اونيۏرسيتي تيكنيكل مليسيا ملاك

UNIVERSITI TEKNIKAL MALAYSIA MELAKA

Faculty of Electrical Engineering

THE CONSTANT SWITCHING FREQUENCY AND TORQUE RIPPLE REDUCTION OF DIRECT TORQUE CONTROLLED INDUCTION MACHINE WITH NEUTRAL POINT CLAMPED INVERTER

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Master of Science in Electrical Engineering

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HUZAINIRAH BINTI ISMAIL

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

2018

DECLARATION

I declare that this thesis entitled "The Constant Switching Frequency and Torque Ripple Reduction of Direct Torque Controlled Induction Machine with Neutral Point Clamped Inverter" 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.

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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 : DR FAZLLI BIN PATKAR

Date : 12/11/2018

DEDICATION

To:

My inspiring parents,

Ismail bin Bujang and Azizah binti Salleh.

My beloved husband,

Azim bin Md Kasim.

My lovely siblings,

Hawa, Haikal, Hafiszullah, Hurmazan, Haziq, Hazim and Hamizah.

For their love, sacrifice, endless support and encouragement to complete this research.

ABSTRACT

Direct Torque Control (DTC) of induction motor drives are widely accepted in variable speed drive applications because it offers high performance in terms of fast torque response as well as simplicity of control structure. However, conventional DTC drives which utilize two-level inverter and hysteresis controllers inherently suffer from two major drawbacks which are large torque ripple and variable switching frequency particularly at low speed operation. This is because the torque is unable to restricted within the hysteresis band (commonly happened in digital implementation of hysteresis controller) that leads to condition of overshoot and undershoot which result in large torque ripple. Secondly, inappropriate selection of voltage vectors for different speed operation as two-level inverter provides only limited numbers of voltage vectors. This research aims to improve the performance of the DTC drives by utilizing a three-level Neutral Point Clamped (NPC) inverter as appropriate voltage vectors can be utilized for different speed operations due to availability of larger number of voltage vectors. Nevertheless, the utilisation of NPC inverter lead to imbalance of upper and lower capacitor voltage due to application of short amplitude of voltage vectors which have two redundant switching states and each switching state produces different effect towards the capacitor voltage. Therefore, a simple capacitor voltage balancing strategy is also proposed to select the appropriate switching states based on capacitor voltage status. Next, the selection of appropriate voltage vectors according to speed operation are determined to produce reduction of torque ripple and switching frequency. Furthermore, a constant switching frequency operation is obtained by replacing the hysteresis torque controller with constant switching frequency (CSF) torque controller. The proposed improvement method was conducted experimentally using DTC-NPC inverter drives with CSF torque controller (with acronym DTC-NPC-CSF) and was compared with conventional DTC drives as well as DTC drives with NPC inverter and hysteresis torque controller (with acronym DTC-NPC-HTC) for performance analysis. The performance result showed that the torque ripple was minimized and the switching frequency was remained constant for all range of speeds.

ABSTRAK

Kawalan dayakilas langsung (DTC) bagi pemacu motor induksi telah diterima secara meluas dalam aplikasi pemacu laju berubah-ubah kerana ia menawarkan prestasi tinggi dari segi kawalan dayakilas yang cepat serta struktur kawalan yang ringkas. Walau bagaimanapun, DTC konvensional yang menggunakan sebuah penyongsang dua peringkat dan pengawal histerisis sememangnya mengalami dua kekurangan yang utama iaitu riak dayakilas yang besar dan frekuensi pensuisan berubah-ubah terutamanya pada operasi kelajuan yang rendah. Kekurangan ini disebabkan oleh dayakilas tidak dapat dihadkan dalam jalur histeresis (kebiasaannya berlaku dalam implementasi pengendali histerisis secara digital) yang menyebabkan keadaan dayakilas yang terlajak naik dan turun sehingga menghasilkan riak dayakilas yang besar. Selain itu, pemilihan vektor voltan yang tidak sesuai untuk keadaan operasi kelajuan yang berlainan kerana penyongsang dua peringkat menyediakan bilangan vektor voltan yang terhad. Kajian ini bertujuan untuk meningkatkan prestasi pemacu DTC dengan menggunakan penyongsang Apitan Titik Neutral (NPC) tiga peringkat di mana vektor voltan yang sesuai dapat digunakan untuk operasi kelajuan yang berbeza-beza kerana terdapat bilangan vektor voltan yang lebih banyak. Walau bagaimanapun, penggunaan penyongsang NPC menyebabkan ketidakseimbangan voltan atas dan bawah kapasitor disebabkan oleh penggunaan vektor voltan beramplitud pendek yang mempunyai dua keadaan pensuisan berulang dan setiap keadaan pensuisan menghasilkan kesan yang berbeza ke atas voltan kapasitor. Oleh itu, strategi pengimbang voltan kapasitor yang mudah juga dicadangkan untuk memilih keadaan pensuisan yang sesuai mengikut keadaan voltan kapasitor. Seterusnya, pemilihan vektor voltan yang sesuai mengikut operasi kelajuan ditentukan supaya dapat menghasilkan dayakilas dan frekuensi pensuisan yang minimum. Selain itu, operasi frekuensi pensuisan yang tetap diperolehi dengan menggantikan pengawal histerisis dayakilas dengan pengawal dayakilas frekuensi pensuisan tetap (CSF). Kaedah penambahbaikan yang dicadangkan dijalankan secara eksperimen menggunakan pemacu penyongsang DTC-NPC dengan pengawal dayakilas CSF (dengan singkatan DTC-NPC-CSF) dan dibandingkan dengan pemacu DTC konvensional serta pemacu DTC dengan penyongsang NPC dan pengawal histerisis dayakilas (dengan singkatan DTC-NPC-HTC) untuk menganalisis prestasi. Keputusan prestasi menunjukkan bahawa riak dayakilas dapat diminimumkan dan frekuensi pensuisan kekal untuk tetap bagi semua julat kelajuan.

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LIST OF ABBREVIATIONS

AC	-	Alternating Current
ADC	-	Analog to digital converter
B	-	Viscous friction
CHMI	-	Cascaded H-Bridge Multilevel Inverter
CSF	-	Constant Switching Frequency
DAC	-	Digital to analogue converter
DC	-	Direct current
DSP	-	Digital Signal Processor
DT	-	Sampling Time
DTC	-	Direct Torque Control
DTC-NPC-CSF	-	Referred to DTC using NPC with Proposed Constant Switching Frequency Torque Controller
DTC-NPC-HTC	-	Referred to DTC utilizing NPC with Hysteresis Torque Controller
DTC-SVM	-	Direct Torque Control using Space Vector Modulation
FC	-	Flying Capacitor
FOC	-	Field Oriented Control
FPGA	-	Field Programmable Gate Arrays
IGBT	-	Insulated Gate Bipolar Transistor
IM	-	Induction Motor

J	-	Moment of inertia
LB	-	Lower Band
MB	-	Middle Band
NP	-	A point between two capacitors or neutral point
NPC	-	Neutral Point Clamped
P	-	Number of pole pairs
PI	-	Proportional-Integral
SVM	-	Space Vector Modulated
UB	-	Upper Band
VHDL	-	VHSIC hardware description language
VSI	-	Voltage Source Inverter
VSC	-	Variable-Structure Control
$C_{pp,H}$		Peak-to-peak carrier for high speed
$C_{pp,M}$		Peak-to-peak carrier for medium speed
$C_{pp,L}$		Peak-to-peak carrier for low speed
C_{upper}, C_{lower}	-	Upper and lower carrier triangular waveform
d, q	-	Direct and quadrature of the stationary reference frame
d^r, q^r	-	Real and imaginary and real of the rotor
f	-	Frequency
HB_{ψ}	-	Flux hysteresis bandwidth
HB_{Te}	-	Torque hysteresis bandwidth
$\bar{i}_s$, $\bar{i}_r$	-	Stator and rotor current vector
i_a, i_b, i_c		Current of phase a. b and c
i_{sd}, i_{sq}	-	Real and imaginary stator current in stationary reference frame

i_{rd}, i_{rq}	-	Real and imaginary rotor current in stationary reference frame
K_p	-	Proportional gain
K_i	-	Integral gain
N_c	-	Number of commutation of switching state
N_s	-	Number of Sample
L_m	-	Mutual self-inductance
L_s, L_r	-	Stator and rotor self-inductance
L_{ls}, L_{lr}	-	Stator and rotor leakage-inductance
R_s, R_r	-	Stator and rotor resistance
S_a, S_b, S_c	-	Upper switching state of phase a, b and c
$\overline{S_a}, \overline{S_b}, \overline{S_c}$	-	Lower switching state of phase a, b and c
S_f	-	Switching Frequency
T_{ave}	-	Average torque
$T_{e,ref}$	-	Reference of electromagnetic torque
T_e	-	Electromagnetic torque
T_{load}	-	Torque load
T_{max}	-	Maximum of torque
T_{min}	-	Minimum of torque
T_{pi}	-	Torque error from PI controller
T_r	-	Torque ripple reduction
V_{dc}	-	DC voltages
$\bar{v}_s$	-	Voltage vectors
v_{c1}, v_{c2}	-	Upper and lower capacitor voltage
v_{an}, v_{bn}, v_{cn}	-	Phase voltage of stator winding using two-level inverter

v_{sd}, v_{sq}	-	Real and imaginary stator voltage in stationary reference frame
$v_{sd,ref}, v_{sq,ref}$	-	Reference of real and imaginary stator voltage in stationary reference frame
$\bar{x}$	-	Referred to voltage or current or flux linkage
$\psi_{s,ref}$	-	Reference of flux
ψ_s	-	Estimated of flux
$\bar{\psi}_s, \bar{\psi}_r$	-	Stator and rotor flux linkage space vector in stationary reference frame
ψ_{sd}, ψ_{sq}	-	Real and imaginary stator flux linkage in stationary reference frame
σ	-	Total flux leakage factor ($\sigma = 1 - L_m^2/L_s L_r$)
σ_B	-	Balancing status
σ_{CSF}	-	Torque error status from CSF torque controller
σ_ψ	-	Flux error status
σ_T	-	Torque error status for conventional DTC
ε_ψ	-	Flux error
ε_T	-	Torque error
ω	-	Steady state synchronous frequency in rad/s
ω_r	-	Rotor electrical speed in rad/s
ω_m	-	Mechanical angular speed in rad/s
θ_f	-	Field angle
θ_{sr}	-	Load angle or angle between stator flux and rotor flux linkage
θ^s	-	The angle between d axis and $\bar{x}$
θ^r	-	The angle between d^r axis and $\bar{x}$