Analysis and Design of Single-Sided, Slotted AMM Axial-Field Permanent Magnet Machines

by

Gene Shane Liew

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To my parents

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Abstract

Most electrical machines available in the market utilise some form of silicon iron (SI) as the core material. Although SI based electrical machine manufacturing methods are well established and simple, SI has significant iron losses specifically in high frequency variable-speed motor drive applications. Two alternative magnetic materials have recently been developed: amorphous magnetic material (AMM) and soft magnetic composite, which can each offer unique characteristics that can be utilised to improve the performance of electric machines. AMM offers extremely low iron losses which makes it a good candidate for high-efficiency and variable-speed motor applications. However, due to handling and cutting limitations, AMM has not been utilised widely in rotating electrical machines.

A commercially viable AMM cutting technique was recently developed by the industrial partner of this project. It is thus now practical to cut the AMM ribbon into a machine stator, particularly for axial-field stators which generally require less cutting than radial-field stators. This thesis investigates an innovative motor design based on applying the cut AMM in an axial-field permanent magnet (AFPM) machine for general drive applications. It includes a detailed review of the analytical approach, finite element analysis (FEA), iron loss investigation and prototype performance comparisons.

Analytical analysis of the AFPM machine was performed and the key design variables were evaluated to optimise the design parameters based on the use of AMM. The AMM cutting constraints, design and performances trade-offs were also investigated in the design. The research study provides a design procedure to determine the basic physical size and configuration (e.g. combination of the number of slots and poles, slot width and depth, number of winding layers, air gap length, magnet thickness) based on certain basic specifications. In addition, a comprehensive investigation was conducted on the iron loss of various materials to compare these with AMM. Due to the three dimensional (3D) nature of the AFPM structure, the theoretical design was validated using 3D FEA and extensive simulation results are provided.

A number of AMM AFPM prototypes were successfully designed and constructed. Due to limited available materials, the prototypes were built using uncoated AMM ribbon which has substantially higher iron loss characteristics. Nevertheless, it is believed that it would still provide a valuable understanding of the real machine characteristics and allow initial design validation. The prototype was tested in a custom-built test rig to validate the analytical and 3D FEA predictions. Overall, a good correspondence between the results and predictions has been achieved.

Extensive experiments have been conducted to investigate and demonstrate the characteristics of the AMM prototype machines which are based on fractional-slot concentrated-winding single-sided AFPM machines. This includes comparisons against identical silicon iron and soft magnetic composite prototypes. In addition, the laboratory experimental results also highlighted the significant effect of the open-circuit losses on the overall machine performance. Therefore, the open-circuit loss components which includes bearing, windage, magnet and iron losses were separated based on 3D FEA and experimental results.

The above research studies demonstrated the potential and feasibility of cut AMM to produce highly efficient AFPM machines. In addition, the innovative cutting technique also has the potential for mass production of low-cost AMM machines. The research work in this thesis makes a significant contribution to the design of axial-field permanent magnet machines based on AMM.

Statement of Originality

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.

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Publications

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Nomenclature

α	flux density term, the iron loss dependence on flux density	
α_m	ratio of magnet width to pole pitch	
β	frequency term, the variation of iron loss with frequency	
δ	skin depth	m
η	efficiency	%
η_{air}	dynamic viscosity of air at $1atm$ and $20^\circ C$	$Pa.s$
Γ_{depth}	slot depth	m
Γ_{slot}	arc length of stator slot	m
Γ_{StackL}	stack length	m
Γ_{tooth}	arc length of stator tooth	m
$\hbar_{Rot}$	rotor back-iron thickness	m
$\hbar_{Sta}$	stator yoke thickness	m
λ_{1e}	coefficient of the leakage permeance of end-windings	
λ_{1tt}	coefficient of tooth tip leakage	
λ_{ls}	coefficient of slot leakage permeance	
μ_o	free space recoil permeability	N/A^2
μ_r	relative recoil permeability of the magnet	
ω_M	mechanical rotational speed	rad/s
ω_e	electrical angular speed	rad/s
$\overrightarrow{E}_i$	EMF phasor for each winding elements	V
$\overrightarrow{E}_{phase,pu}$	Phase EMF phasor	pu

Φ_{pk}	peak flux in the stator teeth	Wb
ψ_a	magnet flux-linkage	Wb
$\Re$	reluctance	AT/wb
ρ_M	material density	kg/m^3
ρ_{air}	air density at $1atm$ and $20°C$	kg/m^3
ρ_{cu}	electrical resistivity of copper	Ωm
σ	electrical conductivity of core materials	S/m
σ_1	electrical conductivity of intralamination	S/m
σ_2	electrical conductivity of interlamination	S/m
σ_{cu}	electrical conductivity of copper	S/m
τ_{pole}	pole pitch	m
τ_{slot}	slot pitch	m
Θ_{Mag}	arc angle of magnet pole	rad
Θ_{slot}	arc angle of slot from center point	rad
Θ_{tooth}	arc angle of tooth from center point	rad
$\widehat{\Phi}$	peak flux	Wb
$\widehat{B}$	peak flux density	T
$\widetilde{\lambda}$	relative permeance function	
A_{core}	cross-sectional area of the magnetic core	m^2
A_{cu}	area of the copper wire	m^2
A_{lam}	laminated toroidal core cross-sectional area	m^2
a_p	number of parallel current paths	
A_{slot}	cross-sectional area of slot	m^2
A_{tooth}	tooth surface area	m^2

A_{wire}	wire cross-sectional area	m^2
a_w	number of parallel conductors	
$B(t)$	core flux density waveform	T
B_{ave}	average magnetic flux density	T
B_{gPM}	airgap flux distribution for a non-slotted core	T
B_{gSlot}	airgap flux distribution for a slotted core	T
B_g	airgap flux density	T
B_{RBI}	rotor back-iron flux density	T
B_r	magnet remanent flux density	T
B_t	tooth flux density under the stator tooth tip	T
B_y	yoke flux density under the stator slots	T
C_{Ave}	average circumference of a laminated toroidal core	m
C_e	eddy-current loss coefficient	
c_f	coefficient of drag for turbulent flow	
C_h	hysteresis loss coefficient	
D_{wire}	diameter of wire	m
E	phase induced voltage	V
f	operating frequency	Hz
$H(t)$	magnetic field strength waveform	A/m
I_{dc}	dc current	A
i_{main}	instantaneous value of the main coil current	A
I_{PhMax}	maximum phase current	A
I_{ph}	phase current	A
ID	inner diameter	mm

J	current density	A/mm^2
K	iron loss at a flux density of $1T$ and a frequency of $50Hz$	
k	phase induced back-EMF constant (mechanical)	$V/rad/s$
k_r	ratio of inner to outer radius	
k_{cu}	thermal conductivity of copper	$W/(mK)$
k_c	Carter's coefficient	
k_{dc}	dc motor torque constant	$V/rad/s$
k_e	eddy-current loss coefficient (Steinmetz)	
k_{fb}	coefficient of bearing friction	
k_f	form factors of armature reaction	
k_h	hysteresis loss coefficient (Steinmetz)	
k_{w1}	fundamental winding factor	
k_w	winding factor	
l'_{em}	fictitious airgap	m
L_{1ein}	inner radius end-windings leakage inductance	H
L_{1eout}	outer radius end-windings leakage inductance	H
L_{1s}	slot leakage indutance	H
L_{1tt}	tooth tip leakage inductance	H
L_{ad}	armature reaction d-axis inductance	H
L_{aq}	armature reaction q-axis inductance	H
l_{core}	mean length of the magnetic flux path	m
l_g	airgap length	m
l_{lam}	average lamination length of a laminated toroidal core	m
l_m	magnet thickness	m

l_{wire}	average length of wire per coil around a tooth	m
Lam	number of laminations	
Le_1	stator leakage inductance	H
M	mass	kg
m	number of phases	
n	rotational speed	rpm
$N_{cSeries}$	number of coil connected in series	
N_c	number of turns per coil	
N_{main}	number of turns of the main coil	
N_{Ph}	number of turns per phase	
N_{sense}	number of turns of the search coils	
$N_{Toothwire}$	number of teeth wound with wire	
N_{wires}	number of wire turns	
OD	outer diameter	mm
p	pole pairs	
P_{culoss}	copper loss	W
P_{EddyM1}	Eddy-current loss model 1	W
P_{EddyM2}	Eddy-current loss model 2	W
P_{EddyM3}	Eddy-current loss model 3	W
P_{EddyM4}	Eddy-current loss model 4	W
P_{feDen}	core loss density for analysis	W/kg
P_{FEloss}	analytical core loss	W/kg
P_{fe}	non-slotted core power loss	W
P_{in}	input power	W

P_{Out}	mechanical output power	W
pf_{Slot}	slot packing factor	%
q	number of slots per pole per phase	
Q_s	number of slots	
R_{MagIn}	magnet inner radius	m
R_{MagOut}	magnet outer radius	m
R_{RotIn}	rotor back-iron inner radius	m
R_{RotOut}	rotor back-iron outer radius	m
SD	slot depth	mm
sf	stacking factor	%
SW	slot width	mm
T	electromagnetic torque	Nm
T_M	mechanical output torque	Nm
T_{DCloss}	dc motor loss torque at the given speed	W
T_{Gross}	gross electromagnetic output torque	Nm
t_h	thickness of lamination	m
T_{OC}	open-circuit loss torque	Nm
V_{DC}	DC link of inverter	V
V_{Lpk}	peak line-to-line voltage	V
v_{sense}	instantaneous value of the search coil voltage	V
Vol_{cal}	calculated core volume	m^3
X_{sd}	d-axis synchronous reactance	Ω
X_{sq}	q-axis synchronous reactance	Ω
YT	stator yoke height	mm

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