Faculty of Electrical Engineering

REDUCED TORQUE RIPPLE AND SWITCHING FREQUENCY USING OPTIMAL DTC SWITCHING STRATEGY FOR OPEN-END WINDING INDUCTION MACHINES

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DECLARATION

I declare that this thesis entitled “Reduced Torque Ripple and Switching Frequency Using Optimal DTC Switching Strategy for Open-end Winding Induction Machines” is the result of my own research except as cited in the references. The thesis has not been accepted for any degree and is not concurrently submitted in candidature of any other degree.

Signature : ....
Name : ....
Date : ....

APPROVAL

I hereby declare that I have read this thesis and in my opinion this thesis is sufficient in terms of scope and quality for the award of Master of Science in Electrical Engineering.

Signature : ....
Supervisor Name : ....
Date : ....

DEDICATION

Special Dedication to:

My Lovely Wife,
Nor Farhanna Binti Abd Aziz
For supporting and encouraging me to complete this research.

My Beloved Parents,
Abdul Rahim Bin Ismail and Che Asiah Binti Saad
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May God bless and protect them with happiness.

ABSTRACT

Direct Torque Control (DTC) of induction machine has received wide acceptance in many Variable Speed Drive (VSD) applications due to its simple control structure and excellent torque dynamic control performances. However, the DTC which employs a two-level inverter and hysteresis controllers produces two major drawbacks, namely, larger torque ripple and variable switching frequency, which might produce a very high switching frequency (or power loss), particularly at a very low speed operation. The root causes of the problems can be identified as follows; 1) delay actions in controlling the torque (which is commonly resulted in digital implementation of hysteresis controller) causes the torque cannot be exactly restricted within the hysteresis band, and hence produces a larger torque ripple 2) inappropriate selection of voltage vector (among a limited number of voltage vectors available in a two-level inverter) cannot restrict the increase of switching frequency in the hysteresis controller, as the torque slopes regulated in hysteresis bandwidth vary during operating conditions. This thesis proposes an optimal DTC switching strategy to reduce torque ripple and switching frequency for open-end winding induction machines. The open-end winding induction machine is supplied by a dual-inverter which can offer a greater number of voltage vectors and hence, gives more options to select the most optimal voltage vectors to minimize the problems. The most optimal voltage vectors for every speed range are identified as the vectors that can produce the minimum torque slopes. By minimizing the torque slopes, the torque ripple and switching frequency can be reduced. The identification is made by investigating the torque slope behaviours and torque control capabilities for every speed range. The selection of the most optimal voltage vectors is accomplished by using a modification of torque error status and a look-up table. To obtain a constant switching frequency, a Constant Switching Frequency Torque Controller (CSFTC) is proposed without the use of a PI controller and a knowledge of machine parameters. Some improvements obtained in the proposed strategy were verified via simulations and experimentations, as well as comparison with the conventional DTC. The improvements obtained are as follows; 1) reduction of torque ripple and switching frequency with the proposed optimal DTC switching strategy, 2) a constant switching frequency with the proposed CSFTC. The main benefit of the proposed strategy is its simplicity, where the DTC improvements can be obtained without the common approach, i.e. the use of Space Vector Modulation (SVM) which involves complex control algorithms. It also shown that the average improvement about 39% and 43% can be achieved toward reduction of torque ripple and switching frequency.

ABSTRAK

Kawalan dayakilas langsung (DTC) bagi motor aruhan telah mendapat penerimaan yang luas dalam kebanyakan aplikasi Pemacu Kelajuan Bolehubah (VSD) disebabkan struktur kawalan ringkasnya dan prestasi cemerlang bagi kawalan dayakilas dinamik. Bagaimanapun, DTC yang menggunakan sebuah penyongsang dua peringkat dan pengawal histeresis menghasilkan dua masalah yang besar, iaitu, riak dayakilas yang besar dan frekuensi pensuisan berubah-ubah, yang berkemungkinan besar menghasilkan frekuensi pensuisan yang sangat tinggi (atau kehilangan kuasa), terutamanya pada operasi kelajuan yang sangat rendah. Punca penyebab masalah tersebut boleh dikenalpasti seperti berikut; 1) tindakan lengah dalam pengawalan dayakilas (yang kebiasaanya dihasilkan dalam pelaksanaan secara digital bagi kawalan histeresis) menyebabkan dayakilas tidak sebetulnya dihadkan dalam jalur histeresis, dan kemudiannya menghasilkan riak dayakilas yang besar, 2) pemilihan vektor voltan yang tidak sesuai (di antara bilangan yang terhad bagi vektor voltan yang terdapat dalam sebuah penyonsang dua peringkat) tidak boleh menghadkan kenaikan bagi frekuensi pensuisan dalam kawalan histeresis, disebabkan kecerunan dayakilas yang dikawal dalam jalur lebar histeresis berubah mengikut keadaan operasi. Tesis ini mencadangkan sebuah strategi pensuisan DTC yang optimal untuk mengurangkan riak dayakilas dan frekuensi pensuisan bagi belitan tamatan terbuka motor aruhan. Belitan tamatan terbuka motor aruhan dibekalkan dengan sebuah dwi penyonsang yang boleh menawarkan sebuah bilangan vektor voltan yang besar dan kemudiannya, memberikan lebih banyak pilihan untuk memilih vektor voltan yang paling optimal untuk meminimakan masalah tersebut. Vektor voltan yang paling optimal bagi setiap julat kelajuan dikenalpasti sebagai vector yang boleh menghasilkan kecerunan dayakilas yang minimum. Dengan meminimakan kecerunan dayakilas, riak dayakilas dan frekuensi pensuisan boleh dikurangkan. Pengenalpastian dibuat dengan menyiasat sifat kecerunan dayakilas dan keupayaan kawalan dayakilas bagi setiap julat kelajuan. Pemilihan vektor voltan yang paling optimal disempurnakan dengan menggunakan sebuah pengubahsuaian bagi status ralat dayakilas dan sebuah jadual carian. Untuk menghasilkan frekuensi pensuisan yang tetap, sebuah Pengawal Dayakilas Frekuensi Pensuisan Tetap (CSFTC) dicadangkan tanpa penggunaan sebuah pengawal PI dan maklumat parameter motor. Beberapa penambahbaikan diperoleh dalam strategi cadangan telah dikenalpasti melalui simulasi dan eksperimentasi, begitu juga perbandingan dengan konvensional DTC. Penambahbaikan diperoleh adalah seperti berikut; 1) pengurangan riak dayakilas dan frekuensi pensuisan dengan cadangan strategi pensuisan optimal DTC, 2) sebuah frekuensi pensuisan tetap dengan cadangan CSFTC. Manfaat utama bagi cadangan strategi adalah keringkasan kawalannya, yang mana penambahbaikan DTC tersebut boleh dicapai tanpa pendekatan biasa, iaitu penggunaan Modulasi Ruang Vektor (SVM) yang membabitkan algoritma kawalan yang kompleks. Ia juga menunjukkan bahawa peningkatan purata kira-kira 39% dan 43% boleh dicapai kearah pengurangan riak dayakilas dan frekuensi kekerapan.

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

Ultra-Capacitor

LIST OF APPENDICES

LIST OF ABBREVIATIONS

d, q - Real and imaginary of the stationary reference frame

d^r, q^r - Real and imaginary of the rotating reference frame

d^e, q^e - Real and imaginary of the excitation reference frame

φ_s^* - Reference of stator flux

φ_s - Estimated of stator flux

φ_r - Rotor flux

$\bar{\varphi}_r^e$ - Rotor flux linkage space vector in excitation reference frame

$\bar{\varphi}_r^r, \bar{\varphi}_s^r$ - Rotor and stator flux linkage vector in rotating reference frame

$\bar{\varphi}_s, \bar{\varphi}_r$ - Stator and rotor flux linkage space vector in stationary reference frame

$\varphi_{sd}, \varphi_{sq}$ - Real and imaginary stator flux linkage in stationary reference frame

$\varphi_{rd}^e, \varphi_{rq}^e$ - Real and imaginary rotor flux linkage in excitation reference frame

$\theta_{\varphi s}$ - angle with respect to stator axis

T_e - Electromagnetic torque

T_L - Torque Load

T_{pi} - Torque error from PI controller

σ_{T^+} - Modified torque error status

σ_T - Torque error status

σ_φ - Stator Flux error status

ε_T - Torque error

ε_φ - Stator flux error

ω_e - Steady state synchronous frequency in rad/s

ω_r - Rotor electrical speed in rad/s

ω_m - Mechanical angular speed in rad/s

δ_{sr} - Load angle (or angle between stator and rotor flux vector)

$\bar{\imath}_s^e$ - Stator current space vector in excitation reference frame
$\bar{\imath}_s, \bar{\imath}_r$ - Stator and rotor current vector
i_d, i_q - Real and imaginary current in reference frame
i_{sd}, i_{sq} - Real and imaginary stator voltage in stationary reference frame
i_{sd}^e, i_{sq}^e - Real and imaginary stator current in excitation reference frame
i_a, i_b, i_c - Three phases stator current (i.e. phase a, b and c)
$S_a\ , S_b\ , S_c$ - Switching states of phases a, b and c
S_a^+, S_b^+, S_c^+ - Upper switching states of phases a, b and c
S_a^-, S_b^-, S_c^- - Lower switching states of phases a, b and c
V_{DC} - DC voltages
$\bar{v}_{sK,n}$ - Stator voltage space vector
$\bar{v}_s^*$ - Reference of stator voltage vector
v_{sd}, v_{sd} - Real and imaginary stator voltage in stationary reference frame
v_{sd}^*, v_{sq}^* - Reference of real and imaginary stator voltage in stationary reference frame
v_{sd}^{e*}, v_{sq}^{e*} - Reference of real and imaginary stator voltage in excitation reference frame
v_{an}, v_{bn}, v_{cn} - Phase voltages of stator winding using two-level inverter
$v_{AA'}, v_{BB'}, v_{CC'}$ - Phase voltage of stator winding using Open-end winding induction machine drive
v_{AN}, v_{BN}, v_{CN} - Pole or Leg voltage of inverter 1
$v_{A'N'}, v_{B'N'}, v_{C'N'}$ - Pole or Leg voltage of inverter 2
$v_{NN'}$ - Common mode voltage
t_a, t_b, t_c - Voltage vectors switching on-duration
T - Switching period of modulator
τ_r - rotor time constant ($\tau_r = L_r/R_r$)
R_s - Stator Resistance
L_m - Mutual self-inductance
L_s - Stator self-inductance
L_r - Rotor self-inductance
P - Number of stator pole pairs
σ - Total flux leakage factor ($\sigma = 1 - L_m^2/L_sL_r$)

J - Moment of inertia

B - Viscous friction

DTC - Direct Torque Control

FOC - Field Oriented Control

SVM - Space Vector Modulation

CSFTC - Constant switching frequency torque controller

DTC-SVM - Direct Torque Control using Space Vector Modulation

CH - Cascaded H-bridge Multilevel Inverter

FC - Flying Capacitor Multilevel Inverter

NPC - Neutral-Point-Clamped Multilevel Inverter

DTC-HYS - Referred to conventional DTC Hysteresis based using two-level Inverter

DTC-HYS$^+$ - Referred to proposed DTC with optimal switching strategy

DTC-CSF - Referred to conventional DTC employ CSFTC using two level inverter

DTC-CSF$^+$ - Referred to proposed DTC employ CSFTC with optimal switching strategy

DTC-SVM2 - Referred to conventional DTC-SVM using two-level inverter

DTC-SVM3 - Referred to DTC-SVM using three-level inverter (i.e. CHMI)

C_{upper}, C_{lower} - Upper and lower carrier triangular waveform

m.m.f - magnetomotive force

a.c - Alternating Current

DC - Direct Current

DT - Sampling Time

VSI - Voltage Source Inverter

UB - Upper Hysteresis Band

MB - Middle Hysteresis Band

LB - Lower Hysteresis Band

HB_T - Torque hysteresis bandwidth

HB_φ - Stator flux hysteresis bandwidth

IGBT - Insulated Gate Bipolar Transistor

FPGA - Field Programmable Gate Array

LIST OF PUBLICATIONS

Journal Paper

M. Khairi Rahim, Auzani Jidin and Tole Sutikno, 2016. Enhanced Torque Control and Reduced Switching Frequency in Direct Torque Control Utilizing Optimal Switching Strategy for Dual-Inverter Supplied Drive. *International Journal of Power Electronics and Drive Systems (IJPEDS),* Vol. 7, No. 2, pp. 328-339.

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