SIMULATION OF MRAS BASED SPEED SENSORLESS ESTIMATION TECHNIQUES FOR INDUCTION MACHINE DRIVES USING MATLAB/SIMULINK

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For you,

My dearest mother and father,
My brothers and sisters,
My lovely wife, son and daughter…

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Alhamdullilah, praise be to Allah S.W.T., the Most Merciful and the Most Compassionate. Peace be upon him, Muhammad, the messenger of God.

"To engage into this research was an experience to gain, knowledge to dig, friendships to build and passion to achieve"

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ABSTRACT

This thesis is about the study of the speed sensorless estimation techniques of the induction machine drives. Large variations of techniques are available depending on the estimation requirement. MRAS based speed sensorless estimation is one of the most versatile techniques available due to its good performance and straightforward stability approach. This technique uses two different models (the reference model and the adjustable model) which has made the speed estimation a reliable scheme especially when the motor parameters are poorly known or having large variations. Rotor flux based MRAS (RF-MRAS) and back e.m.f based MRAS (BEMF-MRAS) are two variants of MRAS based speed estimation techniques which differ in terms of quantity used but share almost the same structure realization. These facts give a good platform for comparison. The tracking capability and sensitivity to parameters variation are two key criteria of comparison in assessing the performance of the estimators. Implemented in the direct torque control (DTC) structure and simulated in the MATLAB/Simulink, the results obtained justify the dynamic performance of the RF-MRAS and BEMF-MRAS estimators.

ABSTRAK

Tesis ini berkenaan dengan kajian teknik-teknik anggaran laju tanpa penderia di dalam pemacu mesin aruhan. Pelbagai variasi teknik-teknik boleh didapati bergantung kepada kehendak anggaran. Anggaran laju tanpa penderia berasaskan MRAS adalah salah satu daripada teknik-teknik yang sangat berkebolehan yang boleh didapati kerana prestasinya yang baik dan menggunakan pendekatan kestabilan secara terus. Teknik ini menggunakan dua model berbeza (model rujukan dan model boleh laras) yang menjadikan anggaran laju satu skim yang bolehharap terutamanya bila parameter-parameter motor kurang diketahui atau mempunyai variasi yang besar. MRAS berasaskan fluks pemutar (RF-MRAS) dan MRAS berasaskan d.g.e balik (BEMF-MRAS) adalah dua varian teknik-teknik anggaran laju berasaskan MRAS yang berbeza dari segi kuantiti yang digunakan tetapi berkongsi struktur yang hampir sama. Fakta-fakta ini memberikan platform yang baik untuk perbandingan. Kemampuan untuk menjejak dan kepekaan kepada variasi parameter-parameter adalah dua kriterium utama perbandingan dalam menilai prestasi kedua-dua penganggar. Kedua-dua penganggar menggunakan struktur kawalan terus daya kilas (DTC) untuk tujuan simulasi. Keputusan-keputusan yang diperolehi dari MATLAB/Simulink mengesahkan prestasi kedua-dua penganggar RF-MRAS dan BEMF-MRAS.

CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF SYMBOLS

B	-	Motor friction constant
$\bar{i}_{ds}$	-	d-axis stator current expressed in stationary reference frame
$\bar{i}_{qs}$	-	q-axis stator current expressed in stationary reference frame
$\bar{i}_{dr}$	-	d-axis rotor current expressed in stationary reference frame
$\bar{i}_{qr}$	-	q-axis rotor current expressed in stationary reference frame
L_m	-	Magnetizing self-inductance
J	-	Motor moment of inertia constant
L_r	-	Rotor self-inductance
L_s	-	Stator self-inductance
P	-	Pair of poles
R_r	-	Rotor resistance
n_p	-	Number of pole pairs
R_s	-	Stator resistance
Te	-	Instantaneous value of electromagnetic torque
T_L	-	Load torque
T_r	-	Rotor time constant
$\bar{v}_{ds}$	-	d-axis stator voltage expressed in stationary reference frame
$\bar{v}_{qs}$	-	q-axis stator voltage expressed in stationary reference frame
$\bar{v}_{dr}$	-	d-axis rotor voltage expressed in stationary reference frame
$\bar{v}_{qr}$	-	q-axis rotor voltage expressed in stationary reference frame
ω	-	Angular speed
V_s	-	Stator voltage
ω_r	-	Rotor speed

$\hat{\omega}_r$	-	Estimated rotor speed
θ_e	-	Stator voltage angle
ω_e	-	Synchronous speed
$\overline{\psi}_{ds}$	-	d-axis stator flux linkage expressed in stationary reference frame
$\overline{\psi}_{qs}$	-	q-axis stator flux linkage expressed in stationary reference frame
$\overline{\psi}_{dr}$	-	d-axis rotor flux linkage expressed in stationary reference frame
$\overline{\psi}_{qr}$	-	q-axis rotor flux linkage expressed in stationary reference frame
σ	-	Total leakage reactance

LIST OF ABBREVIATIONS

IM	Induction machine/motor
IGBT	Insulated Gate Bipolar Transistor
DC	Direct Curent
AC	Asynchronous Current
V/F	Volts per Hertz
FOC	Field Oriented Control
DTC	Direct Torque Control
PWM	Pulse Width Modulated
DSP	Digital Signal Processor
MRAS	Model Reference Adaptive System
E.M.F	Electromotive Force
RF-MRAS	Rotor Flux Based Model Reference Adaptive System
BEMF-MRAS	Back E.M.F Based Model Reference Adaptive System
ANN	Artificial Neural Network
OLS	Ordinary Least-Square
BPN	Backpropagation Network

CHAPTER 1

INTRODUCTION

1.1 Overview

Induction motor (IM) can be considered as the ‘workhorse’ of the industry because of its special features such as low cost, high reliability, low inertia, simplicity and ruggedness. Even today IMs especially the squirrel cage type, are widely used for single speed applications rather than variable speed applications due to the complexity of controlling algorithm and higher production cost of IM variable speed drives. However, there is a great interest on variable speed operation of IM within the research community mainly because IMs can be considered as a major industrial load of a power system. On the other hand the IMs consume a considerable amount of electricity generated. The majority of IMs are operated at constant speed, determined by the pole pair number and the stator supply frequency.

It is well known fact that electric energy consumption of the appliances can be reduced by controlling the speed of the motor. The three phase variable speed IM drives are therefore encouraged to be used in the industry today as an attractive solution forever increasing electricity generation cost.

During the last decade, with the advancement of power electronics technology, a high speed switching devices such as IGBTs were introduced and a more precise motor control strategies, such as vector control techniques, were developed. As a result, today IMs can be used in any kind of variable speed applications, even as a servomechanism, where high-speed response and extreme accuracy is required.

Vector control technique is used for high performance variable drive systems. In the vector control scheme, a complex current is synthesized from two quadrature components. One of which is responsible for the flux level in the motor and another, which controls the torque production in the motor. In actual fact the control problem is reformulated to resemble control of a DC motor. Vector control offers attractive benefits including wide range of speed control, precise speed regulation, fast dynamic response, operation above based speed and etc. The principals of vector control are now well established at high performance IM drives.

In order to implement the vector control technique, the motor speed information is required. Tachogenerators, resolvers or incremental encoders are used to detect the rotor speed. However, these sensors impair the ruggedness, reliability and simplicity of the IM. Moreover, they require careful mounting and alignment and special attention is required with electrical noises. Speed sensor needs additional space for mounting and maintenance and hence increases the cost and the size of the drive system. However, in one aspect, the speed sensor elimination reduces the total cost of the drive system. On the other hand the sensorless drive system is more versatile due to the absence of the numerous problems associated with the speed sensor as discussed previously. Therefore it is encouraged to use the sensorless system where the speed is estimated by means of a control algorithm instead of measuring. However eliminating the speed sensor without degrading the performance is still a challenge for engineers.

In this thesis, the speed sensorless estimation concept via implementation of Model Reference Adaptive System (MRAS) schemes was studied. It is a well known fact that the performance of MRAS based speed estimators is beyond par from other speed estimators with regards to its stability approach and design complexity. Although this thesis is all about MRAS based speed estimators, but it is also the aim of this project to investigate several speed sensorless estimation strategies for IMs. Explanations on the type of control strategies also were briefly discussed. As far as simulation works is concerned, the MRAS based speed sensorless estimation schemes chosen in this thesis has been implemented in the direct torque control structure (DTC) to evaluate the estimators' performance.

1.2 Significance of study

With the maturing technology of the vector-controlled drives, the need for speed information is crucial for control purposes and traditionally, this information can be extracted using mechanical sensor mounted on the motor shaft. However, the presence of such sensor has reduced the system reliability and increases the drives system's size and the overall cost. These problems have attracted the interest of many researchers to develop techniques that can eliminate the use of shaft sensor. This effort has lead to growth of various speed sensorless estimation schemes based on the simplified motor models.

Therefore, it is the intention of this work to share the motivation of the previous researchers to study the speed sensorless estimation strategies. Though it has gone through a maturing period of over 20 years, improvement and enhancement of such system is still required. This effort might become a first step to the author to involved into detail researches of the speed sensorless control in future.

The reason behind adopting the MRAS based speed sensorless estimation strategies in this research is so obvious because it has been proclaimed as one of the best methods available, especially when the motor parameters are poorly known or have large variations. Though the performance of MRAS based estimators is considerably good at high speed but operation at low and zero speed is still a problem to overcome.

1.3 Objectives

The objectives of this research are outlined as follows:

1) To study the various speed estimation schemes available with main focus will be on the MRAS based schemes.

2) To model and simulate rotor flux based MRAS (RF-MRAS) and back e.m.f based MRAS (BEMF-MRAS) speed estimators for IM drives using toolboxes available in MATLAB/Simulink.

3) To evaluate and compare the performance of the selected MRAS based of speed estimators in terms of tracking capability and parameters sensitivity.

1.4 Scope of study

The works undertaken in this project are limited to the following aspects to ensure the scopes of study are within the anticipated boundary.

1. Sensorless estimation of rotor speed using open loop, RF-MRAS and BEMF-MRAS estimators only.

2. IM parameters are known or readily available.

3. Simulation of MRAS based speed estimators will consider the effect of parameters variation.

4. Speed estimators are implemented in the direct torque control (DTC) structure.

5. Simulation in MATLAB/Simulink.

1.5 Work methodology

The research methodology is undertaken according to these stages:

1. Study of the IM dynamic equations related to RF-MRAS and BEMF-MRAS speed estimator’s structure.

2. Construct the RF-MRAS and BEMF-MRAS using Simulink blocks.

3. Implementation in direct torque control scheme.

4. Examine the estimated and actual rotor speed response, with and without effect of parameters variation in MATLAB/Simulink.

5. Evaluate performance of RF-MRAS and BEMF-MRAS based on simulation results.

1.6 Literature review

Speed sensorless estimation has greatly evolved from an open loop, low performance strategy to closed loop, high performance strategy over the past decades. The need of developing such technique is essential to adapt to the advancement in the control strategy, especially the vector control techniques. Looking back into the past, Abbondanti [1] has become the first to propose calculating of rotor speed based on the motor model. His innovation has been further improved by Nabae [2], Jotten and Maeder [3], and Baader [4] and they had used it in some practical AC drive systems. The fact is that, the real time calculating of the speed has difficulties for the realization because it is largely dependent on the motor's parameters.

Tamai [5] and Schauder [6] had opened a new horizon to speed sensorless field for which they had introduced the MRAS to identify the rotor speed. Their contribution is widely used and referred because identification of speed is more robust than calculation of speed. Shauder [6] in his paper has proposed a RF-MRAS technique to estimate the rotor speed based on comparison between the outputs of two estimators known as the reference model and the adjustable model. The performance is acceptably good but effect of parameter variation and drift problem is a drawback to be carefully study.

Peng and Fukao [7] has proposed a new technique of MRAS based speed estimation to overcome the problem in RF-MRAS proposed by Schauder [6]. The scheme which is based on back e.m.f, shows a better performance and robustness due to elimination of pure integrators in the reference and adjustable model. Another scheme which an extension of BEMF-MRAS also has been proposed. This scheme uses reactive power information as the tuning signal rather than the back e.m.f or rotor flux quantity. This scheme is further investigate by M. Ta-Cao et al. [8] which shows superior robustness compared to previous MRAS schemes.

A more powerful and robust estimator based on artificial neural network MRAS has been proposed by Ben-Brahim et al. [9] which exploit the classical backpropagation network (BPN) algorithm for the online training of the neural network to estimate the rotor speed. It is experimentally verified at the lowest speed limit and even at zero-speed operation. Cirrincione and Pucci [10] proposed an improvement of the MRAS artificial-neural-network (ANN)-based speed observer presented by Ben-Brahim et al. [9]. In spite of using BPN algorithm, it uses the ordinary least-square (OLS) algorithm to solve the problem associated with linearity. From the study, it is observed that the OLS MRAS outperforms the BPN MRAS proposed previously.

Although there are various techniques available for speed sensorless estimation, but not enough effort has been put to review the schemes comparatively. Illas et al. [11] have investigated and compared several speed sensorless estimation schemes for field oriented control of IM drives. Speed estimations using speed estimator, MRAS, speed observer, Kalman filter and rotor slot ripple have been review and simulated to evaluate the performance based on some figures of merit. Marwali and Kehyani [12] have performed a comparative study of the RF-MRAS and BEMF-MRAS evaluated in indirect vector control system. The studies focus on the level of the difficulty in tuning the adaptive gains and the speed tracking performances. From the simulation and experimental studies, they have shown that the BEMF-MRAS is better compared to RF-MRAS. Bodson and Chiasson [13] have considered three representative approaches such as the adaptive method, least-square method and nonlinear method for speed estimation. The methods are compared in terms of their sensitivity to parameters variation, their ability to handle load and their speed tracking capability.

Some studies related to parameter variation effects in sensorless vector controlled drives are already available [14][15]. For example, impact of rotor resistance variation on transient behavior of the drive was studied by Ilas et a1. [11] and by Griva et a1. [16] through simulation. Viorel and Hidesiu [17] and Armstrong et al. [18] have studied impact of rotor resistance, stator resistance and mutual inductance variation in low speed region experimentally. The only available comprehensive investigations of steady-state speed estimation errors caused by parameter variation effects appear to be works by Gimenez et a1. [19] and Jansen and Lorenz [20]. However, in both cases structure of the drive dealt with is direct rotor flux oriented control that combines a MRAS based speed estimator with a closed loop flux observer and includes a mechanical system model. The validity of results obtained by Gimenez and Jansen is thus restricted to that specific drive structure.

1.7 Thesis organization

Speed sensorless estimation is a vast subject of research. MRAS speed estimators constitute one part of it which significantly influence the maturing of this field. To study such a vast subject at one time is almost possible; therefore, only MRAS framework will be studied thoroughly in this work. For that reason, the organization of the materials in this thesis is indeed intentionally to make available all the information related to the subject of study. The organization of this thesis is outlined as follows:

Chapter 2 presents the general theory of the IM dynamics. The IM dynamics equations extensively used for estimation algorithm were explained. Brief explanation on IM control strategy also was included.

Chapter 3 gives an overview of speed sensorless estimation strategies available in literature. Speed estimation techniques are briefly reviewed to give an idea of the concept and the need for a robust and stable speed estimator. Since the estimators are uniquely best in its own class, therefore, their trends and trade off were highlighted at the end of this chapter.

Chapter 4 presents the rotor speed estimation using MRAS based strategy; the RF-MRAS and the BEMF-MRAS. All the schemes were described thoroughly in terms of mathematical equations, construction, implementation and performance. The simulation setup for selected schemes i.e. the RF-MRAS and BEMF-MRAS were presented.

Chapter 5 discusses the simulation results for the two estimators. Estimators' response at different values of speed reference was studied. The performance of the estimators with effect of parameters variation was also examined. Analysis and discussion were made to critically evaluate the performance of the two estimators.

In Chapter 6, a thorough conclusion of the research was presented. Some suggestions for future works also were highlighted.