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Modelling, Simulation and Implementation of a Fault Tolerant Permanent Magnet AC Motor Drive with Redundancy

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Abstract

Fault tolerant motor drives are becoming more important in safety critical applications. Although a single motor module fault tolerant drive may be sufficient in some applications, this motor drive only offers limited redundancy. This thesis investigated the dual motor module fault tolerant drive system in which two motor modules were connected electrically in phase and on a common shaft provide redundancy and to increase the reliability of the entire drive system.

A general phase current mathematical model to produce the desired output torque was developed to minimize copper loss and torque ripple in the motor drive, which is applicable to both sinusoidal and trapezoidal brushless permanent magnet motor types. A detailed fault effect investigation was performed in this thesis and it is concluded that switch short-circuit fault is the most serious fault since it reduces the electromagnetic torque output significantly and generates larger torque ripple in the motor drive due to the presence of large drag torque. Three fault remedial strategies were proposed to compensate the torque loss and to reduce the torque ripple under different faulty conditions. It is concluded from the analytical results that fault remedial strategy 3 is the tradeoff algorithm in which the zero torque ripple factor can be achieved with only a modest increase in copper loss comparing with the minimum possible value.

Two practical dual motor module fault tolerant brushless permanent magnet drive test arrangements with different motor structures were developed in this thesis. The computer simulation studies using the MATLAB Simulink were performed to verify the effectiveness of the proposed fault remedial strategies. The efficiency of the motor drive was predicted based on torque loss measurements and the results were verified in the simulation study. The effect of faults on the drive efficiency was investigated as well.

The entire fault tolerant motor drive control system was also developed to verify the analytical and simulation results. A fault detection and identification method to detect switch open-circuit faults, switch short-circuit faults, and the winding short-circuit faults was also proposed. Its advantages are the simplicity of the implementation and reduction of the cost of the drive system. The experimental results demonstrated that the proposed fault remedial strategies can be implemented in real time motor control and are effective to compensate the torque loss and reduce the torque ripple.

Declaration

The work in this thesis is based on research carried out at School of Electrical and Electronic Engineering, The University of Adelaide, Australia. This work contains no material which has been accepted for the award of any other degree or diploma in any university or other tertiary institution and, to the best of my knowledge and belief, contains no material previously published or written by another person, except where due reference has been made in the text.

I give consent to this copy of my thesis, when deposited in the University Library, being made available for loan and photocopying, subject to the provisions of the Copyright Act 1968.

Signed: ____________________ **Date:** ____________________

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Symbols and Abbreviations

Abbr.	**Variable Name**
B	Damping coefficient
$e_{1, 2, 3, 4, 5, 6}$	Phase back-EMF voltages
$e_{1, 2, 3, 4, 5, 6}(\theta_e)$	Phase back-EMF functions
E_m	Amplitude of back-EMF voltage
I_{in}	Input phase current of current sensor
I_m	Peak phase current in a dual module motor drive
I_{m0}	Peak phase current in a single module motor drive
$i_{measured}$	Measured current
I_{mRS}	Peak phase current in a dual module motor drive after the fault remedial strategy is adopted
I_R	Current in the rheostat
$i_{reference}$	Reference current
I_{SCm}	Peak value of short-circuit current
I_{SCpu}	Per unit value of short-circuit current
$i_{1, 2, 3, 4, 5, 6}$	Phase currents
J	Moment of inertia
k_e, k_{e1}, k_{e2}	Back-EMF constant
$K_1(\theta_e)$, $K_2(\theta_e)$ $K_3(\theta_e)$	Coefficients for reference current calculation when one phase open-circuit fault with fault remedial strategy 3
$K_4(\theta_e)$, $K_5(\theta_e)$ $K_6(\theta_e)$	Coefficients for reference current calculation when two different phase open-circuit fault with fault remedial strategy 3
$K_{k\,j}(\theta_e)$	Phase j reference current coefficient when Phase k suffers open-circuit fault with fault remedial strategy 3
$K_{k\,l\,j}(\theta_e)$	Phase j reference current coefficient when Phases k and l suffer open-circuit fault with fault remedial strategy 3
L	Equivalent winding inductance

L_{11}, L_{22}, L_{33}	Self-inductances in phases 1, 2, and 3
L_{pu}	Per unit the inductance
m	The number of phase with open-circuit fault
M_{12} M_{23} M_{31}	Mutual inductances between phases 1, 2, and 3
n	Total number of phase in the motor drive
N_p	Number of pole pairs
P_{ave}	Average copper loss in a dual module motor drive
P_{cu}	Instantaneous copper loss of a dual motor module
P_{cu0}	Instantaneous copper loss of a single motor module
$P_{curelative0}$	Relative copper loss in a single motor module drive
$P_{curelative}$	Relative copper loss in a dual motor module drive
P_{cuRS}	Copper loss of a dual motor module under a fault remedial strategy
P_{cuSC}	Copper loss in a short-circuit winding
P_{cuSCpu}	Per unit copper loss in a short-circuit winding
P_{in0}	Total input power of a single module motor drive
P_{in}	Total input power of a dual module motor drive
P_{mech0}	Mechanical power of a single module motor drive
$P_{openloss}$	Open-circuit power loss in a dual motor module drive
P_{out}	Output power of a dual motor module drive
R	Equivalent winding resistance
R_{pu}	Per unit winding resistance
T_0	Electromagnetic torque of a single module motor drive
T	Electromagnetic torque of a dual module motor drive
T_{ave}	Average torque in a dual module motor drive
$T_{avedrag}$	Average drag torque in a short-circuit winding
$T_{avedragpu}$	Per unit average drag torque

T_{F0}	Output torque of a single module motor drive under faulty condition
T_F	Output torque of a dual module motor drive under faulty condition
T_{L0}	Load torque of a single module motor drive
T_L	Load torque of a dual module motor drive
$T_{\max}$, $T_{\min}$	Maximum and minimum total instantaneous torque values
$T_{openloss0}$	Open-circuit torque loss in a single motor module drive
$T_{openloss}$	Open-circuit torque loss in a dual motor module drive
T_{ripple}	Torque ripple factor
T_{RS0}	Output torque of a single module motor drive under a fault remedial strategy
T_{RS}	Output torque of a dual module motor drive under a fault remedial strategy
$v_{1,2,3,4,5,6}$	Instantaneous values of phase voltages
$V_{DC1,2}$	DC link voltage
V_{in}	Current sensor output voltage
V_{out}	Amplifier output voltage of phase current measurement
V_{phase}	Phase voltage for Hysteresis current control
V_R	Voltage of the rheostat
Δh	Bandwidth of the hysteresis current control
Δi	Current error between the reference current and measured current
ΔT	Integration time
η	Efficiency of the motor drive
$\psi_{pm1,\ pm2,\ pm3}$	Three phase flux linkages of the rotor permanent magnets
θ_e	Electrical rotor position
θ_r	Mechanical rotor position
ω_m	Mechanical angular speed

ω_{pu}	Per unit value of the mechanical angular speed
ω_r	Electrical angular speed
ω_e	Electrical angular speed
ϕ	The phase difference between the back-EMF voltage and the short-circuit current
$\psi_{1, 2, 3, 4, 5, 6}$	Total values of the phase flux linkages
F	Fault
OC	Open-circuit fault
RS	Remedial strategy
SC	Short-circuit fault
*	Superscript denoting reference values