Analysis of Idle Power and Iron Loss Reduction in an Interior PM Automotive Alternator

by

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To my dear teachers…

Abstract

In recent years there has been considerable interest in high power automotive alternators. As part of earlier work, an interior permanent magnet machine had been built as a concept demonstrator for a 6 kW automotive alternator. Test results on this machine had shown good field-weakening performance but that the machine fell 16% short of the idle power requirement and had high iron losses.

This thesis describes the development of a finite-element model for this machine and how it was validated using experimental test results and used to examine the cause of the low idle power and high iron losses. A limited optimisation of the machine design to reduce iron losses was examined and demonstrated experimentally.

It was found that the cause of the low idle power was due to cross-saturation effects in the machine, particularly in the stator teeth. Both the finite-element analysis and experimental tests showed a substantial reduction in the *q*-axis inductance due to the presence of the magnet flux. It was predicted that the machine would have met the idle power requirement if saturation and cross-saturation had not been present.

The high iron loss during field-weakening was identified as being due to large amplitude, higher harmonic flux components caused by the interaction of the rotor barriers and the *d*-axis flux distribution. This was seen in the spatial airgap flux density and the time-varying stator tooth flux waveforms. The analysis also showed that eddy-current loss was dominant in this machine at higher speeds, and that under short-circuit conditions the majority of the iron loss was due to large thirteenth and eleventh harmonic flux density components. This was confirmed experimentally using the stator tooth flux waveforms and the total iron loss measurement.

A limited design optimisation was performed by examining three machine design changes to reduce the high stator iron loss under short-circuit conditions. Of these, increasing the stator slot opening using flat stator teeth offered the greatest calculated iron loss reduction (19%). This was tested experimentally by machining the stator teeth of the prototype machine. The measured iron loss reduction (21%) at high speed was comparable to the calculated effect, and the output power was shown to improve slightly.

The results of the detailed iron loss investigation in this thesis forms a basis for development for more general machine design approaches for reducing stator iron loss under field-weakening conditions in interior permanent magnet machines.

Statement of Originality

This work contains no materials 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

V. Zivotic-Kukolj, W.L. Soong, N. Ertugrul, “Modelling of Saturation and Cross-Saturation Effects in an Interior PM Automotive Alternator,” *Australasian Universities Power Engineering Conference (AUPEC 2004), Brisbane, Australia*, Sep-Oct 2004.

V. Zivotic-Kukolj, W.L. Soong, N. Ertugrul, “Investigation of Iron Losses in a High Flux Interior PM Automotive Alternator,” *Australasian Universities Power Engineering Conference (AUPEC 2004), Brisbane, Australia*, Sep-Oct 2004.

V. Zivotic-Kukolj, W.L. Soong, N. Ertugrul, “Modelling of Saturation and Cross-saturation Effects in an Interior PM Automotive Alternator,” *Australian Journal of Electrical and Electronics Engineering*, Vol 2, No 3, pp. 209 - 216, 2005.

V. Zivotic-Kukolj, W.L. Soong, N. Ertugrul, “Iron Loss Reduction in an Interior PM Automotive Alternator,” *Conference Record of Industrial Application Society (IAS 2005), Hong Kong, China*, Vol 3, pp. 1736 – 1743, Oct 2005.

V. Zivotic-Kukolj, W.L. Soong, N. Ertugrul, “Iron Loss Reduction in an Interior PM Automotive Alternator,” *IEEE Transactions on Industrial Applications*, Vol 42, No 6, pp. 1478 - 1486, Nov – Dec 2006.

Nomenclature

a, b	constants dependent on thickness and type of ferromagnetic material;
a_n, b_n	harmonic coefficients;
A_m	magnet area [mm^2];
A_{slot}	slot area [mm^2];
$B(t)$	flux density [T];
B_{pk}	peak value of flux density [T];
B_{pk_n}	magnitude of n-harmonic component of the magnetic flux density [T];
B_r	equivalent remanence [T];
$B_r(t)$	radial component of the flux density [T];
$B_t(t)$	tangential component of the flux density [T];
C_e	eddy-current loss coefficient for sinusoidal flux density waveforms;
C_{e1}	eddy-current loss coefficient for arbitrary-shaped flux density waveforms;
C_h	hysteresis loss coefficient;
C_i	capacitance of the low-pass filter;
DC	direct current;
$e(t)$	induced search-coil voltage [V rms];
E	induced EMF due to magnets [V rms];
f	frequency [Hz];
$\varphi(t)$	flux in a tooth [Wb];
Ψ_m	magnet flux-linkage [Vs rms];
$g(t)$	periodic function of t with a period of T;
g''	effective air gap [mm];
γ	angle between the stator phase current phasor and q-axis;
$H(t)$	magnetic field [Wb];
$i(t)$	instantaneous current waveform [A];
$i_1(t)$	instantaneous current [A];
I	stator phase current [A rms];
I_d	d-axis component of stator phase current [A rms];
I_q	q-axis component of stator phase current [A rms];
I_0	rated phase current [A rms];

L	inductance [mH];
L_d	d-axis synchronous inductance [mH];
$L_{d(sat)}$	saturated value of the d-axis synchronous inductance [mH];
$L_{d(unsat)}$	unsaturated value of the d-axis synchronous inductance [mH];
L_{dmi}	intrinsic d-axis inductance [mH];
L_{end}	end winding inductance [mH];
L_m	magnetising inductance [mH];
L_q	q-axis synchronous inductance [mH];
$L_{q(sat)}$	saturated value of the q-axis synchronous inductance [mH];
$L_{q(unsat)}$	unsaturated value of the q-axis synchronous inductance [mH];
L_{slot}	slot-leakage inductance [mH];
λ_a	flux-linkage in phase a [Vs rms];
λ_b	flux-linkage in phase b [Vs rms];
λ_c	flux-linkage in phase c [Vs rms];
λ_{ph}	total flux-linkage per phase [Vs rms];
$\lambda(t)$	instantaneous flux linkage [Vs rms];
m	number of phases;
n	Steinmetz exponent (typically 1.6, but can vary between 1.6 and 2.3);
N	number of turns in the search coil;
ω	electrical angular speed [rad/s];
p	pole-pairs;
PM	permanent magnet;
P_{Cu}	copper loss [W];
P_e	eddy-current loss [W];
P_{Fe}	iron loss [W];
P_h	hysteresis loss [W];
P_{in}	input power [W];
P_{Mech}	mechanical loss [W];
P_{out}	output power [W];
R	resistance of the phase winding [Ω];
R_a	armature resistance or stator resistance per phase [Ω];
R_i	resistance of the low-pass filter [Ω];
$R_i C_i$	time constant of the low-pass filter;
t	time [sec.];

T	output phase torque [Nm];
Θ	rotor angle [rad];
$v(t)$	instantaneous voltage waveform [V];
$v_i(t)$	output of the integrator [V];
V	stator phase voltage [V rms];
V_0	rated phase voltage [V rms];
V_d	*d*-axis component of stator phase voltage [V rms];
V_q	*q*-axis component of stator phase voltage [V rms];

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