UNIVERSITI PUTRA MALAYSIA

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

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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

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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

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

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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.

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I certify that an Examination Committee met on 23rd July 2004 to conduct the final examination of Eyad Moh'd Moh'd Radwan on his Doctor of Philosophy thesis entitled "Indirect Rotor Field Oriented Control of Induction Motor with Rotor Time Constant Estimation" in accordance with Universiti Pertanian Malaysia (Higher Degree) Act 1980 and Universiti Pertanian Malaysia (Higher Degree) Regulations 1981. The Committee recommends that the candidate be awarded the relevant degree. Members of the Examination Committee are as follows:

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DECLARATION

I hereby declare that the thesis is based on my original work except for quotations and citations which have been duly acknowledged. I also declare that it has not been previously or concurrently submitted for any other degree at UPM or other institutions.

EYAD MOH'D MOH'D RADWAN

Date: 30/8/04

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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)