingga

65%. Keputusan eksperimen dan simulasi mengesahkan bahawa peningkatan beban akan juga meningkatkan tempoh masa permulaan. Tempoh masa mesin dengan satu bar rotor pecah juga meningkat jika berbanding keadaan normal. Selain itu, bar rotor pecah juga memberi kesan pada kejatuhkan nilai permulaan tork. Dalam analisis domain masa, tiga ciri, iaitu puncak ke puncak, faktor bentuk dan faktor dorongan tidak dapat membezakan kerosakan nyata motor dalam keadaan normal berdasarkan trend ke atas atau ke bawah. Kepencongan juga gagal untuk mengesan bar rotor pecah apabila permulaan tork tinggi. Dalam analisis domain masa menggunakan isyarat envelop, empat ciri, iaitu RMS, RSSQ, Tenaga dan Varians tidak dapat membezakan kerosakan nyata motor pada keadaan normal yang berada pada tahap rendah beban. Ciri varians juga gagal untuk mengesan kerosakan berdasarkan trend ke atas atau ke bawah. Apabila tork permulaan yang tinggi, ciri Kurtosis adalah tidak sesuai untuk mengesan bar rotor pecah. Dalam analisis domain masa-frekuensi, ciri Log Tenaga Entropy mempunyai prestasi yang memuaskan bagi pengesanan bar rotor pecah jika dibandingkan dengan ciri Shannon Entropi. Keputusan juga menunjukkan sub-band frekuensi yang berkesan adalah Perincian Tahap 7 yang merangkumi julat jalur frekuensi bagi [39,06-19,53] Hz. Oleh itu, keputusan eksperimen dan simulasi menyokong antara satu sama lain dan mengesahkan kerja-kerja secara keseluruhan.

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LIST OF ABBREVIATIONS

a	Wavelet scale
$A_{m0,n}$	Approximate coefficients
AC	Alternative current
b	Wavelet position
B_{ag}	Air-gap flux density
CWT	Continuous wavelet transform
c_1	T_{Cage} correction factor
$D_{m,n}$	Detail coefficients
DC	Direct current
DFT	Discrete Fourier transform
DWT	Discrete wavelet transform
f_{brb}	Broken rotor bar frequency feature
f_{fbrb}	Fluctuating frequency related to broken rotor bar
f_{LSH}	Left Sideband Harmonic Frequency
f_r	Rotor frequency
f_s	Sampling frequency
f	Fundamental frequency
f_{sh}	Rotor slot harmonic frequency
$f_{T^{\pm}}$	Frequency related to electromagnetic torque
f_{Tbrb}	Frequency related to the broken rotor bar fault in torque spectrum
FFT	Fast Fourier transform
GUI	Graphical Interface Unit
$i(t)$	Instantaneous stator current
i_A, i_B, and i_C	Three-phase line currents
$I^K_{(1-2ks)f}$	Amplitude for harmonic component $f_{(1-2ks)f}$
$I^K_{(1+2ks)f}$	Amplitude for harmonic component $f_{(1+2ks)f}$
I_f	Amplitude of stator current at fundamental frequency
I_{PN}	Primary nominal RMS
I_P	Primary current
J	Total moment of inertia
k	$k = 1,2,3, ..$
$k' = 1\ or\ 0$	When exists or not effect of saturation
LS-PMSM	Line start permanent magnet motor
l_x	Length of the rotor
$l = 1,2,3, \ldots$	The rotor slot related harmonic rank number
MCSA	Motor current signature analysis
MMF_{ag}	Air-gap magneto-motive force
μ	The rotor harmonic rank number
N_R	The number of rotor bars
m	Stator phases
N_{BRB}	The number of broken rotor bar
n	Rotor speed
n'	A sum or difference of any two integers n'=2,-1, 0, 1, 2, ...
n_{sys}	Synchronous speed

n_{RATED}	Rated asynchronous speed
p	Number of pole pairs
P_{ag}	Air-gap permeance
R	Half of the line-to-line resistance
R_c	The contact resistance between the bar and the rotor core
R_b	Number of broken bars
RMS	Root mean square
RSH	Rotor slot harmonics
R_1	Stator resistance
R_2'	Rotor resistance referred
s	Slip
S_{RF}	Severity of the fault
STFT	Short-time Fourier transform
T_{Break}	Dynamic braking torque
T_{Cage}	Cage torque
T_{Load}	Load torque
T_{Sync}	Synchronous torque
v	The stator harmonic rank number
v_{AB}, v_{Bc}, v_{CA}	Line to Line voltages
V_{ph}	rms phase voltage
W	Window position
W_{cwt}	Continuous wavelet coefficient
ω_{bMMF}	Speed of the backward MMF with respect to the stator
ω_m	Rotor speed
ω_{syn}	Synchronous speed
X_1	Stator leakage reactance
X_2'	Rotor leakage reactance referred
Z_b	The bar impedance
ψ	Mother wavelet or wavelet functions
ω	Angular frequency
ω_s	Electrical synchronous speed
ϕ	Scaling functions or scaling functions
φ_s	Stator angular position
φ	Main phase shift angle of stator current
$\varphi^k_{(1-2ks)f}$	Phase shift angle of harmonic component $f_{(1-2ks)f}$
$\varphi^k_{(1+2ks)f}$	Phase shift angle of harmonic component $f_{(1+2ks)f}$
θ_{rm}	Mechanical rotor position
δ	Load angle (rad)

CHAPTER 1

INTRODUCTION

In this chapter, after presenting the research problem statement, the aim and objectives and scopes of this dissertation are presented. A short background about the extent of this research work is discussed and the contribution to the knowledge is specified. This chapter ends with the layout of the thesis.

1.1 General Background

Electrical machines facilitate and expedite production processes and related services leading to immense changes in the human life style. They are extensively employed in the entire aspects of domestic, industrial, commercial, utility and special-purpose commercial markets. The rugged configuration of squirrel-cage electrical machines (induction machine) with reasonable price and size make them suitable for all these applications. The other desired characteristics of squirrel-cage electrical machines are their adaptability and operation with an easily available power supply because of using squirrel-cage bars. However, induction machines suffer from low efficiency and low power factor that means the loss of energy is high. This issue is viewed as an important disadvantage because of the energy cost and global energy concerns.

The improvement of induction machine efficiency was examined through an optimal design of these motors. However, due to several inherent limitations, it is difficult to improve the efficiency of its significantly. An option is to substitute induction machine by high efficiency permanent magnet Synchronous motors (PMSMs). An important obstacle for ordinary PMSMs is they need inverter to start, which is not economical for single speed applications. To overcome this problem, the permanent magnet motors equipped with squirrel-cage bars, called Line Start Permanent Magnet Synchronous motors (LS-PMSMs), have been introduced. LS-PMSMs also allow reaching Super Premium Efficiency levels [1,2]. A LS-PMSM consists of a stator (single or poly-phase) and a hybrid rotor comprising electricity conducting squirrel cage and pairs of permanent magnet poles. Squirrel-cage bars in electrical machine produce adequate high starting torque when the motor is run from standstill. Similar to asynchronous motors, squirrel-cage bars in LS-PMSM develop the startup performance during motor run up by enabling the rotor to have direct-on-line movement. When the load situation is unbalanced or the rotation speed is fluctuated, an important role of squirrel-cage bars is to lessen the counter-rotating fields of the air gap, which otherwise would lead to significant losses [3].

In the practical applications, LS-PMSMs are subjected to unavoidable stresses, such as electrical, environmental, mechanical and thermal stresses. These stresses produce some failures and imperfections in different parts of the LS-PMSMs. The created faults disturb the safe operation of the LS-PMSMs, threaten the normal manufacturing, and therefore result in the substantial cost penalties. An efficient fault detection technique can reduce the maintenance costs by preventing the high expense failures and unscheduled downtimes.

Breakage of the rotor bars is usually the serious failure in the squirrel cage motors, because it progressively increase different stresses and also brings possible secondary failures in machine. These failures will also reduce the motor efficiency, threaten its safe operation, shorten its lifetime and thus increase the operational cost. Broken rotor bar generates unbalanced currents and torque pulsation, and as a result reduces the developed torque and increases the speed fluctuations of the motor [4]. Changes in the rotor current distribution due to bar breakage progressively deteriorates the condition of the neighboring bars. For instance, once a bar breaks, the current in the neighboring bars increases up to 50% of rated current and overheat them [5,6]. The overheated bars bow and cause the rotor bends over that results an eccentricity, which causes basic rotor unbalance and a greater unbalanced magnetic pull [7]. Broken rotor bar may also cause a shaft vibration that results failures in bearing and eccentricity in the air gap [8]. In permanent magnet motor, the extra heat can also demagnetize the permanent magnets [9]. During operation of the motor, the broken rotor bar may rise out itself, or broken pieces of the rotor bar may exit the slot due to the centrifugal force and damage the stator windings or laminations [10]. Broken rotor bar is mainly accounted for noise during the motor start-up as well as destructive sparking that threatens the operation safety [11]. Accordingly, diagnosis of broken bars in electrical machine can preserve its good performance and its normal lifetime [12]. As the LS-PMSMs have a hybrid rotor with squirrel-cage bars and permanent magnets, it is not distinct from this part, broken rotor bars can also occur in this motor.

Manufacturing companies are making great efforts to ensure proper condition of the motors by predicting motors imperfection and failures using machinery maintenance plan. The maintenance plans are relied on observation of the machines operating condition for diagnosing the existent failure at an early stage, *i.e.* before it causes the machines to stop. An operative condition monitoring technique that can manifest the situation of electrical machine in order to detect the fault is a key requirement of maintenance. This system should be able to detect any change in the machine quantities to predict the necessity of maintenance before major breakdown occurs. Hitherto, a variety of condition monitoring techniques, which monitor a certain parameter of the electrical machines allowing its health to be determined, have been developed [13].

1.2 Problem statement

The most recent global motor market survey and forecast assumes that the number of low voltage motors sold between 2014 and 2019 will increase by 11% and IE4 appears on the horizon with 1.5% of the global market share of motors by 2019 [14]. The LS-PMSMs are the latest electrical machine selection of researchers owing to their high efficiency and power density, quiet operation and compact size. The LS-PMSMs provide efficiency close to NEMA Super Premium Efficiency standard

(IE4). As the number of LS-PMSMs used in different fields is increasing, presence of maintenance scheme for fault detection in this type of motor becomes important and vital. Early detection of irregularity in the motor with a proper fault diagnosis scheme will help to prevent high cost failures and hence reduces maintenance costs and more importantly prevents unexpected downtimes that cease the production and cause loss of financial income. Since, the productivity of LS-PMSM for various applications is in its infancy; the lack of an accurate broken rotor bar fault detection technique does not exist and also no research work is reported in this case. Accordingly, this research intends to investigate the ability of fault-related features for broken rotor bars fault in LS-PMSMs in different signal processing methods.

1.3 Aim and Objectives

The main aim of this dissertation is to study the effects of broken bars that may occur in LS-PMSMs on motor performance and propose a fault-related feature indicative of this failure in LS-PMSMs. In this respect, relevant papers were accurately surveyed and studied to select suitable methods for condition monitoring and signal processing. Research methodology was then designed and conducted according to the objectives of this dissertation. This study embarks on the following objectives:

- to obtain and simulate a three-phase, 4-pole LS-PMSM with different starting torque of case study machine using finite element method in order to procure the stator current signal for both healthy and faulty conditions,
- to investigate the machine performance in the presence of fault,
- to investigate and validate the statistical fault-related features extracted from startup current signal using time domain analysis in order to identify the broken rotor bars fault in simulation and experimental study,
- to investigate and validate the statistical fault-related features extracted from the startup current signals using time domain envelope analysis in order to identify the broken rotor bars fault in simulation and experimental study, and
- to investigate and validate the features extracted from the startup current signals using Wavelet analysis (Time-frequency domain analysis) in order to identify the broken rotor bars fault in simulation and experimental study.

1.4 Thesis Scope

This dissertation provides a comprehensive study on broken rotor bars fault condition monitoring in electrical machine. The main focus is given to introduce features for detection of broken rotor bars fault in three-phase, 4-pole LS-PMSM during the startup operation condition. Accordingly, the effect of broken rotor bars in case study motor is investigated. The accuracy of research outcomes are examined through a professional laboratory examination in addition to a simulation performance. The influence of starting load on fault-related features is investigated and data acquisition has been collected while the motor running at 0%, 21.7%, 43.47% and 65.21% of its rated starting torque. Motor current signature analysis has been selected for condition monitoring of the motor during its startup operation. The signals acquired through this method are processed using Time and Time-frequency domain to find the feature related to the fault detection in LS-PMSM. At the last stage, statistical analysis is used to validate the method that proposed for fault detection.

A three-phase, 4-pole LS-PMSM is simulated based on finite element method (FEM) using Maxwell 2-D software. The specifications of simulated LS-PMSM and the motor used in the laboratory test exactly match. Three phase sinusoidal voltages are applied to the motor terminals as windings excitation. To obtain the startup current signal of LS-PMSM, a transient solver with time integration method based on backward Euler is employed. In the simulation method, starting loads are obtained and set equal to the load percentages implemented in the experimental activities. Either the current signals of stator obtained through simulation or experiment is then analyzed to extract the fault-related features for fault detection. The obtained features are compared to validate the results and determine the most reliable fault-related features.

The area of current research is limited to the objectives mentioned above in order to investigate the effect of broken rotor bar in three-phase, 4-pole LS-PMSM. Accordingly, investigation on other types of faults, application of further condition monitoring methods and other signal processing techniques are beyond the objectives of this thesis.

1.5 Contribution of the Thesis

- This work is a new research in broken rotor bar detection in LS-PMSM and none of the previous researches published has attempted to detect this fault. The reason is LS-PMSM was launched to the market recently, and its application is growing gradually. The other reason may be the complexity of broken rotor bar detection in LS-PMSM. Detection of broken rotor bar in LS-PMSM is one of the major contributions of this dissertation.
- This research attempts to investigate the effects of broken bar on the performance of machine through simulation and experimental analyses.
- The reliable features are proposed for broken rotor bar detection in three-phase 4-pole LS-PMSM based analysis of transient current signal. The reason for monitoring of stator current is its accessibility, being cost effective and having noninvasive characteristics.
- Finally, this research provides remarkable outcomes for further research in the area of fault detection techniques in LS-PMSMs.

1.6 Thesis Layout

Chapter one presents a brief introduction on the research background of current study. The research requirements are stated as the problem statement to define the key research aspects used. The aim and objectives of the study are listed to present the focus of the research. Afterward, the scope of research work and relevant contributions are highlighted.

Chapter Two provides an extensive literature review related to the dissertation topic. The general structure of LS-PMSM is described. The broken rotor bars fault and its effects on Squirrel-cage electrical machine are described. Different methods for signal acquisition and signal processing with the purpose of fault detection in electrical machines are comprehensively documented. The chapter ends with research trends in broken rotor bar detection for LS-PMSM.

Chapter three presents the research methodology designed and conducted according to the objectives of this dissertation. In the first section of Chapter three, the simulation of LS-PMSM with finite element method software is introduced. In the second section, full demonstration of experimental set up, devices, instruments is explained. In the final section of this chapter, signal-processing methods implemented in this case study and features used as fault signature are introduced. At the end of chapter, statistical analysis is explained for features validation.

Chapter four presents the results and discussions on the effect of broken rotor bar on startup current captured from LS-PMSM. Different features with three methods of signal processing are discussed and statistical analysis is used to validate the ability of each methods. The relevant explanations and interpretations on the results and observations presented provide a promising conclusion.

Chapter Five finally presents conclusion drawn from this research for broken rotor bar detection in three-phase, 4-pole LS-PMSM, as well as recommendations for future study that can be implemented in the field of fault detection in LS-PMSM.

REFERENCES

[1] H. A. Toliyat and G. B. Kliman, *Handbook of Electric Motors*. 2004.

[2] WEG, *WQuattro-Super Premium Efficiency Motor*. 2015.

[3] J. Pyrhonen, T. Jokinen, and V. Hrabovcova, *Design of Rotating Electrical Machines*. Wiley, 2009.

[4] J. Ilonen, J.-K. Kamarainen, T. Lindh, J. Ahola, H. Kalviainen, and J. Partanen, “Diagnosis Tool for Motor Condition Monitoring,” *IEEE Transactions on Industry Applications*, vol. 41, no. 4, pp. 963–971, Jul. 2005.

[5] R. Fiser and S. Ferkolj, “Application of a finite element method to predict damaged induction motor performance,” *IEEE Transactions on Magnetics*, vol. 37, no. 5, pp. 3635–3639, 2001.

[6] A. Bellini, F. Filippetti, C. Tassoni, and G.-A. Capolino, “Advances in Diagnostic Techniques for Induction Machines,” *IEEE Transactions on Industrial Electronics*, vol. 55, no. 12, pp. 4109–4126, Dec. 2008.

[7] W. R. Finley, M. M. Hodowanec, and W. G. Holter, “An Analytical Approach to Solving Motor Vibration Problems,” in *IEEE 46th Annual Industry Applications Society*, 1999, pp. 217–232.

[8] P. Zhang, Y. Du, T. G. Habetler, and B. Lu, “A Survey of Condition Monitoring and Protection Methods for Medium-Voltage Induction Motors,” *IEEE Transactions on Industry Applications*, vol. 47, no. 1, pp. 34–46, Jan. 2011.

[9] H. M. Zubayer, “Design Analysis of Line-start Interior Permanent Magnet Synchronous Motor,” Memorial University of Newfoundland, 2011.

[10] I. Culbert and W. Rhodes, “Using Current Signature Analysis Technology to Reliably Detect Cage Winding Defects in Squirrel Cage Induction Motors,” *IEEE Transactions on Industry Applications*, vol. 43, no. 2, pp. 95–101, 2007.

[11] A. H. Bonnett and G. C. Soukup, “Rotor Failures in Squirrel Cage Induction Motors,” *IEEE Transactions on Industry Applications*, vol. IA-22, no. 6, pp. 1165–1173, Nov. 1986.

[12] J. Faiz, B. M. Ebrahimi, and M. B. B. Sharifian, “Time Stepping Finite Element Analysis of Broken Bars Fault in a Three-Phase Squirrel-Cage Induction Motor,” *Progress In Electromagnetics Research*, vol. 68, pp. 53–70, 2007.

[13] M. R. Mehrjou, N. Mariun, M. Hamiruce Marhaban, and N. Misron, “Rotor fault condition monitoring techniques for squirrel-cage induction machine—A review,” *Mechanical Systems and Signal Processing*, vol. 25, no. 8, pp. 2827–2848, Nov. 2011.

[14] International Energy Agency, “Energy Efficiency Roadmap for Electric Motors and Motor Systems,” 2015.

[15] I. Ahmed, R. Supangat, J. Grieger, N. Ertugrul, and W. Soong, “A Baseline Study for On-Line Condition Monitoring of Induction Machines,” in *Australasian Universities Power Engineering Conference*, 2004.

[16] P. WaIde and C. Brunner, “Energy-efficiency policy opportunities for electric motor-driven systems,” 2011.

[17] A. Hassanpour Isfahani and S. Vaez-Zadeh, “Line start permanent magnet synchronous motors: Challenges and opportunities,” *Energy*, vol. 34, no. 11. Elsevier Ltd, pp. 1755–1763, 2009.

[18] O. Arabacı, Hayri and Bilgin, “Analysis of Rotor Faults Effects on Submersible Induction Motor’ Efficiency,” in *Proceedings of The World*

Congress on Engineering and Computer Science, 2013.

[19] C. da Costa, M. Kashiwagi, and M. H. Mathias, “Rotor failure detection of induction motors by wavelet transform and Fourier transform in non-stationary condition,” *Case Studies in Mechanical Systems and Signal Processing*, vol. 1, pp. 15–26, 2015.

[20] Y. Gritli, S. Bin Lee, F. Filippetti, and L. Zarri, “Advanced Diagnosis of Outer Cage Damage in Double-Squirrel-Cage Induction Motors Under Time-Varying Conditions Based on Wavelet Analysis,” *IEEE Transactions on Industry Applications*, vol. 50, no. 3, pp. 1791–1800, May 2014.

[21] Ž. Kanovi, D. Mati, Z. Jeli, M. Rapai, B. Jakovljevi, and M. Kapetina, “Induction Motor Broken Rotor Bar Detection Using Vibration Analysis – A Case Study,” in *9th IEEE International Symposium on Diagnostics for Electric Machines, Power Electronics and Drives*, 2013, pp. 64–68.

[22] F. W. Merrill, “Permanent magnet excited synchronous motors,” *Electrical Engineering*, vol. 74, no. 2, pp. 143–143, Feb. 1955.

[23] T. J. E. Miller, “Synchronization of Line-Start Permanent-Magnet AC Motors,” *IEEE Transactions on Power Apparatus and Systems*, vol. PAS-103, no. 7, pp. 1822–1828, 1984.

[24] A. Chama, A. J. Sorgdrager, and R. Wang, “Analytical synchronization analysis of line-start permanent magnet synchronous motors,” *Progress In Electromagnetics Research M*, vol. 48, no. May, pp. 183–193, 2016.

[25] T. J. E. Miller, M. Popescu, C. Cossar, M. McGilp, G. Strappazzon, N. Trivillin, and R. Santarossa, “Line-Start Permanent-Magnet Motor Single-Phase Steady-State Performance Analysis,” *IEEE Transactions on Industry Applications*, vol. 40, no. 2, pp. 516–525, Mar. 2004.

[26] G. Huth and R. Fischer, “Running up and pulling into step of PM line-start motors with surface-mounted magnets,” *Electrical Engineering*, vol. 97, no. 1, pp. 13–24, 2014.

[27] J. Faiz, B. M. Ebrahimi, and M. B. B. Sharifian, “Different Faults and Their Diagnosis Techniques in Three-Phase Squirrel-Cage Induction Motors—A Review,” *Electromagnetics*, vol. 26, no. 7, pp. 543–569, 2006.

[28] S. Nandi, H. A. Toliyat, and X. Li, “Condition monitoring and fault diagnosis of electrical motors-A review,” *IEEE Transactions on Energy Conversion*, vol. 20, no. 4, pp. 719–729, Dec. 2005.

[29] G. . Singh and S. Ahmed Saleh Al Kazzaz, “Induction machine drive condition monitoring and diagnostic research—a survey,” *Electric Power Systems Research*, vol. 64, no. 2. pp. 145–158, 2003.

[30] A. H. Bonnett and G. C. Soukup, “Cause and analysis of stator and rotor failures in three-phase squirrel-cage induction motors,” *IEEE Transactions on Industry Applications*, vol. 28, no. 4, pp. 921–937, 1992.

[31] N. Bethel, “Motor Efficiency and Fault Zone Analysis,” *PdMA® Corporation*, 2013. [Online]. Available: http://www.pdma.com/pdfs/Articles/WhitePapers/Motor_Efficiency_and_Fault_Zone_Analysis.pdf. [Accessed: 07-Feb-2016].

[32] H. Arabaci, O. Bilgin, and Á. Squirrel, “Efficiency Analysis of Submersible Induction Motor with Broken Rotor Bar,” in *Transactions on Engineering Technologies*, H. K. Kim, S.-I. Ao, and M. A. Amouzegar, Eds. Dordrecht: Springer Netherlands, 2014, pp. 27–40.

[33] M. M. Rahimian, “Broken Bar Detection in Synchronous Machines Based Wind Energy Conversion System,” Texas A&M University, 2011.

[34] G. B. Kliman, R. A. Koegl, J. Stein, R. D. Endicott, and M. W. Madden, "Noninvasive Detection of Broken Rotor Bars in Operating Induction Motors," *IEEE Transactions on Energy Conversion*, vol. 3, no. 4, pp. 873–879, 1988.
[35] B. M. Ebrahimi, J. Faiz, S. Lotfi-fard, and P. Pillay, "Novel Indices for Broken Rotor Bars Fault Diagnosis in Induction Motors Using Wavelet Transform," *Mechanical Systems and Signal Processing*, vol. 30, pp. 131–145, Jul. 2012.
[36] R. Burnett, J. F. Watson, and S. Elder, "The Application of Modern Signal Processing Techniques for Use in Rotor Fault Detection and Location within Three-Phase Induction Motors," *Signal Processing*, vol. 49, no. 1, pp. 57–70, Feb. 1996.
[37] K. Bacha, H. Henao, M. Gossa, and G.-A. Capolino, "Induction Machine Fault Detection Using Stray Flux EMF Measurement and Neural Network-Based Decision," *Electric Power Systems Research*, vol. 78, no. 7, pp. 1247–1255, Jul. 2008.
[38] J. Faiz and M. Ojaghi, "Different indexes for eccentricity faults diagnosis in three-phase squirrel-cage induction motors: A review," *Mechatronics*, vol. 19, no. 1, pp. 2–13, Feb. 2009.
[39] K. F. Martin, "A review by discussion of condition monitoring and fault diagnosis in machine tools," *International Journal of Machine Tools and Manufacture*, vol. 34, no. 4, pp. 527–551, May 1994.
[40] A. Y. Ben Sasi, F. Gu, B. Payne, and A. Ball, "Instantaneous Angular Speed Monitoring of Electric Motors," *Journal of Quality in Maintenance Engineering*, vol. 10, no. 2, pp. 123–135, 2004.
[41] N. Tandon and A. Choudhury, "A review of vibration and acoustic measurement methods for the detection of defects in rolling element bearings," *Tribology International*, vol. 32, no. 8, pp. 469–480, Aug. 1999.
[42] W. Li and C. Mechefske, "Detection of Induction Motor Faults A Comparison of Stator Current, Vibration and Acoustic Methods," *Journal of vibration and Control*, vol. 12, no. 2, pp. 165–188, Feb. 2006.
[43] E. Germen, M. Başaran, and M. Fidan, "Sound Based Induction Motor Fault Diagnosis using Kohonen Self-Organizing Map," *Mechanical Systems and Signal Processing*, vol. 46, no. 1, pp. 45–58, May 2014.
[44] A. Gaylard, A. Meyer, and C. Landy, "Acoustic evaluation of faults in electrical machines," *Electrical Machines and Drives conference*, no. 412, pp. 147–150, 1995.
[45] S. P. Verma, "Noise and vibrations of electrical machines and drives; their production and means of reduction," in *Proceedings of International Conference on Power Electronics, Drives and Energy Systems for Industrial Growth*, 1996, vol. 2, pp. 1031–1037.
[46] S. P. Verma and W. Li, "Measurement of Vibrations and Radiated Acoustic Noise of Electrical Machines," *Electrical Machines and Systems, 2003. ICEMS 2003. Sixth International Conference on*, vol. 2, pp. 861–866 vol.2, 2003.
[47] S. Umans, A. Fitzgerald, and C. Kingsley, *Fitzgerald and Kingsley's electric machinery*. McGraw-Hill Higher Education, 2013.
[48] J. S. Hsu, "Monitoring of Defects in Induction Motors Through Air-gap Torque Observation," *IEEE Transactions on Industry Applications*, vol. 31, no. 5, pp. 1016–1021, 1995.

[49] J. Faiz, V. Ghorbanian, and B. M. Ebrahimi, “Locating Broken Bars in Line-Start and Inverter-Fed Induction Motors Using Modified Winding Function Method,” *Electromagnetics*, vol. 32, no. 3, pp. 173–192, Mar. 2012.
[50] K. N. Gyftakis, D. V. Spyropoulos, J. C. Kappatou, and E. D. Mitronikas, “A Novel Approach for Broken Bar Fault Diagnosis in Induction Motors Through Torque Monitoring,” *IEEE Transactions on Energy Conversion*, vol. 28, no. 2, pp. 267–277, Jun. 2013.
[51] F. Thollon, G. Grellet, and A. Jammal, “Asynchronous motor cage fault detection through electromagnetic torque measurement,” *European Transactions on Electrical Power*, vol. 3, no. 5, pp. 375–378, Sep. 2007.
[52] H. Yahoui and G. Grellet, “Detection of an End-Ring Fault in Asynchronous Machines by Spectrum Analysis of the Observed Electromagnetic Torque,” *Journal de Physique III*, vol. 6, no. 4. pp. 443–448, 1996.
[53] X. Huang, “Diagnostics oF Air Gap Eccentricity IN Closed-Loop Drive-Connected Induction Motors,” Georgia Institute of Technology, 2005.
[54] R. S. Wieser, M. Schagginger, C. Kral, and F. Pirker, “The integration of machine fault detection into an indirect field oriented induction machine drive control scheme-the Vienna Monitoring Method,” in *Conference Record of 1998 IEEE Industry Applications Conference. Thirty-Third IAS Annual Meeting (Cat. No.98CH36242)*, 1998, vol. 1, pp. 278–285.
[55] C. Kral, F. Pirker, and G. Pascoli, “Detection of Rotor Faults in Squirrel-Cage Induction Machines at Standstill for Batch Tests by Means of the Vienna Monitoring Method,” *IEEE Transactions on Industry Applications*, vol. 38, no. 3, pp. 618–624, May 2002.
[56] C. Kral, F. Pirker, and G. Pascoli, “Model-Based Detection of Rotor Faults Without Rotor Position Sensor—The Sensorless Vienna Monitoring Method,” *IEEE Transactions on Industry Applications*, vol. 41, no. 3, pp. 784–789, May 2005.
[57] L. Wu, “Separating Load Torque Oscillation and Rotor Faults in Stator Current Based-Induction Motor Condition Monitoring,” Georgia Institute of Technology, 2007.
[58] V. V. Thomas, K. Vasudevan, and V. J. Kumar, “Online cage rotor fault detection using air-gap torque spectra,” *IEEE Transactions on Energy Conversion*, vol. 18, no. 2, pp. 265–270, 2003.
[59] A. M. da Silva, “Rotor Bar Fault Monitoring Method Based on Analysis of Air-Gap Torques of Induction Motors,” *IEEE Transactions on Industrial Informatics*, vol. 9, no. 4, pp. 2274–2283, Nov. 2013.
[60] V. Ghorbanian and J. Faiz, “A survey on time and frequency characteristics of induction motors with broken rotor bars in line-start and inverter-fed modes,” *Mechanical Systems and Signal Processing*, vol. 54–55, pp. 427–456, Mar. 2015.
[61] M. El Hachemi Benbouzid, “A review of induction motors signature analysis as a medium for faults detection,” *IEEE Transactions on Industrial Electronics*, vol. 47, no. 5, pp. 984–993, 2000.
[62] A. Siddique, G. S. Yadava, and B. Singh, “A Review of Stator Fault Monitoring Techniques of Induction Motors,” *IEEE Transactions on Energy Conversion*, vol. 20, no. 1, pp. 106–114, Mar. 2005.
[63] O. Article, “MachineLibrary^{TM} – Broken Rotor Bar and Motor Malfunctions,” 1999. [Online]. Available: http://www.ge-mcs.com/download/orbit-archives/2001-2005/2nd_quarter_2001/2q01machinelib.pdf. [Accessed: 08-

Feb-2016].
[64] J. F. Bangura and N. a. Demerdash, “Diagnosis and Characterization of Effects of Broken Bars and Connectors in Squirrel-Cage Induction Motors by a Time-Stepping Coupled Finite Element-State Space Modeling Approach,” *IEEE Transactions on Energy Conversion*, vol. 14, no. 4, pp. 1167–1176, 1999.
[65] B. Mirafzal, “Incipient Fault Diagnosis in Squirrel-Cage Induction Motors,” Marquette University, 2005.
[66] C. Hargis, B. Gaydon, and Kamash, K, “The detection of rotor defects in induction motors,” in *IEE Int. Conf. Electrical Machines, Design and Application*, 1989, pp. 216–220.
[67] A. Bellini, F. Filippetti, G. Franceschini, C. Tassoni, and G. B. Kliman, “Quantitative Evaluation of Induction Motor Broken Bars by Means of Electrical Signature Analysis,” *IEEE Transactions on Industry Applications*, vol. 37, no. 5, pp. 1248–1255, 2001.
[68] H. Douglas, P. Pillay, and A. K. Ziarani, “A New Algorithm for Transient Motor Current Signature Analysis Using Wavelets,” *IEEE Transactions on Industry Applications*, vol. 40, no. 5, pp. 1361–1368, Sep. 2004.
[69] B. G. Gaydon, “An Instrument to Detect Induction Motor Rotor Circuit Defects by Speed Fluctuation Measurements,” in *InProc. Electr. Test Meas. Instrum.–Testmex*, 1979, pp. 5–8.
[70] W. Deleroi, “Squirrel cage motor with broken bar in the rotor-physical phenomena and their experimental,” in *In Proc. of Int. Conf.On Electrical Machines*, 1982, pp. 767–770.
[71] W. Thomson, N. Deans, R. Leonard, and A. Milne, “Monitoring strategy for discriminating between different types of rotor defects in induction motors.,” in *InProceedings of the Universities Power Engineering Conference*, 1983, pp. 241–246.
[72] R. Fiser and S. Ferkolj, “Calculation of Magnetic Field Asymmetry of Induction Motor with Rotor Faults,” in *9th Mediterranean Electrotechnical Conference. Proceedings , (MELECON 98).*, 1998, vol. 2, pp. 1175–1179.
[73] T. Vaimann and A. Kallaste, “Detection of Broken Rotor Bars in Three-Phase Squirrel-Cage Induction Motor using Fast Fourier Transform,” in *10th International Symposium “Topical Problems in the Field of Electrical and Power Engineering,”* 2011, pp. 52–56.
[74] J. Faiz and B. M. Ebrahimi, “Locating Rotor Broken Bars in Induction Motors Using Finite Element Method,” *Energy Conversion and Management*, vol. 50, no. 1, pp. 125–131, Jan. 2009.
[75] M. Riera-Guasp, M. F. Cabanas, J. A. Antonino-Daviu, M. Pineda-Sanchez, and C. H. R. Garcia, “Influence of Nonconsecutive Bar Breakages in Motor Current Signature Analysis for the Diagnosis of Rotor Faults in Induction Motors,” *IEEE Transactions on Energy Conversion*, vol. 25, no. 1, pp. 80–89, Mar. 2010.
[76] X. Ying, “Performance Evaluation and Thermal Fields Analysis of Induction Motor With Broken Rotor Bars Located at Different Relative Positions,” *IEEE Transactions on Magnetics*, vol. 46, no. 5, pp. 1243–1250, May 2010.
[77] J. Faiz, B. M. Ebrahimi, and H. A. Toliyat, “Signature Analysis of Electrical and Mechanical Signals for Diagnosis of Broken Rotor Bars in an Induction Motor,” *Electromagnetics*, vol. 27, no. 8, pp. 507–526, Nov. 2007.
[78] R. Hirvonen, “On-line condition monitoring of defects in squirrel cage

motors," in *In Proc. Int. Conf. Electrical Machines*, 1994, pp. 267–272.

[79] M. Benbouzid, M. Vieira, and C. Theys, "Induction motors' faults detection and localization using stator current advanced signal processing techniques," *IEEE Transactions on Power Electronics*, vol. 14, no. 1, pp. 14–22, 1999.

[80] W. T. Thomson and M. Fenger, "Current Signature Analysis to Detect Induction Motor Faults," *IEEE Industry Applications Magazine*, vol. 7, no. 4, pp. 26–34, 2001.

[81] J. M. B. Siau, A. L. Graff, W. L. Soong, and N. Ertugrul, "Broken bar detection in induction motors using current and flux spectral analysis," *Australian Journal of Electrical and Electronics Engineering*, vol. 1, no. 3, pp. 171–177, 2004.

[82] W. Thomson, "On-Line Fault Diagnosis in Induction Motor Drives via MCSA," *EM Diagnostics Ltd., Scotland*, 2001.

[83] F. Filippetti, M. Martelli, G. Franceschini, and C. Tassoni, "Development of expert system knowledge base to on-line diagnosis of rotor electrical faults of induction motors," in *Conference Record of the 1992 IEEE Industry Applications Society Annual Meeting*, 1992, pp. 92–99.

[84] C. Bruzzese, O. Honorati, E. Santini, and D. Sciunnache, "New Rotor Fault Indicators for Squirrel Cage Induction Motors," in *Conference Record of the 2006 IEEE Industry Applications Conference Forty-First IAS Annual Meeting*, 2006, vol. 3, no. c, pp. 1541–1548.

[85] O. V. Thorsen and M. Dalva, "Failure identification and analysis for high-voltage induction motors in the petrochemical industry," *IEEE Transactions on Industry Applications*, vol. 35, no. 4, pp. 810–818, 1999.

[86] N. M. Elkasabgy, A. R. Eastham, and G. E. Dawson, "The detection of broken bars in the cage rotor of an induction machine," in *Conference Record of the 1988 IEEE Industry Applications Society Annual Meeting*, 1992, vol. 28, no. 1, pp. 181–187.

[87] D. H. Hwang, S. B. Han, B. C. Woo, J. H. Sun, D. S. Kang, B. K. Kim, and Y. H. Cho, "Detection of air-gap eccentricity and broken-rotor bar conditions in a squirrel-cage induction motor using the radial flux sensor," in *Journal of Applied Physics*, 2008, vol. 103, no. 7, pp. 129–132.

[88] G. Niu, J.-D. Son, A. Widodo, B.-S. Yang, D.-H. Hwang, and D.-S. Kang, "A Comparison of Classifier Performance for Fault Diagnosis of Induction Motor using Multi-type Signals," *Structural Health Monitoring*, vol. 6, no. 3, pp. 215–229, Sep. 2007.

[89] Y.-W. Youn, D.-H. Hwang, J.-H. Sun, and D.-S. Kang, "A Method for Indentifying Broken Rotor Bar and Stator Winding Fault in a Low-voltage Squirrel-cage Induction Motor Using Radial Flux Sensor," *Journal of Electrical Engineering and Technology*, vol. 6, no. 5, pp. 666–670, Sep. 2011.

[90] Y. Xie, "Investigation of Broken Rotor Bar Faults in Three-Phase Squirrel-Cage Induction Motors," in *Finite Element Analysis - From Biomedical Applications to Industrial Developments*, InTech, 2012, pp. 477–496.

[91] R. Pusca, R. Romary, V. Fireteanu, and A. Ceban, "Finite Element Analysis and Experimental Study of the Near-Magnetic field for Detection of Rotor Faults in Induction Motors," *Progress In Electromagnetics Research B*, vol. 50, no. February, pp. 37–59, 2013.

[92] A. Yazidi, H. Henao, G. A. Capolino, M. Artioli, and F. Filippetti, "Improvement of frequency resolution for three-phase induction machine fault diagnosis," in *Fourtieth IAS Annual Meeting. Conference Record of the 2005*

Industry Applications Conference, 2005., 2005, vol. 1, no. 1, pp. 20–25.
[93] C. Concari, G. Franceschini, and C. Tassoni, “Differential Diagnosis Based on Multivariable Monitoring to Assess Induction Machine Rotor Conditions,” *IEEE Transactions on Industrial Electronics*, vol. 55, no. 12, pp. 4156–4166, 2008.
[94] S. H. Kia, A. M. Mabwe, H. Henao, and G.-A. Capolino, “Wavelet Based Instantaneous Power Analysis for Induction Machine Fault Diagnosis,” in *IECON 2006 - 32nd Annual Conference on IEEE Industrial Electronics*, 2006, pp. 1229–1234.
[95] N. Elkasabgy, A. R. Eastham, and G. E. Dawson, “Detection of Broken Bars in the Cage Rotor on an Induction Machine,” *IEEE Transactions on Industry Applications*, vol. 28, no. 1, pp. 165–171, 1992.
[96] W. T. Thomson, D. Rankin, and D. G. Dorrell, “On-line current monitoring to diagnose airgap eccentricity in large three-phase induction motors-industrial case histories verify the predictions,” *IEEE Transactions on Energy Conversion*, vol. 14, no. 4, pp. 1372–1378, 1999.
[97] M. Feldman and S. Seibold, “Damage Diagnosis of Rotors: Application of Hilbert Transform and Multihypothesis Testing,” *Journal of Vibration and Control*, vol. 5, no. 3, pp. 421–442, May 1999.
[98] F. Gu, I. Yesilyurt, Y. Li, G. Harris, and A. Ball, “An Investigation of The Effects of Measurement Noise in The Use of Instantaneous Angular Speed for Machine Diagnosis,” *Mechanical Systems and Signal Processing*, vol. 20, no. 6, pp. 1444–1460, Aug. 2006.
[99] R. Maier, “Protection of Squirrel-Cage Induction Motor Utilizing Instantaneous Power and Phase Information,” *IEEE Transactions on Industry Applications*, vol. 28, no. 2, pp. 376–380, 1992.
[100] S. F. Legowski, A. H. M. Sadrul Ula, and A. M. Trzynadlowski, “Instantaneous Power as a Medium for the Signature Analysis of Induction Motors,” *IEEE Transactions on Industry Applications*, vol. 32, no. 4, pp. 904–909, 1996.
[101] A. M. Trzynadlowski, M. Ghassemzadeh, and S. F. Legowski, “Diagnostics of Mechanical Abnormalities in Induction Motors Using Instantaneous Electric Power,” *IEEE Transactions on Energy Conversion*, vol. 14, no. 4, pp. 1417–1423, 1999.
[102] P. Tavner and J. Penman, *Condition Monitoring of Electrical Machines*. Research Studies Press and John Wiley & Sons, 1987.
[103] M. Drif, N. Benouzza, and J. A. Dente, “Rotor Cage Faults Detection in 3-Phase Induction Motors Using Instantaneous Power Spectrum,” in *Modelling and Simulation of Electric Machines Converters and Systems (IMACS)*, 1999, pp. 287–292.
[104] S. M. a. Cruz and A. J. M. Cardoso, “Rotor Cage Fault Diagnosis in Three-Phase Induction Motors By The Total Instantaneous Power Spectral Analysis,” *Conference Record of the 1999 IEEE Industry Applications Conference. Thirty-Forth IAS Annual Meeting (Cat. No.99CH36370)*, vol. 3, pp. 1929–1934, 1999.
[105] a. M. Trzynadlowski and E. Ritchie, “Comparative Investigation of Diagnostic Media for Induction Motors A Case of Rotor Cage Faults,” *IEEE Transactions on Industrial Electronics*, vol. 47, no. 5, pp. 1092–1099, 2000.
[106] M. Drif, N. Benouzza, A. Bendiabdellah, and J. A. Dente, “Induction motor load effect diagnostic utilizing instantaneous power spectrum,” in *In Proc. of*

EPE, 2001.

[107] Z. Liu, X. Yin, Z. Zhang, D. Chen, and W. Chen, “Online Rotor Mixed Fault Diagnosis Way Based on Spectrum Analysis of Instantaneous Power in Squirrel Cage Induction Motors,” *IEEE Transactions on Energy Conversion*, vol. 19, no. 3, pp. 485–490, Sep. 2004.

[108] M. Drif and a J. M. Cardoso, “Rotor Cage Fault Diagnostics in Three-Phase Induction Motors, by the Instantaneous Phase-Angle Signature Analysis,” in *Proceedings of IEEE International Electric Machines and Drives Conference, IEMDC 2007*, 2007, vol. 2, pp. 1440–1445.

[109] M. Drif and A. J. M. Cardoso, “Rotor Cage Fault Diagnostics in Three-Phase Induction Motors, by the Instantaneous Non-Active Power Signature Analysis,” in *IEEE International Symposium on Industrial Electronics*, 2007, vol. 3, pp. 1050–1055.

[110] M. Drif and A. J. Marques Cardoso, “The Instantaneous Power Factor Approach for Rotor Cage Faults Diagnosis in Three-Phase Induction Motors,” in *2008 International Symposium on Power Electronics, Electrical Drives, Automation and Motion*, 2008, pp. 173–178.

[111] M. Drif and A. J. Marques Cardoso, “On-line fault diagnostics in operating three-phase induction motors by the active and reactive power media,” in *2008 18th International Conference on Electrical Machines*, 2008, pp. 1–6.

[112] M. Drif and A. J. M. Cardoso, “The Instantaneous Reactive Power Approach for Rotor Cage Fault Diagnosis in Induction Motor Drives,” in *2008 IEEE Power Electronics Specialists Conference*, 2008, pp. 1548–1552.

[113] M. Drif and A. J. M. Cardoso, “The Use of the Instantaneous-Reactive-Power Signature Analysis for Rotor-Cage-Fault Diagnostics in Three-Phase Induction Motors,” *IEEE Transactions on Industrial Electronics*, vol. 56, no. 11, pp. 4606–4614, Nov. 2009.

[114] M. Drif and A. J. Marques Cardoso, “Discriminating the Simultaneous Occurrence of Three-Phase Induction Motor Rotor Faults and Mechanical Load Oscillations by the Instantaneous Active and Reactive Power Media Signature Analyses,” *IEEE Transactions on Industrial Electronics*, vol. 59, no. 3, pp. 1630–1639, Mar. 2012.

[115] C. H. De Angelo, G. R. Bossio, and G. O. García, “Discriminating Broken Rotor Bar from Oscillating Load Effects Using the Instantaneous Active and Reactive Powers,” *IET Electric Power Applications*, vol. 4, no. 4, p. 281, 2010.

[116] Y. Maouche, M. El Kamel Oumaamar, M. Boucherma, and A. Khezzar, “A New Approach for Broken Bar Fault Detection in Three-Phase Induction Motor Using Instantaneous Power Monitoring under Low Slip Range,” *International Journal of Electrical and Computer Engineering (IJECE)*, vol. 4, no. 1, pp. 52–63, Feb. 2014.

[117] K. Yahia, A. J. Marques Cardoso, A. Ghoggal, and S.-E. Zouzou, “Induction Motors Broken Rotor Bars Diagnosis Through the Discrete Wavelet Transform of the Instantaneous Reactive Power Signal under Time-varying Load Conditions,” *Electric Power Components and Systems*, vol. 42, no. 7, pp. 682–692, Apr. 2014.

[118] J. Kim, S. Shin, S. Bin Lee, K. N. Gyftakis, M. Drif, and A. J. M. Cardoso, “Power Spectrum-Based Detection of Induction Motor Rotor Faults for Immunity to False Alarms,” *IEEE Transactions on Energy Conversion*, pp. 1–10, 2015.

[119] H. W. Penrose and J. Jette, “Static Motor Circuit Analysis: an Introduction to Theory and Application,” *IEEE Electrical Insulation Magazine*, vol. 16, no. 4, pp. 6–10, Jul. 2000.
[120] H. W. Penrose, “Estimating motor life using motor circuit analysis predictive measurements. Part II,” in *Conference Record of the 2004 IEEE International Symposium on Electrical Insulation*, 2004, no. September, pp. 15–17.
[121] V. Climente-Alarcon, J. A. Antonino-Daviu, F. Vedreno-Santos, and R. Puche-Panadero, “Vibration Transient Detection of Broken Rotor Bars by PSH Sidebands,” *IEEE Transactions on Industry Applications*, vol. 49, no. 6, pp. 2576–2582, Nov. 2013.
[122] C. Kral, T. G. Habetler, R. G. Harley, F. Pirker, G. Pascoli, H. Oberguggenberger, and C. J. M. Fenz, “A comparison of rotor fault detection techniques with respect to the assessment of fault severity,” in *4th IEEE International Symposium on Diagnostics for Electric Machines, Power Electronics and Drives, 2003. SDEMPED 2003.*, 2003, no. August, pp. 265–270.
[123] P. J. Tavner, B. G. Gaydon, and D. M. Ward, “Monitoring generators and large motors,” *IEE Proceedings B Electric Power Applications*, vol. 133, no. 3, p. 169, 1986.
[124] M. Kang and J. Kim, “Reliable Fault Diagnosis of Multiple Induction Motor Defects Using a 2-D Representation of Shannon Wavelets,” *IEEE Transactions on Magnetics*, vol. 50, no. 10, pp. 1–13, Oct. 2014.
[125] P. J. McCully, “Evaluation of current and vibration signals for squirrel cage induction motor condition monitoring,” in *Eighth International Conference on Electrical Machines and Drives*, 1997, vol. 1997, no. 444, pp. 331–335.
[126] G. Muller and C. Landy, “A Novel Method to Detect Broken Rotor Bars in Squirrel Cage Induction Motors When Interbar Currents are Present,” *IEEE Transactions on Energy Conversion*, vol. 18, no. 1, pp. 71–79, Mar. 2003.
[127] B. Liang, S. D. Iwnicki, and A. D. Ball, “Asymmetrical Stator and Rotor Faulty Detection Using Vibration, Phase Current and Transient Speed Analysis,” *Mechanical Systems and Signal Processing*, vol. 17, no. 4, pp. 857–869, Jul. 2003.
[128] J. Milimonfared, H. Kelk, S. Nandi, A. D. Minassians, and H. A. Toliyat, “A Novel Approach for Broken-Rotor-Bar Detection in Cage Induction Motors,” *IEEE Transactions on Industry Applications*, vol. 35, no. 5, pp. 1000–1006, 1999.
[129] R. Supangat, J. Grieger, N. Ertugrul, W. L. Soong, D. A. Gray, and C. Hansen, “Detection of Broken Rotor Bar Faults and Effects of Loading in Induction Motors during Rundown,” in *2007 IEEE International Electric Machines & Drives Conference*, 2007, pp. 196–201.
[130] F. Cupertino, E. DeVanna, L. Salvatore, and S. Stasi, “Analysis Techniques for Detection of IM Broken Rotor Bars After Supply Disconnection,” *IEEE Transactions on Industry Applications*, vol. 40, no. 2, pp. 526–533, Mar. 2004.
[131] H. Razik and G. Didier, “A novel method of induction motor diagnosis using the line-neutral voltage,” in *Proc. EPE-PEMC, Riga, Latvia*, 2004.
[132] M. E. K. Oumaamar, F. Babaa, A. Khezzar, and M. Boucherma, “Diagnostics of Broken Rotor Bars in Induction Machines Using the Neutral Voltage,” in *International Conference on Electrical Machines*, 2006, no. 679, pp. 1–6.
[133] F. Babaa, M. E. K. Oumaamar, A. Khezzar, and M. Boucherma, “Multiple Coupled Circuit Modeling of squirrel- cage Induction Motors Including Space

Harmonics and Line Neutral Voltage,” in *proceedings of the International Conference on Electrical Machines*, 2006, no. 680.
[134] M. E. K. Oumaamar, A. Khezzar, M. Boucherma, H. Razik, R. N. Andriamalala, and L. Baghli, “Neutral Voltage Analysis for Broken Rotor Bars Detection in Induction Motors Using Hilbert Transform Phase,” in *2007 IEEE Industry Applications Annual Meeting*, 2007, pp. 1940–1947.
[135] A. Khezzar, M. El Kamel Oumaamar, M. Hadjami, M. Boucherma, and H. Razik, “Induction Motor Diagnosis Using Line Neutral Voltage Signatures,” *IEEE Transactions on Industrial Electronics*, vol. 56, no. 11, pp. 4581–4591, Nov. 2009.
[136] P. Jayaswal, A. K. Wadhwani, and K. B. Mulchandani, “Machine Fault Signature Analysis,” *International Journal of Rotating Machinery*, vol. 2008, pp. 1–10, 2008.
[137] A. WIDODO and B. S. YANG, “Wavelet Support Vector Machine for Induction Machine Fault Diagnosis based on Transient Current Signal,” *Expert Systems with Applications*, vol. 35, no. 1–2, pp. 307–316, Jul. 2008.
[138] J. Wang, S. Liu, R. X. Gao, and R. Yan, “Current Envelope Analysis for Defect Identification and Diagnosis in Induction Motors,” *Journal of Manufacturing Systems*, vol. 31, no. 4, pp. 380–387, 2012.
[139] S. H. Kia, H. Henao, and G. -a. Capolino, “Diagnosis of Broken-Bar Fault in Induction Machines Using Discrete Wavelet Transform Without Slip Estimation,” *IEEE Transactions on Industry Applications*, vol. 45, no. 4, pp. 1395–1404, Jul. 2009.
[140] W. Laala, S.-E. Zouzou, and S. Guedidi, “Induction motor broken rotor bars detection using fuzzy logic: experimental research,” *International Journal of System Assurance Engineering and Management*, vol. 5, no. 3, pp. 329–336, 2014.
[141] I. Jaksch, “Faults diagnosis of three-phase induction motors using envelope analysis,” in *4th IEEE International Symposium on Diagnostics for Electric Machines, Power Electronics and Drives, 2003. SDEMPED 2003.*, 2003, pp. 289–293.
[142] A. M. da Silva, R. J. Povinelli, and N. A. O. Demerdash, “Induction Machine Broken Bar and Stator Short-Circuit Fault Diagnostics Based on Three-Phase Stator Current Envelopes,” *IEEE Transactions on Industrial Electronics*, vol. 55, no. 3, pp. 1310–1318, Mar. 2008.
[143] R. Puche-Panadero, M. Pineda-Sanchez, M. Riera-Guasp, J. Roger-Folch, E. Hurtado-Perez, and J. Perez-Cruz, “Improved Resolution of the MCSA Method Via Hilbert Transform, Enabling the Diagnosis of Rotor Asymmetries at Very Low Slip,” *IEEE Transactions on Energy Conversion*, vol. 24, no. 1, pp. 52–59, Mar. 2009.
[144] W. T. Thomson and D. Rankin, “Case Histories of On-Line Rotor Cage Fault Diagnosis,” in *in Proc. Int. Conf: Condition Monitoring*, 1987, pp. 798–819.
[145] G. a. Jiménez, A. O. Muñoz, and M. a. Duarte-Mermoud, “Fault Detection in Induction Motors Using Hilbert and Wavelet Transforms,” *Electrical Engineering*, vol. 89, no. 3, pp. 205–220, Feb. 2006.
[146] D. Matić, F. Kulić, M. Pineda-Sánchez, and I. Kamenko, “Support Vector Machine Classifier for Diagnosis in Electrical Machines: Application to Broken Bar,” *Expert Systems with Applications*, vol. 39, no. 10, pp. 8681–8689, Aug. 2012.
[147] D. Matic, Z. Kanovic, D. Reljic, F. Kulic, D. Oros, and V. Vasic, “Broken bar

detection using current analysis-A case study," in *2013 9th IEEE International Symposium on Diagnostics for Electric Machines, Power Electronics and Drives (SDEMPED)*, 2013, pp. 407–411.
[148] T. W. S. Chow and H.-Z. Tan, "HOS-Based Nonparametric and Parametric Methodologies for Machine Fault Detection," *IEEE Transactions on Industrial Electronics*, vol. 47, no. 5, pp. 1051–1059, 2000.
[149] B. Ayhan and H. J. Trussell, "On the Use of a Lower Sampling Rate for Broken Rotor Bar Detection With DTFT and AR-Based Spectrum Methods," *IEEE Transactions on Industrial Electronics*, vol. 55, no. 3, pp. 1421–1434, Mar. 2008.
[150] A. Widodo, B. S. Yang, D. S. Gu, and B. K. Choi, "Intelligent fault diagnosis system of induction motor based on transient current signal," *Mechatronics*, vol. 19, no. 5, pp. 680–689, Aug. 2009.
[151] V. T. Tran and B.-S. Yang, "Machine Fault Diagnosis and Condition Prognosis Using Classification and Regression Trees and Neuro-Fuzzy Inference Systems," *Control and Cybernetics*, vol. 39, no. 1, pp. 25–54, 2010.
[152] J. Cusido, L. Romeral, J. A. Ortega, J. A. Rosero, and A. Garcia Espinosa, "Fault Detection in Induction Machines Using Power Spectral Density in Wavelet Decomposition," *IEEE Transactions on Industrial Electronics*, vol. 55, no. 2, pp. 633–643, 2008.
[153] L. A. García-Escudero, O. Duque-Perez, D. Morinigo-Sotelo, and M. Perez-Alonso, "Robust Condition Monitoring for Early Detection of Broken Rotor Bars in Induction Motors," *Expert Systems with Applications*, vol. 38, no. 3, pp. 2653–2660, Mar. 2011.
[154] B. M. Ebrahimi, J. Faiz, and B. Akin, "Pattern Recognition for Broken Bars Fault Diagnosis in Induction Motors Under Various Supply Conditions," *European Transactions on Electrical Power*, vol. 22, no. 8, pp. 1176–1190, Nov. 2012.
[155] M. Seera, C. P. Lim, D. Ishak, and H. Singh, "Offline and Oonline Fault Detection and Diagnosis of Induction Motors using a Hybrid Soft Computing Model," *Applied Soft Computing*, vol. 13, no. 12, pp. 4493–4507, Dec. 2013.
[156] E. H. El Bouchikhi, V. Choqueuse, and M. Benbouzid, "Induction Machine Faults Detection Using Stator Current Parametric Spectral Estimation," *Mechanical Systems and Signal Processing*, vol. 52–53, pp. 447–464, Feb. 2015.
[157] H. Çalış and A. Çakır, "Experimental Study for Sensorless Broken Bar Detection in Induction Motors," *Energy Conversion and Management*, vol. 49, no. 4, pp. 854–862, Apr. 2008.
[158] W. B. Collis, P. R. White, and J. K. Hammond, "Higher-Order Spectra: The Bispectrum and Trispectrum," *Mechanical Systems and Signal Processing*, vol. 12, no. 3, pp. 375–394, May 1998.
[159] M. E. H. Benbouzid and G. B. Kliman, "What stator current processing-based technique to use for induction motor rotor faults diagnosis?," *IEEE Transactions on Energy Conversion*, vol. 18, no. 2, pp. 238–244, 2003.
[160] B. Liang, S. D. Iwnicki, and Y. Zhao, "Application of power spectrum, cepstrum, higher order spectrum and neural network analyses for induction motor fault diagnosis," *Mechanical Systems and Signal Processing*, vol. 39, no. 1–2, pp. 342–360, 2013.
[161] S. Chen, "Induction Machine Broken Rotor Bar Diagnostics Using Prony Analysis," 2008.

[162] S. Chen and R. Živanović, “Estimation of Frequency Components in Stator Current for the Detection of Broken Rotor Bars in Induction Machines,” *Measurement*, vol. 43, no. 7, pp. 887–900, Aug. 2010.
[163] M. Sahraoui, A. J. M. Cardoso, and A. Ghoggal, “The Use of a Modified Prony Method to Track the Broken Rotor Bar Characteristic Frequencies and Amplitudes in Three-Phase Induction Motors,” *IEEE Transactions on Industry Applications*, vol. 51, no. 3, pp. 2136–2147, May 2015.
[164] D. McGaughey, G. King, and M. Tarbouchi, “Current signature analysis of induction machine rotor faults using the fast orthogonal search algorithm,” in *5th IET International Conference on Power Electronics, Machines and Drives (PEMD 2010)*, 2010, vol. 2010, pp. 215–215.
[165] G. King, M. Tarbouchi, and D. McGaughey, “Rotor fault detection in induction motors using the fast orthogonal search algorithm,” in *2010 IEEE International Symposium on Industrial Electronics*, 2010, pp. 2621–2625.
[166] S. Kia, H. Henao, and G. Capolino, “A High-Resolution Frequency Estimation Method for Three-Phase Induction Machine Fault Detection,” *IEEE Transactions on Industrial Electronics*, vol. 54, no. 4, pp. 2305–2314, Aug. 2007.
[167] I. Aydin, M. Karakose, and E. Akin, “A New Method for Early Fault Detection and Diagnosis of Broken Rotor Bars,” *Energy Conversion and Management*, vol. 52, no. 4, pp. 1790–1799, Apr. 2011.
[168] S. V. Vaseghi, *Advanced Digital Signal Processing and Noise Reduction*. John Wiley & Sons, 2008.
[169] V. Climente-Alarcon, J. a. Antonino-Daviu, M. Riera-Guasp, R. Puche-Panadero, and L. Escobar, “Application of The Wigner–Ville Distribution for The Detection of Rotor Asymmetries and Eccentricity Through High-Order Harmonics,” *Electric Power Systems Research*, vol. 91, pp. 28–36, Oct. 2012.
[170] V. Climente-Alarcon, J. A. Antonino-Daviu, M. Riera-Guasp, and M. Vlcek, “Induction Motor Diagnosis by Advanced Notch FIR Filters and the Wigner–Ville Distribution,” *IEEE Transactions on Industrial Electronics*, vol. 61, no. 8, pp. 4217–4227, Aug. 2014.
[171] a. K. S. Jardine, D. Lin, and D. Banjevic, “A review on machinery diagnostics and prognostics implementing condition-based maintenance,” *Mechanical Systems and Signal Processing*, vol. 20, no. 7. pp. 1483–1510, 2006.
[172] I. Daubechies, “The wavelet transform, time-frequency localization and signal analysis,” *IEEE Transactions on Information Theory*, vol. 36, no. 5, pp. 961–1005, 1990.
[173] S. G. Mallat, “A Theory for Multiresolution Signal Decomposition: the Wavelet Representation,” *IEEE Transactions on Pattern Analysis and Machine Intelligence*, vol. 11, no. 7, pp. 674–693, Jul. 1989.
[174] H. Keskes and A. Braham, “Recursive Undecimated Wavelet Packet Transform and DAG SVM for Induction Motor Diagnosis,” *IEEE Transactions on Industrial Informatics*, vol. 11, no. 5, pp. 1059–1066, Oct. 2015.
[175] A. J. Ellison and S. J. Yang, “Effects of Rotor Eccentricity on Acoustic Noise from Induction Machines,” in *Proceedings of the Institution of Electrical Engineers*, 1971, vol. 118, no. 1, p. 174.
[176] R. Wieser, C. Kral, F. Pirker, and M. Schagginger, “On-line rotor cage monitoring of inverter-fed induction machines by means of an improved method,” *IEEE Transactions on Power Electronics*, vol. 14, no. 5, pp. 858–

865, 1999.
[177] G. G. Acosta, C. J. Verucchi, and E. R. Gelso, “A Current Monitoring System for Diagnosing Electrical Failures in Induction Motors,” *Mechanical Systems and Signal Processing*, vol. 20, no. 4, pp. 953–965, May 2006.
[178] G. Didier, E. Ternisien, O. Caspary, and H. Razik, “A New Approach to Detect Broken Rotor Bars in Induction Machines by Current Spectrum Analysis,” *Mechanical Systems and Signal Processing*, vol. 21, no. 2, pp. 1127–1142, Feb. 2007.
[179] Z. Ye, A. Sadeghian, and B. Wu, “Mechanical Fault Diagnostics for Induction Motor with Variable Speed Drives using Adaptive Neuro-Fuzzy Inference System,” *Electric Power Systems Research*, vol. 76, no. 9–10, pp. 742–752, Jun. 2006.
[180] P. V. J. Rodríguez, M. Negrea, and A. Arkkio, “A Simplified Scheme for Induction Motor Condition Monitoring,” *Mechanical Systems and Signal Processing*, vol. 22, no. 5, pp. 1216–1236, Jul. 2008.
[181] B. Ayhan, M.-Y. Chow, and M.-H. Song, “Multiple Discriminant Analysis and Neural-Network-Based Monolith and Partition Fault-Detection Schemes for Broken Rotor Bar in Induction Motors,” *IEEE Transactions on Industrial Electronics*, vol. 53, no. 4, pp. 1298–1308, Jun. 2006.
[182] R. R. Schoen, B. K. Lin, T. G. Habetler, J. H. Schlag, and S. Farag, “An Unsupervised, On-Line System for Induction Motor Fault Detection Using Stator Current Monitoring,” *IEEE Transactions on Industry Applications*, vol. 31, no. 6, pp. 1280–1286, 1995.
[183] A. Bellini, A. Yazidi, F. Filippetti, C. Rossi, and G.-A. Capolino, “High Frequency Resolution Techniques for Rotor Fault Detection of Induction Machines,” *IEEE Transactions on Industrial Electronics*, vol. 55, no. 12, pp. 4200–4209, Dec. 2008.
[184] S. Günal, D. Gökhan Ece, and Ö. Nezih Gerek, “Induction Machine Condition Monitoring Using Notch-Filtered Motor Current,” *Mechanical Systems and Signal Processing*, vol. 23, no. 8, pp. 2658–2670, Nov. 2009.
[185] V. F. Pires, J. F. Martins, and A. J. Pires, “Eigenvector/Eigenvalue Analysis of a 3D Current Referential Fault Detection and Diagnosis of an Induction Motor,” *Energy Conversion and Management*, vol. 51, no. 5, pp. 901–907, May 2010.
[186] A. Bellini, G. Franceschini, and C. Tassoni, “Monitoring of InductionMachines by Maximum Covariance Method for Frequency Tracking,” *IEEE Transactions on Industry Applications*, vol. 42, no. 1, pp. 69–78, Jan. 2006.
[187] Kyusung Kim and A. Parlos, “Induction motor fault diagnosis based on neuropredictors and wavelet signal processing,” *IEEE/ASME Transactions on Mechatronics*, vol. 7, no. 2, pp. 201–219, Jun. 2002.
[188] Z. Ye, B. Wu, and A. Sadeghian, “Current Signature Analysis of Induction Motor Mechanical Faults by Wavelet Packet Decomposition,” *IEEE Transactions on Industrial Electronics*, vol. 50, no. 6, pp. 1217–1228, Dec. 2003.
[189] H. Bae, S. Kim, Y. T. Kim, and S. Lee, “Application of Time-Series Data Mining for Fault Diagnosis of Induction Motors,” in *Computational Science and Its Applications*, 2005, pp. 1085–1094.
[190] J.-H. Jung, J.-J. Lee, and B.-H. Kwon, “Online Diagnosis of Induction Motors Using MCSA,” *IEEE Transactions on Industrial Electronics*, vol. 53, no. 6,

pp. 1842–1852, Dec. 2006.
[191] S. Lee, S.-P. Cheon, Y. Kim, and S. Kim, “Fourier and Wavelet Transformations for the Fault Detection of Induction Motor with Stator Current,” in *International Conference on Intelligent Computing*, 2006, pp. 557–569.
[192] A. Sadeghian, Y. Zhongming, and B. Wu, “Online Detection of Broken Rotor Bars in Induction Motors by Wavelet Packet Decomposition and Artificial Neural Networks,” *IEEE Transactions on Instrumentation and Measurement*, vol. 58, no. 7, pp. 2253–2263, Jul. 2009.
[193] Y. Liu, L. Guo, Q. Wang, G. An, M. Guo, and H. Lian, “Application to Induction Motor Faults Diagnosis of The Amplitude Recovery Method Combined With FFT,” *Mechanical Systems and Signal Processing*, vol. 24, no. 8, pp. 2961–2971, Nov. 2010.
[194] J. Cusidó, L. Romeral, J. a. Ortega, A. Garcia, and J. R. Riba, “Wavelet and PDD as fault detection techniques,” *Electric Power Systems Research*, vol. 80, no. 8, pp. 915–924, Aug. 2010.
[195] F. Briz, M. W. Degner, P. Garcia, and D. Bragado, “Broken Rotor Bar Detection in Line-Fed Induction Machines Using Complex Wavelet Analysis of Startup Transients,” *IEEE Transactions on Industry Applications*, vol. 44, no. 3, pp. 760–768, 2008.
[196] Z. Zhang, Z. Ren, and W. Huang, “A Novel Detection Method of Motor Broken Rotor Bars Based onWavelet Ridge,” *IEEE Transactions on Energy Conversion*, vol. 18, no. 3, pp. 417–423, Sep. 2003.
[197] H. Douglas, P. Pillay, and A. K. Ziarani, “Broken Rotor Bar Detection in Induction Machines With Transient Operating Speeds,” *IEEE Transactions on Energy Conversion*, vol. 20, no. 1, pp. 135–141, Mar. 2005.
[198] J. A. Antonino-Daviu, M. Riera-Guasp, J. R. Folch, and M. P. M. Palomares, “Validation of a New Method for the Diagnosis of Rotor Bar Failures via Wavelet Transform in Industrial Induction Machines,” *IEEE Transactions on Industry Applications*, vol. 42, no. 4, pp. 990–996, Jul. 2006.
[199] J. A. Antonino-Daviu, P. Jover Rodriguez, M. Riera-Guasp, M. Pineda-Sánchez, and A. Arkkio, “Detection of Combined Faults in Induction Machines With Stator Parallel Branches Through the DWT of the Startup Current,” *Mechanical Systems and Signal Processing*, vol. 23, no. 7, pp. 2336–2351, Oct. 2009.
[200] S. M. A. Cruz, A. J. Marques Cardoso, “Rotor Cage Fault Diagnosis in Three-Phase Induction Motors by Extended Park’s Vector Approach,” *Electric Machines & Power Systems*, vol. 28, no. 4, pp. 289–299, Apr. 2000.
[201] M. Haji and H. Toliyat, “Pattern Recognition-A Technique for Induction Machines Rotor Broken Bar Detection,” *IEEE Transactions on Energy Conversion*, vol. 16, no. 4, pp. 312–317, 2001.
[202] Zhenxing Liu, Xiaolong Zhang, Xianggen Yin, and Zhe Zhang, “Rotor Cage Fault Diagnosis in Induction Motors Based on Spectral Analysis of Current Hilbert Modulus,” in *IEEE Power Engineering Society General Meeting, 2004.*, 2004, vol. 2, pp. 1500–1503.
[203] R. Supangat, N. Ertugrul, W. L. Soong, D. A. Gray, C. Hansen, and J. Grieger, “Broken Rotor Bar Fault Detection in Induction Motors Using Starting Current Analysis,” in *European Conference on Power Electronics and Applications*, 2005, p. 10 pp.-pp.P.10.
[204] A. Khezzar, M. El Kamel Oumaamar, M. Hadjami, M. Boucherma, and H.

Razik, “Induction Motor Diagnosis Using Line Neutral Voltage Signatures,” *IEEE Transactions on Industrial Electronics*, vol. 56, no. 11, pp. 4581–4591, Nov. 2009.

[205] B.-S. Yang and K. J. Kim, “Application of Dempster–Shafer Theory in Fault Diagnosis of Induction Motors Using Vibration and Current Signals,” *Mechanical Systems and Signal Processing*, vol. 20, no. 2, pp. 403–420, Feb. 2006.

[206] A. Widodo, B. S. Yang, and T. Han, “Combination of Independent Component Analysis and Support Vector Machines for Intelligent Faults Diagnosis of Induction Motors,” *Expert Systems with Applications*, vol. 32, no. 2, pp. 299–312, Feb. 2007.

[207] A. Widodo and B. S. Yang, “Application of Nonlinear Feature Extraction and Support Vector Machines for Fault Diagnosis of Induction Motors,” *Expert Systems with Applications*, vol. 33, no. 1, pp. 241–250, Jul. 2007.

[208] G. Niu, T. Han, B.-S. Yang, and A. C. C. Tan, “Multi-Agent Decision Fusion for Motor Fault DiagnosiS,” *Mechanical Systems and Signal Processing*, vol. 21, no. 3, pp. 1285–1299, Apr. 2007.

[209] V. T. Tran, B.-S. Yang, M.-S. Oh, and A. C. C. Tan, “Fault Diagnosis of Induction Motor Based on Decision Trees and Adaptive Neuro-fuzzy Inference,” *Expert Systems with Applications*, vol. 36, no. 2, pp. 1840–1849, Mar. 2009.

[210] G. F. Bin, J. J. Gao, X. J. Li, and B. S. Dhillon, “Early fault diagnosis of rotating machinery based on wavelet packets—Empirical mode decomposition feature extraction and neural network,” *Mechanical Systems and Signal Processing*, vol. 27, pp. 696–711, 2012.

[211] H. Keskes, A. Braham, and Z. Lachiri, “Broken rotor bar diagnosis in induction machines through Stationary Wavelet Packet Transform under lower sampling rate,” in *2012 First International Conference on Renewable Energies and Vehicular Technology*, 2012, vol. 97, pp. 452–459.

[212] M. R. Mehrjou, N. Mariun, M. Karami, N. Misron, S. Toosi, and M. R. Zare, “Evaluation of Wavelet-Functions for Broken Rotor Bar Detection of Induction Machine Using Coefficient-Related Features,” *International Journal of Applied Electronics in Physics & Robotics*, vol. 1, no. 1, pp. 18–23, 2013.

[213] A. Reece and T. Preston, *Finite Element Methods in Electrical Power Engineering*. Courier Corporation, 2000.

[214] M. K. Chari and P. Silvester, “Analysis of Turboalternator Magnetic Fields by Finite Elements,” *IEEE Transactions on Power Apparatus and Systems*, vol. PAS-90, no. 2, pp. 454–464, Mar. 1971.

[215] A. Y. Hannalla and D. C. MacDonald, “Numerical Analysis of Transient Field Problems in Electric Machines,” in *IEE Proceedings*, 1976, pp. 893–898.

[216] S. Tandon, A. Armor, and M. V. K. Chari, “Nonlinear Transient Finite Element Field Computation for Electrical Machines and Devices,” *IEEE Transactions on Power Apparatus and Systems*, vol. PAS-102, no. 5, pp. 1089–1096, May 1983.

[217] S. Ho, W. Fu, and H. Wong, “Application of Automatic Choice of Step Size for Time Stepping Finite Element Method to Induction Motors,” *IEEE Transactions on Magnetics*, vol. 33, no. 2, pp. 1370–1373, Mar. 1997.

[218] M. a. Jabbar, Zhejie Liu, and Jing Dong, “Time-Stepping Finite-Element Analysis for the Dynamic Performance of a Permanent Magnet Synchronous Motor,” *IEEE Transactions on Magnetics*, vol. 39, no. 5, pp. 2621–2623, Sep.

2003.
[219] T. Göktaş, M. Arkan, and Ö. F. Özgüven, "Detection of rotor fault in three-phase induction motor in case of low-frequency load oscillation," *Electrical Engineering*, vol. 97, no. 4, pp. 337–345, 2015.
[220] H. Akcay and E. Germen, "Subspace-Based Identification of Acoustic Noise Spectra in Induction Motors," *IEEE Transactions on Energy Conversion*, vol. 30, no. 1, pp. 32–40, Mar. 2015.
[221] T. Han, B.-S. Yang, W.-H. Choi, and J.-S. Kim, "Fault Diagnosis System of Induction Motors Based on Neural Network and Genetic Algorithm Using Stator Current Signals," *International Journal of Rotating Machinery*, vol. 2006, pp. 1–13, 2006.
[222] J. Ben Ali, N. Fnaiech, L. Saidi, B. Chebel-Morello, and F. Fnaiech, "Application of empirical mode decomposition and artificial neural network for automatic bearing fault diagnosis based on vibration signals," *Applied Acoustics*, vol. 89, no. 2015, pp. 16–27, Mar. 2015.
[223] A. Sapena-Bano, M. Pineda-Sanchez, R. Puche-Panadero, J. Martinez-Roman, and Z. Kanovic, "Low-Cost Diagnosis of Rotor Asymmetries in Induction Machines Working at a Very Low Slip Using the Reduced Envelope of the Stator Current," *IEEE Transactions on Energy Conversion*, pp. 1–11, 2015.
[224] J. Zhang, N. Zhu, L. Yang, Q. Yao, and Q. Lu, "A Fault Diagnosis Approach for Broken Rotor Bars Based on EMD and Envelope Analysis," *Journal of China University of Mining and Technology*, vol. 17, no. 2, pp. 205–209, Jun. 2007.
[225] B. Mirafzal and N. a O. Demerdash, "Effects of Load Magnitude on Diagnosing Broken Bar Faults in Induction Motors Using the Pendulous Oscillation of the Rotor Magnetic Field Orientation," *IEEE Transactions on Industry Applications*, vol. 41, no. 3, pp. 771–783, 2005.
[226] J. Pons-Llinares, J. A. Antonino-Daviu, M. Riera-Guasp, S. Bin Lee, T. J. Kang, and C. Yang, "Advanced Induction Motor Rotor Fault Diagnosis Via Continuous and Discrete Time–Frequency Tools," *IEEE Transactions on Industrial Electronics*, vol. 62, no. 3, pp. 1791–1802, 2015.
[227] E. Y. Hamid and Z.-I. Kawasaki, "Wavelet-based data compression of power system disturbances using the minimum description length criterion," *IEEE Transactions on Power Delivery*, vol. 17, no. 2, pp. 460–466, Apr. 2002.
[228] M. Pineda-Sanchez, M. Riera-Guasp, J. A. Antonino-Daviu, J. Roger-Folch, J. Perez-Cruz, and R. Puche-Panadero, "Instantaneous Frequency of the Left Sideband Harmonic During the Start-Up Transient: A New Method for Diagnosis of Broken Bars," *IEEE Transactions on Industrial Electronics*, vol. 56, no. 11, pp. 4557–4570, Nov. 2009.
[229] J. Tukey, *Exploratory data analysis*. Addison-Wesley, 1977.
[230] M. R. Spiegel, J. Schiller, and A. Srinivasan, *Theory And Problems Of Probability And Statistics*. McGraw-Hill Education, 2003.
[231] R. Christensen, "Analysis of Variance, Design, and Regression: Applied Statistical Methods," Chapman and Hall/CRC, 1996.
[232] M. Riera-Guasp, J. A. Antonino-Daviu, J. Rusek, and J. Roger-Folch, "Diagnosis of Rotor Asymmetries in Induction Motors Based on the Transient Extraction of Fault Components Using Filtering Techniques," *Electric Power Systems Research*, vol. 79, no. 8, pp. 1181–1191, Aug. 2009.
[233] V. T. Tran, F. AlThobiani, A. Ball, and B.-K. Choi, "An Application to Transient Current Signal Based Induction Motor Fault diagnosis of Fourier–

Bessel expansion and Simplified Fuzzy ARTMAP," *Expert Systems with Applications*, vol. 40, no. 13, pp. 5372–5384, Oct. 2013.
[234] E. Cabal-Yepez, R. J. Romero-Troncoso, A. Garcia-Perez, and R. a. Osornio-Rios, "Single-Parameter Fault Identification Through Information Entropy Analysis at the Startup-Transient Current in Induction Motors," *Electric Power Systems Research*, vol. 89, pp. 64–69, Aug. 2012.

LIST OF PUBLICATIONS

Book Chapter

M.R.Mehrjou, et al., Wavelet-based Analysis of MCSA for Fault Detection in Electrical Machine, InTech, Wavelet Transform and Some of Its Real-World Applications, ISBN 978-953-51-2230-2, 2015.

Journal

M.R. Mehrjou, et al., Evaluation of Wavelet-Functions for Broken Rotor Bar Detection of Induction Machine using Coefficient-Related Features, *International Journal of Applied Electronics in Physics and Robotics*,1(1) 2013. *(Index-Cited Publication)*

M. Karami, N. Mariun, M.R. Mehrjou, MZAMAb Kadir, N Misron, MA Mohd Radzi, Static Eccentricity Fault Recognition in Three-Phase Line Start Permanent Magnet Synchronous Motor Using Finite Element Method. Mathematical Problems in Engineering, 2014. (ISI-Q2)

M.R. Mehrjou, et al., Wireless Sensors System for Broken Rotor bar Fault Monitoring using Wavelet Analysis, IOP Conference Series: Materials Science and Engineering (MSE), 99 (1), 2015. (Index-Scopus)

M.R. Mehrjou, et al., Analysis of Statistical Features based on Start-up Current Envelope for Broken Rotor Bar Fault Detection in Line Start Permanent Magnet Synchronous Motor, Electrical Engineering, (ISI-Q3)

S. Zolfaghari, S.B.M. Noor, M.H. Marhaban, N. Mariun, M.R. Mehrjou, Broken Rotor Bar Fault Detection in No Load Condition Based on Wavelet Packet Signature Analysis. International Journal of Control Theory and Applications, 2016. (Index-Cited Publication)

M.R. Mehrjou, et al., Broken Rotor Bar Fault Detection of Line Start Permanent Magnet Synchronous Motor using Binary Logistic Statistical Method. Journal of the Chinese Institute of Engineers, 2017. (ISI-Q4)

J. C. Quiroz, N. Mariun, M. R. Mehrjou, M. Izadi, N. Misron, M.A.M. Radzi, Fault Detection of Broken Rotor Bar in LS-PMSM Using Random Forests. Measurement, 2017, Under review (ISI-Q2)

M.R. Mehrjou, et al., A New Method for Broken Rotor Bar Fault Detection in Line Start Permanent Magnet Synchronous Motors under No-Load Condition. Journal of Mechanical Science and Technology, Under review (ISI-Q3)

Conference

M.R.Mehrjou, et al.,Performance analysis of line-start permanent magnet synchronous motor in presence of rotor fault. IEEE Student Conference

on In Research and Development (SCOReD, 2014), Malaysia, pp. 1-4, (Index-Cited Publication).

M.R.Mehrjou, et al., Statistical Features Analysis of Transient Current Signal for Broken Bars Fault Detection in LS-PMSMs. IEEE The International Conference on Smart Instrumentation, Measurement and Application (ICSIMA, 2015), Putrajaya, Malaysia. (Index-Cited Publication)

M.R.Mehrjou, et al., Broken Rotor Bar Detection in LS-PMSMs Based on Statistical Features Analysis of Start-up Current Envelope. IEEE The International Conference on Smart Instrumentation, Measurement and Application (ICSIMA, 2015), Putrajaya, Malaysia. (Index-Cited Publication)

M.R.Mehrjou, et al., A Survey of Broken Rotor Bar Detection Using PT and HT in Squirrel Cage Electrical Machine. IEEE Student Conference on Research and Development (SCOReD, 2015). Kuala Lumpur, Malaysia. (Index-Cited Publication)

M. Izadi, N. Mariun, M.R. Mehrjou, M.Z.A. Ab Kadir, N. Misron, M.A.M. Radzi, Broken Rotor Bar Fault Detection in Line Start Permanent Magnet Synchronous Motor Using Transient Current Signal. IEEE International Conference on Automatic Control and Intelligent Systems, 2016. (Index-Cited Publication)

S. Zolfaghari, S.B. Mohd Noor, M.H. Marhaban, N. Mariun, M.R. Mehrjou, Broken Rotor Bar Fault Detection in No Load Condition Based on Wavelet Packet Signature Analysis. International Conference on Electrical & Electronic Technology (2016)