UNIVERSITI PUTRA MALAYSIA

INDIRECT ROTOR FIELD ORIENTED CONTROL OF INDUCTION MOTOR WITH ROTOR TIME CONSTANT ESTIMATION

EYAD MOH'D MOH'D RADWAN.

INDIRECT ROTOR FIELD ORIENTED CONTROL OF INDUCTION MOTOR WITH ROTOR TIME CONSTANT ESTIMATION

By

EYAD MOH'D MOH'D RADWAN

Thesis Submitted to the School of Graduate Studies, Universiti Putra Malaysia
in Fulfilment of the Requirement for the Degree of Doctor of Philosophy

July 2004

To my parents Mr. Moh'd & Mrs. Asma'Radwan
with love

Abstract of thesis presented to the Senate of Universiti Putra Malaysia in fulfilment of the requirements for the degree of Doctor of Philosophy

INDIRECT ROTOR FIELD ORIENTED INDUCTION MOTOR WITH ROTOR TIME CONSTANT ESTIMATION

By

EYAD MOH'D MOH'D RADWAN

July 2004

Chairman: **Associate Professor Ir. Norman Mariun, Ph.D.**

Faculty: **Engineering**

This thesis presents an estimation technique of the inverse rotor time constant for Indirect Rotor Field Oriented Control (IRFOC) induction motor application. In this estimation technique two different equations are used to estimate the rotor flux in the stator reference frame. One of the equations is a function of the rotor time constant, rotor angular velocity and the stator currents, and the other equation is a function of measured stator currents and voltages. The equation that uses the voltage and the current signals of the stator serves as reference model, while the other equation works as an adjustable model with respect to the variation of the rotor time constant. Measurements of two phases of the current, and speed using an optical encoder are required in this estimation technique. The stator phase voltages are estimated from the DC bus voltage and the switching commands signals with compensation of the dead time effect.

Field oriented control of induction motor is gaining wide acceptance in high performance AC motor drive applications. Field oriented control, in its both forms

as a direct or indirect, gives the AC motor dynamics that are equivalent to that of a DC motor. However, direct and indirect field oriented control suffer from specific theoretical and practical problems. The approach of direct field oriented control with Hall sensors for flux sensing has limitations governed by the physical structure of the machine itself. On the other hand, the approach of indirect field oriented control of induction machines is highly dependent on the rotor parameters, which are not easily accessible for measurements except for the rotor speed.

In a DC motor, spatial relationship of the torque and flux is maintained by the physical construction of the motor armature and field circuits. However, in an induction motor such spatial relationship does not maintain as such machine has usually a single terminal where electric power is supplied. Therefore, such relationship is maintained by external control methods. In a basic IRFOC of an induction motor, speed and phase currents are sensed in order to control the stator current vector such a way so it can be resolved into two components, one is to control the rotor flux and the other to control the motor torque. Successful decomposition of stator current vector into these two components requires the knowledge of the instantaneous position of the rotor flux vector. Since the position of the rotor flux vector is estimated in an IRFOC scheme, and is dependent on the motor model (more specifically the rotor parameters), these parameters must be obtained accurately and match the motor parameters at all times. Unfortunately, rotor parameters vary and are not easily accessible for measurements. Therefore, this uncertainty about the rotor flux vector position degrades the dynamic operation of the drive.

Enormous efforts have been made to improve IRFOC scheme by design of complicated hardware and software in order to compensate for such imperfection. Hence, this work focuses on the Indirect Rotor Field Oriented Control of induction motors with estimation of the rotor time constant. A simple yet effective rotor time constant identification method is presented and used for updating the slip calculator used by the IRFOC algorithms.

A complete simulation model of an induction motor and IRFOC scheme is presented and tested using SIMULINK/MATLAB, and experimentally implemented on a DSP Board (MCK243) without any need for voltage phase sensors. Simulation and experimental results were presented and compared to verify the validity of the proposed estimator for different operating conditions.

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

INDUKSI MOTOR BERASASKAN ROTOR TIDAK LANGSUNG DENGAN ANGGARAN PEMALAR MASA ROTOR

Oleh

EYAD MOH'D MOH'D RADWAN

July 2004

Pengerusi : **Professor Madya Ir. Dr. Norman Mariun, Ph.D.**

Fakulti: **Kejuruteraan**

Tesis ini membentangkan teknik anggaran kepada pemalar masa rotor berkadar songsang kepada kawalan motor berasaskan medan secara tidak langsung (IRFOC). Di dalam teknik anggaran ini terdapat dua persamaan/formulasi yang digunakan bagi membuat anggaran fluks rotor di dalam bingkai rujukan stator. Antara persamaan yang terlibat ialah fungsi pemalar masa rotor, halaju bersudut rotor dan arus stator. Manakala persamaan-persamaan lain yang terlibat ialah fungsi arus dan voltan stator yang telah diukur. Persamaan yang menggunakan isyarat arus dan voltan bagi stator berfungsi sebagai model yang boleh diubahsuai bergantung kepada variasi pemalar masa rotor. Ukuran bagi dua fasa arus dan kelajuan menggunakan pengekod optik diperlukan di dalam teknik anggaran ini. Fasa voltan stator dianggarkan daripada voltan bus arus terus dan isyarat arahan pengsuisan dengan gantirugi bagi kesan masa tamat.

Kawalan berasaskan medan bagi induksi motor kini telah mendapat tempat dan penerimaan yang tinggi dalam bidang aplikasi pemacu motor arus ulang-alik yang

berkebolehan tinggi. Kawalan motor berasaskan medan ini, samada secara langsung mahupun tidak langsung, mampu memberikan dinamik motor arus ulang-alik yang serupa seperti motor arus terus.Walaubagaimanapun,kawalan motor berasaskan medan secara langsung mahupun tidak langsung ini, menghadapi masalah teori dan praktik yang tertentu. Pendekatan bagi kawalan motor berasaskan medan secara langsung dengan alat pengesan Hall bagi pengesanan fluks mempunyai had yang terhasil daripada kesan struktur fizikal mesin itu sendiri. Selain daripada itu, pendekatan bagi IRFOC bagi induksi mesin amat bergantung kepada parameter rotor, yang mana tidak mudah untuk diukur kecuali bagi kelajuan rotor.

Di dalam motor arus terus, hubungan antara tork dan fluks diselenggarakan oleh binaan fizikal armatur motor dan litar-litar medan. Walaubagaimanapun, di dalam induksi motor hubungan seperti itu tidak dapat diselenggarakan kerana mesin seperti itu kebiasaannya mempunyai terminal tunggal di mana kuasa elektrik dibekalkan. Oleh itu, hubungan tersebut diselenggarakan melalui kaedah kawalan luaran. Di dalam asas kawalan motor berasaskan medan secara tidak langsung bagi induksi motor, kelajuan dan fasa arus dikesan bagi mengawal vektor arus statik di mana ia membolehkannya diselesaikan kepada dua komponen, satu untuk mengawal fluks rotor dan satu lagi bagi mengawal tork motor. Nyahkomposisi yang berjaya bagi vektor arus statik kepada dua komponen tersebut memerlukan pengetahuan tentang posisi segera bagi vector fluks rotor. Memandangkan posisi vektor fluks rotor dianggarkan di dalam skema IRFOC, dan ianya bergantung kepada jenis motor (secara lebih spesifik parameter rotor), parameter-parameter ini perlulah diperolehi secara tepat dan sepadan dengan parameter motor sepanjang masa. Malangnya,parameter rotor berubah-ubah(tidak tetap) dan tidak mudah diukur. Oleh itu, ketidaktetapan tentang posisi vektor fluks rotor menurunkan operasi dinamik pemacu tersebut.

Pelbagai usaha telah dijalankan bagi meningkatkan skema IRFOC denagn merekabentuk perkakasan dan perisian yang kompleks bagi menyempurnakannya. Kaji selidik ini memfokuskan ke atas kawalan induksi motor berorientasikan medan rotor secara tidak langsung atau IRFOC dengan bercirikan kemampuan untuk membuat anggaran bagi pemalar masa rotor. Kaedah pengenalpastian pemalar masa rotor yang mudah tetapi efektif telah dipersembahkan dan digunakan di dalam kajiselidik ini bagi mengemaskini mesin kira gelinciran yang digunakan oleh logaritma-logaritma IRFOC.

Satu modal simulasi lengkap bagi induksi motor dan skema IRFOC telah dipersembahkan dan diuji menggunakan SIMULINK / MATLAB dan diimplementasikan secara eksperimen di atas papan pemprosesan Isyarat Digital (MCK243) tanpa menggunakan pengesan voltan bagi pengiraan fasa voltan. Keputusan bagi simulasi dan eksperimen telah dipersembahkan dan dibandingkan bagi mengesahkan kesahihan penganggar yang dicadangkan bagi keadaan pengoperasian yang berbeza.

ACKNOWLEDGEMENTS

Thanks to Almighty ALLAH, for giving me the health and the power to be able to complete this work.

First of all, I wish to express my profound gratitude and appreciation to my main supervisor, Associate Professor Ir. Dr. Norman Mariun, Head of Electrical Engineering Department, Universiti Putra Malaysia, for his supervision, guidance, encouragement, and continuous support throughout this work. Since I met him on 1997, he has been giving me all the confidence and support to achieve what I am reaching today, thank you again Dr. Norman.

I would also like to express my deepest appreciations to all members of my supervisory committee, Associate Professor Dr. Ishak Aris, Associate Professor Dr. Sinan Mahmoud, Faculty of Engineering UPM, and Professor Ir. Dr. Abd Halim Yatim, Faculty of Electrical Engineering Universiti Teknologi Malaysia (UTM). My gratitude goes to all the Faculty of Engineering staff in UPM and especially to Dr. Shamsul Bahri for providing the financial support for this work.

Thanks are also extended to the management and the staff of UCSI, especially the President & V.C. Dato' Peter Ng for all kinds of confidence and understanding.

I am also grateful to all my friends, Dr. Khedr Abo Hassan, Dr. Suliman Al Zuhair, Mr. Mutasim Nour, Mr. Ghassan Shaheen, and Dr. Mohammad Salih for their encouragement and support.

Lastly, but certainly not least, I heartily thank my parents Mr. Moh'd Radwan & Mrs Asma' Radwan, brothers, and sisters back in Jordan, who endured several hundred days of my time being away from them, towards the completion of this work. Without their continued prayers, patience and understanding, the completion of this work really would have been impossible.

TABLE OF CONTENTS

Page

DEDICATION ii
ABSTRACT iii
ABSTRAK vi
ACKNOWLEDGMENS ix
APPROVAL x
DECLARATION xii
LIST OF TABLES xiii
LIST OF FIGURES xiv
LIST OF SYMBOLS xxi

CHAPTER

1 INTRODUCTION 1.1
- 1.1 Background 1.1
- 1.2 Objectives 1.4
- 1.3 Contributions 1.4
- 1.4 Overview of the Thesis 1.5

2 LITERATURE REVIEW 2.1
- 2.1 Motor Drives Control Strategies 2.1
- 2.2 Induction Motor Dynamic Model 2.3
  - 2.2.1 Stator Reference Frame 2.3
  - 2.2.2 Excitation Reference Frame 2.11
  - 2.2.3 Torque Production in Induction Motor 2.15
- 2.3 Field Oriented Control (FOC) 2.21
- 2.4 Direct Field Oriented Control (DFOC) 2.26
  - 2.4.1 Direct Rotor Field Orientation 2.27
  - 2.4.2 Direct Stator Field Orientation 2.31
  - 2.4.3 Direct Air Gap Field Orientation 2.34
- 2.5 Indirect Field Orientation Control (IFOC) 2.36
  - 2.5.1 Indirect Rotor Field Orientation 2.36
  - 2.5.2 Indirect Stator Field Orientation 2.40
  - 2.5.3 Indirect Air Gap Field Orientation 2.44
- 2.6 Sensitivity of IFOC to Rotor Time Constant 2.46

3 IRFOC Model Structure 3.1
- 3.1 Introduction 3.1
- 3.2 Principles of the Proposed IRFOC 3.1
- 3.3 Current Controllers Design 3.11
- 3.4 Speed Controller Design 3.20
- 3.5 Rotor Time Constant Estimator 3.26
- 3.6 Induction Motor in the Stator Reference Frame 3.45

4 REAL TIME IMPLEMENTATION USING MCK 243 4.1
- 4.1 MCK243 Hardware Overview 4.2

4.2 TMS320F243 DSP Controller Overview 4.4
- 4.2.1 PWM Waveform Generation 4.6
- 4.2.2 Quadrature Encoder Pulse Circuit 4.13
- 4.2.3 Analogue to Digital Converter 4.15

4.3 Software Structure 4.16
4.4 Speed Measurement 4.22
4.5 Current Measurement 4.23
4.6 Current and Speed PI Controllers 4.25
4.7 Reference Frame Transformation 4.34
4.8 Inverse Rotor Time Constant Estimation 4.38
4.9 DMC Developer 4.45

5 RESULTS AND DISCUSSION 5.1
5.1 Low Speed Operation 5.1
5.2 Cyclic Step in Reference Speed 5.11
5.3 Step in the Reference Speed Under no Load with Error in the Inverse Rotor Time Constant 5.19
5.4 Step in Load at Constant Reference Speed 5.25
5.5 Low Speed with an Error in the Initial Estimation of the Inverse Rotor Time Constant 5.30

5.6 Evaluation of Results 5.34

6 CONCLUSION AND FUTURE TOPICS 6.1

REFERENCES R.1
APPENDICES A.1
BIODATA OF THE AUTHOR B.1

LIST OF TABLES

Table		Page
2.1	Features of Control Strategies	2.2
4.1	Lookup Table for Generating the Sine in Q15 Format	4.38

LIST OF FIGURES

Figure		Page
2.1	Stator mmf Vectors at $\omega_s t = 0°$	2.5
2.2	Stator mmf Vectors at $\omega_s t = 60°$	2.5
2.3a,b	Rotor at $\theta_m = 0°$, and $\theta_m = 30°$, with Respect to Stator Reference Frame Respectively.	2.9
2.4	Resistive-Plus-Inductive Equivalent Circuit of Either the Stator or Rotor Winding	2.9
2.5a,b	Stator mmf Vector in the Stator and Excitation Reference Frames at $\omega_s t = 0^{\circ}$ and $\omega_s t = 60^{\circ}$ Respectively	2.13
2.6	Orthogonal Armature Current and Stator Flux Vectors in DC Machine	2.16
2.7	The Stator and the Rotor Current Space Vectors	2.20
2.8	Dynamic Model of an Induction Motor in a Synchronously Rotating Reference Frame	2.25
2.9	Alignment of the Rotor Flux Component λ_{DR} with the D axis of the Synchronously Rotating Reference Frame	2.26
2.10	Block Diagram of DRFO	2.30
2.11	Torque Calculator	2.30
2.12	Block Diagram of DSFO	2.33
2.13	Block Diagram of DAFO	2.35
2.14	Rotor Flux Vector Position with Respect to Stator Reference Frame	2.39
2.15	Block Diagram of IRFO Control	2.39
2.16	Decoupling Network for ISFO Control	2.42
2.17	The Position of the Stator Flux Vector with Respect to the Stator (Stationary) Reference Frame	2.42
2.18	Block Diagram of ISFO Control Scheme	2.43
2.19	Decoupling Network for IAFO Control	2.45

2.20 The Position of the Airgap Flux Vector with Respect to the Stator (Stationary) Reference Frame 2.45

2.21 Block Diagram of IAFO Control Scheme 2.46

2.22 Estimated and Real Rotor Flux Plane when $\hat{\tau}_r > \tau_r$ 2.50

2.23 Estimated and Real Rotor Flux Plane when $\hat{\tau}_r < \tau_r$ 2.50

2.24 Output Torque Vs. Commanded Torque when $\hat{\tau}_r > \tau_r$ 2.54

2.25 Output Torque Vs. Commanded Torque when $\hat{\tau}_r < \tau_r$ 2.54

3.1 General Block Diagram of an Induction Motor Field Oriented Control System 3.3

3.2 Linear Model of Induction Motor in an IRFOC 3.3

3.3 Indirect Rotor Field Oriented Controller 3.5

3.4 Rotor Flux Angle Calculator 3.9

3.5 The Transformation From Rotor Flux Reference Frame to Stator Reference Frame 3.9

3.6 Subsystem Block of the DQ → dq Transformation Matrix 3.10

3.7 The Transformation From Stator Reference Frame to Rotor Flux Reference Frame 3.12

3.8 Subsystem Block of the dq→DQ Transformation Matrix 3.12

3.9 D axis PI Current Controller Loop 3.15

3.10 Q axis PI Current Controller Loop 3.15

3.11 Direct Current PI Regulator Implementation 3.19
3.12 Quadrature Current PI Regulator Implementation 3.19

3.13 PI Speed Controller Basic Configuration 3.21

3.14 Speed PI Regulator Implementation 3.23

3.15 Complete IRFOC 3.24

3.16 Subsystem Block of an IRFOC 3.25

3.17 IFOC GUI 3.25

3.18 Rotor Time Constant Estimation Mechanism 3.29
3.19 Reference Rotor Flux Model Calculator 3.32
3.20 Subsystem Block of Reference Model Rotor Flux Calculator 3.32
3.21 Adjustable Rotor Flux Model Calculator 3.33
3.22 Subsystem Block of Adjustable Model Rotor Flux Calculator 3.33
3.23 Block Diagram Representing the Estimator Dynamic Response 3.39
3.24 Root Locus Plot at Rated Speed 3.40
3.25 Root Locus Plot Near Zero Speed 3.40
3.26 Oscillatory Response k_o=24.0 ($k_1 < k_o < k_2$) 3.41
3.27 General Process for Tuning Using Ziegler-Nichols Rules 3.42
3.28 Measurement of the Oscillation Period (T_{osc} =0.023s) 3.43
3.29 Responses of Regulated Closed Loop System at Rated Speed 3.44
3.30 Responses of Regulated Closed Loop System Near Zero Speed 3.44
3.31 Direct Component of the Stator Current in the Stator Reference Frame 3.47
3.32 Quadrature Component of the Stator Current in the Stator Reference Frame 3.47
3.33 Direct Component of the Rotor Current in the Stator Reference Frame 3.49
3.34 Quadrature Component of the Rotor Current in the Stator Reference Frame 3.49
3.35 Calculation of the Rotor Angular Speed 3.50
3.36 Induction Motor Subsystem Showing the Inputs and the Outputs to the Model 3.51
3.37 Induction Motor Graphical User Interface 3.51
3.38 Complete Model of IRFOC System Using Simulink 3.52
4.1 MCK and Three-Phase Inverter 4.3
4.2 TMS320F243 DSP Controller Block Diagram 4.5

4.3 GP Timer1 in Continuous UP/DOWN Mode 4.7

4.4 Block Diagram of the Internal Units of the DSP Connected to One Leg of a Six Switches Inverter 4.9

4.5 Generation of One of the Motor Phase Voltage 4.11

4.6 Three Phase Inverter Reference Signals and Phase to Mid Point Voltages 4.12

4.7 Generation of Three Phase Inverter Line Voltages 4.12

4.8 Quadrature Encoder Pulse Circuit 4.14

4.9 Generation of Quadrature Clock to GP Timer 2 and Direction of Counting from Input Signals QEP0 and QEP1 4.14

4.10 Initialisation and Run Modules 4.17

4.11 Interrupt Configuration 4.18

4.12 Main Program Flow Chart and Other Tasks Performed 4.19

4.13 Representation of Positive and Negative Numbers in Q15 Format 4.21

4.14 Motor Speed in rpm Vs. Encoder Number of Pulses 4.23

4.15 The Signal Conditioning of Sensed Motor Phase Current to the DSP ADC Unit 4.25

4.16 Block Diagram of a Digitised PI Controller 4.28

4.17 PI Current Controller Loop 4.31

4.18 PI Speed Controller Loop 4.33

4.19 Project File Window 4.47

4.20 Output Menu 4.47

5.1 Motor Speed When a Step Change in Reference Speed from 0 to 5Hz Under No Load (Simulation) 5.4

5.2 Motor Speed When a Step Change in Reference Speed from 0 to 5Hz Under No Load (Experimental) 5.4

5.3 Motor Current (i^e_{SQ}) When a Step Change in Reference Speed from 0 to 5Hz Under No Load (Simulation) 5.5

5.4 Motor Current (i^e_{SQ}) When a Step Change in Reference Speed from 0 to 5Hz Under No Load (Experimental) 5.5

5.5 Motor Current (i^e_{SD}) When a Step Change in Reference Speed from 0 to 5Hz Under No Load (Simulation) 5.6

5.6 Motor Current (i^e_{SD}) When a Step Change in Reference Speed from 0 to 5Hz Under No Load (Experimental) 5.6

5.7 Estimated Rotor Flux When a Step Change in Reference Speed from 0 to 5Hz Under No Load (Simulation) 5.7

5.8 XY Plot of Estimated Rotor Flux When a Step Change in Reference Speed from 0 to 5Hz Under No Load (Simulation) 5.7

5.9 Estimated Rotor Flux When a Step Change in Reference Speed from 0 to 5Hz without Dead Time Compensation and Under No Load (Experimental) 5.8

5.10 XY Plot of Estimated Rotor Flux When a Step Change in Reference Speed from 0 to 5Hz without Dead Time Compensation and Under No Load (Experimental) 5.8

5.11 Estimated Rotor Flux When a Step Change in Reference Speed from 0 to 5Hz with Dead Time Compensation and Under No Load (Experimental) 5.9

5.12 XY Plot Estimated Rotor Flux When a Step Change in Reference Speed from 0 to 5Hz with Dead Time Compensation and Under No Load (Experimental) 5.9

5.13 Estimated Inverse Rotor Time Constant When a Step Change in Reference Speed from 0 to 5Hz (Simulation) 5.10

5.14 Estimated Inverse Rotor Time Constant When a Step Change in Reference Speed from 0 to 5Hz (Experimental) 5.10

5.15 Cyclic Step in Speed (10π to 94π rad/s) Under No Load (Simulation) 5.13

5.16 Cyclic Step in Speed (10π to 94π rad/s) Under No Load (Experimental) 5.13

5.17 Quadrature Stator Current (i^e_{SQ}) for Cyclic Step in Speed (Simulation) 5.14

5.18 Quadrature Stator Current (i^e_{SQ}) for Cyclic Step in Speed (Experimental) 5.14

5.19 Direct Stator Current (i^e_{SD}) for Cyclic Step in Speed (Simulation) 5.15

5.20 Direct Stator Current (i^e_{SD}) for Cyclic Step in Speed (Experimental) 5.15

5.21 Estimated Rotor Flux for Cyclic Step in Speed (Simulation) 5.16

5.22 XY Plot of Estimated Rotor Flux for Cyclic Step in Speed (Simulation) 5.16

5.23 Estimated Rotor Flux for Cyclic Step in Speed (Experimental) 5.17

5.24 XY Plot of Estimated Rotor Flux for Cyclic Step in Speed (Experimental) 5.17

5.25 Estimated Inverse Rotor Time Constant for Cyclic Step in Speed (Simulation) 5.18

5.26 Estimated Inverse Rotor Time Constant for Cyclic Step in Speed (Experimental) 5.18

5.26 Effect of Error in Inverse Rotor Time Constant on a Step Change in Speed (Simulation) 5.21

5.27 Effect of Error in Inverse Rotor Time Constant on a Step Change in Speed (Experimental) 5.21

5.28 Motor Current (i^e_{SQ}) When a Step Change in Reference Speed From 31.4 to 235.6 rad/s Under No Load and Error in Inverse Rotor Time Constant (Simulation) 5.22

5.30 Experimental Motor Current (i^e_{SQ}) When a Step Change in Reference Speed From 31.4 to 235.6 rad/s Under No Load and Error in Inverse Rotor Time Constant (Experimental) 5.22

5.31 Motor Current (i^e_{SD}) When a Step Change in Reference Speed From 31.4 to 235.6 rad/s Under No Load and Error in Inverse Rotor Time Constant (Simulation) 5.23

5.32 Motor Current (i^e_{SD}) When a Step Change in Reference Speed From 31.4 to 235.6 rad/s Under No Load and No Error in the Inverse Rotor Time Constant (Experimental) 5.23

5.33 Motor Current (i^e_{SD}) When a Step Change in Reference Speed From 31.4 to 235.6 rad/s Under No Load and Error of +50% in Inverse Rotor Time Constant (Experimental) 5.24

5.34 Motor Current (i^e_{SD}) When a Step Change in Reference Speed From 31.4 to 235.6 rad/s Under No Load and Error of -50% in Inverse Rotor Time Constant (Experimental) 5.24

5.35 Motor Speed for a Step Change in Load Torque at Constant Reference Speed of 235.6 rad/s (Simulation) 5.27

5.36 Motor Speed for a Step Change in Load Torque at Constant Reference Speed of 235.6 rad/s (Experimental) 5.27

5.37 Quadrature Stator Current for a Step Change in Load Torque at Constant Reference Speed (Simulation) 5.28

5.38 Quadrature Stator Current for a Step Change in Load Torque at Constant Reference Speed (Experimental) 5.28

5.39 Inverse Rotor Time Constant Estimation for a Step Change in Load Torque at Constant Reference Speed (Simulation) 5.29

5.40 Inverse Rotor Time Constant Estimation for a Step Change in Load Torque at Constant Reference Speed (Experimental) 5.29

5.41 Start up at Low Speed with Initial Error in Inverse Rotor Time Constant (Simulation) 5.31

5.42 Start up at Low Speed with Initial Error in Inverse Rotor Time Constant (Experimental) 5.31

5.43 Quadrature Stator Current at Low Speed and Initial Error in the Estimated Inverse Rotor Time Constant (Simulation) 5.32

5.44 Quadrature Stator Current at Low Speed and Initial Error in the Estimated Inverse Rotor Time Constant (Experimental) 5.32

5.45 Estimation of Inverse Rotor Time Constant at Low Speed with an Initial Error (Simulation) 5.33

5.46 Estimation of Inverse Rotor Time Constant at Low Speed with an Initial Error (Experimental) 5.33

LIST OF SYMBOLS

B	Friction coefficient, N.m/(rad/s)
$e(t)$	Time domain error signal
$e(n)$	Error signal at sample n
F_{as}	Magnetomotive force space vector (mmf) of phase a, A
F_{bs}	Magnetomotive force space vector of phase b, A/ph
F_{cs}	Magnetomotive force space vector of phase c, A/ph
$F^s{}_s$	Stator magnetomotive force space vector in stator reference frame, A
$F^s{}_{sd}$	Direct component of the magnetomotive force space vector, A
$F^s{}_{sq}$	Quadrature component of the magnetomotive force space vector, A
G_r	Inverse rotor time constant, $\frac{1}{\tau_r}$, Hz
$\hat{G}_r$	Estimated Inverse rotor time constant, Hz
$\hat{G}_{r(n)}$	Value of estimated inverse rotor time constant at sample n, Hz
G_{rnom}	Nominal inverse rotor time constant, Hz
G_{ro}	Operating point inverse rotor time constant value, Hz
G_T	Torque proportionality constant defined as, $G_T = \frac{4\times L_r}{3\times P\times L_m}$
i_{as}	Motor stator current Phase a, A
i^*_{as}	Command signal of stator current Phase a, A
i_{bs}	Motor stator current Phase b, A
i^*_{bs}	Command signal of stator current Phase b, A
i_{corr}	Correction current signal used for the decoupler in DSFO, A
i_{cs}	Motor stator current Phase c, A
i^*_{cs}	Command signal of stator current Phase c, A
$i^r{}_r$	Rotor current vector in rotor reference frame, A
$i^s{}_r$	Rotor current vector in stator reference frame, A
$i^e{}_{RD}$	Direct component of rotor current in excitation reference frame, A
$i^s{}_{rd}$	Direct component of rotor current vector in stator reference frame, A
$i^e{}_{RQ}$	Quadrature component of rotor current in excitation reference frame, A
$i^s{}_{rq}$	Quadrature component of rotor current vector in stator reference frame, A
$i^s{}_s$	Stator current vector in stator reference frame, A
$i^e{}_{SD}$	Direct component of stator current in excitation reference frame, A
$i^{e*}{}_{SD}$	Reference direct component of stator current in excitation reference frame, A
$i^s{}_{sd}$	Direct component of stator current vector in stator reference frame, A
$i^s{}_{sd(n)}$	Value of direct component of stator current vector in stator reference frame at sample n, A
$i^e{}_{SQ}$	Quadrature component of stator current in excitation reference frame, A
$i^{e*}{}_{SQ}$	Reference quadrature component of stator current in excitation reference frame, A

i^s_{sq}	Quadrature component of stator current vector in stator reference frame, A
$i^s_{sq(n)}$	Value of quadrature component of stator current vector in stator reference frame at sample n, A
J	Total moment of inertia of the motor and load, kg.m^2
k_1, k_2	Critical proportional gains for closed loop root locus system (Ch.3)
K_{corn}	Correction gain used when saturation of a PI controller occurs
K_{cur}	Constant that translates measured current into Q15 format (Ch.4)
K_{czn}	Ziegler-Nichols critical proportional gain (Ch.3)
K_{enc}	Conversion factor between encoder number of pulses and speed (Ch.4)
K_{flx}	Scaling factor adjusts flux in Q15 format for flux estimation from rotor quantities (Ch.4)
K_i	Integral gain (used for a general PI controller in Ch.4)
K_I	Integral gain (used for current PI controller in Ch.3)
K_{iGr}	Integral gain of inverse rotor time constant PI controller (Ch.3)
K_{in}	Discrete integral gain (used for a general PI controller in Ch.4)
K_{inv}	Constant that translates inverter voltage into Q15 format (Ch.4)
K_{iQ15}	Current controller integral gain in Q15 format (Ch.4)
K_{is}	Scaling factor adjusts current in Q15 format for flux estimation from stator quantities (Ch.4)
K_{is1}	Scaling factor adjusts current in Q15 format for flux estimation from rotor quantities (Ch.4)
K_{iscl}	Scaled value of current controller integral gain (Ch.4)
$K_{I\omega}$	Integral gain of speed controller (Ch.3)
$K_{I\omega\_Q15}$	Integral gain of speed controller in Q15 format (Ch.4)
$K_{I\omega m}$	Integral gain of digital speed controller (Ch.4)
$K_{I\omega scl}$	Scaled Integral gain of speed controller (Ch.4)
k_o	Root locus system proportional tuning gain (Ch.3)
K_{omg}	Scaling factor adjusts speed in Q15 format for flux estimation from rotor quantities (Ch.4)
K_p	Proportional gain (used for a general PI controller in Ch.4)
K_P	Proportional gain (used for current PI controller Ch.3)
K_{pGr}	Proportional gain of inverse rotor time constant PI controller
K_{pn}	Discrete proportional gain (used for a general PI controller in Ch.4)
K_{pQ15}	Current controller proportional gain in Q15 format (Ch.4)
K_{pscl}	Scaled value of current controller proportional gain (Ch.4)
$K_{P\omega}$	Proportional gain of speed controller (Ch.3)
$K_{P\omega\_Q15}$	Proportional gain of speed controller in Q15 format (Ch.4)
$K_{P\omega m}$	Proportional gain of digital speed controller (Ch.4)
$K_{P\omega scl}$	Scaled proportional gain of speed controller (Ch.4)
K_{QS}	Slip frequency adjustment factor (Ch.4)
K_{QSscl}	Slip frequency adjustment factor (Ch.4)
k_T	Torque proportionality constant in DC machine
K_{TD}	Scaling factor adjusts dead time term in Q15 format (Ch.4)
K_{ton}	Scaling factor adjusts ON time $T_{xon(x=a, b, or c)}$ in Q15 format (Ch.4)
K_{vs}	Scaling factor adjusts voltage in Q15 format for flux estimation from stator quantities (Ch.4)
K_{zn}	Ziegler-Nichols closed loop proportional tuning gain (Ch.3)