

# A High Power Interior Permanent Magnet Alternator for Automotive Applications

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## Abstract

This thesis examines the operation of a 6 kW interior permanent magnet machine as a generator and its use in conjunction with a switched-mode rectifier as a controllable current source. The interior permanent magnet machine was designed for optimum field-weakening performance which allows it to achieve a wide constant-power speed range. This configuration has possible applications in power generation, e.g. as an alternator in automotive electrical systems and in renewable energy systems such as small-scale wind turbines.

The thesis starts from a study of the behaviour of the interior PM machine while generating into a three-phase resistive load and also through a rectifier into a voltage source load. Steady-state and dynamic d-q models are developed which describe the machine generation characteristics. The concept of the VI locus is introduced which provides insights into the generating performance of interior PM machines. In particular, the phenomenon of hysteresis in the current versus speed characteristic of highly salient interior PM machines is explained using the VI locus and for the first time is experimentally demonstrated.

The steady-state and transient response of the 6 kW interior PM machine while operating with a switched-mode rectifier is modeled and experimentally measured, forming the basis for the design of a closed-loop controller to regulate the output voltage. The experimental performance and stability of the closed-loop system is examined and evaluated. Further improvements to the output power of the system at low speed using a switched-mode rectifier modulation scheme are investigated and a 66% improvement in output power from 2.8 kW to 4.7 kW is experimentally demonstrated.

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## Statement of Originality

I, Chong-Zhi Liaw certify that 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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# Nomenclature

$\beta_n$	normalised magnetic saturation parameter
$\delta$	the angle between the back-emf $E$ and the output voltage $V_o$ of an electrical machine
$\omega_e$	electrical frequency
$\Psi_m$	magnet flux linkage
$\xi$	saliency ratio of an interior PM machine
$C$	DC link capacitance
$d$	PWM duty-cycle
$E$	induced back-EMF of an electrical machine
$Gm$	gain margin of a transfer function
$I_d$	$d$ -axis current
$i_d$	time-varying $d$ -axis current
$I_f$	field current in an alternator winding
$I_q$	$q$ -axis current
$i_q$	time-varying $q$ -axis current
$I_{IN}$	DC current before the SMR switch
$I_{LOAD}$	current delivered to a load
$I_{OUT}$	DC current after the SMR switch
$I_{qn}$	normalised $q$ -axis current

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$I_{SW}$	DC current flowing through the SMR switch to ground
$K_p$	proportional gain of a closed-loop controller
$L_d$	$d$ -axis inductance
$L_q$	$q$ -axis inductance
$L_{dn}$	normalised $d$ -axis inductance
$L_{qno}$	normalised unsaturated $q$ -axis inductance
$L_{qn}$	normalised $q$ -axis inductance
$R_L$	load resistance
$R_n$	normalised resistance
$R_S$	stator resistance
$R_T$	total resistance
$R_{ph}$	stator resistance of an electrical machine
$T$	reaction torque of an electrical machine
$T_s$	sampling time of a closed-loop controller
$V_d$	$d$ -axis voltage
$v_d$	time-varying $d$ -axis voltage
$V_o$	open-circuit voltage of an electrical machine
$V_o$	output voltage
$V_q$	$q$ -axis voltage
$v_q$	time-varying $q$ -axis voltage
$V_s$	line voltage of an electrical machine
$V_{DC}$	DC link voltage
$V_{EFF}$	effective voltage seen at the terminals of an electrical machine



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$V_{max}$  maximum voltage obtained on a voltage-current locus

$X_d$   $d$ -axis reactance

$X_q$   $q$ -axis reactance

$Z_S$  source impedance

# Abbreviations

AC	Alternating Current
CPSR	Constant Power Speed Ratio
DC	Direct Current
FET	Field Effect Transistor
LCD	Liquid Crystal Display
PWM	Pulse-Width Modulation
SAE	Society of Automotive Engineers
SLI	Starting, Lighting and Ignition
SMR	Switched-Mode Rectifier
UCG	Uncontrolled Generation
VI	Voltage-Current