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Contributions to Control of an Asymmetrical Six-phase Induction Machine

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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 elektromekanikal 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 dikonfigurasi 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.

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List of Symbols and Abbreviations

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 variable
s	Stator variable
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
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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)