UNIVERSITI MALAYA

ORIGINAL LITERARY WORK DECLARATION

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Name of Degree: Doctor of Philosophy (Ph.D.)

Title of Project Paper/Research Report/Dissertation/Thesis ("this Work"):

Contributions to Control of an Asymmetrical Six-phase Indcution Machine

Field of Study: Engineering (Electrical)

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Abstract

This thesis aims to provide additional contributions to control of multiphase machine, with a focus on asymmetrical six-phase induction machine (machine with two three-phase windings spatially displaced by 30°). Using the VSD approach, the machine's six phase variables can be transformed into six decoupled variables, namely α-β, x-y and two zero sequence variables. For machine with distributed windings, only the α-β components provide useful electro-mechanical energy conversion, while the other components merely produce losses. The studies presented in this thesis are based on this VSD approach, and are separated into three main parts: x-y current control methods, operation with series-connected converters and post-fault control. The first part of this research work looks into the x-y current control methods of the machine using PI controllers. It was found that the x-y currents can be physically interpreted as the circulating current between the two three-phase windings. Depending on the type of asymmetry, x-y currents can appear as positive sequence component, negative sequence component or a combination of both. Hence, performance of PI controller implemented under different reference frame is compared and discussed. In this part of the study, a dead time compensator implemented using resonant controller for x-y currents is also presented. The second part of this work investigates the operation of the six-phase machine with series-connected machine-side converters. Under this topology, the two three-phase windings are supplied by two separate two-level voltage source converters (VSCs) with their dc-link cascaded in series. The series-topology elevates dc-link voltage which gives a reduction in dc-link current and cable size. However, the additional dc-link voltage balancing control is needed to ensure equal voltage sharing.

This is accomplished by controlling *x-y* currents, which is a new concept introduced in this work. The final part of the research work deals with post-fault control of six-phase induction machine for a single open-circuit fault. Post-fault control is based on the full order decoupling transformation, to minimise reconfiguration of the controller. Effect of the single open-circuit fault on the machine is discussed. Here, the leg-to-phase voltage relation is identified as an important issue that needs to be addressed when using PI controllers for post-fault operation. Different modes of post-fault operation are analysed and compared. The study considers both the cases where the six-phase machine is configured with single as well as with two isolated neutrals, such that a unified comparison is achieved. In conclusion, this thesis provides insights on the control of *x-y* currents in six-phase machine based on PI controllers in different reference frame. Two interesting uses of these currents, i.e. for dead time compensation and dc-link voltage balancing have also been presented. In terms of alternative converter topology, the operation of six-phase machine with series-connected machine-side converter is detailed, addressing the merits and demerits of the topology. Lastly, the operation of six-phase induction machine under different modes of post-fault control is studied and compared. All studies are based on simulation in Matlab/Simulink environment and are further verified on a 1.1 kW prototype asymmetrical six-phase induction machine.

Abstrak

Tesis ini bertujuan untuk memberi sumbangan tambahan untuk mengawal mesin berbilang-fasa, dengan tumpuan kepada mesin aruhan enam fasa asimetri (mesin dengan dua belitan tiga fasa yang disesarkan sebanyak 30 °). Menggunakan pendekatan VSD, enam pembolehubah fasa mesin boleh ditransformasikan menjadi enam pembolehubah ternyahganding, iaitu *α-β*, *x-y* dan dua pembolehubah urutan sifar. Bagi mesin dengan belitan teredar, hanya komponen *α-β* menyumbang kepada penukaran tenaga elektro-mekanikal yang berguna, manakala komponen-komponen lain menghasilkan kerugian semata-mata. Kajian yang dibentangkan di dalam tesis ini adalah berdasarkan kepada pendekatan ini VSD, dan dibahagikan kepada tiga bahagian utama: kaedah kawalan arus *x-y*, operasi dengan penukar bersiri dan kawalan lepas-silap. Bahagian pertama kerja penyelidikan memperlihatkan kaedah kawalan arus *x-y* mesin menggunakan pengawal PI. Ia telah mendapati bahawa arus *x-y* boleh ditafsirkan, secara fizikal, sebagai arus edaran antara kedua-dua belitan tiga fasa. Bergantung kepada jenis ketidakseimbangan, arus *x-y* boleh muncul sebagai komponen urutan positif, komponen urutan negatif atau gabungan kedua-duanya. Oleh itu, prestasi pengawal PI di bawah rangka rujukan yang berbeza telah dibandingkan dan dibincangkan dalam tesis ini. Selain itu, suatu pemampas masa mati yang diimplementasikan dengan menggunakan pengawal resonans untuk arus *x-y* juga dibentangkan. Bahagian kedua karya ini menyiasat operasi mesin enam fasa dengan penukar bersiri. Dalam topologi ini, kedua-dua belitan tiga fasa disambungkan kepada dua penukar sumber voltan (VSC) yang berasingan, dengan dc-link mereka disambungkan secara bersiri. Topologi siri ini menaikkan voltan dc-link, seterusnya mengurangkan arus dc-link dan saiz kabel. Walau bagaimanapun, tambahan kawalan keseimbangan voltan diperlukan untuk memastikan perkongsian voltan yang sama pada dc-link. Ini dapat dicapai dengan mengawal arus *x-y*, yang merupakan satu konsep baru yang diperkenalkan dalam kerja ini. Bahagian akhir kerja penyelidikan ini membincangkan kawalan lepas-sila mesin aruhan enam fasa bagi suatu silap litar terbuka. Kawalan lepas-silap adalah berdasarkan perintah penuh nyahgandingan transformasi, untuk mengurangkan konfigurasi pengawal. Kesan daripada silap litar terbuka pada mesin itu dibincangkan. Di sini, hubungan voltan kaki dan voltan fasa dikenalpasti sebagai satu isu penting yang perlu ditangani apabila menggunakan pengawal PI untuk operasi lepas-silap. Beberapa mod operasi lepas-silap turut dianalisis dan dibandingkan. Kajian ini mempertimbangkan kedua-dua kes di mana mesin enam fasa dikonfigurasikan dengan neutral terpencil tunggal dan dengan dua neutral terpencil, supaya suatu perbandingan meyeluruh diperolehi. Kesimpulannya, projek ini memberikan pemahaman mengenai kawalan arus *x-y* dalam mesin enam fasa berdasarkan pengawal PI dalam rangka rujukan yang berbeza. Dua kegunaan menarik arus ini, iaitu bagi pampasan masa mati dan mengimbangi voltan dc-link juga telah dibentangkan. Dari segi topologi penukar alternatif, operasi mesin enam fasa dengan penukar siri telah diperinci, dengan mengkaji kebaikan dan kelemahan topologi tersebut. Akhir sekali, operasi mesin induksi enam fasa di bawah mod pandangan yang kawalan selepas kesalahan dikaji dan dibandingkan. Semua kajian adalah berdasarkan kepada simulasi dalam Matlab / Simulink dan selanjutnya disahkan pada 1.1 kW mesin aruhan prototaip enam fasa asimetri.

Acknowledgments

First and foremost, I would like to express my sincere gratitude and appreciation towards Prof. Emil Levi and Dr. Martin Jones, my supervisors in Liverpool John Moores University (LJMU), for their supervision and guidance which have directly contributed to the completion of this thesis. The experience of working with them has been both rewarding and enjoyable. I regard myself to be truly blessed to have the opportunity to be supervised by these two mentors who are admirable, both in terms of knowledge and personalities.

Next, I would like to sincerely thank my supervisors in University of Malaya (UM) Prof. Nasrudin Abd Rahim and Prof. Hew Wooi Ping, who have introduced me to the field of power electronics and machine drives, and eventually inspired me to pursue my graduate degree. Their advice and support have been crucial, especially during the initial stage of my study. The completion of this thesis will never be possible without them.

I especially appreciate the contribution of Dr. Mario J. Duran, for his inspiration and assistance. Discussions with Dr. Mario had been tremendously helpful and contributed to a big part of my thesis. I would also like to acknowledge the useful advice and suggestions provided by Dr. Federico J. Barrero and Dr. Alejandro G. Yepes, which have facilitated the completion of my research.

My sincere appreciation goes to Kuok Foundation Berhad and University of Malaya Bright Sparks Unit, for sponsoring my study in UM and LJMU, respectively. I am truly grateful to University of Malaya Power Energy Dedicated Advanced Centre (UMPEDAC) as well, for providing the much needed additional financial support.

Furthermore, I would like to thank Mr. Jeffery Soong and his team, who have made the UM-LJMU dual PhD program possible. Not to forget all the administration and technical staff members in Kuok Foundation Berhad, UM and LJMU, who have been helpful and kind.

I would like to express my gratitude towards my friends and colleagues in UM and LJMU: Dr. Daniel Lin, Fazlli Patkar, Ivan Subotić, Jigang Ma, Dr. Jose Riveros, Lim Chee Shen, Michal Rolak, Milan Darijević, Nondor Bodo, Dr. Obrad Dodević, Sharrifah Fatmadiana, Teoh Jee Khoon, Tey Chin Soon, Tok Chia Hua and Dr. Wahyu Satiawan. Thank you for your unselfish assistance, constructive critics and most importantly for your companions and friendships. Without you guys, PhD study would have been much less fun.

Last and most importantly, I have to thank my family for all their support. To my dearest parents, Che The Siong and Kee Sew Huang, and sisters, Seow Foon and Sheau Wei, thank you for your unconditional love and care. To my beloved wife, Samantha, and my son En Khai, thank you for your perseverance, encouragement and love. Your support has always been my core motivation and inspiration. This thesis is especially dedicated to you all.

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Symbols

Main Symbols

a	Derating factor
a_d	Derating factor for d-current
a_q	Derating factor for q-current
a_o	Threshold derating factor
$[A]$	Leg-to-phase voltage transformation matrix
C	Capacitance (F)
$[D]$	Rotational transformation matrix
$[D']$	Modified rotational transformation matrix
δ	Angle between stator phase current and rotor flux space vectors
Δ	Difference
e	Feedforward decoupling voltage (V)
E	Back EMF (V)
E_{ks}'	Component of phase-*k* back EMF associated with time derivative of stator currents (V)
E_{ks}''	Component of phase-*k* back EMF associated with time derivative of Rotor currents (V)
f	Frequency (Hz)
$f_{switching}$	Switching frequency (Hz)
$f_{sampling}$	Sampling frequency (Hz)
i	Ac current (A)
i_s	Stator current (A)
i_r	Rotor current (A)
I	Dc current (A)
I_{cap}	Capacitor current (A)
I_{dc}	Dc-link current (A)
I_{dc_VSC1}	Dc-link current of VSC1 (A)
I_{dc_VSC2}	Dc-link current of VSC2 (A)
$\vec{I}_s$	Stator current space vector (A)
I_{sn}	Rated rms stator phase current (A)
J	Moment of inertia (kg m^2)
k	Coefficient
K	Coefficient (for post-fault control)

K_p	Proportional gain
K_i	Integral gain
K_R	Resonance gain
L	Inductance (H)
L_{lm}	Mutual leakage inductance (H)
L_{lr}	Rotor leakage inductance (H)
L_{ls}	Stator leakage inductance (H)
L_m	Mutual/magnetising inductance in machine equivalent circuit (H)
L_r	Rotor inductance (H)
L_s	Stator inductance (H)
M	Mutual/magnetising inductance (H)
λ	Arbitrary machine variable
$\vec{\Lambda}$	Space vector of an arbitrary machine variable
ω	Arbitrary angular frequency (rad/s)
ω_r	Rotor electrical speed (rad/s)
ω_m	Rotor mechanical speed (rad/s)
ω_s	Synchronous frequency (rad/s)
ω_{sl}	Slip speed (rad/s)
p	Number of pole pairs
P	Active power (W)
ψ	Flux (Wb)
ψ_s	Stator flux (Wb)
ψ_r	Rotor flux (Wb)
R	Resistance (Ω)
$R_{external}$	External resistance (Ω)
R_s	Stator resistance (Ω)
R_r	Rotor resistance (Ω)
S	Switching state of VSC
T	Torque (Nm)
T_e	Electrical torque (Nm)
T_{en}	Rated electrical torque (Nm)
T_m	Mechanical torque (Nm)
$[T]$	Decoupling (stationary) transformation matrix
τ_r	Rotor time constant (s)
θ_s	Rotational transformation angle (rad)
v	Ac voltage (V)
v_s	Stator voltage (V)
v_r	Rotor voltage (V)
v_{dis}	Disturbance voltage (V)
v_{drop}	Voltage drop (V)
V	Dc voltage (V)
$\vec{V}_s$	Stator voltage space vector (V)
V_{dc}	Dc-link voltage (V)

Subscripts (for identifying the current, voltage or flux components)

$0+$	Positive zero sequence components after decoupling transformation
$0-$	Negative zero sequence components after decoupling transformation
α	α-component after decoupling transformation
$\alpha\beta$	Component in α-β plane
$\alpha\beta+$	Positive sequence component in α-β plane
$\alpha\beta-$	Negative sequence component in α-β plane
β	β-component after decoupling transformation
d	d-component after rotational transformation
dq	Component in d-q plane
k	Variable for phase-k, $k = a, b, c$ for three-phase or $k = a1, b1, c1, a2, b2, c2$ for six-phase
ko	Variable for phase-k with respect to an arbitrary point O
q	q-component after rotational transformation
r	Rotor *v*ariable
s	Stator *v*ariable
x	x-component after decoupling transformation
xy	Component in x-y plane
x'	x'-component after anti-synchronous rotational transformation
$x'y'$	Component in x'-y' plane
$xy+$	Positive sequence component in x-y plane
$xy-$	Negative sequence component in x-y plane
y	y-component after decoupling transformation
y'	y'-component after anti-synchronous rotational transformation

Superscripts

$*$	Reference value

Abbreviations

CMV	Common mode voltage
EMF	Electro-motive force
FOC	Flux oriented control
HVDC	High voltage direct current
IRFOC	Indirect rotor flux oriented control
LUT-DTC	Look-up-table-based direct torque control
MPC	Model predictive control
MPPT	Maximum power point tracking
NPC	Neutral-point clamped (converter)
PI	Proportional integral (controller)
PWM	Pulse-width modulation
VSC	Voltage source converter
VSD	Vector space decomposition (method)