



THE UNIVERSITY OF ADELAIDE

School of Electrical and Electronic Engineering

**Phase Advance Modulation of
Low-Cost Power Electronic Converters
for SPM Wind Turbine Generators**

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A thesis presented for the degree of Doctor of Philosophy

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Dedicated to my parents

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Abstract

This research investigates the control of low-cost power electronic converters for small-scale wind turbines under standalone applications. The system utilizes a surface permanent magnet (SPM) generator operating with a semi-bridge switched-mode rectifier (SMR) into a DC voltage load.

Conventional control of a semi-bridge SMR results in lower output power than an inverter (i.e. fully-controlled voltage source rectifier) due to the SMR's inability to control its input power factor. Phase-advance modulation was introduced by Rivas et al. as a method of generating increased output power from a semi-bridge SMR by modulating the leg voltage of each phase at three different levels during the phase current positive half cycle. This method produced a controllable leading phase shift on the phase current waveform with respect to the phase voltage.

Previous studies focussed on using phase advance modulation to extract maximum power from Lundell alternator and interior permanent magnet (IPM) generators at a fixed speed (1,800 rpm). No research had been conducted on the performance of SPM generators under phase advance modulation techniques. This study examines how the voltage and power factor angle of a SPM generator can be controlled to ensure that the generator produces maximum output power at a given speed. A simplified version of phase advance

modulation, called zero-epsilon modulation, is used to implement voltage-power factor angle control and hence extract the maximum value of power at a given SPM generator speed.

Wind turbine generators are required to have controllable values of torque in order to perform maximum power point tracking. It is desirable therefore to be able to control a SPM generator used in wind turbines to a commanded value of torque while maintaining a high value of efficiency. This study will present the techniques required to use zero-epsilon modulation to control a SPM generator under maximum torque per ampere conditions, thereby minimizing generator copper losses. The voltage and power factor required by an inverter operating under maximum torque per ampere control for a given generator speed and commanded torque is used to calculate the required zero-epsilon control parameters. A closed-loop current controller was used to minimize the error between the commanded and actual values of generator torque. Simulation and experimental results are used to validate the proposed approach.

The above research has demonstrated the feasibility of phase advance modulation as a low-cost alternative to inverter modulation for controlling a SPM generator to produce maximum output power at a given speed. In addition, phase advance modulation has been shown to be capable of controlling a SPM generator to produce a commanded value of torque under maximum torque per ampere conditions at a given speed. These results make a significant contribution towards the development of low-cost, high performance small-scale wind turbine generators.

Statement of Originality

I, Mehanathan Pathmanathan 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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List of Publications

- [1] **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 International Conference on Sustainable Energy Technologies*, Nov. 2008, Singapore, pp. 950-955.
- [2] **M. Pathmanathan**, C. Tang, W.L. Soong and N. Ertugrul, “Comparison of Power Converters for Small-Scale Wind Turbine Operation”, *Australasian Universities Power Engineering Conference (AUPEC)*, Dec. 2008, Sydney, Australia, pp. 1-6.
- [3] 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, Sydney, Australia, pp. 1-6.
- [4] **M. Pathmanathan**, W.L. Soong and N. Ertugrul, “Investigation of Phase Advance Modulation with Surface Permanent Magnet Generators”, *Australasian Universities Power Engineering Conference (AUPEC)* Sep. 2009, Adelaide, Australia, pp. 1-6.

[5] **M. Pathmanathan**, W.L. Soong and N. Ertugrul, “Output Power Capability of Surface PM Generators with Switched-Mode Rectifiers”, *IEEE International Conference on Sustainable Energy Technologies*, Dec. 2010, Kandy, Sri Lanka, pp. 1-6.

[6] **M. Pathmanathan**, W.L. Soong and N. Ertugrul, “Maximum Torque per Ampere Control of Phase Advance Modulation of a SPM Wind Generator”, *IEEE Energy Conversion Congress and Exposition*, Sep. 2011, Phoenix, USA, pp. 1676-1683.

Pending Publication

[1] **M. Pathmanathan**, W.L. Soong and N. Ertugrul, “Maximum Torque per Ampere Control of Phase Advance Modulation of a SPM Wind Generator”, accepted by *IEEE Transactions on Industry Applications*, Apr. 2012.

[2] C. Tang, **M. Pathmanathan**, W.L. Soong, N. Ertugrul, and P. Freere “Dynamic Wind Turbine Output Power Reduction Under Varying Speed Conditions Due to Inertia”, submitted to *Wind Energy*, Feb. 2012.

Nomenclature

δ	Phase advance interval 1	deg
ε	Phase advance interval 2	deg
ϕ	Phase advance interval 3	deg
γ	Generator phase current angle	deg
Ψ_M	Magnet flux linkage	Wb
θ	Angle between phase current and voltage	deg
ω	Electrical frequency	c/s
ω_M	Generator speed	c/s
ω_O	Generator rated angular speed	c/s
d	Duty cycle	%
d_δ	Duty cycle during interval δ	%
d_ε	Duty cycle during interval ε	%
d_ϕ	Duty cycle during interval ϕ	%
E	Generator back EMF voltage	V_{rms}
I	Generator phase current	A_{rms}
I_d	Generator d -axis phase current	A_{rms}

I_q	Generator q -axis phase current	A_{rms}
I_X	Generator characteristic current	A_{rms}
I_{SC}	Generator short circuit current	A_{rms}
I_{DC}	Generator DC link current	A
I_O	Generator limiting current	A_{rms}
I_{OUT}	Generator load current	A
k	Generator back EMF constant	$V_{\text{rms}}/\text{cs}^{-1}$
L_S	Generator synchronous inductance	H
L_d	Generator d -axis inductance	H
L_q	Generator q -axis inductance	H
m	Number of generator phases	
n	Generator speed	rpm, pu
p	Number of generator pole pairs	
P	Generator output power	W
P_M	Generator mechanical power	W
P_O	Generator base power	W
R_S	Generator stator resistance	Ω
R_O	Generator base stator resistance	Ω
R_L	Generator load resistance	Ω
R_L'	Adjusted SMR load resistance	Ω
T	Generator input torque	Nm
V	Generator phase voltage	V_{rms}
V_d	Generator d -axis phase voltage	V_{rms}
V_q	Generator q -axis phase voltage	V_{rms}
V_O	Generator limiting voltage	V_{rms}
V_{OUT}	Generator load voltage	V
V_d	Generator d -axis voltage	V
V_q	Generator q -axis voltage	V
V_D	Power electronic converter voltage drop	V
V_{DC}	Generator DC link voltage	V
V_L	Generator line to line voltage	V_{rms}
X_S	Generator stator reactance	Ω

Acronyms

SPM	Surface Permanent Magnet
IPM	Interior Permanent Magnet
SMR	Switched-mode rectifier
PWM	Pulse width modulation
PA	Phase advance
ZE	Zero-epsilon