Low-Cost Small-Scale Wind Power Generation

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Dedicated to my late grandmother, Χρισούλα Ηλιάδου (*Chryssoula Iliadis*)

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Abstract

This research investigates a low-cost generator and power electronics unit for small-scale (<10kW) wind turbines, for both standalone and grid-connected applications. The proposed system uses a high-inductance permanent magnet generator together with a switched-mode rectifier (SMR) to produce a variable magnitude output current. The high inductance characteristic allows the generator to operate as a current source, which has the following advantages over conventional low-inductance generator (voltage source) systems: it offers simple control, and avoids the need for bulky / costly energy storage elements, such as capacitors and inductors.

The SMR duty-cycle is controlled in an open-loop manner such that 1) maximum power is obtained for wind speeds below rated, and 2) the output power and turbine speed is limited to safe values above rated wind speed. This topology also has the ability to extract power at low wind speeds, which is well suited to small-scale wind turbines, as there is often limited flexibility in their location and these commonly see low average wind speeds.

The thesis is divided into two parts; the first part examines the use of the SMR as a DC-DC converter, for use in standalone applications. The duty-cycle is essentially kept constant, and is only varied for maximum power tracking and turbine speed / power limiting purposes. The SMR operates in to a fixed voltage source load, and has the ability to allow current and hence power to be drawn from the generator even at low wind and hence turbine speeds, making it ideal for battery charging applications. Initial dynamometer testing and limited wind-tunnel testing of a commercially available wind turbine show that turbine power can be maximised and its speed can be limited by adjusting the SMR duty-cycle in an open-loop manner.

The second part of the thesis examines the use of the SMR as a DC-AC converter for grid-connected applications. The duty-cycle is now modulated sinusoidally at the mains frequency such that the SMR produces an output current that resembles a full-wave rectified sinewave that is synchronised to the mains voltage. An additional H-bridge inverter circuit and low-pass filter is used to unfold, filter and feed the sinusoidal output current in to the utility grid. Simulation and initial resistive load and preliminary grid-connected tests were used to prove the inverter concept, however, the permanent magnet generator current source is identified as non-ideal and causes unwanted harmonic distortion.

The generator harmonics are analysed, and the system performance is compared with the Australian Standard THD requirement. It is concluded that the harmonics are caused by 1) the low-cost single-phase output design, 2) the use of an uncontrolled rectifier, and 3) the finite back-EMF voltage. The extent of these harmonics can be predicted based on the inverter operating conditions. A feed-forward current compensation control algorithm is investigated, and shown to be effective at removing the harmonics caused by the non-ideal current source. In addition, the unipolar PWM switching scheme, and its harmonic components are analysed. The low-pass filter design is discussed, with an emphasis on power factor and THD grid requirements. A normalised filter design approach is used that shows how design aspects, such as cutoff frequency and quality factor, affect the filter performance. The filter design is shown to be a trade-off between the output current THD, power loss, and quality factor.

The final chapter summarises the thesis with the design and simulation of a 1kW single-phase grid-connected inverter. The inverter is designed based on the low-pass filter and feed-forward compensation analysis, and is shown to deliver an output current to the utility grid that adheres to the Australian Standards.

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 to David M. Whaley 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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Signed

Date

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List of Publications

[1] G. Ertasgin, **D.M. Whaley**, N. Ertugrul and W.L. Soong, "Implementation and Performance Evaluation of a Low-Cost Current-Source Grid-Connected Inverter for PV Application", *in Proceedings of the IEEE International Conference on Sustainable Energy Technologies*, Nov. 2008, Singapore.

[2] G. Ertasgin, **D.M. Whaley**, N. Ertugrul and W.L. Soong, "Analysis and Design of Energy Storage for Current-Source 1-ph Grid-Connected PV Inverters", *in Proceedings of the IEEE Applied Power Electronics Conference and Exposition*, Feb., 2008, pp. 1229 – 1234.

[3] G. Ertasgin, **D.M. Whaley**, N. Ertugrul, and W.L. Soong, "A Current-Source Grid-Connected Converter Topology for Photovoltaic Systems", *in Proceedings of Australasian Universities Power Engineering Conference*, 2006.

[4] **D.M. Whaley**, G. Ertasgin, W.L. Soong, N. Ertugrul, J. Darbyshire, H. Dehbonei, and C.V. Nayar, "Investigation of a Low-Cost Grid-Connected Inverter for Small-Scale Wind Turbines Based on a Constant-Current Source PM Generator", *in Proceedings of the IEEE Industry Electronics*, Nov., 2006, pp. 4297 – 4302.

[5] C.Z. Liaw, **D.M. Whaley**, W.L. Soong, and N. Ertugrul, "Implementation of Inverterless Control of Interior Permanent Magnet Alternators", *in IEEE Transactions on Industry Applications*, vol. 42, no. 2, Mar. - Apr., 2006, pp. 536 – 544.

[6] **D.M. Whaley**, W.L. Soong, and N. Ertugrul, "Investigation of Switched-Mode Rectifier for Control of Small-Scale Wind Turbines", *in Proceedings of the IEEE Industry Applications Conference*, vol. 4, Oct., 2005, pp. 2849 – 2856.

[7] C.Z. Liaw, **D.M. Whaley**, W.L. Soong, and N. Ertugrul, "Implementation of Inverterless Control of Interior Permanent Magnet Alternators", *in Proceedings of the IEEE Industry Applications Conference*, Oct., 2004.

[8] **D.M. Whaley**, W.L. Soong, and N. Ertugrul, "Extracting More Power from the Lundell Car Alternator", *in Proceedings of Australasian Universities Power Engineering Conference*, 2004.

Portions of the work presented in this thesis have been previously published. The material in Chapters 2 and 3 correspond to work in publications [6], whilst Chapter 4 corresponds to the work presented in publication [4]. Reprints of these publications are found in appendix B, for convenience.

Conventions

This thesis employs the IEEE reference style for citations, and is written using Australian English, as defined by the Macquarie English Dictionary 2005.

All voltages and currents shown in figures and equations are expressed as RMS (root-mean squared) quantities, unless otherwise stated.

The *hat* symbol is used in Chapters 5 and 6 to indicate peak value, i.e. $\widehat{\alpha}$ and $\widehat{\alpha}_0$ indicate the peak values of α and α_0, respectively. Similarly, the *check* symbol is used in Chapter 6 to represent the nadir (minimum) value, e.g. $\overset{\vee}{\beta}$ represents the minimum value of β.

Measured data is represented by hollow points, e.g. circles, squares, diamonds etc. and is often accompanied by solid lines that correspond to the equivalent analytical or computer based simulations. Multiple cases of measured (and simulated) data commonly appear on a single figure, and are differentiated by colour and shape. In contrast, coloured / shaded points represent calculated data. These are also shown with solid lines, however, these are for aesthetic purposes, i.e. they simply join the calculated data.

The above convention is used for the majority of this thesis, i.e. Chapters 2 to 5, however, the convention is modified for Chapter 6, as the data presented in this chapter is either simulated or analytically calculated. The simulated data, of Chapter 6 is hence shown as shaded points, whilst the analytical calculations are shown by the solid lines.

Nomenclature

α	normalised rectifier voltage	pu
α_0	ratio of grid to open-circuit rectifier voltage	
α_{cu}	temperature coefficient of copper	/°C
β	normalised rectifier current	pu
$\check{\beta}$	normalised minimum inverter input current	pu
β_{app}	normalised approximated rectifier current	pu
β_{exp}	normalised experimental rectifier current	pu
β_{id}	normalised ideal rectifier current	pu
Δ	difference	
δ	skin depth	m
η_{gen}	generator efficiency	%
η_{inv}	inverter efficiency	%
λ	tip-speed ratio	
μ	permability	H/m
ω	machine angular speed	rad/s
ω	turbine angular speed	rad/s
ω_{cn}	normalised cutoff frequency (relative to f_1)	pu
ω_e	electrical angular frequency	rad/s

ω_g	grid angular frequency	rad/s
ω_m	mechanical angular frequency	rad/s
ϕ	filter delay	deg
ϕ	power factor angle	deg
Ψ_m	RMS flux linkage	Wb or Vs
ρ	air density	kg/m^3
σ	conductivity	$(\Omega \text{ m})^{-1}$
$\widehat{\alpha}_0$	peak value of α_0	
ξ	saliency ratio	
C	capacitance	F
c_p	turbine coefficient of performance	
d	duty-cycle	%
d_a	adjusted duty-cycle	%
d_i	stored duty-cycle	%
dB	decibels	
E	induced back-EMF voltage	V
f	frequency	Hz
f_1	fundamental frequency	Hz
f_{cn}	normalised cutoff frequency (relative to f_{sw})	pu
f_c	cutoff frequency	Hz
f_m	machine frequency	Hz
f_{res}	resonant frequency	Hz
f_{sw}	switching frequency	Hz

$H(s)$	filter transfer function	
h_1	fundamental harmonic magnitude	%
h_f	harmonic frequency	Hz
h_m	harmonic magnitude at m multiples of f_1	%
h_{tot}	total harmonic components	%
I	current	A
I^*	compensation current command	A
$i_{c\ exp}(t)$	compensated current using the experimental I-V locus	pu
$i_{c\ id}(t)$	compensated current using the ideal I-V locus	pu
I_{ch}	characteristic current	A
$i_c(t)$	time-varying compensated current	A
I_{DC}	DC current	A
I_d	damping resistor current	A
I_f	damping resistor current (from inverter)	A
I_g	grid drawn current (from grid)	A
I_{inv}	inverter output current	A
I_{in}	input current	A
I_L	line current	A
$i_{out\ (id)}(t)$	normalised time-varying ideal output current	pu
I_{out}	output current	A
I_{ph}	phase current	A
$i_{R\ (id)}(t)$	normalised time-varying ideal rectifier voltage	pu
$I_{R\ min}$	minimum rectifier output current	A

I_R	rectifier output current	A
$i_R(t)$	normalised time-varying rectifier current	pu
$i_{ws\ (id)}(t)$	normalised time-varying ideal wave-shaper current	pu
I_{ws}	wave-shaper current	A
j	$\sqrt{-1}$	
k	back-EMF constant	V/rpm
k_{ph}	phase back-EMF constant	V/rpm
L	inductance	H
L_1	transformer primary inductance	H
L_2	transformer secondary inductance	H
L_{eq}	equivalent inductance	H
L_{ph}	phase inductance	H
L_s	stator inductance	H
m	number of machine phases	
m	positive integer	
m_a	modulation index	%
n	machine / generator speed	rpm
n	positive odd integer	
n	transformer turns ratio	
n_k	machine speed	k rpm
P	power	W
P	real power	W
p	number of machine pole-pairs	

P_{CU}	copper loss	W
P_d	damping resistor power loss	W
P_{IFW}	machine iron, friction and windage loss	W
$P_{inv\ in}$	total inverter input power	W
P_{inv}	inverter output power	W
P_{in}	input power	W
P_{loss}	SMR / generator power loss	W
P_L	machine power loss	W
P_{SMR}	SMR output power	W
P_{sw}	switching power loss	W
P_T	wind turbine power	W
P_W	wind power	W
$pk - pk$	peak to peak	
Q	quality factor	
Q	reactive power	VAr
Q_C	capacitive reactive power	VAr
Q_L	inductive reactive power	VAr
R	resistance	Ω
r	blade radius	m
R_1	transformer primary resistance	Ω
R_2	transformer secondary resistance	Ω
R_{cold}	cold resistance	Ω
R_d	damping resistance	Ω

R_{eq}	equivalent resistance	Ω
R_{hot}	hot resistance	Ω
R_L	load resistance	Ω
R_{ph}	phase resistance	Ω
R_s	stator resistance	Ω
$rect(t)$	normalised time-varying rectifier ripple	pu
S	apparent power	VA
S	number of stator slots	
s	$j\,\omega$	
T	torque	Nm
t	time	s
t_{off}	device *turn-off* time	s
t_{on}	device *turn-on* time	s
t_q	thyristor turn-off time	s
V	voltage	V
v	wind speed	m/s
V_C	capacitor voltage	V
V_{DC}	DC link voltage	V
V_{DC}	DC voltage	V
v_{eq}	turbine equivalent wind speed	m/s
$V_{g\ pk}$	peak grid voltage	V
V_g	grid voltage	V
$v_g(t)$	normalised time-varying grid voltage	pu

v_i	internal wind tunnel wind speed	m/s
V_L	line voltage	V
$V_{ph\ pk}$	generator phase peak voltage	V
$V_{R\ pk\ OC}$	peak rectifier voltage	V
v_r	rated wind speed	m/s
$v_R(t)$	normalised time-varying rectifier voltage	pu
$v_{ws}(t)$	normalised time-varying current wave-shaper voltage	pu
X	reactance	Ω
X_{ph}	phase reactance	Ω
X_s	stator reactance	Ω
Z_{0n}	normalised characteristic impedance	pu
Z_0	characteristic impedance	Ω
Z_s	stator impedance	Ω

Acronyms

AC	alternating current
AS	Australian Standard
CCS	constant current source
CM	control modes
CSI	current-source inverter
CWS	current wave-shaper
DC	direct current
DCC	duty-cycle command

DFT	discrete Fourier transform
ESR	equivalent series resistance
F&P	Fisher & Paykel®
FC	filter configuration
FFT	fast Fourier transform
GC	grid connected
GCI	grid-connected inverter
HF	high-frequency
IFW	iron, friction and windage
IPM	interior permanent magnet
IR	International Rectifier®
ISA	integrated starter alternator
LA	*Lundell* alternator
LF	line-frequency
MPPT	maximum power point tracker
NEG	net energy gain
NICS	non-ideal current source
OC	open circuit
PM	permanent magnet
pu	per-unit
PV	photovoltaic
PWM	pulse-width modulation
RMS	root-mean-squared

rpm	revolutions per minute	
RR	rectifier ripple	
SC	short circuit	
SC	squirrel cage	
SG	synchronous generator	
SMR	switched-mode rectifier	
SPM	surface permanent magnet	
THD	total harmonic distortion	%
TL	transformerless	
TSR	tip-speed ratio	
UCG	uncontrolled generation	
VSI	voltage-source inverter	
WF	wound field	
WR	wound rotor	

Abbreviations

CL	capacitive-inductive
I-V	current vs. voltage
LC	inductive-capacitive
LCL	inductive-capacitive-inductive
P-V	power vs. voltage
RLC	resistive-inductive-capacitive
SPP	slots per phase per pole

SW	switch
THY	thyristor

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