THE UNIVERSITY OF ADELAIDE

School of Electrical and Electronic Engineering

Design of Permanent Magnet Machines for Field-Weakening Operation

Chun Tang

A thesis presented for the degree of Doctor of Philosophy

2015

Dedicated to my parents

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Abstract

This research focuses on the electromagnetic design of permanent magnet (PM) machines in terms of the iron loss, torque pulsations and field-weakening performance. It covers the investigation of the effect of stator-slot and rotor-pole number combinations for surface-mounted PM (SPM) machines, and the stator-slot and rotor-effective-slot number combinations for interior permanent magnet (IPM) machines.

The effect of changing the number of slots and poles on the performance of a particular SPM machine design is studied in detail using finite element analysis. This includes examining the back-EMF, the open-circuit/full-load power losses, the cogging/ripple torque, and the field-weakening performance. The simulation results are compared with the expected relationships to provide electric machine designers useful insights on the effect of the number of slots and poles on the performance of SPM machines.

Operation at high speed in traction drives corresponds to deep field-weakening conditions. Due to the high electrical frequencies, the iron loss of IPM machines at high speeds can significantly affect the overall efficiency. This thesis investigates the rotor-cavity positioning and the combination of stator-slot and rotor-effective-slot number on the eddy-current loss for IPM/reluctance machines operating under deep field-weakening conditions. A new closed-form expression for the stator and rotor eddy-current loss is developed. The optimal barrier-positioning for the minimum total loss and the effect on the eddy-current loss of varying the stator-slot and rotor-effective-slot number are investigated for 1-, 2-, 3- and full-layered rotors.

FEM optimisation and experimental verification of an example IPM machine design are presented. An optimized 30 slot, 4 pole (slot/pole/phase = 2.5) three-layered IPM machine with a significantly reduced iron loss under field-weakening operation is proposed and compared to the baseline 36-slot 4-pole (slot/pole/phase = 3) three-layered IPM machine. The detailed comparison of the optimized and baseline designs using a combination of the analytical, FEM and experimental tests are presented.

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Statement of Originality

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List of Publications

[P1] **C. Tang**, W.L. Soong, T. M. Jahns and N. Ertugrul, "Analysis of Iron Loss in Interior PM Machines with Distributed Windings under Deep Field-Weakening", *IEEE Trans. Ind. Appl.*, 2015 (accepted).

[P2] **C. Tang**, W.L. Soong, T. M. Jahns, G.S. Liew and N. Ertugrul, "Analysis of Stator Iron Loss in Interior PM Machines under Open and Short-Circuit Conditions", *IEEE Energy Conversion Congress and Exposition (ECCE)*, 2013, Denver.

[P3] **C. Tang**, W.L. Soong, G.S. Liew and N. Ertugrul, "Modelling of a Bonded Magnet Ring Surface PM Machine using Soft Magnetic Composites", *Int. Conf. on Elect. Machines* (*ICEM*), 2012, France.

[P4] **C. Tang**, W.L. Soong, G.S. Liew and N. Ertugrul, "Effect of Pole and Slot Number Changes on the Performance of a Surface PM Machine", *Int. Conf. on Elect. Machines* (*ICEM*), 2012, France.

[P5] **C. Tang**, W.L. Soong, P. Freere, M. Pathmanathan and N. Ertugrul, "Dynamic Wind Turbine Output Power Reduction under Varying Wind Speed Conditions Due to Inertia", *Wind Energy* 2012; DOI: 10.1002/we.1507.

[P6] G.S. Liew, **C. Tang**, W.L. Soong, N. Ertugrul and D.B. Gehlert, "Finite-Element Analysis and Design of a Radial-Field Brushless PM Machine Utilizing Soft Magnetic Composites", *IEEE Int. Electric Machines and Drives Conf.* (*IEMDC*), 2011, Canada, pp. 930-935.

[P7] M. Pathmanathan, **C. Tang**, W.L. Soong and N. Ertugrul, “Detailed Investigation of Semi-Bridge Switched-Mode Rectifier for Small-Scale Wind Turbine Applications”, *IEEE Int. Conf. on Sustainable Energy Technologies* (*ICSET*), 2008, Singapore, pp. 950-955.

[P8] **C. Tang**, M. Pathmanathan, W.L. Soong and N. Ertugrul, “Effects of Inertia on Dynamic Performance of Wind Turbines”, *Australasian Universities Power Engineering Conference* (AUPEC), Dec. 2008, Australia.

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Nomenclature

θ	Stator circumferential coordinates	elec. deg
ω_e	Synchronous angular frequency	rad/s
μ_o	Magnetic permeability of vacuum	H/m
α_j	rotor cavity angular position	elec. deg
Δ_s	Stator tooth pitch angle	elec. deg
Δ_r	Rotor channel pitch angle	elec. deg
ξ_j	Rotor channel circumferential position	elec. deg
δ	Angle between the cavity and *d*-axis	mech. deg
Ψ_m	Magnet flux linkage	Wb
Ψ_d	Stator *d*-axis flux linkage	Wb
Ψ_q	Stator *q*-axis flux linkage	Wb
Φ_{rem}	Magnet remanent flux	Wb
Φ_{lk}	Rotor-rib leakage flux	Wb
B_g	Radial airgap flux density	T
B_{gm}	Magnet created airgap flux density	T
B_{gr}	Rotor-MMF contributed airgap flux density	T
B_r	Magnet remanent flux density	T

B_t	Stator-teeth flux density	T
B_y	Stator-yoke flux density	T
B_{chl}	Rotor-channel tunnelling flux density	T
E_{ph}	Phase back-EMF voltage	V_{rms}
f_1	Synchronous frequency	Hz
f_s	Stator MMF	At
f_{sh}	Stator MMF spatial harmonics	At
f_r	Rotor MMF	At
f_{rn}	Rotor MMF spatial harmonics	At
g_e	Effective airgap length	m
h	Stator MMF spatial harmonic order	
I_m	*S*tator peak phase current	A_{pk}
I_d	Stator *d*-axis current	A_{rms}
I_q	Stator *q*-axis current	A_{rms}
I_{ch}	Characteristic current	A_{rms}
I_{sc}	Stator short-circuit current	A_{rms}
k_{sh}	Stator winding factors	
k_{w1}	Synchronous winding factor	
k_{d1}	Synchronous winding distribution factor	
k_{p1}	Synchronous winding pitch factor	
k_t	Stator tooth-pitch-at-airgap to body-width ratio	
k_y	Pole-pitch-at-airgap to stator-yoke-thickness ratio	
k_{chl}	Rotor channel pitch-at-airgap to width ratio	
k_e	Eddy-current loss coefficient	W/m^3
l_{stk}	Lamination stack length	m
l_{teeth}	Stator-teeth radial length	m
l_{chl}	Rotor-channel mean length	m
L_d	*d*-axis inductance	H
L_q	*q*-axis inductance	H
L_{end}	Stator end-winding inductance	H
n	Rotor MMF spatial harmonic order	
n_s	Number of stator slot per pole-pair	

n_r	Number of rotor slot per pole-pair	
N_t	Number of series turns per phase	
p	Number of pole-pairs	
P	Number of poles	
p_{eddy}	Eddy-current loss density	W/m^3
p_{teeth}	Stator-teeth eddy-current loss density	W/m^3
p_{yoke}	Stator-yoke eddy-current loss density	W/m^3
p_{chl}	Rotor channel eddy-current loss density	W/m^3
r_g	Average airgap radius	m
r_j	Rotor channel magnetic potential	At
R_s	Stator phase resistance	ohms
R_b	Rotor barrier magnetic reluctance	H^{-1}
R_g	Sectional airgap magnetic reluctance	H^{-1}
R_{yoke}	Stator-yoke average radius	m
R_{teeth}	Stator-teeth average radius	m
R_{rot}	Rotor outer radius	m
S	Stator slot number	
T_{ave}	Total average torque	Nm
T_{mag}	Magnet torque	Nm
T_{rel}	Reluctance torque	Nm
V_{ph}	Stator phase voltage	V_{rms}
V_{yoke}	Stator-yoke volume	m^3
V_{teeth}	Stator-teeth volume	m^3
V_{chl}	Rotor-channel volume	m^3
w_{chl}	Rotor-channel mean width	m
w_c	Cavity thickness	m
X_d	*d*-axis reactance	ohms
X_q	*q*-axis reactance	ohms

Acronyms

CPSR	Constant Power Speed Ratio
EMF	Electric-Motive Force
FEM	Finite-Element Method
FW	Field-Weakening
IPM	Interior Permanent Magnet
MMF	Magneto-Motive Force
MTPA	Maximum Torque per Ampere
PM	Permanent Magnet
SPM	Surface Permanent Magnet
SPP	Slots/Pole/Phase
THD	Total Harmonic Distortion