



Faculty of Electrical Engineering

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

Muhd Khairi Bin Abd Rahim

Master of Science in Electrical Engineering

2017

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

MUHD KHAIRI BIN ABD RAHIM

**A thesis submitted
in fulfillment of the requirements for the degree of Master of Science
in Electrical Engineering**

Faculty of Electrical Engineering

UNIVERSITI TEKNIKAL MALAYSIA MELAKA

2017

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

Thank you for your both strong and gentle soul who making who I am today.

My Respected Supervisor,

Dr. Auzani Bin Jidin

Thank you for your continuous guidance and supervision to accomplish this research.

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 kebiasaannya 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 penyongsang 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 penyongsang yang boleh menawarkan sebuah bilangan vektor voltan yang besar dan kemudiannya, memberikan lebih banyak pilihan untuk memilih vektor voltan yang paling optimal untuk meminimalkan masalah tersebut. Vektor voltan yang paling optimal bagi setiap julat kelajuan dikenalpasti sebagai vector yang boleh menghasilkan kecerunan dayakilas yang minimum. Dengan meminimalkan 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.

ACKNOWLEDGEMENTS

In the name of Allah, Most Gracious, Most Merciful, Blessing and prayers be upon the Prophet Muhammad S.A.W, members of his family and his friends. Alhamdulillah, grateful to Allah S.W.T for giving me the chance to complete this master research entitled Reduced Torque Ripple and Switching Frequency using Optimal DTC Switching Strategy for Open-End Winding Induction Machines.

First of all, I would like to express my sincere gratitude and appreciation to Universiti Teknikal Malaysia Melaka (UTeM) which has given me opportunity in gaining knowledge and soft skills. Special thanks to Dr. Auzani Bin Jidin for his valuable guidance supervision and knowledge. The support and supervision from him were truly a big help for smoothness of my master progress.

Thus, with this occasion I would like to express my gratitude to many people who have contributed to this research. Especially to my colleagues under the same supervision such as Zharif Rifqi, Wan Ahmas, Sundram, Huzainirah, Syamim and others on their help with opinion and knowledge in order to accomplish this project. Thousands of appreciation and thanks to anyone whom involved either directly or indirectly helped me in this projects.

Last but not least, privileges of appreciation and affection direct to my wife, parents and siblings for their support and encouraging me to never give up in completing this master thesis.

TABLE OF CONTENTS

	PAGE
DECLARATION	
APPROVAL	
DEDICATION	
ABSTRACT	i
ABSTRAK	ii
ACKNOWLEDGEMENTS	iii
TABLE OF CONTENTS	iv
LIST OF TABLES	vi
LIST OF FIGURES	vii
LIST OF APPENDICES	xv
LIST OF ABBREVIATIONS	xvi
LIST OF PUBLICATIONS	xix
CHAPTER	
1. INTRODUCTION	1
1.1 Research Background	1
1.2 Problem Statements	8
1.3 Objectives of Research	11
1.4 Scopes of Work	11
1.5 Research Methodology	12
1.6 Thesis Contributions	14
1.7 Thesis Outlines	15
2. LITERATURE REVIEW	17
2.1 Introduction	17
2.2 Field Oriented Control of Induction Machines	17
2.2.1 Principle of Field Orientation Control	19
2.3 Direct Torque Control of Induction Machines	22
2.3.1 Principle of Direct Torque Control	29
2.4 Major Problem of Direct Torque Control	37
2.5 Performances Improvements of Direct Torque Control	38
2.5.1 DTC using Carrier Based Modulation	39
2.5.2 DTC using Space Vector Modulation (SVM)	43
2.5.2.1 SVM for the Conventional Two-Level Inverter	45
2.5.2.2 SVM for Multilevel Inverter	48
2.5.2.3 Analysis of Torque Ripple via Simulation Results	55
2.5.2.4 Complexity of DTC-SVM Structure	59
2.6 Summary	62
3. METHODOLOGY	64
3.1 Introduction	64
3.2 Mathematical Modelling of an Induction Machine	65
3.3 Dual Voltage Source Inverters	70
3.4 Proposed Optimal DTC Switching Strategy	78
3.4.1 Principle of Torque Control Based on Load Angle δ_{sr}	79
3.4.2 Capability of Torque Control for Wide-Speed Operations	83

3.4.3	Identification of Optimal Voltage Vectors	85
3.4.4	Modification of Torque Error Status	96
3.4.5	Definition of Flux Sectors for Selecting Optimal Voltage Vectors	104
3.4.6	Look-Up Table for Selecting Optimal Voltage Vectors	106
3.4.7	Proposed Control Structure	107
3.5	Proposed Constant Switching Frequency Strategy	109
3.6	Simulation Model of the Proposed DTC	112
3.7	Experimental Setup of the Proposed DTC	115
3.8	Summary	117
4.	RESULTS AND DISCUSSION	119
4.1	Introduction	119
4.2	Reduction of Torque Ripple and Switching Frequency for a Constant Torque Control	119
4.3	Reduction of Torque Ripple and Switching Frequency for a Torque Dynamic Control	128
4.4	Reduction of Torque Ripple with a Constant Switching Frequency	139
4.5	Summary	150
5.	CONCLUSION AND RECOMMENDATIONS FOR FUTURE RESEARCH	153
5.1	Conclusion	153
5.2	Recommendations for Future Research	155
	REFERENCES	158
	APPENDICES	173

LIST OF TABLES

TABLE	TITLE	PAGE
1.1	Advantages and Disadvantages of Different Inverter Topologies	7
2.1	Look-up Table for Selecting Voltage Vectors	28
3.1	Look-Up Table for Selection Optimal Voltage Vectors in Dual Inverters	106
4.1	Summarization of Torque Ripple Obtained in DTC-HYS and DTC-HYS+ for Different Speed Operations	150
4.2	Summarization of Switching Frequency Obtained in DTC-HYS and DTC-HYS ⁺ for Different Speed Operations	151
4.3	Summarization of Torque Ripple Reduction Obtained in DTC-CSF ⁺ for Different Triangle Frequencies	152

LIST OF FIGURES

FIGURE	TITLE	PAGE
1.1	Comparison of Structure for Two Different Schemes (a) Field-Oriented Control and (b) Direct Torque Control	3
1.2	Comparison of Three Different Inverter Topologies (a) Two-Level Inverter, (b) Conventional Multilevel (CHMI) and (c) Dual-Inverters for Open-End Winding Induction Machine Drive	6
1.3	Problems of Larger Torque Ripple and Variable Switching Frequencies in Hysteresis-Based DTC (a) Simulation Result (b) Selection of Voltage Vectors in Two-Level Inverter	10
2.1	Comparison Structures (a) Indirect FOC and (b) Direct FOC	18
2.2	Rotor Flux Vector is Aligned to d^e -axis	20
2.3	Simulation Result of Field Oriented Control (FOC)	21
2.4	Structure of DTC of Induction Machine	23
2.5	Three-Phase Voltage Source Inverter (a) Topology Circuit (b) Simplified Circuit	24
2.6	Voltage Space Vectors of a Three-phase Inverter with the Corresponded Switching States	25
2.7	Control of Stator Flux (a) Two-Level Hysteresis Comparator (b)	30

	Typical Waveforms	
2.8	Two Possible Active Voltages are Switched for Each Sector to Control the Stator Flux within its Hysteresis Band	32
2.9	Control of Torque (a) Three-Level Hysteresis Comparator (b) Typical Waveforms for Controlling Positive and Negative Torque	33
2.10	Motions of Stator Flux and Rotor Flux Vectors	35
2.11	Simulation Result of Direct Torque Control (DTC)	36
2.12	Problems of Larger Torque Ripple and Variable Switching Frequency in DTC	38
2.13	Structure of DTC with Dithering Signals (as Proposed in (Noguchi et al., 1999))	40
2.14	Structure of DTC with a Constant Switching Frequency Torque Controller (as Proposed in (Jidin et al., 2011))	41
2.15	Significant Reduction of Torque Ripple with Application of Higher Constant Switching Frequency (a) at Low Carrier Frequency (b) at High Carrier Frequency	42
2.16	Structure of DTC-SVM (as Proposed in (Lascu et al., 2000a))	44
2.17	Reference of Space Voltage Vector based on (2.23)	47
2.18	Generation of Switching of Vectors and its Effect on Torque Variations	48
2.19	Topologies of Multilevel Inverters for (a) Diode Clamped or Neutral Point Clamped, (b) Capacitor Clamped or Flying Capacitor and (c) Cascaded H-Bridge Multilevel Inverters	50

2.20	Comparison Between (a) Two-Level Space Vector Diagram and (b) Three-Level Space Vector Diagram, e.g. for Sector I.	52
2.21	Generation of Switching of Vectors and its Effect on Torque Variations	54
2.22	Simulation Results of Torque, Phase Voltage and d - and q -axis Components of Reference of Voltage Vector in (a) DTC-HYS (b) DTC-SVM2 and (c) DTC-SVM3	57
2.23	Locus of Reference of Voltage Vector (\vec{v}_s^*) as Input of SVM Modulator for (a) DTC-SVM2 and (b) DTC-SVM3	58
2.24	Structures of DTC-SVM using PI Controller (a) DTC-SVM Scheme with Closed Torque Control, (b) DTC-SVM Scheme Operated in Stator Flux Polar Coordinates and (c) DTC-SVM Scheme Operated in Stator Flux Cartesian Coordinates	61
3.1	Cross-Section of a Symmetrical Two-Pole Three-Phase Induction Machine	66
3.2	A Block diagram of Mathematical Modeling of an Induction Machine	70
3.3	Configuration of Open-End Winding Induction Machine Supplied using Dual Inverters	71
3.4	Space Vector of Stator Voltage in d - and q -Axis Coordinates System	75
3.5	Space Voltage Vectors Including Their Switching States Produced in Dual Inverters	78
3.6	Behavior of Torque Control due to Variation of Load Angle δ_{sr}	83

3.7	Control of Torque using the Proposed Method (dotted line) and the Conventional DTC (solid line) at Low Speed Operations (a) the Selection of Voltage Vectors and (b) the Variation of Torque in the Hysteresis Band	88
3.8	Control of Torque using the Proposed Method (Dotted Line) and the Conventional DTC (Solid Line) at Medium Speed Operations (a) the Selection of Voltage Vectors and (b) Variation of Torque in the Hysteresis Band	91
3.9	Control of Torque using the Proposed Method (Dotted Line) and the Conventional DTC (Solid Line) at High-Speed Operations (a) the Selection of Voltage Vectors and (b) Variation of Torque in the Hysteresis Band	94
3.10	Capability of Control of Torque at a Constant Flux which Constraints by Amplitude of Vectors, i.e. Short Amplitude for Region 1, Medium Amplitude for Region 2 and Long Amplitude for Region 3	100
3.11	Flowchart of Modification of Torque Error Status	103
3.12	Two Definitions of Flux Sector for (a) Short and Long Amplitudes of Vectors and (b) Medium Amplitude of Vectors	105
3.13	Proposed Control Structure of DTC for Open-End Winding Induction Machine with Inclusion of a Modification of Torque Error Status	108
3.14	Proposed Constant Switching Frequency Torque Controller (CSFTC)	109

3.15	Typical Waveforms for Controlling Positive and Negative Torque Demands Utilizing the Proposed CSFTC	112
3.16	Simulation Model of Entire Direct Torque Control (DTC) System with the Proposed Strategy	114
3.17	Complete Experimental Set-up (a) Block Diagrams (b) Photo of Laboratory Set-up	117
4.1	Waveforms of Torque (T_e), Three-Phase Current (i_a, i_b, i_c), and Phase Voltage (v_{an}) with Optimal and Non-Optimal Switching at Low-Speed in (a) Simulation Result (b) Experimental Result	121
4.2	Magnified Results as Shown in Figure 4.1	122
4.3	Waveforms of Torque (T_e), Three-Phase Current (i_a, i_b, i_c), and Phase Voltage (v_{an}) with Optimal and Non-Optimal Switching at Medium-Speed in (a) Simulation Result (b) Experimental Result	124
4.4	Magnified Results as Shown in Figure 4.3	125
4.5	Waveforms of Torque (T_e), Three-Phase Current (i_a, i_b, i_c), and Phase Voltage (v_{an}) with Optimal and Non-Optimal Switching at High-Speed in (a) Simulation Result (b) Experimental Result	126
4.6	Magnified Results as Shown in Figure 4.5	127
4.7	Simulation and Experimental Results of Torque, Phase Voltage and Phase Current for a Step Change of Reference Torque in DTC with Non-Optimal Switching Strategy	129
4.8	Magnified Results as Shown in Figure 4.7	130
4.9	Simulation and Experimental Results of Torque, Phase Voltage	132

	and Phase Current for a Step Change of Reference Torque in DTC with Non-Optimal Switching Strategy	
4.10	Magnified Results as Shown in Figure 4.9	133
4.11	Simulation and Experimental Results of Torque, Phase Voltage and Phase Current for a Step Reduction of Reference Torque in DTC with Non-Optimal Switching Strategy	135
4.12	Magnified Results as Shown in Figure 4.11	136
4.13	Simulation and Experimental Results of Torque, Phase Voltage and Phase Current for a Step Reduction of Reference Torque in DTC with Optimal Switching Strategy	137
4.14	Magnified Results as Shown in Figure 4.13	138
4.15	Comparison of Torque Control Performances at Low-Speed in (a) DTC-CSF and DTC-HYS (with Non-Optimal Switching in Two-Level Inverter) and (b) DTC-CSF ⁺ and DTC-HYS ⁺ (With Optimal Switching in Dual-Inverter) for Open-End Windings of an Induction Machine	141
4.16	Comparison of Torque Control Performances at Medium-Speed in (a) DTC-CSF and DTC-HYS (with Non-Optimal Switching in Two-Level Inverter) and (b) DTC-CSF ⁺ and DTC-HYS ⁺ (With Optimal Switching in Dual-Inverter) for Open-End Windings of an Induction Machine	142
4.17	Comparison of Torque Control Performances at High-Speed in (a) DTC-CSF and DTC-HYS (with Non-Optimal Switching in Two-Level Inverter) and (b) DTC-CSF ⁺ and DTC-HYS ⁺ (With	143

	Optimal Switching in Dual-Inverter) for Open-End Windings of an Induction Machine	
4.18	Comparison Results of Torque (T_e), d - and q -Axis Components of Stator Flux Vector (φ_{sd} and φ_{sq}), Stator Current (i_a) and Frequency Spectrum of Stator Current (i_a) for DTC-HYS ⁺ at a Constant Torque Hysteresis Band of 25 % from Its Rated, but at Three Different Speeds (a) Low-Speed (b) Medium-Speed and (c) High-Speed	146
4.19	Comparison Results of Torque (T_e), d - and q -Axis Components of Stator Flux Vector (φ_{sd} and φ_{sq}), Stator Current (i_a) and Frequency Spectrum of Stator Current (i_a) for DTC-CSF ⁺ at a Constant Switching Frequency of 5 kHz, but at Three Different Speeds (a) Low-Speed (b) Medium-Speed and (c) High-Speed	147
4.20	Comparison Results of Torque (T_e), d - and q -Axis Components of Stator Flux Vector (φ_{sd} and φ_{sq}), Stator Current (i_a) and Frequency Spectrum of Stator Current (i_a) for DTC-CSF ⁺ at Low-Speed Operation, However at three different switching frequencies (a) 1250Hz (b) 2500Hz (c) 5000Hz	148
4.21	Experimental Results of Estimated Torque (T_e), Reference Torque (T_e^e), Torque Error (ε_T) and Carrier Frequency (v_{tri}) for a Step Change of Reference Torque in DTC-CSF ⁺ with Optimal Switching Strategy	149
5.1	Recommendation of Open-End Winding Induction Machine Supplied by Dual-Inverter with an Isolated DC Source and	156

Ultra-Capacitor

LIST OF APPENDICES

APPENDIX	TITLE	PAGE
A	Simulation Model of DTC-SVM	172
B	MATLAB Source Code Listing	175
C	VHDL Source Code Listing	183
D	Simulation Model of the Proposed Optimal DTC Switching Strategy for Open-end Winding Induction Machines	188
E	Experimental Setup	198
F	List of Achievements	209

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{i}_s^e	- Stator current space vector in excitation reference frame
\bar{i}_s, \bar{i}_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_{sq}	- 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.

Published Conference Proceeding

M. Khairi Rahim, Auzani Jidin, S. Azura Tarusan, Atikah Razi, R. Sundram and Huzainirah Ismail, 2016. Constant Switching Frequency Using Proposed Controller with Optimal DTC Switching Strategy for Dual-Inverter Supplied Drive. *IEEE 6th International Conference on Power and Energy (PECON)*.

M. Khairi Rahim, Auzani Jidin, Fazlli Patkar, R. Sundram, Yusnida Tarmizi, Huzainirah Ismail, S. Azura Tarusan, 2015. Minimization of Torque Ripple and Switching Frequency Utilizing Optimal DTC Switching Strategy for Dual-Inverter Supplied Drive. *IEEE Student Conference on Research and Development (SCORED)*, pp. 49-54.

M. Khairi Rahim, Fazlli Patkar, Auzani Jidin, M. Z. R. Z. Ahmadi, R. N. Firdaus, Wahidah Abd. Halim, Atikah Razi, 2015. Reduced Torque Ripple and Switching Frequency using Optimal DTC Switching Strategy for Open-End Winding of Induction Machines. *IEEE 11th International Conference on Power Electronics and Drive Systems*, pp. 767-772.