



بسم الله الرحمن الرحيم

∞∞∞∞

تم رفع هذه الرسالة بواسطة / مني مغربي أحمد

بقسم التوثيق الإلكتروني بمركز الشبكات وتكنولوجيا المعلومات دون أدنى

مسئولية عن محتوى هذه الرسالة.

ملاحظات: لا يوجد





Cairo University

# **PROPOSED PROTECTION SCHEMES FOR DETECTING AND DIAGNOSIS INCIPIENT BROKEN BARS AND BEARING FAULTS IN INDUCTION MOTORS**

By

**Mohamed Esam El-dine Atta Abd El-Halim**

A Thesis Submitted to the  
Faculty of Engineering at Cairo University  
In Partial Fulfillment of the  
Requirements for the Degree of

**DOCTOR OF PHILOSOPHY**

In

**Electrical Power and Machines Engineering**

FACULTY OF ENGINEERING, CAIRO UNIVERSITY  
GIZA, EGYPT  
2022

# **PROPOSED PROTECTION SCHEMES FOR DETECTING AND DIAGNOSIS INCIPIENT BROKEN BARS AND BEARING FAULTS IN INDUCTION MOTORS**

By

**Mohamed Esam El-dine Atta Abd El-Halim**

A Thesis Submitted to the  
Faculty of Engineering at Cairo University  
In Partial Fulfillment of the  
Requirements for the Degree of

**DOCTOR OF PHILOSOPHY**

In

**Electrical Power and Machines Engineering**

**Under the Supervision of**

**Prof. Dr. Mahmoud Ibrahim Gilany**  
Electrical Power Engineering Department  
Faculty of Engineering,  
Cairo University

**Prof. Dr. Doaa Khalil Ibrahim**  
Electrical Power Engineering Department  
Faculty of Engineering,  
Cairo University

FACULTY OF ENGINEERING, CAIRO UNIVERSITY  
GIZA, EGYPT  
2022

# **PROPOSED PROTECTION SCHEMES FOR DETECTING AND DIAGNOSIS INCIPIENT BROKEN BARS AND BEARING FAULTS IN INDUCTION MOTORS**

By

**Mohamed Esam El-dine Atta Abd El-Halim**

A Thesis Submitted to the  
Faculty of Engineering at Cairo University  
In Partial Fulfillment of the  
Requirements for the Degree of

**DOCTOR OF PHILOSOPHY**

In

**Electrical Power and Machines Engineering**

Approved by the Examining Committee:

---

**Prof. Dr. Mahmoud Ibrahim Gilany**

**Thesis Main Advisor**

---

**Prof. Dr. Doaa Khalil Ibrahim**

**Advisor**

---

**Prof. Dr. Khairy Farahat Ali Helwa**

**Internal Examiner**

---

**Prof. Dr. Essam Eddin Mohamed Rashad**

Faculty of Engineering, Tanta University

---

**External Examiner**

FACULTY OF ENGINEERING, CAIRO UNIVERSITY  
GIZA, EGYPT  
2022

**Engineer's Name:** Mohamed Esam El-dine Atta Abd El-Halim  
**Date of Birth:** 26 / 9 / 1988  
**Nationality:** Egyptian  
**E-mail:** [Eng.mesam2010@gmail.com](mailto:Eng.mesam2010@gmail.com)  
**Phone:** +201272011155  
**Address:** Toukh, Al Qalyūbiyah, Egypt  
**Registration Date:** 10 /2017  
**Awarding Date:** .... /.... / 202  
**Degree:** Doctor of Philosophy  
**Department:** Electrical Power and Machines Engineering  
**Supervisors:**



**Prof. Dr. Mahmoud Ibrahim Gilany** (Thesis Main Advisor)  
**Prof. Dr. Doaa Khalil Ibrahim** (Advisor)

**Examiners:**

**Prof. Dr. Mahmoud Ibrahim Gilany** (Thesis Main Advisor)  
**Prof. Dr. Doaa Khalil Ibrahim** (Advisor)  
**Prof. Dr. Khairy Farahat Ali Helwa** (Internal Examiner)  
**Prof. Dr. Essam Eddin Mohamed Rashad** (External Examiner)  
Faculty of Engineering, Tanta University

**Title of Thesis:**

**PROPOSED PROTECTION SCHEMES FOR DETECTING AND DIAGNOSIS  
INCIPIENT BROKEN BARS AND BEARING FAULTS IN INDUCTION MOTORS**

**Key Words:**

**Bearing Faults, Broken Bar Faults, Detecting and diagnosis, Induction Motors, Variable load.**

**Summary:**

With the increased dependence on induction motors (IMs) in the modern industry, the detection of incipient motor faults becomes an imperative requirement to reduce maintenance costs and avoid unscheduled shutdowns. Broken bar faults (BBFs) and bearing faults are around 60% of motor faults. These faults are developed from high thermal stresses, excessive forces, environmental stresses and high currents that occur in the motor cage. This thesis proposes three protection schemes to detect and diagnose BBFs and bearing faults.

The first scheme is introduced to detect BBFs and estimate fault severity in IMs under start-up conditions. It includes three main stages, applying a powerful optimized S-transform to the current signal, extracting the LSH from the  $(t-f)$  domain using a proposed adaptive  $(t-f)$  filter, and estimating a proposed fault severity index based on the energy of RLSH.

The second scheme provides a novel adaptive scheme to detect and diagnosis BBFs in IMs during steady-state conditions. It can detect BBFs in their incipient phases including non-adjacent faults under variable inertia, variable loading conditions, and in a noisy environment. The main idea is to monitor continuously the variation in phase angle of the main sideband frequency components by applying Fast Fourier Transform for only one phase of stator current.

The third scheme is introduced for bearing faults detection and diagnosis under fixed and time-varying speed conditions. It utilizes the persistence spectrum for monitoring bearing health condition, as it provides some features related to bearing health and fault conditions. In addition, a multi-scale structural similarity index is used as a robust basis for bearing faults detection and classification without the need for training process or expert knowledge

The proposed schemes are extensively validated using simulation tests and/or experimental data that proved their effectiveness to detect and diagnose BBFs and bearing faults.

## **DISCLAIMER**

I hereby declare that this thesis is my own original work and that no part of it has been submitted for a degree qualification at any other university or institute.

I further declare that I have appropriately acknowledged all sources used and have cited them in the references sections.

Name: Mohamed Esam El-dine Atta Abd El-Halim

Date: -- / -- / 2022

Signature:

## ACKNOWLEDGMENT

Before all and after all, I would like to thank "ALLAH" who supported and strengthened me all through my life and in completing my studies for the Doctor of Philosophy Degree.

Then, I would like to thank my supervisors for their contributions to this thesis and for their support in the field of scientific research, and I hope to keep in touch in the future.

Prof. Dr. Mahmoud Ibrahim Gilany, thank you for your guidance, encouragement, and your advice throughout the work. Finally, asking my God Allah, blessing your health.

Prof. Dr. Doaa Khalil Ibrahim, thank you for your guidance, encouragement, and your advice throughout the work. Finally, asking my God Allah, blessing your health.

I want also to express thanks to Prof. Ahmed F. Zobaa (Brunel University London, UK) for supplying me with important advices in my work to diagnose broken bar faults under steady-state operating conditions.

A special and dedicated thank for the spirit of my mother, and continuous support, encouragement from my father and brothers.

Special thanks to my wife for her continuous support. In addition, I do not forget my sons Omar, Abdullah, and Abdulrahmman.

## TABLE OF CONTENTS

<b>DISCLAIMER</b>	<b>I</b>
<b>ACKNOWLEDGMENT</b>	<b>II</b>
<b>TABLE OF CONTENTS</b>	<b>III</b>
<b>LIST OF TABLES</b>	<b>VII</b>
<b>LIST OF FIGURES</b>	<b>VIII</b>
<b>LIST OF SYMBOLS AND ABBREVIATIONS</b>	<b>XI</b>
<b>ABSTRACT</b>	<b>XV</b>

<b>CHAPTER (1): INTRODUCTION</b>	<b>1</b>
1.1 Overview	1
1.2 Broken Bar Faults	1
1.2.1 Causes of broken bar faults	1
1.2.2 Challenges of BBFs diagnosis	3
1.3 Bearing Faults and Challenges	4
1.4 Thesis Objectives and Motivations	5
1.5 Thesis Contributions	6
1.6 Thesis Organization	7

<b>CHAPTER (2): BROKEN BAR FAULTS</b>	
<b>LITERATURE REVIEW</b>	<b>8</b>
2.1 Introduction	8
2.2 Modeling of BBF and Its Effects on IM Variables	9
2.2.1 Modeling of BBF	9
2.2.2 Signatures of BBF	10
2.3 Model-Based Methods	16
2.3.1 Resistance estimation based methods	17
2.3.2 Other parameters estimation based methods	18
2.3.3 Discussion on model-based methods	18
2.4 Signal Processing–Based Methods	19
2.4.1 Time-domain based methods	19
2.4.2 Frequency-domain based methods	22
2.4.3 Time-frequency domain based methods	27
2.4.4 Discussion on signal processing-based methods	29



2.5	Data-Driven Based Methods.....	31
2.6	Conclusion and Ideas for Future Work .....	31

### **CHAPTER (3): BROKEN BAR FAULTS DETECTION UNDER INDUCTION MOTOR STARTING CONDITIONS .....33**

3.1	Introduction.....	33
3.2	Overview on Stockwell Transform (ST) and Its Modifications .....	34
3.3	Methodology of the proposed scheme.....	36
3.3.1	The optimized Stockwell Transform .....	36
3.3.2	The proposed adaptive $t - f$ filter .....	36
3.3.3	Proposed fault severity index .....	38
3.4	The Data Used for Testing the Proposed Scheme.....	39
3.5	Applying the Proposed Scheme on an IM with BBFs Using Simulated and Real Data .....	41
3.5.1	Verifying the performance of optimized ST for $t - f$ decomposition.....	41
3.5.2	Verifying the performance of the proposed adaptive $t - f$ filter using simulated data.....	44
3.6	Extensive Testing and Validation of the Proposed Scheme .....	46
3.6.1	Examining the proposed scheme using simulation based approach.....	46
3.6.2	Examining the proposed scheme using real experimental data.....	47
3.6.3	Determination of the thresholds .....	48
3.6.4	Comparison with other methods.....	49
3.7	Conclusions.....	50

### **CHAPTER (4): DETECTING INDUCTION MOTOR INCIPIENT BROKEN BAR FAULTS AT VARIOUS LOAD AND INERTIA CONDITIONS.....52**

4.1	Introduction.....	52
4.2	Simulating Broken Bar Faults in IM .....	53
4.3	Methodology of the Proposed Scheme.....	55
4.4	Analyzing the Variation of Main Sideband Phase Angle under Different Conditions.....	60
4.4.1	Main sideband phase angle variation under healthy conditions.....	60
4.4.2	Main sideband phase angle variation under fault conditions .....	62

4.5	Implementation of the Proposed Scheme .....	65
4.5.1	Data acquisition stage .....	65
4.5.2	Data processing stage.....	65
4.5.3	Adaptive threshold determination and fault detection stage.....	66
4.5.4	Severity index calculation stage .....	67
4.6	Testing Results for Proposed Scheme Performance .....	67
4.6.1	Under different system inertia.....	68
4.6.2	Under different loading conditions.....	68
4.6.3	Under different fault severity .....	69
4.6.4	In a noisy environment .....	69
4.6.5	Faulty severity determination.....	69
4.7	Conclusions.....	72

## **CHAPTER (5): DETECTION AND DIAGNOSIS OF BEARING FAULTS UNDER FIXED AND TIME-VARYING SPEED CONDITIONS .....73**

5.1	Introduction.....	73
5.2	Overview on the Proposed Scheme.....	74
5.3	The Density Persistence Histogram .....	75
5.3.1	Construction of density persistence histogram.....	75
5.3.2	Illustrative examples of persistence spectrum using vibration signals.....	76
5.4	Multi-Scale Structural Similarity .....	79
5.4.1	The single-scale structural similarity index (SSIM).....	79
5.4.2	The multi-scale structural similarity index (MS-SSIM) .....	81
5.5	Experiments and Results .....	81
5.5.1	Performance validation for bearing faults detection.....	81
5.5.2	Performance validation for bearing faults diagnosis under fixed speed conditions .....	83
5.5.3	Performance validation for bearing faults diagnosis under variable speed conditions .....	85
5.6	Conclusion .....	87

## **CHAPTER (6): CONCLUSIONS AND SUGGESTIONS FOR FUTURE WORK .....88**

6.1 Future Work.....	89
<b>REFERENCES .....</b>	<b>90</b>
<b>PUBLISHED WORK .....</b>	<b>107</b>
<b>المخلص .....</b>	<b>أ</b>

## LIST OF TABLES

Table 2-1: Comparison between different BBF signatures types. ....	16
Table 2-2: Abbreviations used in Tables 2-3, 2-4, 2-5, 2-6, and 2-7. ....	18
Table 2-3: Comparison among different model-based methods.....	21
Table 2-4: Comparison among different time-domain based fault detection methods	21
Table 2-5: Comparison among different frequency-domain based fault detection methods.....	25
Table 2-6: Comparison among different time-frequency domain based fault detection methods.....	30
Table 2-7: Comparison among different Data-driven based methods. ....	31
Table 3-1: Electrical data of the simulated induction motor [184] .....	41
Table 3-2: Testing the proposed scheme on 11 kW simulated motor for different BBFs at different inertial and loading levels.....	47
Table 3-3: Different ranges of the proposed index for different healthy/ BBFs conditions on 11 kW simulated motor .....	48
Table 3-4: Mean ( $\mu$ ) and standard deviation ( $\sigma$ ) of RLSH energy for 10 and 20 test cases for each study case .....	49
Table 3-5: Comparing the proposed scheme versus some previous schemes .....	49
Table 4-1: Electrical data of the two tested motors.....	54
Table 4-2: Testing proposed scheme on Motor I .....	71
Table 4-3: Testing proposed scheme on Motor II.....	71
Table 5-1: The description of the groups used in this chapter for bearing fault diagnosis of data provided in [210] .....	84
Table 5-2: Comparison between the proposed scheme performance and the performance of other methods in the literature under fixed speed conditions .....	84
Table 5-3: Comparison between the proposed scheme performance and the performance of other methods in the literature under varying speed conditions .....	87

## LIST OF FIGURES

Figure 1-1: Photo of rotor of 460 kW, 6.6 kV motor with one broken bar (marked with red color) taken by the author .....	2
Figure 1-2: Photo of Rotor of 380 kW, 6.6 kV motor with multiple broken bars (marked with yellow-colored arrows) taken by the author.....	2
Figure 1-3: Classification of false diagnosis sources in the case of BBFs.....	4
Figure 1-4: Different bearing fault types .....	4
Figure 2-1: BBF detection and diagnosis methods classification. ....	9
Figure 2-2: Effects on LSH and RSH band in the motor current spectrum.....	12
Figure 2-3: Steady-state stator current waveform in case of: .....	13
Figure 2-4: Theoretical trajectories produced by the author of LSH and RSH of an induction motor in time-frequency plane (a) line-fed starting and (b) Inverter-fed starting with (V/F) control strategy.....	13
Figure 2-5: Magnetic flux distribution during starting of 11 kW IM using FEM simulation (a) Healthy and (b) with one BBF.....	15
Figure 2-6: General scheme of model-based fault methods [84].....	17
Figure 3-1: The Instantaneous frequency of the generated LSH at starting period ....	37
Figure 3-2: Motor speed and 50 Hz power component of the current signal with/without window delay compensation during starting of 11 kW motor with two BRBs at full load conditions .....	38
Figure 3-3: Flowchart of the proposed scheme.....	39
Figure 3-4: Modeling the starting of the induction motor in [184] with one BRB.....	40
Figure 3-5: The $t - f$ representations of the current signal for the 11 kW simulated motor with one BBF at no load using different Transforms.....	42
Figure 3-6: The $t - f$ representations of real current signal (provided in [182]) of 0.746 kW motor with two BRBs at 12.5% full load using different Transforms .....	43
Figure 3-7: Application of the proposed adaptive filter in case of starting 11 kW motor with 2 BRBs at full load with 20 db noise .....	45
Figure 3-8: The $t - f$ representation of the current signal for the 11 kW simulated healthy motor at full load.....	46
Figure 3-9: Boxplot of the proposed scheme performance on real experimental data of 0.746 kW motor for different BBFs at different loading levels.....	48

Figure 4-1: Characteristics for modeling Motor I with 2 BRBs (a) The magnetic flux lines distribution, (b) Periodic oscillation in the stator current envelop, (c) The main sideband frequency components for stator current (40-60 Hz), (d) Phase angle of the main sideband components. ....	55
Figure 4-2: Electromagnetic and mechanical phenomena of BBF [68] .....	56
Figure 4-3: Reaction loop of BBF [68] .....	56
Figure 4-4: The effect of main sideband current components magnitude variation on their angles variation based on equations. 4-9 and 4-10 (a) The effect of right sideband component magnitude variation on $\Delta\theta_2''$ , (b) The effect of left sideband component magnitude variation on $\Delta\theta_1''$ .....	59
Figure 4-5: The impact of inertia changes on $i_1''$ and $i_2''$ current components phasor diagram .....	60
Figure 4-6: Motor I phase angle of left sideband and right sideband components for healthy conditions at inertia of: .....	61
Figure 4-7: Motor II phase angle of left sideband and right sideband components for healthy conditions at: .....	61
Figure 4-8: The impact of load variation (from full loading to partial loading).....	62
Figure 4-9: Motor I phase angle of left sideband, right sideband and fundamental components for healthy conditions at: .....	63
Figure 4-10: The impact of BBF on $i_1''$ and $i_2''$ current components phasor diagram.....	63
Figure 4-11: Motor I vector representation of left sideband and right sideband components for: .....	64
Figure 4-12: Motor II vector representation of left sideband and right sideband components for: .....	64
Figure 4-13: Severity index of Motor I against number of broken bars.....	70
Figure 5-1: Block diagram of density persistence histogram .....	76
Figure 5-2: Illustrative examples of persistence spectrum of vibration signal provided in [210] for motor bearing at fixed speed 1750 rpm under the following conditions: (a) Healthy, (b) Inner racer fault, (c) Ball fault, and (d) Outer racer fault. ....	77
Figure 5-3: Illustrative examples of persistence spectrum of vibration signal of length 1s that provided in [211] for bearing at variable speed under the different health conditions.....	78

Figure 5-4: the $MS - SSIM$ indices for signal 4 and confidence intervals .....	82
Figure 5-5: The variable speed bearing test rig [211] .....	86