Low-Cost Small-Scale Wind Power Generation

David Michael Whaley

Thesis submitted for the degree of
Doctor of Philosophy

The School of Electrical & Electronic Engineering,
Faculty of Engineering, Computer & Mathematical Sciences
The University of Adelaide, Australia

July, 2009
Dedicated to my late grandmother, Χρυσούλα Ηλιάδου (Chryssoula Iliadis)
# Table of Contents

Table of Contents ........................................... v
Abstract .......................................................... xi
Statement of Originality ........................................ xiii
Acknowledgements ................................................ xv
List of Publications ............................................. xvii
Conventions ....................................................... xix
Nomenclature .................................................... xxi
List of Figures .................................................... xxxi
List of Tables .................................................... xxxix

1 Introduction .................................................... 1
   1.1 Wind Energy .............................................. 1
   1.1.1 Electricity Usage and Conventional Generation .......... 2
   1.1.2 Alternative Energy Sources .............................. 3
   1.1.3 Large and Small-Scale Turbine Classification .......... 4
   1.1.4 Small-Scale Turbine Development ......................... 5
   1.1.5 Technology Improvement ................................ 6
   1.1.6 Market Growth .......................................... 6
   1.2 Principles of Wind Power .................................. 7
   1.2.1 Wind and Turbine Power ................................ 7
   1.2.2 Coefficient of Performance ............................... 8
# Table of Contents

1.2.3 Principles of Turbine Operation .............................................. 9

1.3 Small-Scale Wind Turbines ....................................................... 11
  1.3.1 Applications ................................................................. 11
  1.3.2 Turbine Properties ......................................................... 12
  1.3.3 Generator Varieties ......................................................... 13
  1.3.4 Current Trends ............................................................. 15
  1.3.5 Inductance Classification of PM Generators .......................... 16

1.4 Standalone Power Converters .................................................. 18
  1.4.1 Common Power Converters ................................................ 18
  1.4.2 Uncontrolled Rectifier Operation ...................................... 21
  1.4.3 Switched-Mode Rectifier ................................................. 23
  1.4.4 Inverter Operation ......................................................... 25
  1.4.5 Power Comparison of Standalone Converters ....................... 27

1.5 Grid-Connected Inverters ....................................................... 29
  1.5.1 Introduction ................................................................. 29
  1.5.2 Line-Commutated Inverters ............................................. 30
  1.5.3 Self-Commutated Inverters .............................................. 32
  1.5.4 Transformer Type .......................................................... 35
  1.5.5 Voltage Source Topologies .............................................. 37
  1.5.6 Current Source Topologies .............................................. 40
  1.5.7 Current Trends ............................................................. 42
  1.5.8 Proposed Grid-Connected Inverter .................................... 43

1.6 Thesis Overview ................................................................. 44
  1.6.1 Aim of Research ........................................................... 44
  1.6.2 Justification for Research ................................................ 44
  1.6.3 Original Contributions ................................................... 45
  1.6.4 Thesis Structure ............................................................ 45

I Investigation of Switched-Mode Rectifier for Standalone Power Converter 49

2 High Inductance PM Generator Characteristics 51
  2.1 Introduction ................................................................. 51
    2.1.1 Ideal Machine Model and Current vs. Voltage Locus ............ 54
6 Design and Simulation of 1kW GC Inverter System

6.1 Turbine Sizing and Machine Parameter Selection
   6.1.1 System Assumptions
   6.1.2 Turbine Power and Size Calculations
   6.1.3 Generator Equivalent Circuit Parameter Selection

6.2 Low-Pass Filter Design
   6.2.1 Design Criteria
   6.2.2 Component Selection
   6.2.3 Filter Simulation - Ideal Current Source
   6.2.4 Filter Simulation - PM Generator Current Source

6.3 Demonstration of Feed-Forward Control
   6.3.1 Control Implementation
   6.3.2 Proof of Concept at Rated Wind Speed
   6.3.3 Current Command Variation at Rated Wind Speed

6.4 Inverter Simulation for Wide Wind Speed Range
6.4.1 Turbine Characteristics ........................................ 252
6.4.2 Power Control Modes ........................................ 254
6.4.3 Optimised Component Selection ................................. 255
6.4.4 Inverter Simulations .......................................... 256
6.4.5 Efficiency Analysis ........................................ 259
6.5 Chapter Summary ............................................. 262

7 Conclusions and Future Work ..................................... 263
  7.1 Summary and Conclusions .................................. 263
  7.2 Original Contributions .................................... 265
  7.3 Recommendations for Future Work ........................... 267

Appendices ......................................................... 269

A PWM Control Strategies and Low-Pass Filter Design Trade-Offs .... 269
  A.1 PWM Switching Schemes .................................... 269
      A.1.1 Bipolar and Unipolar Pulse-Width Modulation .......... 269
      A.1.2 Selective Harmonic Elimination ........................ 269
      A.1.3 Current Hysteresis ..................................... 270
      A.1.4 Space Vector Modulation ................................ 271
  A.2 Low-Pass Filter Design ..................................... 272
      A.2.1 Power Loss vs. THD Trade-Off - Unipolar PWM Case .... 272

B Relevant Publications ........................................... 273
  B.1 Wind Turbine Control using SMR Paper ....................... 274
  B.2 Novel Low-Cost Grid-Connected Inverter Paper ................ 284

C Microcontroller Code ........................................... 291
  C.1 Switched-Mode Rectifier .................................... 291
  C.2 Grid-Connected Inverter .................................... 294

References ....................................................... 299
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 into 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.

I give consent to this copy of my thesis, when deposited in the University Library, being made available for loan and photocopying, subject to the provisions of the Copyright Act 1968.

I also give permission for the digital version of my thesis to be made available on the web, via the University's digital research repository, the Library catalogue, the Australasian Digital Theses Program (ADTP) and also through web search engines, unless permission has been granted by the University to restrict access for a period of time.

__________________________  __________________________
Signed                        Date
Acknowledgements

First and foremost I wish to thank my supervisor and mentor, Dr Wen L. Soong, for his constant guidance, support, encouragement, help and advice during the course of my postgraduate studies. I also thank my co-supervisor, Associate Professor Nesimi Ertugrul, for his assistance and advice.

I am sincerely grateful to the School of Electrical and Electronic Engineering and the Adelaide Graduate Centre, at The University of Adelaide, for providing financial assistance as part of an Australian Research Council Discovery Grant, DP0342874. I would also like to thank the School of Electrical and Electronic Engineering for providing facilities to allow me to carry out this research. I am extremely grateful for the support from the School’s workshop staff in the construction of the test rigs and machine set-up, in particular the assistance provided by Stuart Brand and Ian Linke. I am also thankful to Stan Woithe and Bruce Lucas from the School of Civil and Environmental Engineering in allowing the use of their wind tunnel. I would also like to thank Dr Damien Leclercq, from the School of Mechanical Engineering, for technical discussions regarding wind turbines.

I thank all the members of the School of Electrical and Electronic Engineering and especially the members of the 'Power and Control Systems’ group, the administration team, and the members of the Computer Support Request team, for their friendliness and help over the years.

Finally, I wish to thank members of my family for their constant support throughout this journey, especially from my fiancè, Allison J.K. Gill. I would also like to thank my brother, Paul J. Whaley for providing financial assistance at various times throughout the course of the project. Lastly, a special thanks to my mother, Anastasia Whaley, for providing much needed financial assistance and patience during the latter stages of this research project.
List of Publications


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. $\hat{\alpha}$ and $\hat{\alpha}_0$ indicate the peak values of $\alpha$ and $\alpha_0$, respectively. Similarly, the check symbol is used in Chapter 6 to represent the nadir (minimum) value, e.g. $\check{\beta}$ represents the minimum value of $\beta$.

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

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\alpha$</td>
<td>normalised rectifier voltage</td>
<td>pu</td>
</tr>
<tr>
<td>$\alpha_0$</td>
<td>ratio of grid to open-circuit rectifier voltage</td>
<td></td>
</tr>
<tr>
<td>$\alpha_{cu}$</td>
<td>temperature coefficient of copper</td>
<td>°C</td>
</tr>
<tr>
<td>$\beta$</td>
<td>normalised rectifier current</td>
<td>pu</td>
</tr>
<tr>
<td>$\beta_\text{app}$</td>
<td>normalised approximated rectifier current</td>
<td>pu</td>
</tr>
<tr>
<td>$\beta_\text{exp}$</td>
<td>normalised experimental rectifier current</td>
<td>pu</td>
</tr>
<tr>
<td>$\beta_\text{id}$</td>
<td>normalised ideal rectifier current</td>
<td>pu</td>
</tr>
<tr>
<td>$\Delta$</td>
<td>difference</td>
<td></td>
</tr>
<tr>
<td>$\delta$</td>
<td>skin depth</td>
<td>m</td>
</tr>
<tr>
<td>$\eta_{\text{gen}}$</td>
<td>generator efficiency</td>
<td>%</td>
</tr>
<tr>
<td>$\eta_{\text{inv}}$</td>
<td>inverter efficiency</td>
<td>%</td>
</tr>
<tr>
<td>$\lambda$</td>
<td>tip-speed ratio</td>
<td></td>
</tr>
<tr>
<td>$\mu$</td>
<td>permability</td>
<td>H/m</td>
</tr>
<tr>
<td>$\omega$</td>
<td>machine angular speed</td>
<td>rad/s</td>
</tr>
<tr>
<td>$\omega$</td>
<td>turbine angular speed</td>
<td>rad/s</td>
</tr>
<tr>
<td>$\omega_{cn}$</td>
<td>normalised cutoff frequency (relative to $f_1$)</td>
<td>pu</td>
</tr>
<tr>
<td>$\omega_e$</td>
<td>electrical angular frequency</td>
<td>rad/s</td>
</tr>
<tr>
<td>Symbol</td>
<td>Description</td>
<td>Unit</td>
</tr>
<tr>
<td>--------</td>
<td>-----------------------------------</td>
<td>---------------</td>
</tr>
<tr>
<td>$\omega_g$</td>
<td>grid angular frequency</td>
<td>rad/s</td>
</tr>
<tr>
<td>$\omega_m$</td>
<td>mechanical angular frequency</td>
<td>rad/s</td>
</tr>
<tr>
<td>$\phi$</td>
<td>filter delay</td>
<td>deg</td>
</tr>
<tr>
<td>$\phi$</td>
<td>power factor angle</td>
<td>deg</td>
</tr>
<tr>
<td>$\Psi_m$</td>
<td>RMS flux linkage</td>
<td>Wb or Vs</td>
</tr>
<tr>
<td>$\rho$</td>
<td>air density</td>
<td>kg/m$^3$</td>
</tr>
<tr>
<td>$\sigma$</td>
<td>conductivity</td>
<td>$(\Omega \cdot m)^{-1}$</td>
</tr>
<tr>
<td>$\tilde{\alpha}_0$</td>
<td>peak value of $\alpha_0$</td>
<td></td>
</tr>
<tr>
<td>$\xi$</td>
<td>saliency ratio</td>
<td></td>
</tr>
<tr>
<td>$C$</td>
<td>capacitance</td>
<td>F</td>
</tr>
<tr>
<td>$c_p$</td>
<td>turbine coefficient of performance</td>
<td></td>
</tr>
<tr>
<td>$d$</td>
<td>duty-cycle</td>
<td>%</td>
</tr>
<tr>
<td>$d_a$</td>
<td>adjusted duty-cycle</td>
<td>%</td>
</tr>
<tr>
<td>$d_i$</td>
<td>stored duty-cycle</td>
<td>%</td>
</tr>
<tr>
<td>$dB$</td>
<td>decibels</td>
<td></td>
</tr>
<tr>
<td>$E$</td>
<td>induced back-EMF voltage</td>
<td>V</td>
</tr>
<tr>
<td>$f$</td>
<td>frequency</td>
<td>Hz</td>
</tr>
<tr>
<td>$f_1$</td>
<td>fundamental frequency</td>
<td>Hz</td>
</tr>
<tr>
<td>$f_{cn}$</td>
<td>normalised cutoff frequency (relative to $f_{sw}$)</td>
<td>pu</td>
</tr>
<tr>
<td>$f_c$</td>
<td>cutoff frequency</td>
<td>Hz</td>
</tr>
<tr>
<td>$f_m$</td>
<td>machine frequency</td>
<td>Hz</td>
</tr>
<tr>
<td>$f_{res}$</td>
<td>resonant frequency</td>
<td>Hz</td>
</tr>
<tr>
<td>$f_{sw}$</td>
<td>switching frequency</td>
<td>Hz</td>
</tr>
</tbody>
</table>
\begin{align*}
H(s) & \quad \text{filter transfer function} \\
h_1 & \quad \text{fundamental harmonic magnitude} \\
h_f & \quad \text{harmonic frequency} \quad \text{Hz} \\
h_m & \quad \text{harmonic magnitude at } m \text{ multiples of } f_1 \quad \% \\
h_{\text{tot}} & \quad \text{total harmonic components} \quad \% \\
I & \quad \text{current} \quad \text{A} \\
I^* & \quad \text{compensation current command} \quad \text{A} \\
ic_{\text{exp}}(t) & \quad \text{compensated current using the experimental I-V locus} \quad \text{pu} \\
ic_{\text{id}}(t) & \quad \text{compensated current using the ideal I-V locus} \quad \text{pu} \\
I_{ch} & \quad \text{characteristic current} \quad \text{A} \\
ic(t) & \quad \text{time-varying compensated current} \quad \text{A} \\
I_{DC} & \quad \text{DC current} \quad \text{A} \\
I_d & \quad \text{damping resistor current} \quad \text{A} \\
I_f & \quad \text{damping resistor current (from inverter)} \quad \text{A} \\
I_g & \quad \text{grid drawn current (from grid)} \quad \text{A} \\
I_{\text{inv}} & \quad \text{inverter output current} \quad \text{A} \\
I_{\text{in}} & \quad \text{input current} \quad \text{A} \\
I_L & \quad \text{line current} \quad \text{A} \\
ic_{\text{out (id)}}(t) & \quad \text{normalised time-varying ideal output current} \quad \text{pu} \\
I_{\text{out}} & \quad \text{output current} \quad \text{A} \\
I_{ph} & \quad \text{phase current} \quad \text{A} \\
ic_{\text{R (id)}}(t) & \quad \text{normalised time-varying ideal rectifier voltage} \quad \text{pu} \\
I_{R_{\text{min}}} & \quad \text{minimum rectifier output current} \quad \text{A}
\end{align*}
\( I_R \)  rectifier output current  \( \text{A} \)
\( i_R(t) \)  normalised time-varying rectifier current  \( \text{pu} \)
\( i_{ws_{(id)}}(t) \)  normalised time-varying ideal wave-shaper current  \( \text{pu} \)
\( I_{ws} \)  wave-shaper current  \( \text{A} \)
\( j \) \( \sqrt{-1} \)
\( k \)  back-EMF constant  \( \text{V/rpm} \)
\( k_{ph} \)  phase back-EMF constant  \( \text{V/rpm} \)
\( L \)  inductance  \( \text{H} \)
\( L_1 \)  transformer primary inductance  \( \text{H} \)
\( L_2 \)  transformer secondary inductance  \( \text{H} \)
\( L_{eq} \)  equivalent inductance  \( \text{H} \)
\( L_{ph} \)  phase inductance  \( \text{H} \)
\( L_s \)  stator inductance  \( \text{H} \)
\( m \)  number of machine phases
\( m \)  positive integer
\( m_a \)  modulation index  \( \% \)
\( n \)  machine / generator speed  \( \text{rpm} \)
\( n \)  positive odd integer
\( n \)  transformer turns ratio
\( n_k \)  machine speed  \( \text{k rpm} \)
\( P \)  power  \( \text{W} \)
\( P \)  real power  \( \text{W} \)
\( p \)  number of machine pole-pairs
\begin{align*}
P_{CU} & \quad \text{copper loss} \quad \text{W} \\
P_d & \quad \text{damping resistor power loss} \quad \text{W} \\
P_{IFW} & \quad \text{machine iron, friction and windage loss} \quad \text{W} \\
P_{\text{inv in}} & \quad \text{total inverter input power} \quad \text{W} \\
P_{\text{inv}} & \quad \text{inverter output power} \quad \text{W} \\
P_{\text{in}} & \quad \text{input power} \quad \text{W} \\
P_{\text{loss}} & \quad \text{SMR / generator power loss} \quad \text{W} \\
P_L & \quad \text{machine power loss} \quad \text{W} \\
P_{\text{SMR}} & \quad \text{SMR output power} \quad \text{W} \\
P_{sw} & \quad \text{switching power loss} \quad \text{W} \\
P_T & \quad \text{wind turbine power} \quad \text{W} \\
P_W & \quad \text{wind power} \quad \text{W} \\
pk - pk & \quad \text{peak to peak} \\
Q & \quad \text{quality factor} \\
Q & \quad \text{reactive power} \quad \text{VAr} \\
Q_C & \quad \text{capacitive reactive power} \quad \text{VAr} \\
Q_L & \quad \text{inductive reactive power} \quad \text{VAr} \\
R & \quad \text{resistance} \quad \text{Ω} \\
r & \quad \text{blade radius} \quad \text{m} \\
R_1 & \quad \text{transformer primary resistance} \quad \text{Ω} \\
R_2 & \quad \text{transformer secondary resistance} \quad \text{Ω} \\
R_{\text{cold}} & \quad \text{cold resistance} \quad \text{Ω} \\
R_d & \quad \text{damping resistance} \quad \text{Ω} \\
\end{align*}
\( R_{eq} \) equivalent resistance \( \Omega \)

\( R_{hot} \) hot resistance \( \Omega \)

\( R_L \) load resistance \( \Omega \)

\( R_{ph} \) phase resistance \( \Omega \)

\( R_s \) stator resistance \( \Omega \)

\( rect(t) \) normalised time-varying rectifier ripple \( \text{pu} \)

\( S \) apparent power \( \text{VA} \)

\( S \) number of stator slots

\( s \) \( \omega \)

\( T \) torque \( \text{Nm} \)

\( t \) time \( \text{s} \)

\( t_{off} \) device *turn-off* time \( \text{s} \)

\( t_{on} \) device *turn-on* time \( \text{s} \)

\( t_q \) thyristor turn-off time \( \text{s} \)

\( V \) voltage \( \text{V} \)

\( v \) wind speed \( \text{m/s} \)

\( V_C \) capacitor voltage \( \text{V} \)

\( V_{DC} \) DC link voltage \( \text{V} \)

\( V_{DC} \) DC voltage \( \text{V} \)

\( v_{eq} \) turbine equivalent wind speed \( \text{m/s} \)

\( V_{g\,pk} \) peak grid voltage \( \text{V} \)

\( V_g \) grid voltage \( \text{V} \)

\( v_g(t) \) normalised time-varying grid voltage \( \text{pu} \)

xxvi
\( v_i \) 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 \( \Omega \)
\( X_{ph} \) phase reactance \( \Omega \)
\( X_s \) stator reactance \( \Omega \)
\( Z_{0n} \) normalised characteristic impedance \( pu \)
\( Z_0 \) characteristic impedance \( \Omega \)
\( Z_s \) stator impedance \( \Omega \)

**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
<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Full Form</th>
</tr>
</thead>
<tbody>
<tr>
<td>DFT</td>
<td>discrete Fourier transform</td>
</tr>
<tr>
<td>ESR</td>
<td>equivalent series resistance</td>
</tr>
<tr>
<td>F&amp;P</td>
<td>Fisher &amp; Paykel®</td>
</tr>
<tr>
<td>FC</td>
<td>filter configuration</td>
</tr>
<tr>
<td>FFT</td>
<td>fast Fourier transform</td>
</tr>
<tr>
<td>GC</td>
<td>grid connected</td>
</tr>
<tr>
<td>GCI</td>
<td>grid-connected inverter</td>
</tr>
<tr>
<td>HF</td>
<td>high-frequency</td>
</tr>
<tr>
<td>IFW</td>
<td>iron, friction and windage</td>
</tr>
<tr>
<td>IPM</td>
<td>interior permanent magnet</td>
</tr>
<tr>
<td>IR</td>
<td>International Rectifier®</td>
</tr>
<tr>
<td>ISA</td>
<td>integrated starter alternator</td>
</tr>
<tr>
<td>LA</td>
<td><em>Lundell</em> alternator</td>
</tr>
<tr>
<td>LF</td>
<td>line-frequency</td>
</tr>
<tr>
<td>MPPT</td>
<td>maximum power point tracker</td>
</tr>
<tr>
<td>NEG</td>
<td>net energy gain</td>
</tr>
<tr>
<td>NICS</td>
<td>non-ideal current source</td>
</tr>
<tr>
<td>OC</td>
<td>open circuit</td>
</tr>
<tr>
<td>PM</td>
<td>permanent magnet</td>
</tr>
<tr>
<td>pu</td>
<td>per-unit</td>
</tr>
<tr>
<td>PV</td>
<td>photovoltaic</td>
</tr>
<tr>
<td>PWM</td>
<td>pulse-width modulation</td>
</tr>
<tr>
<td>RMS</td>
<td>root-mean-squared</td>
</tr>
</tbody>
</table>
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
<table>
<thead>
<tr>
<th>SW</th>
<th>switch</th>
</tr>
</thead>
<tbody>
<tr>
<td>THY</td>
<td>thyristor</td>
</tr>
</tbody>
</table>
## List of Figures

1.1 Breakdown of worldwide electricity production for 2005 .................................. 3  
1.2 Typical 3-bladed wind turbine coefficient of performance ................................. 7  
1.3 Coefficient of performance of various wind turbine rotors ................................ 8  
1.4 Turbine power simulation .................................................................................. 9  
1.5 Turbine power, $c_p$, speed and torque simulation .............................................. 10  
1.6 Furling concept demonstration .......................................................................... 13  
1.7 Comparison of early and modern small-scale turbine topologies used for battery charging .......................................................... 14  
1.8 Current vs. voltage locus of low and high-inductance PM generators ................. 17  
1.9 Comparison of DC power converter equivalent circuits ....................................... 19  
1.10 Rectifier circuit simplified equivalent modelling ............................................... 21  
1.11 Rectifier phasor diagram for various generator speeds ....................................... 22  
1.12 Generator voltage, current and power plot ....................................................... 23  
1.13 SMR phasor diagrams for various generator speeds .......................................... 24  
1.14 SMR current and power plot ........................................................................... 25  
1.15 Simplified machine phase model under inverter operation ............................... 26  
1.16 Inverter phasor diagram for various generator speeds ....................................... 26  
1.17 SMR current and power plot ........................................................................... 27  
1.18 Comparison of power converter output powers ................................................... 28  
1.19 Cost comparison of standalone and grid-connected inverters ............................ 29  
1.20 Line-commutated current-source inverter topology .......................................... 30  
1.21 Current-source inverter with active compensation and passive filters .............. 31  
1.22 Comparison of voltage-source and current-source inverters ............................ 32  
1.23 Comparison of bipolar and unipolar PWM output voltages/currents ............... 33  
1.24 Three-phase voltage-source inverter .............................................................. 37  
1.25 Voltage-source inverter topology with reverse-blocking diode ....................... 38  
1.26 Voltage-source inverter with boost converter .................................................... 38
2.25 PM machine DC voltage loci ........................................... 78
2.26 Maximum DC output power vs. generator speed .................. 79
2.27 DC to RMS line voltage ratio ........................................... 80
2.28 Measured generator and rectifier efficiency vs. DC output power . 81

3.1 SMR equivalent circuit .................................................. 86
3.2 Ideal rectifier and SMR voltage and current vs. duty-cycle ........ 87
3.3 PSIM® model for the switched-mode rectifier ......................... 87
3.4 Voltage, current and power of generator for various load voltages . 89
3.5 SMR operating regions ................................................... 90
3.6 SMR internal components and control circuitry ....................... 91
3.7 SMR test arrangement .................................................. 92
3.8 Rectifier output voltage vs. duty-cycle for various generator speeds .. 93
3.9 Rectifier output current vs. duty-cycle for various machine speeds ... 94
3.10 SMR output current vs. duty-cycle for various generator speeds .... 95
3.11 SMR output power vs. duty-cycle for various machine test speeds .. 96
3.12 Measured torque vs. duty-cycle for various generator speeds ....... 96
3.13 Duty-cycle corresponding to maximum SMR power and generator torque . 97
3.14 Measured SMR efficiency vs. SMR output power for various machine speeds 98
3.15 Total efficiency vs. SMR output power characteristic for various generator speeds .................................................. 99
3.16 Wind tunnel test arrangement .......................................... 100
3.17 Equivalent wind speed calculation at blade sweep area ............... 101
3.18 Estimated coefficient of performance vs. tip-speed ratio curve ....... 102
3.19 Estimated equivalent vs. wind tunnel wind speed curve ............ 103
3.20 Estimated turbine power vs. speed .................................. 104
3.21 Estimated turbine torque vs. speed .................................. 105
3.22 SMR output power vs. duty-cycle .................................... 106
3.23 Turbine speed vs. duty-cycle .......................................... 107
3.24 Measured duty-cycle vs. wind speed comparison for both control modes .. 108
3.25 Turbine and SMR operating characteristics for both control modes .... 109
3.26 Estimated SMR and generator efficiency vs. SMR output power ........ 110

4.1 Simple block diagram of a grid-connected wind turbine, and inverter output current ................................................. 118
4.2 Lagging and leading power factors ..................................... 119
4.3 Overview of proposed grid-connected inverter ........................................... 122
4.4 Circuit diagram and input and output current for the constant current source 123
4.5 Current wave-shaper circuit ................................................................. 124
4.6 Comparison of SMR circuit used for the DC-DC converter, and the modified
SMR circuit used for the inverter ......................................................... 125
4.7 Comparison of constant and time-varying SMR duty-cycle ....................... 125
4.8 Unfolding circuit, and input and output currents .................................... 126
4.9 Inverter low-pass filter circuit, and input and output currents ................. 127
4.10 Preliminary resistive/capacitive load test arrangements .......................... 128
4.11 Grid-connected inverter test arrangement ............................................. 129
4.12 Grid-connected inverter test arrangement equivalent circuit .................. 130
4.13 Measured transformer equivalent inductance and resistance ................. 130
4.14 Photograph of an outer-rotor PM generator .......................................... 131
4.15 I-V locus of PM generator ................................................................. 132
4.16 Photograph of power electronic components of the grid-connected inverter 133
4.17 Microcontroller hardware, and software flow chart ............................... 134
4.18 PSIM® grid-connected inverter model .................................................. 135
4.19 Preliminary PSIM® simulation proving the grid-connected inverter concept 137
4.20 Simulated effect of modulation index variation on inverter operation ....... 137
4.21 Proof of inverter concept using an ideal current source ......................... 139
4.22 Proof of inverter concept using PM generator as current source ............. 140
4.23 Effect of load resistance and generator speed on I-V locus ..................... 142
4.24 Inverter input and output currents for resistive load case 1 .................... 142
4.25 Inverter input and output currents for resistive load case 2 .................... 143
4.26 Inverter input and output currents for resistive load case 3 .................... 144
4.27 Inverter output current and voltage of intermediate grid-connected case .. 145
4.28 Inverter output current and voltage for the pure grid-connected case ...... 146
4.29 Grid-connected inverter output current for various grid voltages ............ 147
4.30 Filter capacitance vs. grid voltage ....................................................... 148
4.31 Resonant frequency and quality factor vs. grid voltage ......................... 149
4.32 Inverter output current THD vs. grid voltage ....................................... 149
4.33 Grid-connected inverter output current for various modulation indices ..... 150
4.34 Grid-connected inverter output current and voltage for various modulation
indices ........................................................................................................... 151
4.35 Inverter output current THD vs. modulation index ................................ 152
<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>5.1 Normalised ideal and non-ideal inverter input and output currents</td>
<td>156</td>
</tr>
<tr>
<td>5.2 Output voltage of various inverter stages</td>
<td>158</td>
</tr>
<tr>
<td>5.3 Normalised ideal and experimental generator I-V loci</td>
<td>158</td>
</tr>
<tr>
<td>5.4 Derivation of normalised ideal inverter input current</td>
<td>159</td>
</tr>
<tr>
<td>5.5 Normalised inverter input and output currents for various values of $\hat{\alpha}$, using the ideal and experimental I-V loci</td>
<td>161</td>
</tr>
<tr>
<td>5.6 Effect of rectifier on normalised inverter input and output current</td>
<td>161</td>
</tr>
<tr>
<td>5.7 Effect of rectifier and fluctuating output power on the normalised ideal inverter input and output currents</td>
<td>162</td>
</tr>
<tr>
<td>5.8 Normalised inverter input and output currents for two cases of $\hat{\alpha}$ equal to 0.2pu</td>
<td>163</td>
</tr>
<tr>
<td>5.9 Effect of the fluctuating input power on the inverter output current and the harmonics for the ideal rectifier I-V locus</td>
<td>165</td>
</tr>
<tr>
<td>5.10 Effect of the fluctuating input power on the inverter output current and the harmonics for the experimental rectifier I-V locus</td>
<td>165</td>
</tr>
<tr>
<td>5.11 THD vs. $\hat{\alpha}$ comparison using the ideal and experiential locus</td>
<td>166</td>
</tr>
<tr>
<td>5.12 Output current distortion and FFT analysis, caused by the rectifier ripple</td>
<td>167</td>
</tr>
<tr>
<td>5.13 Output current distortion and FFT analysis, caused by the rectifier ripple and fluctuating input power</td>
<td>167</td>
</tr>
<tr>
<td>5.14 Output current THD vs. modulation index for various values of $\hat{\alpha}$, using the ideal and experimental I-V loci</td>
<td>168</td>
</tr>
<tr>
<td>5.15 THD vs. $\hat{\alpha}$ comparison using the ideal and experiential locus</td>
<td>169</td>
</tr>
<tr>
<td>5.16 Turbine speed and the resulting $\hat{\alpha}_0$ vs. wind speed</td>
<td>170</td>
</tr>
<tr>
<td>5.17 Modulation index and the resulting $\hat{\alpha}$ vs. wind speed</td>
<td>170</td>
</tr>
<tr>
<td>5.18 Open-loop output current THD vs. wind pseed</td>
<td>171</td>
</tr>
<tr>
<td>5.19 Bipolar and Unipolar PWM waveforms</td>
<td>172</td>
</tr>
<tr>
<td>5.20 Harmonic spectra of the bipolar and unipolar PWM waveforms</td>
<td>172</td>
</tr>
<tr>
<td>5.21 Distortion, fundamental magnitude and THD vs. modulation index for unipolar PWM waveform</td>
<td>173</td>
</tr>
<tr>
<td>5.22 Effect of the rectifier and fluctuating input power on the inverter input and output currents</td>
<td>175</td>
</tr>
<tr>
<td>5.23 Harmonic spectrum of the inverter output current waveform</td>
<td>175</td>
</tr>
<tr>
<td>5.24 THD vs. modulation index for various values of $\hat{\alpha}_0$</td>
<td>176</td>
</tr>
<tr>
<td>5.25 CL type low-pass filter</td>
<td>177</td>
</tr>
<tr>
<td>5.26 Normalised low-pass filter frequency response</td>
<td>178</td>
</tr>
<tr>
<td>Section</td>
<td>Description</td>
</tr>
<tr>
<td>---------</td>
<td>-----------------------------------------------------------------------------</td>
</tr>
<tr>
<td>5.51</td>
<td>Comparison of modulation index, and input and output currents for the</td>
</tr>
<tr>
<td></td>
<td>uncompensated and feed-forward compensation schemes</td>
</tr>
<tr>
<td>5.52</td>
<td>Compensated output current THD vs. rectifier ripple phase angle error</td>
</tr>
<tr>
<td>5.53</td>
<td>Summary of proposed feed-forward controller</td>
</tr>
<tr>
<td>5.54</td>
<td>Comparison of modulation index, and input and output currents for the</td>
</tr>
<tr>
<td></td>
<td>uncompensated and feed-forward compensation schemes</td>
</tr>
<tr>
<td>5.55</td>
<td>Inverter output current THD and fundamental magnitude vs. $\hat{\alpha}_0$</td>
</tr>
<tr>
<td></td>
<td>using the open-loop and both feed-forward control algorithms</td>
</tr>
<tr>
<td>5.56</td>
<td>Comparison of inverter output current and power vs. wind speed, using</td>
</tr>
<tr>
<td></td>
<td>both open-loop and feed-forward control algorithms</td>
</tr>
<tr>
<td>6.1</td>
<td>Turbine $c_p$ curve used to calculate turbine operating speed</td>
</tr>
<tr>
<td>6.2</td>
<td>Inverter input and peak compensated output current</td>
</tr>
<tr>
<td>6.3</td>
<td>Designed machine I-V locus</td>
</tr>
<tr>
<td>6.4</td>
<td>Quality factor, THD, power loss and cutoff frequency tradeoff curves, used</td>
</tr>
<tr>
<td></td>
<td>to design the 1kW grid-connected inverter</td>
</tr>
<tr>
<td>6.5</td>
<td>Simulated inverter output currents and voltage using an ideal current source</td>
</tr>
<tr>
<td></td>
<td>and open-loop control</td>
</tr>
<tr>
<td>6.6</td>
<td>THD prediction using the PM generator current source</td>
</tr>
<tr>
<td>6.7</td>
<td>Simulated inverter currents using the PM generator current source and</td>
</tr>
<tr>
<td></td>
<td>open-loop control</td>
</tr>
<tr>
<td>6.8</td>
<td>Relevant part of PSIM® circuit showing feed-forward control implementation</td>
</tr>
<tr>
<td>6.9</td>
<td>Feed-forward control proof of concept</td>
</tr>
<tr>
<td>6.10</td>
<td>Comparison of feed-forward (compensated) and open-loop inverter output</td>
</tr>
<tr>
<td></td>
<td>currents, for 4 kHz switching case</td>
</tr>
<tr>
<td>6.11</td>
<td>Comparison of compensated and open-loop inverter output currents, for</td>
</tr>
<tr>
<td></td>
<td>10 kHz switching case</td>
</tr>
<tr>
<td>6.12</td>
<td>Apparent power vs. current command, for power less than rated</td>
</tr>
<tr>
<td>6.13</td>
<td>Inverter power factor vs. apparent power, for power less than rated</td>
</tr>
<tr>
<td>6.14</td>
<td>Inverter output current THD vs. apparent power, for power less than rated</td>
</tr>
<tr>
<td>6.15</td>
<td>Inverter input and output currents, for desired power greater than rated</td>
</tr>
<tr>
<td>6.16</td>
<td>Inverter control signals and output current, for power greater than rated</td>
</tr>
<tr>
<td>6.17</td>
<td>Apparent power vs. current command for wide power range</td>
</tr>
<tr>
<td>6.18</td>
<td>Inverter power factor vs. entire apparent power range</td>
</tr>
<tr>
<td>6.19</td>
<td>Output current THD vs. entire range of apparent power</td>
</tr>
</tbody>
</table>
6.20 Wind, turbine, generator and inverter output power vs. wind speed characteristic ........................................... 252
6.21 Turbine and generator operating characteristics vs. wind speed ................................................................. 253
6.22 Generator $\hat{\alpha}$ and $\hat{\beta}$ vs. wind speed ................................................................................................ 254
6.23 Current command vs. wind speed for both control modes ........................................................................... 255
6.24 Inverter simulation using control mode 1, for various wind speeds .............................................................. 257
6.25 Inverter simulation using control mode 2, for wind speeds beyond rated ...................................................... 258
6.26 Comparison of inverter apparent power and compensated current THD vs. wind speed characteristic, using both control modes ........................................... 259
6.27 Inverter power loss break-down .................................................................................................................. 260
6.28 Inverter efficiency breakdown vs. output power .......................................................................................... 261

A.1 Principle of sinusoidal pulse-width modulation .......................................................................................... 270
A.2 Harmonic elimination PWM control signal .............................................................................................. 270
A.3 Principle of current hysteresis control scheme ......................................................................................... 271
A.4 Filter output current THD vs. power loss vs. cut-off frequency ................................................................. 272
## List of Tables

1.1 Net energy gain comparison of various renewable and non-renewable energy sources ................................................................. 4
1.2 Comparison of small and large scale wind turbine properties ........ 5
1.3 Generator and power converter summary, used for automotive and wind power generation ............................................................... 18
1.4 Comparison of small-scale wind turbine generator DC power converters 20
1.5 Comparison of transformer and transformerless inverter properties .... 36
1.6 Comparison of inverter properties for various transformer topologies ... 36
2.1 Physical, measured and calculated PM generator properties .......... 66
3.1 SMR component properties .......................................................... 91
4.1 Current harmonic limits of Australian Standard 4777.2 .................. 119
4.2 Measured PM generator properties ............................................. 132
4.3 Semiconductor properties ........................................................... 136
4.4 Simulated and measured resistive load inverter performance .......... 141
4.5 Simulated and measured inverter performance for cases 1–3 .......... 144
5.1 Unipolar PWM waveform harmonic analysis, for various modulation indices 174
5.2 Low-pass filter property comparison, for four damping resistor locations 187
5.3 Low-pass filter variable vs. parameter ......................................... 188
5.4 Summary of apparent, real and reactive power, under grid power factor requirement extreme cases .............................................. 194
5.5 Comparison of damping resistor current, for various filter configurations 200
5.6 Effect of varying $C_n$ on filter design region ............................... 206
5.7 Effect of varying $f_{sw}$ on filter design region ............................... 207
6.1 Summary of calculated turbine properties for the proposed 1kW GCI .... 228
6.2 Designed generator properties ........................................ 232
6.3 Filter base quantities ................................................. 235
6.4 Filter component values for the proposed 1kW system .......... 236
6.5 Simulated inverter performance using an ideal current source . 237
6.6 Simulated inverter performance using an the PM generator current source . 240
6.7 Current compensated inverter performance using the PM generator and
    rectifier current source ........................................ 243
6.8 Comparison of open-loop and compensated inverter performance .... 245
6.9 Optimised inverter semiconductor properties ...................... 256
6.10 MOSFET vs. IGBT turn on and off times, and maximum* calculated losses 256