# SPEED SENSORLESS WITH MODIFIED ROTOR FLUX FIELD ORIENTED CONTROL OF FAULTY THREE-PHASE INDUCTION MOTOR

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*To my beloved wife and all my family members.*

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# ABSTRACT

This thesis proposes a high performance speed sensorless vector control of star-connected three-phase Induction Motor (TPIM) under open-phase fault. The proposed drive system consists of two parts: Indirect Rotor flux Field-Oriented Control (Indirect RFOC) and speed estimation based on Model Reference Adaptive System (MRAS). In RFOC of TPIM, rotor speed estimation is required in order to implement the control algorithm. The rotor speed can either be obtained using a mechanical speed sensor or it can be estimated from the terminal variables of the TPIM using an observer. In this work, rotor speed is estimated using an observer which is based on MRAS. However, unlike other MRAS based speed estimators, the proposed observer is designed to work for both healthy and faulty TPIM. When a fault occurred, minimum changes to the control parameters and special transformation to the variables of the RFOC and MRAS speed estimator are performed. The ability of the drive system to work in both healthy and faulty conditions is important in some critical applications that require continuous operation of the drive systems. To verify the effectiveness and reliability of the proposed method, simulations and experiments are conducted. In this research, MATLAB/Simulink software is used to evaluate the effectiveness of the proposed method. Verification and validation of the proposed drive system are through hardware implementation using dSPACE DS 1104 ACE KIT and 1.5 kW TPIM. The simulation and experiment results show that satisfactory performance of the indirect RFOC and MRAS for a TPIM under open-phase fault is achieved. It is shown that the torque and speed oscillations caused by the unbalanced structure of the faulty TPIM are effectively reduced by more than 50%. Speed sensorlesss RFOC of TPIM under open-phase fault condition is shown to be capable of operating in speed range from zero to 60 rad/s, however with reduced torque capability.

# ABSTRAK

Tesis ini mencadangkan kaedah kawalan vektor tanpa pengesan kelajuan yang berprestasi tinggi untuk motor aruhan tiga fasa (TPIM) sambungan bintang dengan kerosakan fasa terbuka. Sistem pacuan yang dicadangkan ini terdiri daripada dua bahagian: kawalan berorentasikan medan fluk rotor secara tidak langsung (RFOC tidak langsung) dan penganggaran kelajuan berdasarkan sistem model rujukan mudah suai (MRAS). Untuk RFOC untuk TPIM, penganggaran kelajuan rotor adalah diperlukan untuk melaksanakan algoritma kawalan. Kelajuan rotor boleh diperolehi sama ada dengan menggunakan pengesan kelajuan mekanikal atau ia dapat dianggarkan daripada pengamatan pembolehubah terminal untuk TPIM. Dalam kajian, kelajuan rotor dianggarkan menggunakan pengamatan berdasarkan kepada MRAS. Bagaimanapun, tidak seperti penganggar kelajuan MRAS yang lain, pengamatan yang dicadangkan telah direka bentuk untuk bekerja pada kedua-dua keadaan TPIM yang berkeadaan baik dan juga rosak. Apabila satu kerosakan berlaku, perubahan minimum terhadap parameter kawalan dan transformasi khas bagi pembolehubah RFOC dan penganggar MRAS telah dilakukan. Keupayaan untuk sistem pacuan bekerja dalam kedua-dua keadaan baik dan rosak adalah penting untuk beberapa aplikasi kritikal yang memerlukan operasi sistem pacuan yang berterusan. Untuk mengesahkan keberkesanan dan kebolehpercayaan kaedah yang dicadangkan, simulasi dan eksperimen telah dijalankan. Dalam penyelidikan ini, perisian MATLAB/Simulink digunakan untuk menilai keberkesanan kaedah cadangan. Penentusahan dan pengesahan sistem pacuan yang dicadangkan adalah melalui pelaksanaan perkakasan menggunakan dSPACE DS 1104 ACE KIT dan TPIM dengan kuasa 1.5 kW. Keputusan simulasi dan eksperimen menunjukkan bahawa prestasi yang memuaskan untuk RFOC tidak langsung and MRAS untuk TPIM dengan kerosakan fasa terbuka telah dicapai. Ini menunjukkan bahawa ayunan pada daya kilas dan kelajuan yang disebabkan oleh struktur yang tidak seimbang pada TPIM yang rosak dengan keberkesananya dapat dikurangkan lebih dari 50%. RFOC tanpa pengesan kelajuan untuk TPIM dengan fasa terbuka dibuktikan dapat beroperasi dengan julat kelajuan dan sifar ke 60 rad/s, walaupun dengan keupayaan daya kilas yang lebih rendah.

# TABLE OF CONTENTS

# LIST OF TABLES

# LIST OF FIGURES

# LIST OF ABBREVIATIONS

| | | |
|---|---|---|
| AC | - | Alternating Current |
| ADC | - | Analog to digital converter |
| DAC | - | Digital to analog converter |
| DC | - | Direct Current |
| RFOC | - | Rotor Flux Field-Oriented Control |
| DSP | - | Digital Signal Processor |
| DTC | - | Direct Torque Control |
| EKF | - | Extended Kalman Filter |
| FOC | | Field-Oriented Control |
| HVAC | - | Heating Ventilation and Air Conditioning |
| IE | - | Incremental Encoder |
| IM | - | Induction Motor |
| IRFOC | - | Indirect Rotor Field-Oriented Control |
| ELO | - | Extended Luenburger Observer |
| MRAS | - | Model Reference Adaptive System |
| PI | - | Proportional-Integral |
| PPR | - | Pulse Per Revolution |
| RFOC | - | Rotor Field-Oriented Control |
| SMO | | Sliding Mode Observer |
| TPIM | | Three Phase Induction Motor |
| VFCD | - | Variable Frequency Control Drives |
| VHFIM | - | Virtual High Frequency Injection Method |
| VSI | - | Voltage Source Inverter |

# LIST OF APPENDICES

# CHAPTER 1

# INTRODUCTION

## 1.1 A Look Back on Vector Control Techniques for Three-Phase IM Drives

Induction motors (IMs) are the most applicable motor in industries because of their simple and sustainable design, less expensive, lower maintenance cost, high reliability and ease of connection to the AC power supply. Also in comparison to DC motors, induction motors have several advantages such as simple structure, higher efficiency and higher power rating. More than 85% of electrical motors in industries are induction motors. Induction motors are found in many applications such as robotics, radar, fans, Heating, Ventilation and Air conditioning (HVAC) and etc. [1-6]. Furthermore, the use of AC machine drives in industrial applications has tremendously increased since the introduction of Field Oriented Control (FOC) by F. Blachke in 1970’s.

Many methods have been presented by researchers to control the induction motors, which in general, can be classified into two main categories: scalar based and vector based. The general classification of induction motor control methods are shown in Figure 1.1 [7].

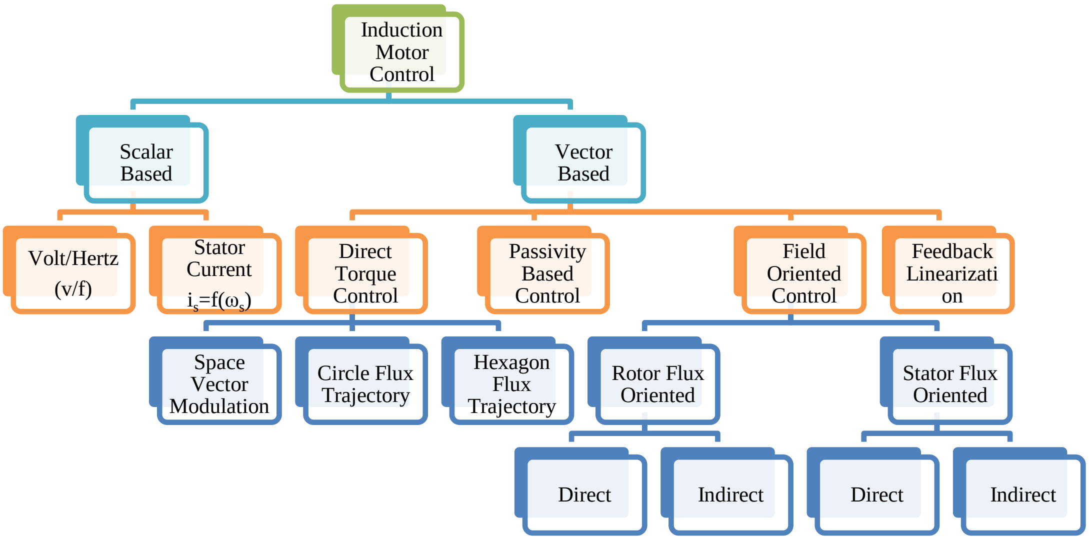

**Figure 1.1** Classifications of IM control methods

Scalar control drives have simpler structure and cheaper when compared to vector control drives. However, they have limited speed range control and applications. Inefficiency is the major drawback of this method. In scalar control, torque and flux are inter-related and both are functions of stator currents; hence independent control of torque and flux is infeasible. Vector control methods are more complex and more expensive, however, they provide accurate torque control with broader speed range operation, from zero to beyond rated speed. Therefore, vector control methods are normally used for sensitive applications, which need high performance control.

## 1.2 Speed Sensorless Control Techniques of Induction Motor

One of the control variables in TPIM drives, which plays an important role, is the motor speed. Accurate knowledge of motor speed in real-time is extremely important since it is normally needed to implement high performance control algorithms in TPIM drives. Normally, the speed sensors are used to provide the speed feedback in speed-controlled drive system and the mechanical sensors such as optical encoders or tachometers can be used for this purpose. The control scheme with speed sensor has several disadvantages over speed sensorless control scheme such as hardware complexity, lower reliability, bigger size and more expensive [8]. Employing speed sensorless techniques in the control of IMs would undoubtedly result in a more reliable and economical drive systems. Many researches on speed sensorless control methods have been carried out, particularly on the speed sensorless techniques that can be operated over a wide speed range. The speed estimation methods can be classified into two main groups: model based methods and signal injection based methods. In model based methods, the terminal variables of the machine, i.e. stator voltages and currents are used to estimate the motor speed but in signal based method, high frequency carrier signals are employed to estimate the rotor position [9]. The model based and signal injection based methods can be further classified into several techniques, which will be discussed in Chapter 2.

## 1.3 Motivation and Significance of Study

The TPIM drives are subjected to several failures [10-13] and various corrective methods have been proposed, depending on the type of failures and on the level of severity that affect the operations of the drives systems [14-19]. One of the most common types of fault in TPIM is when one of the phases failed. This can happen due to the failure in one leg of the three-phase voltage source inverter (VSI) or due to the failure in one of the three-phase windings (open-circuit) of the TPIM [16]. In either case, the drive systems will no longer operate as they are supposed to be. Specifically, in FOC drives for TPIM, failure in one of the phases due to an open-phase fault results in an unbalanced structure of the TPIM. The field orientation is no longer accurate thus causing a severe oscillation in the torque and hence the speed of the motor. In some applications, the degradation in the drive performance after the fault is still acceptable, at least until the drive is stopped and corrective measures are taken to overcome the problems. On the other hand, in some critical applications, the drive systems must be continuously run even after the open-phase fault occur, to avoid expensive damage or for safety reasons. On top of this, for these applications, the severe oscillations in the torque due to the unbalanced structure is unacceptable and hence must be minimized. A more challenging situation is when the open-phase fault occurs in a speed sensorless drive system. In such case, not only control algorithms need to adapt to the failure condition, but the speed observer too, need to be adaptable. For this reason, the analysis and study on the open-phase fault TPIM drives is very important, interesting, as well as very challenging.

## 1.4 Problem Statement

Field-Oriented Control (FOC) of TPIM is one of the most popular control methods for high performance applications. The modelling, control structure and control algorithms of FOC drives for a balanced TPIM are well-known and widely adopted for various industrial applications. On the contrary, the modeling and control of a faulty TPIM, specifically an open-phase fault, is less discussed and less-known. Control algorithms that can seamlessly operate in healthy and faulty modes, although very important, unfortunately are not as well-known as the conventional control algorithm of a healthy TPIM. Obviously, control of faulty TPIM is different from the conventional control approaches simply because of its unbalanced structure. Using conventional FOC (designed for balanced TPIM) to control a faulty TPIM results in significant oscillations in the torque and speed due to the field disorientation and an attempt of injecting balanced currents to the unbalanced structure of the faulty TPIM.

A mathematical model of a TPIM with an open-phase fault is different from a healthy TPIM [20]. Due to the unbalanced structure of a faulty TPIM, a conventional three-phase (a-b-c) to 2-phase (d-q) transformation can no longer be used. In FOC drives, transformation matrix which is used to transform the variables to a rotating field reference frame in healthy TPIM cannot be used in a faulty TPIM, and hence must be modified. For speed sensorless FOC drives, speed estimation algorithm developed using the healthy TPIM model cannot be used to estimate the speed of a faulty TPIM. Unlike the speed estimators for a healthy TPIM, unfortunately, not many works on speed estimators of faulty TPIM are found in literatures. Until now, there is no publication that presents a speed sensorless RFOC for TPIM that works seamlessly between a healthy and faulty (open-phase) modes. In this research, a novel algorithm for speed estimation of TPIM drive based on MRAS is proposed. Different from other speed estimation methods that is based on MRAS, the proposed method works seamlessly under healthy and fault conditions, without requiring two separate algorithms. By combining the proposed MRAS speed estimation and RFOC for faulty TPIM, a speed sensorless RFOC for faulty TPIM can be constructed.

## 1.5 Thesis Objectives

This thesis presents an indirect RFOC and MRAS based speed estimation of a TPIM under open-phase fault. The proposed speed sensorless RFOC drive for TPIM can work in both healthy and faulty (open-phase) conditions. The objectives of this research are:

1) To develop an indirect RFOC for a TPIM with an open-phase fault.
2) To design and propose a speed estimator technique based on MRAS for a faulty TPIM and subsequently integrate it to the RFOC of a faulty TPIM.
3) To verify the effectiveness of the complete speed sensorless indirect RFOC that can work seamlessly between healthy and faulty modes, through simulation and hardware implementation.

## 1.6 Methodology of Research

This thesis presents a new technique of indirect RFOC and MRAS speed estimator for a TPIM with an open-phase fault. To minimize the changes in the control structure and algorithm in faulty mode, it is important to ensure that the model structures of the faulty and healthy TPIM is similar. For this reason, a modified a-b-c to d-q transformation matrix is used to transform the unbalanced structure of a TPIM into a balanced structure (d-q model) with unequal windings; this permits the use of conventional speed estimation algorithm for healthy IM on a faulty TPIM. To seamlessly operate between healthy and faulty modes, switches (implemented in software) are used to switch between these modes. In other words, the proposed method does not require major changes in the control algorithm but only require changes in the machine parameters due to unequal windings. The indirect RFOC and MRAS based speed estimators are developed and tested separately through comprehensive simulations and experiment tests under various operating conditions. The simulations are performed using MATLAB/Simulink software, and using the same Simulink models (with minor changes), C codes are automatically generated and uploaded to the DS1104 controller board for hardware implementation. Finally, the two developed systems are combined to form a speed sensorless indirect RFOC drive system that can work both in healthy and faulty modes. Figure 1.2 shows the summary of the methodology used for the estimation of the speed for the faulty TPIM.

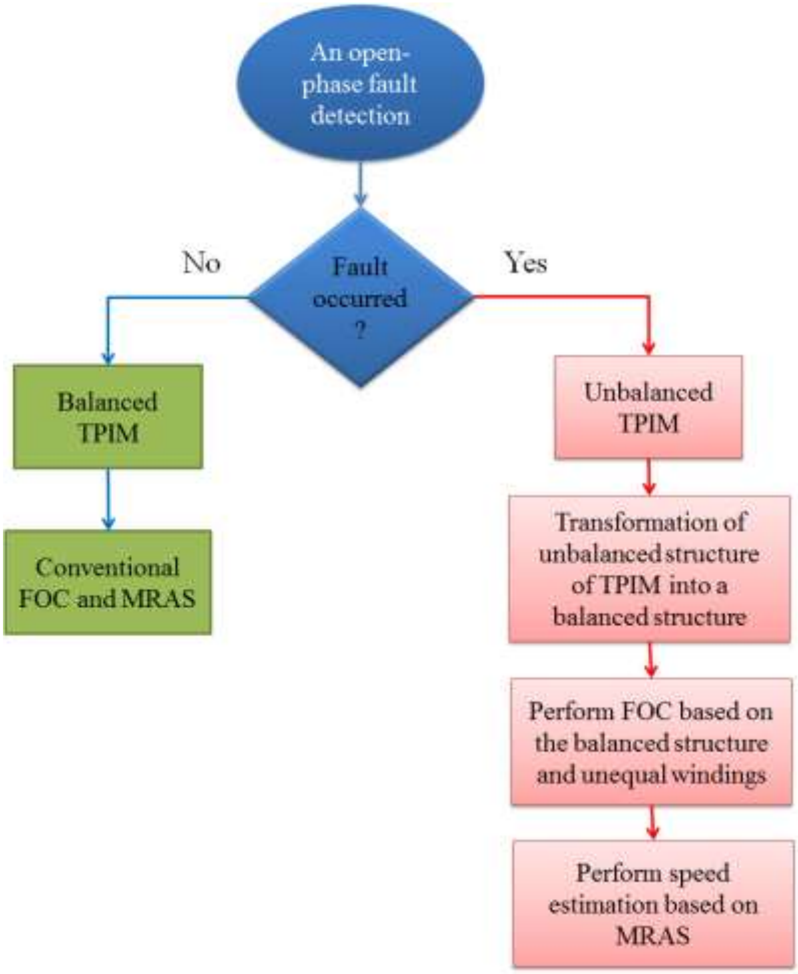

**Figure 1.2** General flowchart of control and speed estimation of TPIM

## 1.7 Scope of Study

In fulfilling the objectives of the thesis, due to the time constraint and limitation on the available resources, the scopes of this study have to be confined within certain conditions and limitations as follows:

a. Only the star connected stator windings of the TPIM is considered in this study. Furthermore, for an independent current control of the remaining phases during the fault, the neutral point of the windings will be connected to the mid-point of the DC link voltage.
b. In this work, a mechanism that will instantaneously detect the open-phase fault is assumed. In other words, it is not part of the scope of the thesis to design the fast fault detection mechanism.
c. Although there are several types of electrical failures in the electrical drive systems, this thesis will only focus on an open-phase type.
d. Development and modification of MRAS based speed estimator for a faulty TPIM will be based on the well-known MRAS based speed estimator that is used in a healthy TPIM.
e. In simulation work, MATLAB/Simulink package is employed. Simulation models are developed using available Simulink blocks and where needed, S-functions will be used.
f. The improvement of the proposed algorithm will be verified through hardware implementation, which is be based on dSPACE 1104 ACE KIT and a 1.5kW TPIM. Rapid Control Prototyping (RCP) process will be used in programming the controller board. Therefore, the C codes that are generated automatically and hence the sampling frequency are not optimized.
g. The rated speed of IM in simulation and experimental tests due to verify the only MRAS based speed estimation method for healthy and faulty TPIM is same as the actual rated speed of IM as 147.6 rad/s.
h. The rated speed of the IM in RFOC and speed sensorless RFOC of faulty TPIM techniques is limited to maximum 60 rad/s of 147.6 rad/s.

## 1.8 Research Contribution

In this thesis, a simple and accurate method that can be used to control a TPIM in healthy and an open-phase fault conditions is developed. The control technique is based on indirect RFOC.  In addition, a modified speed estimator based on MRAS that can work in healthy and faulty TPIM is also designed and presented. Finally, by combining the indirect RFOC and the modified MRAS based speed estimator, a complete speed sensorless RFOC that can seamlessly operate in healthy and faulty (open-phase fault) modes are developed and verified through hardware implementations.

## 1.9 Organization of the Thesis

The thesis is organized as follows:

**Chapter 2**. In this chapter, the d-q modeling of a TPIM under open-phase fault is presented. This chapter also briefly discusses on the TPIM speed estimation methods, which have been proposed by other researchers; focus is given on the MRAS based speed estimation techniques.

**Chapter 3** In this chapter, three-phase (a-b-c) model and in 2-phase (d-q) model of a TPIM are presented. The TPIM control techniques are discussed but the main consideration is on the indirect RFOC technique.  Three main components of the thesis contributions are presented. First vector control of TPIM under fault condition based on indirect RFOC is presented and simulated under different operating conditions. Next, speed estimation based on MRAS for a faulty TPIM is proposed and simulated. Finally, the two proposed methods are combined to form a complete speed sensorless indirect RFOC for both healthy and faulty (open-phase) TPIM. Detail simulations and discussions are performed for each case.

**Chapter 4** The laboratory experimental set-up which is used to verify the proposed methods are presented in this chapter. Descriptions of hardware components and set-up used in the experiments are described in details.

**Chapter 5** In this chapter, experimental results of the proposed indirect RFOC for a faulty TPIM, the proposed MRAS based speed estimator for a faulty TPIM and finally the proposed speed sensorless RFOC for a faulty TPIM are presented. For comparison, the conventional (healthy) RFOC and conventional MRAS speed estimator applied to a faulty TPIM are also presented.

**Chapter 6** Finally in this chapter, the conclusion of the thesis and some suggestions on future work are presented.

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