APPLICATION OF ADVANCED POWER ELECTRONICS IN RENEWABLE ENERGY SOURCES AND HYBRID GENERATING SYSTEMS

DISSERTATION

Presented in Partial Fulfillment of the Requirements for the Degree Doctor of Philosophy in the Graduate School of The Ohio State University

By

Gholamreza Esmaili, M.S.E.E

* * * * *

The Ohio State University

2006

Dissertation Committee:

Professor Longya Xu, Adviser
Professor Donald G. Kasten
Professor Stephen A. Sebo

Approved by

Adviser
Graduate Program in Electrical and Computer Engineering
ABSTRACT

In general, this dissertation discusses application of advanced power electronics in small size wind energy and hybrid generating systems.

A new and simple control method for maximum power tracking by employing a step-up dc-dc boost converter in a variable speed wind turbine system, using permanent magnet machine as its generator, is introduced. Output voltage of the generator is connected to a fixed dc-link voltage through a three-phase diode rectifier and the dc-dc boost converter. A maximum power-tracking algorithm calculates the reference speed, corresponds to maximum output power of the turbine, as the control signal for the dc-dc converter. The dc-dc converter uses this speed command to control the output power of the generator, by controlling the output voltage of the diode rectifier and input current of the boost converter, such that the speed of generator tracks the command speed. A current regulated pulse width modulation voltage source inverter maintains the output voltage of the dc-dc converter at a fixed value by balancing the dc-link input and output power.

Moreover, a new and simple speed estimator for maximum power tracking and a novel vector control approach to control the output voltage and current of a single-phase voltage source inverter are introduced. Using the proposed speed estimator, the system only needs two measurements to estimate the generator speed and implement the
maximum power-tracking algorithm. Furthermore, since the system maintenance is very important and in wind energy systems the generator is not easily assessable, a robust technique for on-line condition monitoring of stator windings is introduced. In this technique the generator terminal voltage and current are utilized as input signals; therefore, this method could help to monitor the stator winding condition very efficiently to prevent catastrophic failure. The generating system has potentials of high efficiency, good flexibility, and low cost.

This dissertation also proposes a hybrid energy system consisting of a wind turbine, a photovoltaic source, and a fuel cell unit designed to supply continuous power to the load. A simple and economic control with dc-dc converter is used for maximum power extraction from the wind turbine and photovoltaic array. Due to the intermittent nature of both the wind and photovoltaic energy sources, a fuel cell unit is added to the system for the purpose of ensuring continuous power flow. The fuel cell is thus controlled to provide the deficit power when the combined wind and photovoltaic sources cannot meet the net power demand. The proposed system is attractive owing to its simplicity, ease of control and low cost. Also it can be easily adjusted to accommodate different number of energy sources. A complete description of this system is presented along with its simulation results which ascertain its feasibility.

The last part of the dissertation focuses on the design of a novel Power Conversion System (PCS), which can be used to convert the energy from the hybrid
system into useful electricity and provide requirements for power grid interconnections. The motivation behind developing such a PCS is to reduce the overall cost of hybrid systems and thus result in increased penetration into today’s energy scenario.
Dedicated to my dear wife Armina and my family
ACKNOWLEDGMENTS

I would like to express my appreciation to all those who gave me the possibility to complete this dissertation. I wish to express my best gratitude and thanks to my adviser, Professor Longya Xu, for his technical guidance, his intellectual support and encouragement of my research work. I am extremely grateful for having the privilege to work with him and learn from his expertise in the past five years.

I would like to thank Professor Donald Kasten and Professor Stephen Sebo for being on my PhD dissertation and candidacy examination committees. Thanks to Professor Vadim Utkin to be in my candidacy examination committee and teach me several courses in control during past five years.

My special thanks to Mr. Anthony Clarke, my best friend at American Electric Power (AEP), where I have been interning since March 2001. I would like to thank Mr. David Nichols, Mr. Kevin Loving, and Mr. Thomas Jones as my managers during past five years for giving me the opportunity to work for one of the largest utility company in the United States.

Many thanks to all my colleagues at AEP, Venu Nair, Debosmita Das, Galen Perry, Dr. Osman Demirci, Dr. Ali Nourai, Dr. John Schneider, Mr. Ray Hays, Linda
Hanlon, Bob Blake, Jan Lenko, Paul Toomey, Ted Sheets, John Mandeville, Dave Klapp, and others for their warm company. Thanks for making me feel at home all the while!

I thank all my colleagues of the Power Group at The Ohio State University and especially to Ms. Carol Liu, Mr. Ozkan Altay, Mr. Song Chi, Dr. Jingbo Liu, Mr. Jiangang Hu, and Dr. Jingchuan Li. We had many fruitful discussions during the past several years and I will always remember the time I shared with you.

Finally, I want to extend my deepest thanks and appreciation to my dear wife Armina and my family for their never-ending support and kindness.
VITA

July 23, 1971................................................................. Born – ABADAN, IRAN

September 1993.......................................................... B.S. Electrical Engineering,
Isfahan University of Technology, Isfahan, IRAN

September 1996.......................................................... M.S. Electrical Engineering,
Isfahan University of Technology, Isfahan, IRAN

December 1996 – September 2000................................. Academic Board Member,
Isfahan University, Isfahan, IRAN

September 2000 – December 2000................................. Graduate Research Assistant

September 2001 – December 2002................................. Graduate Research Assistant

September 2005 – December 2005................................. Graduate Teaching Assistant

Department of Electrical & Computer Engineering,
The Ohio State University, Columbus, Ohio, USA

March 2001 – Present...................................................... Electrical Engineer

American Electric Power, Columbus, Ohio, USA
PUBLICATIONS


FIELDS OF STUDY

Major Field: Electrical Engineering

Major Area of Specialization: Power Electronics, Electrical Machinery and Control
# TABLE OF CONTENTS

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>ABSTRACT</td>
<td>ii</td>
</tr>
<tr>
<td>ACKNOWLEDGEMENTS</td>
<td>vi</td>
</tr>
<tr>
<td>VITA</td>
<td>viii</td>
</tr>
<tr>
<td>LIST OF TABLES</td>
<td>xvi</td>
</tr>
<tr>
<td>LIST OF FIGURES</td>
<td>xvii</td>
</tr>
<tr>
<td>ABBREVIATIONS</td>
<td>xxii</td>
</tr>
<tr>
<td>1. INTRODUCTION</td>
<td></td>
</tr>
<tr>
<td>1.1 Literature Review</td>
<td>1</td>
</tr>
<tr>
<td>1.2 Wind Energy</td>
<td>2</td>
</tr>
<tr>
<td>1.3 Solar Energy Background</td>
<td>4</td>
</tr>
<tr>
<td>1.4 Distributed Generation</td>
<td>6</td>
</tr>
<tr>
<td>1.5 Dissertation Outline</td>
<td>7</td>
</tr>
<tr>
<td>2. APPLICATION OF PERMANENT MAGNET GENERATOR IN VARIABLE</td>
<td></td>
</tr>
<tr>
<td>SPEED WIND TURBINE SYSTEM</td>
<td>10</td>
</tr>
<tr>
<td>2.1 Introduction</td>
<td>10</td>
</tr>
<tr>
<td>2.2 Wind Turbine Basics</td>
<td>10</td>
</tr>
<tr>
<td>2.2.1 Wind Turbine Aerodynamic Characteristic</td>
<td>13</td>
</tr>
</tbody>
</table>
2.2.2 Maximum Power Tracking Algorithm .................................................. 16
2.3 Turbine Generator .......................................................................................... 19
  2.3.1 DC Generator .................................................................................. 20
  2.3.2 Induction Generator .......................................................................... 20
  2.3.3 Permanent Magnet Generator ......................................................... 21
2.4 Power Electronics .......................................................................................... 24
  2.4.1 Supply Side Inverter .......................................................................... 25
    2.4.1.1 Active and Reactive Power in Rotating Reference Frame .......... 25
    2.4.1.2 Inverter Control Strategy ............................................................ 27
  2.4.2 Generator Side Converter .................................................................... 31
    2.4.2.1 Three-Phase Boost Rectifier (dual PWM-VSI) .......................... 31
    2.4.2.2 Diode Bridge and Step up DC-DC Converter ............................... 34
      2.4.2.2.1 Three-Phase Diode Rectifier ............................................... 34
      2.4.2.2.2 DC-DC converter and control algorithm ............................... 35
2.5 Simulation Results .......................................................................................... 37
  2.5.1 Simulation results for three-phase boost converter ............................... 38
  2.5.2 Simulation results for step-up DC-DC boost converter ......................... 40
    2.5.2.1 Speed Control of permanent Magnet Generator ......................... 40
    2.5.2.2 Maximum Power Tracking ............................................................ 44
2.6 Summary ........................................................................................................ 46

3. SENSORLESS CONTROL AND STATOR WINDING CONDITION
   MONITORING OF PERMANENT MAGNET GENERATOR IN WIND
   TURBINE SYSTEM ............................................................................................ 48
3.1 Introduction .................................................................................................... 48
3.2 Power Electronic Circuit and Electric Machines ......................................... 49
4.3.2.1 Thermodynamic Potential/Cell Reversible Voltage .......... 89
4.3.2.2 Activation voltage Drop ......................................................... 90
4.3.2.3 Ohmic Voltage Drop .............................................................. 90
4.3.2.4 Concentration Voltage Drop [54] .......................................... 92
4.3.3 Fuel Cell Power and Efficiency ......................................................... 93
4.3.4 Fuel Cell Modeling and Characteristics ................................................. 93
   4.3.4.1 Characteristics ........................................................................ 94
4.4 Hybrid System Description ................................................................. 97
   4.4.1 Power Electronics and Control ............................................................. 97
      4.4.1.1 Power Circuit Topology ......................................................... 98
      4.4.1.2 DC-DC Boost Converters and their Control ......................... 99
4.5 Simulation Results .................................................................................. 101
4.6 Summary ................................................................................................. 104

5. A NEW POWER CONVERSION SYSTEM FOR DISTRIBUTED ENERGY RESOURCES ........................................................................................................ 106
   5.1 Introduction ............................................................................................. 106
   5.2 DER Requirements and Applications ......................................................... 107
   5.3 PCS Characteristics and Features [61, 62]. .............................................. 110
   5.4 System Description .................................................................................. 111
   5.5 Three-Level Inverters ............................................................................. 113
      5.5.1 Circuit Topology and Switching Scheme ........................................ 113
      5.5.2 Comparison of Two-Level and Three-Level Inverters ............... 116
   5.6 Power Loss Calculations ........................................................................ 117
      5.6.1 Conduction Loss Calculations ..................................................... 117
      5.6.2 Switching Loss Calculations [60] ............................................... 119
LIST OF TABLES

Table 2.1: Permanent magnet generator parameters........................................................ 38
Table 3.1: Machine notation and parameter. ................................................................... 53
Table 3.2: Parameters of PMG used in the test setup. ..................................................... 69
Table 4.1: Shell SQ160PC photovoltaic (PV) module. ................................................... 81
Table 4.2: Parameters of 500W BCS stack [9]................................................................. 94
Table 4.3: Permanent magnet generator specifications. ................................................. 101
Table 4.4: Photovoltaic array specifications................................................................. 101
Table 4.5: Fuel cell specifications. ............................................................................... 102
Table 5.1: Switching states and phase-voltage of the inverter....................................... 113
Table 5.2: Simulation results for three-level inverter losses......................................... 121
Table 5.3: Simulation vs. experimental results............................................................... 122
LIST OF FIGURES

Figure 2.1: Variable speed concept................................................................. 11
Figure 2.2: Increased energy capture using variable speed turbine............... 11
Figure 2.3: A typical small size variable speed wind turbine using PMG...... 12
Figure 2.4: Power coefficient versus tip-speed ratio.................................... 14
Figure 2.5: Output power versus rotor speed for three different wind speeds. 14
Figure 2.6: Adjustment of turbine operating point for maximum power tracking. 17
Figure 2.7: Flowchart of perturbation and observation method for maximum power point tracking. ................................................................. 19
Figure 2.8: Power electronics interface for a wind turbine energy system..... 25
Figure 2.9: Definition of rotating reference frame........................................ 26
Figure 2.10: Supply-side converter arrangement........................................... 28
Figure 2.11: Control strategy schematic for supply side inverter.................... 30
Figure 2.12: Topology of wind power generation system using Three-Phase Boost Rectifier................................................................. 31
Figure 2.13: Vector control block diagram of the permanent magnet generator..... 33
Figure 2.14: Topology of wind power generation system with diode-rectifier and dc-dc boost converter................................................................. 35
Figure 2.15: Power circuit and control topology of the dc-dc boost converter. 36
Figure 2.16: (a) Shaft speed of the generator (b) DC-link voltage ........................................ 39
Figure 2.17: (a) Generator phase voltage and phase current (b) Grid phase voltage and 
phase current of supply side inverter .......................................................... 40
Figure 2.18: Turbine speed tracking ................................................................................. 42
Figure 2.19: Grid phase voltage and phase current of PWM inverter ......................... 43
Figure 2.20: Generator phase voltage and phase current ................................................ 43
Figure 2.21: Turbine characteristics used for simulation ................................................... 44
Figure 2.22: Output power and rotor speed of the generator ........................................... 45
Figure 2.23: Tracking the maximum power by wind turbine .......................................... 46
Figure 3.1: Three-phase voltage source connected to line commutated diode rectifier. 49
Figure 3.2: Equivalent circuit during commutation interval in the presence of inductance. 
.......................................................................................................................... 50
Figure 3.3: Commutation effect on the output voltage of the three-phase diode-rectifier 
under operation with L ................................................................................ 52
Figure 3.4: Direct-drive permanent magnet generator connected to the diode-rectifier. 54
Figure 3.5: Equivalent circuit of permanent magnet generator connected to diode 
rectifier ........................................................................................................... 54
Figure 3.6: Single-phase inverter and its imaginary circuit ............................................. 56
Figure 3.7: Definition of rotating reference frame ......................................................... 57
Figure 3.8: Voltage and current vectors in d-q frame ...................................................... 57
Figure 3.9: Vector control structure with unipolar switching scheme for single-phase 
inverter ............................................................................................................. 60
Figure 3.10: Power circuit topology and control structure for the wind energy conversion system. ................................................................. 62

Figure 3.11: a) Real and estimated speed b) Rectifier output voltage and generator output voltages c) Generator phase currents. .................................................. 64

Figure 3.12: Enlargement of rectifier output voltage and generator voltages and currents. ...................................................................................................................... 65

Figure 3.13: Independent active and reactive power control using iq and id current components. ................................................................................................................................. 66

Figure 3.14: Power factor control by d-axis current while q-axis current is fixed. .... 67

Figure 3.15: Maximum power tracking ................................................................................................................................. 68

Figure 3.16: Experimental test setup ................................................................................................................................. 69

Figure 3.17: Actual and estimated speed of the PMG. ............................................................. 70

Figure 3.18: Percentage of speed error using the speed estimator................................. 70

Figure 3.19: Functional block diagram of the on-line condition monitoring system. ..... 74

Figure 3.20: The fault indicator (index)........................................................................... 76

Figure 3.21: Turbine mechanical speed in r/min ............................................................. 76

Figure 4.1: A typical hybrid energy system........................................................................ 79

Figure 4.2: Solar Cell - Equivalent Circuit Diagram...................................................... 81

Figure 4.3: Simulated current-voltage characteristic of Shell SQ160PC PV module. .... 82

Figure 4.4: Simulated power-voltage characteristic of Shell SQ160PC PV module...... 83

Figure 4.5: Variation of I-V characteristic with isolation level........................................ 84
Figure 4.6: Variation of P-V characteristic with isolation level ........................................ 84
Figure 4.7: Variation of I-V characteristic with temperature. ........................................ 85
Figure 4.8: Variation of P-V characteristic with temperature ......................................... 86
Figure 4.9: Schematic of a fuel cell [53]. ...................................................................... 87
Figure 4.10: Stack Performance Data of 500 W BCS Stack [57] .................................... 94
Figure 4.11: Simulated Voltage-Current Characteristics of 500 W BCS Stack .............. 95
Figure 4.12: Simulated Power-Current Characteristics of 500 W BCS Stack ................ 96
Figure 4.13: Configuration of hybrid energy system ..................................................... 98
Figure 4.14: Boost converter circuit topology ............................................................... 99
Figure 4.15: Control algorithm of boost converter for wind and photovoltaic sources ... 99
Figure 4.16: Boost converter control topology for fuel cell ........................................... 100
Figure 4.17: Generated power by wind turbine, photovoltaic, and fuel cell .................. 103
Figure 4.18: Control of wind turbine, photovoltaic, and fuel cell ................................. 104
Figure 5.1: A grid-connected DER system .................................................................... 107
Figure 5.2: Peak shaving concept using PCS ................................................................. 108
Figure 5.3: Uninterruptible power supply as a backup power source .............................. 108
Figure 5.4: Application of PCS in power conditioning .................................................... 109
Figure 5.5: Use of PCS as a variable voltage source ....................................................... 109
Figure 5.6: Power conversion system block diagram ..................................................... 111
Figure 5.7: Circuit topology of the three-level inverter ................................................... 113
Figure 5.8: Operation of three-level inverter using Sine-Δ -PWM technique [58] ........ 115
Figure 5.9: Bidirectional power flow for charging and discharging the dc source........ 115
Figure 5.10: a) Schematic of one leg of the inverter b) Phase voltage & current........ 118
Figure 5.11: On-state model for transistors and diodes.......................................... 118
Figure 5.12: IGBT-heatsink assembly for thee-level inverter..................................... 123
Figure 5.13: Standard 300 kVA transformer tank.................................................... 124
Figure 5.14: Thermocouple locations for the test set-up........................................... 124
Figure 5.15: Temperature profile of the test set-up................................................... 125
Figure 5.16: Thermal image of the test set-up.......................................................... 126
Figure 5.17: Simple equivalent circuit of grid connected VSI..................................... 127
Figure 5.18: Phasor diagram of system for (a) lagging operation, (b) leading operation.
.............................................................................................................................. 127
Figure 5.19: Locus of active and reactive power of a voltage source inverter............. 129
Figure 5.20: Lagging P.F. Operation........................................................................... 131
Figure 5.21: Leading P.F. Operation.......................................................................... 131
Figure A.1: Basic 2-pole permanent magnet machine model..................................... 138
ABBREVIATIONS

AC : Alternative Current
A/D : Analog to Digital
CHP : Combined Heat and Power
D/A : Digital to Analog
DSP : Digital signal Processor
DER : Distributed Energy Resources
DG : Distributed Generation
EMF : Electromotive Force
LPF : Low Pass Filter
PCS : Power Conversion System
PI : Proportional Integrator
PMG : Permanent Magnet Generator
PWM : Pulse Width Modulation
VSI : Voltage Source Inverter
WES : Wind Energy System
CHAPTER 1

INTRODUCTION

1.1 Literature Review

Since natural energy sources, such as oil, coal, natural gas, and nuclear are finite and generate pollution, use of renewable energy sources, for instance, solar, wave, biomass, wind, minihydro, and tidal power, as a major form of clean technology could be the right solution to solve energy crisis in the recent century. The main advantage of renewable energy over fossil fuels and nuclear power is the absence of harmful emissions, including carbon, sulphur, nitrogen oxides, and radioactive products. In this way renewable energy sources do not have the high external cost and social issues of the alternates. Moreover, supply and consumption of energy based on conventional fossil fuel is considered as a significant factor of global warming and environmental deterioration. The utilization of natural energy is recognized as a new energy source which will eventually replace conventional energy sources [2, 12, 20, 23].

The ever increasing demand for conventional energy sources has driven society towards the need for research and development of alternative energy sources. Many such energy sources, such as wind energy and photovoltaic are now well developed, cost
effective and are being widely used, while others, such as fuel cells are in their advanced developmental stage. As mentioned, these energy sources are preferred for being environmental friendly. The integration of these energy sources to form a hybrid system is an excellent option for distributed energy production.

However, there are some major concerns which obstruct the free and full-fledge development of alternate energy sources. One of the major issues is cost, but it has been observed that the cost of renewable energy shows a down hill trend with the increase in its demand and production. Also rapid advances in the field of power electronics has enabled the cost reduction of renewable energy systems and have also ensured better reliability of such systems. Among the renewable energy sources, photovoltaic cell and wind turbine systems make use of advanced power electronics technologies. The problem of energy storage is also of major concern for renewable energy. Since most of these energy sources are discontinuous in nature, efficient storage devices need to be designed to store such forms of energy. The focus in this dissertation will be on small size variable speed wind energy, photovoltaic, and fuel cell as a hybrid system.

1.2 Wind Energy

The generation of electricity from modern wind turbines is now an established technology, although many developments are yet to come. Worldwide there are more than 20,000 turbines; with the most cost effective for grid integration starting at approximately 400kW capacity and 40m in rotor diameter [1]. A typical capacity factor on a good site (wind speed average > 6m/s) is 25 to 30%. Such turbine can be expected to supply 20 to 40% of its rated annual energy into a local grid, annually [2].
Maximized electricity generation by wind turbines is an interesting topic in electrical engineering and many types of variable speed generating systems have been researched to achieve this goal. Use of a variable speed generating system in wind power applications can increase the captured wind energy by 10-15% annually. This can yield a significant revenue increase over a 20 or 30 years life of operation [27, 41].

Small size variable speed wind turbine systems have been used in grid connected application as well as remote applications, such as water pumping, water heating, and battery charging. Power ratings of these kinds of turbines are less than 100 kW, typically [14]. In ac type generator, a small turbine rotor produces a varying ac voltage. By using modern power electronics and controllers, conversion to an ac voltage with constant magnitude and frequency is performed. In this mode they can be directly connected to the electrical grid to supply residential loads or to return excess power to the grid. Alternatively, they can be directly connected to the electrical grid at the end of remote distribution lines to decrease the need of upgrading old or undersize distribution systems. An example of a small-scale ac-dc-ac wind turbine is the Bergey Excel [29].

In fact, among ac type generation systems, those based on permanent magnet generator is one of the most favorable and reliable methods of power generation for small size wind turbines as well as large units, up to 2.5 MW. However, electricity generated directly by the permanent magnet generator has variable amplitude and frequency, requiring additional conditioning to meet the amplitude and frequency requirements of the utility grid and/or conventional loads. Many types of power electronic converters were introduced to find appropriate and inexpensive solutions to the problem of
electricity conditioning; the results have been promising [3, 4, 7]. The use of the variable speed permanent magnet machine in wind turbine applications can increase the energy capture from wind, resolve other problems such as noise, and improve efficiency. For example, if a gearbox is used in a wind turbine system, noise, power losses, additional cost, and the potential of mechanical failure can be source of problems. Use of a variable speed direct drive permanent magnet generator can solve these problems [10].

In a variable speed wind turbine system, a vector control approach is often employed to achieve nearly decoupled active and reactive power control on the supply side power converter, which is a current regulated voltage source inverter. In this way, the power converter maintains the de-link voltage and improves power factor of the system [6, 7, 11]. Different control methods for maximum power tracking in variable speed wind turbine generators have been discussed in [7-9].

1.3 Solar Energy Background

The earliest use of solar energy was noted in the 7th century BC, when a magnifying glass was used to concentrate the solar rays to light fire. Since then, solar energy has found numerous applications. The most significant discovery in the field of photovoltaics was made by the French scientist Edmund Becquerel in 1839. While experimenting with an electrolytic cell made of two different metal electrodes placed in an electrical conducting solution, he observed that electricity generation increased with exposure to light [49]. Following this discovery, scientists from Europe and the USA concentrated their efforts on researching solar energy.
Later in 1954, the first commercial silicon photovoltaic (PV) cells were invented at Bell Labs, USA. These solar cells were capable of generating enough solar power to run everyday use electrical equipment. Bell labs then went on to produce 6% efficient and then later 11% efficient PV cells. Much of the research in the 1950s and the 1960s were concentrated in finding more efficient solar cells. Researchers in the field experimented with different materials like silicon wafers, cadmium sulphide, selenium, etc, to achieve higher efficiency. During this time photovoltaic cells were being developed for earth orbiting satellites. In 1964 NASA launched the first Nimbus spacecraft – a satellite powered by a 470 W photovoltaic array [49].

Later in the 1980s solar power became a popular energy source for consumer electronics devices such as calculators, watches, radios and battery charges. During this same period photovoltaics started to find applications in residential and small commercial complexes. Rooftop applications were a common trend during this time. Currently, solar power is the most popular form of renewable energy source for residential use.

Worldwide, photovoltaics account for 500 MW of power generation with an annual growth rate greater than 20% . In the near future photovoltaic power is expected to become more cost effective and will be almost price competitive with traditional sources of energy. With development and breakthrough in new cell materials and power electronics technologies solar power can prove to be an efficient, environmental friendly and safe means of power.
1.4 Distributed Generation

Distribution generation systems include any small-scale power generation technology (typically less than 30 MW) that provides electric power at a site closer to customers than central station generation. Typical applications of DG systems are standby power, combined heat and power (CHP), peak shaving, grid support, and stand alone operation. Standby power is usually used for customers that cannot tolerate an interruption of electrical service for either public health and safety reasons, or where power outage costs are unacceptably high. Typical customers are hospitals, water pumping stations, and electronics dependent manufacturing factories. Those types of customers, such as large office buildings and hospitals, which can utilize both power and thermal energy from power generation process, make use of CHP. Peak shaving is a good solution for customers whose need to reduce their energy demand during high cost peak periods. Typical customers are industries that have a high cyclic power demand such as foundries. Grid support will be used to provide additional power system support (voltage and vars) as well as capacity during peak power usage. Moreover, it can be used to delay expensive upgrades or replacement of substation equipment/transmission lines. For customers that are isolated from the power grid by choice or by circumstances as in remote applications, stand alone operation is the right choice. Users that require tight control on the quality of electric power delivered, such as computer chip manufacturers, or customers that are located beyond the local power distribution are the typical customers of stand alone DG systems.
The common technologies used for DG systems are diesel engines, natural gas engines, small combustion turbines, microturbines, fuel cells, wind turbines, and photovoltaics. Chapter 4 introduces a new circuit topology for a hybrid system that includes wind turbine, photovoltaic, and fuel cell for DG application.

1.5 Dissertation Outline

In chapter 2 a new control approach, which is the main contribution of this chapter, and the related power converter topology to track the maximum power without measuring wind speed, which is of great importance for small size and low cost wind turbines, is introduced. Besides, aerodynamic characteristics of the wind turbine and principles of maximum power tracking method are explained. Moreover, different types of generators, which are used in variable and fixed wind turbine generating systems, are reviewed. Two different system configurations and their related power converters and control methods are discussed and compared in section 2.4. In section 2.5, simulation results are presented to confirm that the control method, for speed control and extracting maximum power from wind, works properly. Section 2.6 summarizes the advantages of the overall system and gives some final remarks about future works.

Chapter 3 discusses a new and simple speed estimator, to be used by a permanent magnet generator, for maximum power tracking in a small size variable speed wind turbine. Moreover, a novel vector control approach is introduced to control the output voltage and current of a single-phase voltage source inverter, such that the active and reactive power can be controlled independently. Using the proposed speed estimator, the system needs only two measurements, which are the output voltage of the diode rectifier
and inductor current inside the boost converter, to estimate the generator speed and implement the maximum power-tracking algorithm. The proposed vector control approach provides independent control of active and reactive power with zero steady-state error at its fundamental frequency. In addition, the inverter can improve power factor and inject a current with very low harmonic distortion into the utility grid. The generating system has potentials of high efficiency, good flexibility, and low cost.

In chapter 4 a new power circuit topology using dc-dc boost converter and its control methodology for a hybrid wind, photovoltaic and fuel cell generating system is introduced. The wind and photovoltaic are used as primary energy sources, while the fuel cell is used as secondary or back-up energy source. A simple control method tracks the maximum power from the wind energy source without measuring the wind speed. The same control principle is applied to track maximum power point of the photovoltaic system without sensing the irradiance level and temperature. The fuel cell is also controlled using a dc-dc converter to supply the deficit power when the primary energy sources cannot meet the load demand. In the complete absence of power from the wind and photovoltaic sources the fuel cell supplies its full rated power of 10 kW. The system studied in this paper comprises of a 20 kW wind turbine generator, 15 kW photovoltaic array and 10 kW fuel cell. All the energy sources are modeled using PSIM software tool to analyze their dynamic behavior. The complete hybrid system is simulated for different operating conditions of the energy sources.

A novel approach for developing the power conversion systems (PCS) used in distributed energy systems is introduced in chapter 5. The critical objective of this PCS
design is to reduce cost through modularity and novel thermal and packaging concepts using a low loss inverter technology. Another important feature of the design is to match the dc bus voltage to the required ac output voltage. In this instance a nominal 1000 V dc bus was chosen with an output voltage of 480 V, to match typical distribution class transformers. The selection eliminates the need for expensive dc-dc converters and custom transformers. Moreover, limitations on reactive power control and voltage support are discussed at the end of the chapter.

Chapter 6 summarizes the results and accomplishments and discusses future work that can be done in this area.
CHAPTER 2

APPLICATION OF PERMANENT MAGNET GENERATOR IN VARIABLE SPEED WIND TURBINE SYSTEM

2.1 Introduction

Wind energy is said to be one of the most prominent sources of electrical energy in years to come. Wind power has to overcome some technical as well as economical barriers if it should produce a substantial part of electricity. In this chapter, some of the technical aspects are treated, particularly those regarding the power electronic interface for small-scale wind turbine systems. Wind power plants using the new turbine are expected to interface well with existing utility transmission and distribution systems and offer opportunity for substantial fuel saving. As a renewable technology, wind also offers important environmental benefits including: no emissions of carbon dioxide, sulfur and nitrogen oxides, or other air pollutants and any wastes or residues.

2.2 Wind Turbine Basics

A schematic representation of a variable speed concept is shown in Figure 2.1. The variable speed turbine can generate electricity from winds with speeds ranging from
9 to 65 miles per hour. In conjunction with the variable speed feature, this wide operating envelope increases the turbine’s energy capture by 10 to 15 percent or more over a comparably sized constant speed turbine, as shown in Figure 2.2 [41].

![Figure 2.1: Variable speed concept.](image1)

![Figure 2.2: Increased energy capture using variable speed turbine.](image2)

The variable speed turbine’s rotor can turn faster as wind speed increases, storing some of the wind’s energy as kinetic energy, which generates additional electricity when released. Figure 2.3 shows a typical small size variable speed wind turbine which is using a permanent magnet machine as its generator.
Figure 2.3: A typical small size variable speed wind turbine using PMG.
2.2.1 Wind Turbine Aerodynamic Characteristic

The aerodynamic rotor converts the wind power into mechanical power. Aerodynamic effects throughout the blades convert the wind flow in aerodynamic torque. The aerodynamic model uses the equivalent wind speed as input to compute the available power; moreover, it uses the speed of rotor to calculate the torque on the main shaft. In this way, the amount of mechanical power captured from wind by the turbine could be formulated as [5]:

\[ P_m = \frac{1}{2} \rho A C_p v^3 \] (2.1)

where,  \( \rho \): air density \((\text{Kg/m}^3)\)

\( A \): swept area \((\text{m}^2)\)

\( C_p \): power coefficient of the wind turbine

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

Therefore, if the air density, swept area, and wind speed are constant the output power of the turbine will be a function of power coefficient of the turbine. In addition, the wind turbine is normally characterized by its \( C_p \)-TSR curve; where, TSR, tip-speed ratio, is given by:

\[ TSR = \frac{\omega R}{v} \] (2.2)

In (2.2), \( \omega \), \( R \), and \( v \) are the turbine rotor speed in “rad/s”, radius of the turbine blade in “m”, and wind speed in “m/s”, respectively. Figure 2.4 shows a typical \( C_p \)-TSR
curve for a wind turbine. As can be seen from Figure 2.4, at TSR_{opt}, the power coefficient, C_P, has its maximum value which results in the optimum efficiency. Therefore, in this case maximum power is captured from wind by the wind turbine.

Figure 2.4: Power coefficient versus tip-speed ratio.

Figure 2.5 illustrates the output power of a wind turbine versus rotor speed while speed of wind is changed from v_1 to v_3 (v_3>v_2>v_1).

Figure 2.5: Output power versus rotor speed for three different wind speeds.
As can be seen from Figure 2.5, for example, if the speed of wind is \( v_1 \), then the maximum power could be captured when the rotor speed is \( \omega_1 \); in other words, the operating point of the system is point A, which corresponds to the maximum output power. If wind speed changes from \( v_1 \) to \( v_2 \) while the rotor speed is fixed at \( \omega_1 \), the operating point of the system is point B which does not correspond to maximum power tracking. The rotor speed should be increased from \( \omega_1 \) to \( \omega_2 \) which results in the maximum power at operating point C. Based on (2.2) and Figure 2.4, optimum speed of the rotor can be estimated as follows:

\[
\omega_{opt} = \frac{v}{TSR_{opt}} \Rightarrow v = \frac{R\omega_{opt}}{TSR_{opt}}
\]  

(2.3)

Unfortunately, measuring the wind speed in the rotor of a turbine is very difficult; so, to avoid using wind speed, (2.1) needs to be revised. By substituting the wind speed equivalent from (2.3) into (2.1), the output power of the turbine is given as follows:

\[
P_m = \frac{1}{2} \rho AC_p \left( \frac{R\omega_{opt}}{TSR_{opt}} \right)^3
\]  

(2.4)

Finally, the target torque can be written as follows:

\[
T_{target} = k_{opt} \omega_{opt}^2
\]  

(2.5)

where: 

\[
k_{opt} = \frac{1}{2} \rho AC_{PMax} \left( \frac{R}{TSR_{opt}} \right)^3
\]
2.2.2 Maximum Power Tracking Algorithm

As mentioned in the previous section, the available power provided by the wind turbine depends on and varies with the wind speed. Output power of the wind turbine cannot exceed the available wind power, but it may be reduced by the rotor blade pitch angle control. The variability of the output power from the wind generator implies that, without special interface measures, the turbine will often operate away from its maximum power point. The associated losses can be avoided by the use of maximum power point tracker (MPPT) which ensures that there is always maximum energy transfer from the wind turbine to the grid. Several control schemes, such as duty cycle ratio control [10, 12] and using a look-up table [3, 14, 28] are proposed to improve the performance of maximum wind power extraction; however, these schemes depend on the characteristics of the wind turbine either before or during the execution. An independent maximum power extraction strategy is more flexible since it can be applied in different wind energy conversion systems, is more accurate since it eliminates the turbine characteristic measurement, and is easier to implement [9, 15, 30]. This technique is named “Perturbation and Observation Method” and includes several steps, which are:

1. Choose the initial reference rotor speed and measure the output power of the generator;

2. Increase or decrease the reference rotor speed by one step and measure the output power again;

3. Calculate $\text{Sign}(\Delta P)$ and $\text{Sign}(\Delta \omega)$;
4. \( \omega_{\text{ref}}(n) = \omega_{\text{ref}}(n-1) + \text{Sign}(\Delta P) \text{Sign}(\Delta \omega) \omega_{\text{step}} \);

5. Repeat from step 3 to reach optimum operating point.

Figure 2.6 is used to make this algorithm clearer. Let us assume the wind speed is \( v_1 \) and operating point of the turbine is point A, represented as \((\omega_A, P_A)\) in P-\(\omega\) characteristic curve. Also, let us assume that the turbine speed is increased by \( \omega_{\text{step}} \), which results in a new speed \( \omega_B \). The new operating point will be \((\omega_B, P_B)\) which gives:

\[
\begin{align*}
\Delta P &= P_B - P_A > 0 \Rightarrow \text{sign}(\Delta P) = +1 \\
\Delta \omega &= \omega_B - \omega_A > 0 \Rightarrow \text{sign}(\Delta \omega) = +1 \\
\Rightarrow \omega_{\text{ref}} &= \omega_B + \omega_{\text{step}}
\end{align*}
\]

Figure 2.6: Adjustment of turbine operating point for maximum power tracking.

After the first iteration, the new operating point becomes \((\omega_C, P_C)\). The iterative process will continue until the operating point of the system is found at \((\omega_1, P_1)\), corresponding to the maximum power for the wind speed of \( v_1 \). If the wind speed
changes to $v_3$, the new operating point will be searched starting at $(\omega_D, P_D)$ which results in:

$$\Delta P = P_D - P_1 > 0 \Rightarrow \text{sign}(\Delta P) = +1 \quad \Rightarrow \omega_{\text{ref}} = \omega_1 + \omega_{\text{step}}$$

$$\Delta \omega = \omega_D - \omega_1 = 0 \Rightarrow \text{sign}(\Delta \omega) = +1 \quad \Rightarrow \Delta \omega = \omega_1$$

The next point will be $(\omega_E, P_E)$ and similarly this process will continue in the same manner as explained, until the final operating point is found at $(\omega_3, P_3)$, corresponding to the maximum power capture for the wind speed of $v_3$. Now, if the wind velocity changes to $v_2$, the operating point will move to $(\omega_F, P_F)$ which results in:

$$\Delta P = P_F - P_3 < 0 \Rightarrow \text{sign}(\Delta P) = -1 \quad \Rightarrow \omega_{\text{ref}} = \omega_3 - \omega_{\text{step}}$$

$$\Delta \omega = \omega_F - \omega_3 = 0 \Rightarrow \text{sign}(\Delta \omega) = +1$$

In this case the turbine speed should decrease and the operating point should settle at $(\omega_G, P_G)$:

$$\Delta P = P_G - P_F > 0 \Rightarrow \text{sign}(\Delta P) = +1 \quad \Rightarrow \omega_{\text{ref}} = \omega_3 - \omega_{\text{step}}$$

$$\Delta \omega = \omega_G - \omega_F < 0 \Rightarrow \text{sign}(\Delta \omega) = -1$$

In this case, the reference turbine speed indeed decreases and the operating point shifts towards $(\omega_G, P_G)$. This process will continue until the new operating point arrives in $(\omega_2, P_2)$ which is the optimum operating point for the wind velocity of $v_2$. The principle of the MPPT is demonstrated in Figure 2.7, where $V_{ab}$ and $V_{bc}$ are the output voltage of the generator and $I_a$ and $I_b$ are the generator phase currents.
Figure 2.7: Flowchart of perturbation and observation method for maximum power point tracking.

2.3 Turbine Generator

The wind power conversion unit consists of a wind turbine, a generator and the associated power electronic converters. Various types of generators, such as direct current generator, induction generator, and synchronous generator can be used for variable speed wind power conversion systems. In this section a brief review of different types of generators including their advantages and disadvantages is presented.
2.3.1 DC Generator

The classical dc generator consists of a spinning armature and a surrounding stationary field winding with a constant current. The output or load current is from the armature winding. These types of generators were used in factories, machine shops and vehicles from the early 20th century. The addition of commutators and brushes makes dc designs more expensive and less reliable compared to ac generators. A classical example of an early variable speed dc turbine is the Jacobs machine [28].

2.3.2 Induction Generator

Induction machines have been proposed as generators in many research articles and are currently the predominant commercial wind turbine generator [8, 9, 16, 23, 28, 31]. The induction machine is a well-established technology, as is its application as a wind generator, using a gear drive to a generator with a low number of poles. In general, because of its small air-gap, the induction machine leakage flux increases to an unacceptable limit for machines with many poles. This causes difficulty, in which the machine cannot use the available current flow to generate torque, only leakage flux. Induction machines with a large number of poles must be large enough to accommodate a sufficient number of slots per pole per phase, in order to prevent this situation from taking the upper hand. This means that induction machines with many poles will inevitably be oversized in relation to the rated output [28].

The induction generator applied to conventional wind power generation has advantages which are low maintenance, robustness, and low cost. Furthermore,
advantages include asynchronous operation, which allows some flexibility when the wind speed is fluctuating. These advantages make the induction machine very attractive for wind power application for both fixed and variable speed operation [16, 28]. However, a major disadvantage is the need for excitation of the magnetic field via the supply terminal which results in relatively low power factor for full load operation [13, 21, 30]. For power factor compensation of the reactive power in the generator, ac-capacitor banks are used. The generators are normally compensated over the whole power range. The switching of capacitors is done as a function of average value of measured reactive power during a certain period. The capacitors may be heavy loaded and damaged in case of over-voltages to the grid; therefore, they may increase the maintenance cost. Another solution to improve the power factor is to insert a power converter in series with the armature circuit. In this way, full control is obtained over the induction generator performance, but at the cost of a converter capable of handling the full power of the generator [23, 28].

2.3.3 Permanent Magnet Generator

Essentially, all primary generators employed by electric utilities belong to the synchronous class. Synchronous machines are categorized as: wound-field, switch reluctance, and permanent magnet machines. Wound-field generators are generally used in high-power (multi-megawatt) applications; whereas, the other two are usually used in low to medium-power (up to several hundred horsepower) applications [28].
The switched reluctance generator has been considered for wind power application in the last decade; nevertheless, most of the available literature is focused on aircraft generators [25, 28].

This proposal focuses on permanent magnet machines as a generator for the wind turbine system. Permanent magnet machines may be grouped in several categories, those with surface mounted magnets, those with buried magnets, and those with damper windings. The permanent magnet machine is a newer technology than the induction machine in applications as a wind turbine generator and has been proposed in many research articles [3-5, 7, 10, 15, 20, 21, 28-30]. In general, because of the relatively large air-gap, the permanent magnet machine leakage flux remains below an acceptable limit for machines with many poles. This means that the machine can use the current flowing to generate torque. Permanent magnet machines with a large number of poles may be designed with reasonably small size compared to the output. This means that permanent magnet machines with many poles will have an acceptable size in relation to the rated output, and may be recommended. Permanent magnet machines with surface mounted magnets may be designed with relatively large air-gap. This eases the mechanical problems encountered when building and operating a large generator. On the other hand, surface mounted magnets exacerbate the problems of high voltages at speeds above the base speed, because of lack of field weakening.

The advantages of permanent magnet generator are:

- High power density, lower rotor inertia, simplicity, and more robust construction of the rotor.
- Low level of acoustic noise which is because of direct drive configuration; in other words, the turbine system does not need a gearbox because of the high numbers of magnetic poles.

- Self-excitation, which means the permanent magnet generator differs from the induction generator in that the magnetization is provided by a permanent magnet pole system on the rotor, instead of taking excitation current from the armature winding terminals, as is the case with induction generator.

- Operation at high power factor and efficiency as a result of self-excitation.

Disadvantages are as follows:

- Permanent magnet materials are an expensive initial purchase and are difficult to handle in manufacturing.

- Synchronous operation, which causes a very stiff performance in the case of external short circuits, and when the wind speed is unsteady, this may lead to instabilities.

- Loss of flexibility of field flux control and possible demagnetization effect; in other words, no means to control the strength of the magnetic field and therefore reactive power.

Permanent magnet machines, particularly at low-power range, are widely used in industry. Recently, the interest in their application is growing, particularly up to 100 kW. An example of a Permanent magnet synchronous machine running at variable speed wind turbine system is the Bergey Excel [29].
2.4 Power Electronics

To take advantage of the higher energy capture and increase in the system compliance resulting from variable speed operation, a power electronics interface must be provided between machine terminals and the grid [17-19].

Power electronics is a rapidly developing technology. Higher current and voltage ratings components are being achieved, power losses are decreasing, and devices are becoming more reliable. The devices are also very easy to control with mega scale power amplification. The cost is still decreasing per kVA and power converters are becoming more attractive as a means to improve the performance of a wind turbine system.

The variable-speed capability with power electronics as the interface is considered almost essential for most new designs. The variable speed operation can reduce mechanical stress and smooth the fluctuation of the power injected into the grid, which results in less wear and tear on the tower, gearbox and other components in the drive train. Also the variable speed system can increase the production of energy and reduce noise [20].

This section discusses the generator side and supply side converters in details. Figure 2.8 shows a typical arrangement of a wind turbine system driving an ac generator. For the generator side converter the two most common circuit topologies are selected and discussed with respect to advantages and drawbacks.

One of the technical advantages of the system shown in Figure 2.8, is the capacitor decoupling between the supply side inverter and the generator side converter.
Besides providing some protection, this decoupling offers separate control of the two inverters, allowing compensation of asymmetry both on the generator side and on the grid side, independently. However, in several papers concerning adjustable speed drives, the presence of the dc-link capacitor is mentioned as a drawback, since it is heavy and bulky, it increases the costs and perhaps of most importance, it reduces the overall life time of the system [33-35].

![Power electronics interface for a wind turbine energy system.](image)

**Figure 2.8**: Power electronics interface for a wind turbine energy system.

### 2.4.1 Supply Side Inverter

#### 2.4.1.1 Active and Reactive Power in Rotating Reference Frame

Figure 2.9 shows the vector representation of a balanced three-phase system and their equivalent vectors in a rotating dq reference frame. The variables in the ABC system can be transformed to a rotating dq reference frame by using a time-varying transformation matrix given in (2.6).
\[
T = \frac{2}{3} \begin{bmatrix}
\cos(\theta) & \cos\left(\theta - \frac{2\pi}{3}\right) & \cos\left(\theta + \frac{2\pi}{3}\right) \\
\sin(\theta) & \sin\left(\theta - \frac{2\pi}{3}\right) & \sin\left(\theta - \frac{2\pi}{3}\right) \\
\frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}}
\end{bmatrix}
\] (2.6)

**Figure 2.9:** Definition of rotating reference frame.

\[
\begin{bmatrix}
 f_d \\
 f_q \\
 f_a \\
 f_c
\end{bmatrix} = T \begin{bmatrix}
 f_A \\
 f_B \\
 f_C
\end{bmatrix} \quad (2.7)
\]

\[
T^{-1} = \frac{3}{2} T^T \Rightarrow \begin{bmatrix}
 f_A \\
 f_B \\
 f_C
\end{bmatrix} = T^{-1} \begin{bmatrix}
 f_d \\
 f_q \\
 f_a
\end{bmatrix} \quad (2.8)
\]

In (2.7) and (2.8), variables “f” can be defined as a set of voltages or currents in the system. Also, in a balanced three-phase system \( f_0 \), called the zero sequence...
component, is always equal to zero. The instantaneous power in a three-phase system is given by:

\[
P(t) = V_Ai_A + V_Bi_B + V_Ci_C = \begin{bmatrix} V_A & V_B & V_C \end{bmatrix} \begin{bmatrix} i_A \\ i_B \\ i_C \end{bmatrix}
\]  
\tag{2.9}

Using the transformation matrix and substituting the voltage and current vectors from (2.8) into (2.9) results in:

\[
P = \frac{3}{2}(V_di_d + V_qi_q)
\]  
\tag{2.10}

In Figure 2.9, the orientation of the rotating reference frame is done along the supply voltage vector to obtain a decoupled control of the active and reactive power. As can be seen from Figure 2.9: \(V_q=0\) and \(V_d=|V|\), so the equation of active power can be simplified in the rotating reference frame as:

\[
P = \frac{3}{2}|V|i_d
\]  
\tag{2.11}

In a similar way, the equation of reactive power in the rotating reference frame can be calculated as:

\[
Q = -\frac{3}{2}|V|i_q
\]  
\tag{2.12}

2.4.1.2 Inverter Control Strategy

The output currents, in the ac side of the supply side inverter, are controlled using a vector control approach leading to independent control of active and reactive power flow between the supply side inverter and the grid; therefore, the injected current into the
grid has low distortion and is almost in phase with the grid voltage. In other words, the front-end converter controls the power flow to the ac bus such that to keep the dc-link voltage constant, as well as the output power factor near unity.

Figure 2.10 shows a simplified representation of the supply-side converter which includes a dc-side capacitor, a 3-phase PWM inverter, and series impedances which interface the output of the inverter to the utility grid.

![Supply-side converter arrangement](image)

The voltage equations in Figure 2.10 can be written by using KVL law as

\[
\begin{bmatrix}
    i_A \\
    i_B \\
    i_C
\end{bmatrix} = \begin{bmatrix}
    1 & 0 & 0 \\
    0 & 1 & 0 \\
    0 & 0 & 1
\end{bmatrix} \begin{bmatrix}
    i_A \\
    i_B \\
    i_C
\end{bmatrix} + \begin{bmatrix}
    e_A - V_A \\
    e_B - V_B \\
    e_C - V_C
\end{bmatrix}
\]

(2.13)

Where: \( p = \frac{d}{dt} \)

Transforming the voltage equations into the synchronous reference frame by using the transformation matrices given in (2.6), (2.7) and (2.8) results in:
To provide decoupled control of active power, or $i_d$, and reactive power, or $i_q$, based on (2.14), the output voltage of the inverter in the synchronous reference frame should be:

$$e_d = L_S(x_1 - \omega i_q) + |V|$$  \hspace{1cm} (2.15)

$$e_q = L_S(x_2 + \omega i_d)$$  \hspace{1cm} (2.16)

By substituting (2.15) and (2.16) into (2.14), the decoupled equations of the system can be rewritten as follows:

$$p \begin{bmatrix} i_d \\ i_q \end{bmatrix} = \begin{bmatrix} -\frac{R_S}{L_S} & \omega \\ -\omega & -\frac{R_S}{L_S} \end{bmatrix} \begin{bmatrix} i_d \\ i_q \end{bmatrix} + \begin{bmatrix} \frac{1}{L_S} \left[ e_d - |V| \right] \\ e_q \end{bmatrix}$$  \hspace{1cm} (2.17)

As can be seen from (2.11) and (2.12) the active and reactive power could be controlled through $i_d$ and $i_q$, respectively. Therefore, the control rules of (2.15) and (2.16) can be completed through defining the current feedback loops as follows:

$$x_1 = \left(k_1 + \frac{k_2}{s}\right)(i_q^* - i_q)$$  \hspace{1cm} (2.18)

$$x_2 = \left(k_1 + \frac{k_2}{s}\right)(i_d^* - i_d)$$  \hspace{1cm} (2.19)
As mentioned before, the main task of the front-end converter control strategy is to keep the dc-link voltage, $V_{dc}$, constant at a desired voltage. Neglecting harmonics due to switching and losses in the inductor resistance and converter [24, 31]:

\[
\begin{align*}
P_{inv} &= 1.5V_d i_d \\
V_d &= 0.5m_a V_{dc} \Rightarrow i_{dc} = 0.75m_a i_d \\
V_{dc} \times i_{dc} &= P_{inv}
\end{align*}
\] (2.20)

Therefore, dynamics of the dc-link can be written as follows

\[
C \frac{dV_{dc}}{dt} = I - i_{dc} \Rightarrow C \frac{dV_{dc}}{dt} = I - 0.75m_a i_d
\] (2.21)

As can be seen from (2.21), the dc-link voltage can be controlled via $i_d$. Therefore, the control scheme can be developed for $i_d$ and $i_q$, with the $i_d$ command being derived from dc-link voltage error through a PI controller. The $i_q$ command determines the displacement factor on the supply side of the inductor. Figure 2.11 shows the control block diagram of the supply-side inverter based on the vector-control algorithm.

![Control strategy schematic for supply side inverter.](image)

Figure 2.11: Control strategy schematic for supply side inverter.
2.4.2 Generator Side Converter

Two different circuit topologies are discussed in this section; advantages and disadvantages of each circuit will be explained and simulation result will be added to confirm the performance of each circuit.

2.4.2.1 Three-Phase Boost Rectifier (dual PWM-VSI)

Controlled rectifiers offer distinct advantages over typically used uncontrolled diode, or phase-controlled thyristor rectifiers in ac-dc-ac converters for variable speed dive applications. These advantages include unity power factor and greatly reduced input line current harmonic distortion due to the nearly sinusoidal input line current attainable with controlled rectifiers [22, 25].

The back-to-back circuit topology, which is shown in Figure 2.12, is a bi-directional power converter consisting of two conventional three-phase current regulated pulse width modulated voltage source inverter (CRPWM-VSI).

![Figure 2.12: Topology of wind power generation system using Three-Phase Boost Rectifier.](image-url)
To achieve full control of the grid current, the dc-link voltage must be boosted to a level higher than the amplitude of the grid line-line voltage. As mentioned before, the power flow of the grid side converter is controlled in order to keep the dc-link voltage constant, while the control of the generator side is set to suit the magnetization demand and the reference speed. The control of the back-to-back PWM inverters in the wind turbine application is described in several papers [36-40].

The voltage and torque equations of a nonsalient permanent magnet generator in the rotor reference frame can be written as follows [Appendix]:

\[
\begin{align*}
    P \begin{bmatrix} i_d \\ i_q \end{bmatrix} &= \begin{bmatrix} -\frac{R_s}{L_{ss}} & \omega_r \\ -\omega_r & -\frac{R_s}{L_{ss}} \end{bmatrix} \begin{bmatrix} i_d \\ i_q \end{bmatrix} + \frac{1}{L_{ss}} \begin{bmatrix} -V_d \\ -V_q + \omega_r \lambda_m^* \end{bmatrix} \\
    T_e &= \left( \frac{3}{2} \right) \left( \frac{P}{2} \right) i_q \lambda_m^* 
\end{align*}
\]

(2.22)

(2.23)

A similar analysis for control of dq currents carried out for supply-side converter; likewise, can be done for decoupled control of the stator currents. To implement the vector control method, \( V_d \) and \( V_q \) should be chosen as follows:

\[
\begin{align*}
    V_d &= L_{ss}(-y_1 + \omega_r i_q) \\
    V_q &= -L_{ss}(y_2 + \omega_r i_d) + \omega \lambda_m^* 
\end{align*}
\]

(2.24)

(2.25)

To complete control rules expressed in (2.24) and (2.25), \( y_1 \) and \( y_2 \) can be estimated through the current control loops given by:
Based on the torque equation, which is given in (2.23), the commanded q-axis current may be expressed in terms of the commanded torque as:

\[ i_q^* = \left( \frac{2}{3} \right) \left( \frac{2}{P} \right) \frac{1}{\lambda_m} T_e^* \]  

(2.28)

Vector control block diagram of the permanent magnet machine using Cartesian coordinates is shown in Figure 2.13. Since the zero-sequence stator current is equal to zero, only two stator currents are measured, \( i_A \) and \( i_B \).

Figure 2.13: Vector control block diagram of the permanent magnet generator

The inclusion of a boost inductance in the dc-link circuit increases the component count, but a positive effect is that the boost inductance reduces the demands of the grid
side harmonic filter, and offers some protection of the converter against abnormal conditions on the grid. One of the drawbacks of the back-to-back circuit topology is the switching losses. Every commutation in both the grid inverter and the generator inverter between the upper and lower dc-link branch is associated with hard switching and natural communication. Since the back-to-back topology consists of two inverters, the switching losses might be even more pronounced. The high switching speed to the grid may also require extra EMI-filters, as well.

2.4.2.2 Diode Bridge and Step up DC-DC Converter

In this section an inexpensive wind power generation system is proposed [7, 13, 15, 30]. The current trend is to produce more large-scale wind power systems. Although performance/cost ratio of a large-scale wind power generating system is lower than the small-scale systems, initial costs are relatively high compared with the small-scale systems. The two factors associated with system cost are power electronic interface and the generator [10, 13]. In response to these concerns a low cost power electronic interface will be introduced and discussed in detail.

2.4.2.2.1 Three-Phase Diode Rectifier

The variable speed wind generator produces a voltage which varies in both the magnitude and frequency, but a multi-pulse diode rectifier system can be used to deliver a smooth dc voltage. The diode rectifier is the most commonly used topology in power electronic applications. For a three-phase system it consists of six diodes. The diode rectifier can only be used in one quadrant. It is simple and cheap in comparison with
controlled rectifiers, but it cannot be controlled [20]. The output voltage of the diode rectifier is boosted by a step-up boost chopper.

Figure 2.14 shows the proposed circuit topology for a wind power generation system which is used to realize the principle of maximum winding power capture. This system includes a wind turbine, a permanent magnet generator, a three-phase diode rectifier bridge, a step-up dc-dc converter, and a current regulated PWM voltage source inverter which was explained in section 2.3.1.2.

![Figure 2.14: Topology of wind power generation system with diode-rectifier and dc-dc boost converter.](image)

**2.4.2.2 DC-DC converter and control algorithm**

The basic structure and control topology of the boost converter is shown in Figure 2.15. This converter divides the dc-link into two levels: dc-link voltage at the output terminals of the diode rectifier, which is a variable dc voltage, and the dc-link voltage at the input terminals of the voltage source inverter, which is a constant voltage.

In this section, the operation of the boost chopper is theoretically analyzed. Generator and rectifier circuits which supplied the boost chopper circuit with electric
power are replaced with a variable dc voltage source in order to facilitate the analysis. Moreover, the inverter circuit connected to the output of the boost chopper circuit was simulated as load resistance connected with the dc-ink, since it is controlled in operation at high power factor as a current source. In Figure 2.15-a, it is assumed that the inductance and the capacitance of the equivalent circuit are sufficiently large, the current of the switching device is smoothed by the inductance, and the dc output voltage is smoothed by the capacitance. The state equation that describes the dc-dc boost converter is given by (2.29), where $S_{dc}$ is the status of the switching device. The energy is stored in $L$, when $S_{dc}$ is “1”, and the energy is transferred to $C$, when $S_{dc}$ is “0”.

![Diagram of DC-DC Boost Converter](image)

Figure 2.15: Power circuit and control topology of the dc-dc boost converter.

\[
\begin{bmatrix}
\frac{di_L}{dt} \\
\frac{dV_{dc}}{dt}
\end{bmatrix} =
\begin{bmatrix}
0 & -\frac{1-S_{dc}}{L} \\
\frac{1-S_{dc}}{C} & -\frac{1}{RC}
\end{bmatrix}
\begin{bmatrix}
i_L \\
V_{dc}
\end{bmatrix} +
\begin{bmatrix}
\frac{1}{L} \\
0
\end{bmatrix} V_{in}
\]

(2.29)
The inductor current is controlled based on the turbine speed error, as shown in Figure 2.15-b. The speed error is the difference between commanded speed (from maximum power tracking algorithm) and the actual speed. This error is fed into a proportional integrator (PI) type controller and the PI controller is used to control the duty cycle of the dc-dc converter. The advantages of this system are as follows:

1. The generated ac power is converted to dc power through a diode bridge which is simple, robust, cheap, and requires no control circuit.

2. The ac-dc converter only includes one switching device; therefore, production cost and switching loss of this system are kept low. In other words, the system operates with a higher efficiency at lower cost.

3. We control only the output current to control generating power; because dc voltage is kept constant at the output of boost converter. This simplifies the control circuit.

4. As this system has no reserve power flow for step-up boost chopper, many generating units can be parallel connected to one smoothing unit and inverter. However, it gives rise to current distortion and a lagging power factor.

2.5 Simulation Results

To check the proposed algorithms in Sections 2.4.2.1 and 2.4.2.2 for speed control of the permanent magnet machine, a dynamic simulation is implemented using PSIM software to show the response due to wind speed changes. There are two sets of
simulation results which are explained in the following sections. Table 2.1 shows the parameters of the permanent magnet generator used in the simulation.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rated Power Output</td>
<td>20kW</td>
</tr>
<tr>
<td>Rated Speed</td>
<td>211 r/min</td>
</tr>
<tr>
<td>Stator Connection winding</td>
<td>Star</td>
</tr>
<tr>
<td>Number of Rotor poles</td>
<td>36</td>
</tr>
<tr>
<td>Stator Phase Resistor</td>
<td>0.1764Ω</td>
</tr>
<tr>
<td>Synchronous Inductance</td>
<td>4.24 mH</td>
</tr>
<tr>
<td>Rated Phase Current</td>
<td>35A</td>
</tr>
<tr>
<td>Rated Phase Voltage</td>
<td>205 V</td>
</tr>
</tbody>
</table>

Table 2.1: Permanent magnet generator parameters.

### 2.5.1 Simulation results for three-phase boost converter

Figure 2.16 shows the simulation result for speed control mode. In the simulation the command signal, which is the reference speed, has linearly changed from 80 to 120 r/min and again from 120 to 180 r/min and finally decreases linearly from 180 to 150 r/min, assuming the wind speed has changed. As can be seen from Figure 2.16-a, the generator tracks the command signal very accurately. Meanwhile, the dc-link voltage is kept constant at 810 V by the supply side inverter; the simulation result is shown in Figure 2.16-b.
Figure 2.16: (a) Shaft speed of the generator (b) DC-link voltage.

Figure 2.17 shows the simulation results for power factor control for both the generator and supply-side converter. As can be seen from Figure 2.17-a, the generator is working at unity power factor with greatly reduced input line current harmonic distortion (THD < 2%). Likewise, the supply side converter controls the output currents to operate at unity power factor with a low THD (less than 3%). Simulation results are given in Figure 2.17-b.
By using the speed control method and the maximum power point tracking method, which was explained in section 2.2.2, maximum power would be extracted from the wind. Simulation results will be the same with the dc-dc boost converter, which are given in the next section.

2.5.2 Simulation results for step-up DC-DC boost converter

2.5.2.1 Speed Control of permanent Magnet Generator

In this case the reference turbine speed of the generator is the command signal to prepare a switching pattern for the dc-dc boost converter. Figure 2.18-d shows the speed-
tracking characteristic of the generator when the reference command turbine signal increases linearly from 80 to 120 r/min and again from 120 to 200 r/min and finally decreases linearly from 200 to 160 r/min, assuming the wind speed has changed. As can be seen from Figure 2.18-a, by controlling the input current to the dc-dc boost converter, output voltage of the generator-rectifier system could be controlled so that the generator’s shaft follows the speed command. Figure 2.18-b shows the dc output voltage of the rectifier or the dc input voltage to the dc-dc converter. The dc voltage varies according to the power demand. Note that the dc voltage, in general, follows the rotor speed of the generator which is shown in Figure 2.18-d.

As shown in Figure 2.14 a current regulated PWM voltage source inverter is used to interface the dc-link bus to the utility grid. This inverter can maintain the voltage of the dc-link at a constant voltage. As shown in Figure 2.18-c the dc-link voltage is adjusted at 810 volts in this system. Furthermore, it can improve power factor and reduce current harmonic distortion.

As can be seen from Figure 2.19, power factor of the system is adjusted to almost unity power factor and the total harmonic distortion of injected current is less than 3%.

Figure 2.20 shows one of the drawbacks of this system, which was explained in section 2.4.2.2.2. As can be seen from the figure, the generator phase currents are distorted and are not in phase with the output voltages of the generator.
Figure 2.18: Turbine speed tracking.
Figure 2.19: Grid phase voltage and phase current of PWM inverter

Figure 2.20: Generator phase voltage and phase current
2.5.2.2. Maximum Power Tracking

The simulation program uses the typical wind turbine characteristics that are shown in Figure 2.21. As revealed by the graphs, the optimum operating points of the turbine are (175r/min, 10kW), (188r/min, 15kW), and (203r/min, 20kW) for three different wind speeds.

![Figure 2.21: Turbine characteristics used for simulation.](image)

In this simulation the algorithm iteration period and $\omega_{\text{step}}$ are chosen as 1 second and 2 r/min, respectively. As can be seen from Figure 2.22 the generator speed starts from zero and reaches 175±2 r/min, related to the maximum output power of 10kW for the turbine at the wind speed of $v_1$. In 20 second, it is assumed that the wind speed
increases to \( v_3 \); therefore, the control system changes the required turbine speed by using the maximum power tracking algorithm to capture maximum power from the wind at this speed. As can be seen from Figure 2.22, speed of the permanent magnet generator (or turbine shaft) is adjusted to \( 203 \pm 2 \text{ r/min} \), generating 20kW power. After 42 seconds from the beginning, the wind speed decreases to \( v_2 \) from \( v_3 \). Consequently, the reference turbine speed will be decreased by the control system. Figure 2.22 shows that speed of the turbine shaft is adjusted to \( 188 \pm 2 \text{ r/min} \) in 10 seconds. As a result, output power of the turbine is 15kW. Figure 2.23 shows simulation results for the maximum power tracking concept.

![Graph showing output power and rotor speed of the generator.](image)

**Figure 2.22:** Output power and rotor speed of the generator.
This chapter presents a power electronics converter structure and a related simple speed control method that can be used to implement maximum power tracking in wind turbine applications. The proposed system and control algorithm reduces cost of the system, since there is only one switching device in the dc-dc converter. Moreover, no copper loss in the rotor circuit in the permanent magnet generator ensures higher efficiency. In addition, independent control of active and reactive power on the grid-side
power converter is possible. Finally, many generating units can be parallel connected to one smoothing unit and inverter. Simulation results confirm that control algorithm works well to track the maximum power for different wind speeds.
CHAPTER 3

SENSORLESS CONTROL AND STATOR WINDING CONDITION MONITORING OF PERMANENT MAGNET GENERATOR IN WIND TURBINE SYSTEM

3.1 Introduction

This chapter discusses a new and simple speed estimator, to be used by a permanent magnet generator, for maximum power tracking in a small size variable speed wind turbine. In addition, a vector control approach is introduced to control the output voltage and current of a single-phase voltage source inverter, such that the active and reactive power can be controlled independently.

Moreover, this chapter presents a simple and robust technique for on-line condition monitoring of the stator windings of the permanent magnet generator, which is used in a variable speed wind turbine. In this technique the generator terminal voltage and currents are utilized as input signals. Since system maintenance is very important and in a wind turbine system the permanent magnet machine is not easily assessable; therefore, this method could help to monitor the stator winding condition very efficiently to prevent catastrophic failure.
3.2 Power Electronic Circuit and Electric Machines

3.2.1 Operation of Diode Rectifier with Commutating Inductance

Figure 3.1 shows a simple 3-phase diode rectifier connected to a balanced three-phase voltage source through a set of inductors magnetically coupled in series with resistors.

Let us consider that D₁ and D₂ are conducting. At the instant of switching D₁ to D₃, because of the inductor there is a finite commutation interval that affects the average output voltage of the rectifier. To formulate the average output voltage, we assume that the output current of the converter, i_d, is constant and is equal to its average value I_d. Moreover, we initially ignore the resistive part of the inductor to simplify the output voltage equation. Figure 3.2 shows the equivalent circuit of the system during a commutation interval neglecting, the resistive component of the inductors.
During commutation interval, voltage equations in the internal loops can be written as follows:

\[ v_d = e_{an} - v_{La} + v_{Le} - e_{cn} \]  
\[ (3.1) \]

\[ v_d = e_{bn} - v_{Lb} + v_{Le} - e_{cn} \]  
\[ (3.2) \]

Where:

\[
\begin{bmatrix}
  v_{La} \\
  v_{Lb} \\
  v_{Le}
\end{bmatrix} =
\begin{bmatrix}
  L & M & M \\
  M & L & M \\
  M & M & L
\end{bmatrix}
\begin{bmatrix}
  \frac{d}{dt} i_a \\
  \frac{d}{dt} i_b \\
  \frac{d}{dt} i_c
\end{bmatrix}  
\]  
\[ (3.3) \]

Considering that the neutral point is not grounded, which means \( i_a + i_b + i_c = 0 \), results in:

\[ v_{Le} - v_{La} = (M - L) \frac{di_a}{dt} + (L - M) \frac{di_c}{dt} \]  
\[ (3.4) \]

\[ v_{Le} - v_{Lb} = (M - L) \frac{di_b}{dt} + (L - M) \frac{di_c}{dt} \]  
\[ (3.5) \]

Substituting from (3.4) and (3.5) into (3.1) and (3.2):

\[ v_d = e_{ac} + (M - L) \frac{di_a}{dt} + (L - M) \frac{di_c}{dt} \]  
\[ (3.6) \]
\[ v_d = e_{bc} + (M - L) \frac{di_b}{dt} + (L - M) \frac{di_c}{dt} \]  \hspace{1cm} (3.7)

Solving equations (3.6) and (3.7) for \( v_d \) yields:

\[ v_d = \frac{1}{2} (e_{ac} + e_{bc}) + \frac{1}{2} (M - L) \frac{d(i_a + i_b)}{dt} + (L - M) \frac{di_c}{dt} \]  \hspace{1cm} (3.8)

Since “\( i_d \)” is assumed to be constant, is equal to its average value \( I_d \), during the commutation interval:

\[
\begin{align*}
    i_a + i_b &= i_d \approx I_d \\
    i_c &= -i_d \approx -I_d
\end{align*}
\]

\[ \Rightarrow v_d = \frac{e_{ac} + e_{bc}}{2} \]  \hspace{1cm} (3.9)

Let us to consider that the mean voltage reduction in the output voltage of the diode-rectifier due to the commutation interval is equal to \( E_x \), as shown in Figure 3.3. To calculate \( E_x \), we define \( e_x \) as follows:

\[ e_x \triangleq e_{bc} - v_d \]  \hspace{1cm} (3.10)

Substituting \( v_d \) from (3.9) into (3.10):

\[ e_x = \frac{1}{2} (e_{bc} - e_{ac}) = -\frac{1}{2} e_{ab} \]  \hspace{1cm} (3.11)

By subtracting (3.5) from (3.4) and considering: \( i_b = i_d - i_a \) during the commutation interval (\( D_1 \) is turning off and \( D_3 \) is turning on):

\[ v_{IA} - v_{IB} = 2(L - M) \frac{di_a}{dt} - (L - M) \frac{di_d}{dt} \]  \hspace{1cm} (3.12)
Figure 3.3: Commutation effect on the output voltage of the three-phase diode-rectifier under operation with L.

On the other hand, subtracting (3.2) from (3.1) and assuming $i_d \approx I_d$, results in:

$$v_{La} - v_{Lb} = e_{an} - e_{bn}$$

$$\frac{di_d}{dt} \approx \frac{dI_d}{dt} = 0$$

$$\Rightarrow \frac{di_a}{dt} = \frac{e_{an} - e_{bn}}{2(L - M)} \Rightarrow \frac{di_a}{dt} = \frac{e_{ab}}{2(L - M)}$$

(3.13)

Let us assume: $e_{an}(t)=E_m\sin(\omega t+150^\circ)$, this results in: $e_{ab}(t)=\sqrt{3}E_m\sin(\omega t+180^\circ)$. Solving (3.13) under initial condition $i_a(t=0)=I_d$ concludes that:

$$i_a(t) = I_d + \frac{\sqrt{3}E_m}{2(L - M)\omega} (\cos \omega t - 1)$$

(3.14)

To calculate the commutation angle “$\gamma$”, which is needed for calculating the average value of $e_x(t)$, this reality can be use that in the end of commutation process $i_a(\gamma)=0$.

$$i_a(\gamma) = 0 \Rightarrow 1 - \cos \gamma = \frac{2(L - M)\omega}{\sqrt{3}E_m} I_d$$

(3.15)
Therefore, the average value of \( e_x \) can be calculated as follows:

\[
E_x = \frac{1}{\pi/3} \int_0^{\pi/3} e_x(\theta) d\theta = \frac{-3}{2\pi} \int_0^{\pi/3} e_{ab} d\theta = \frac{3\sqrt{3}E_m}{2\pi} (1 - \cos \gamma)
\]

(3.16)

Substituting from (3.15) into (3.16) concludes:

\[
E_x = \frac{3\omega(L - M)}{\pi} I_d
\]

(3.17)

Finally, the average output voltage of the diode-rectifier considering the resistive component of the inductor can be simply written as:

\[
V_d = \frac{3\sqrt{3}E_m}{\pi} - \frac{3\omega(L - M)}{\pi} I_d - 2RI_d
\]

(3.18)

### 3.2.2 Generator Model and Speed Estimator

Machine notations and prototype parameters of the surface-mounted permanent magnet generator (PMG) are given in Table 3.1.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>( P_r )</td>
<td>Rated output power in kW</td>
<td>20</td>
</tr>
<tr>
<td>( N_r )</td>
<td>Rated mechanical speed in rpm</td>
<td>211</td>
</tr>
<tr>
<td>Pole</td>
<td>Number of poles</td>
<td>36</td>
</tr>
<tr>
<td>( E_{NL} )</td>
<td>Peak line-to-neutral back emf in no-load</td>
<td>295.6</td>
</tr>
<tr>
<td>( R_s )</td>
<td>Stator winding resistance in ( \Omega )</td>
<td>1.764</td>
</tr>
<tr>
<td>( L_{ls} )</td>
<td>Stator leakage inductance in mH</td>
<td>0.28</td>
</tr>
<tr>
<td>( L_{ms} )</td>
<td>Stator magnetizing inductance in mH</td>
<td>2.8</td>
</tr>
<tr>
<td>( K_m )</td>
<td>Peak line-to-neutral back emf constant in V/rpm</td>
<td>1.4</td>
</tr>
<tr>
<td>( J )</td>
<td>Moment of inertia in kg/m(^2)</td>
<td>10</td>
</tr>
</tbody>
</table>

Table 3.1: Machine notation and parameter.
The permanent magnet generator can be modeled by the phase equations as follows:

\[
\begin{bmatrix}
    e_{an} \\
e_{bn} \\
e_{cn}
\end{bmatrix}
= 
\begin{bmatrix}
v_{an} \\
v_{bn} \\
v_{cn}
\end{bmatrix} 
+ 
\begin{bmatrix}
    R_s & 0 & 0 \\
    0 & R_s & 0 \\
    0 & 0 & R_s
\end{bmatrix} 
\begin{bmatrix}
i_a \\
i_b \\
i_c
\end{bmatrix} 
+ 
\begin{bmatrix}
    I_{ls} + L_{ms} & -0.5L_{ms} & -0.5L_{ms} \\
    -0.5L_{ms} & L_{ls} + L_{ms} & -0.5L_{ms} \\
    -0.5L_{ms} & -0.5L_{ms} & L_{ls} + L_{ms}
\end{bmatrix} 
\frac{d}{dt} 
\begin{bmatrix}
i_a \\
i_b \\
i_c
\end{bmatrix}
\tag{3.19}
\]

Figure 3.4 shows the permanent magnet generator connected to the three-phase rectifier. The equivalent circuit of the permanent magnet generator, based on (3.19), connected to the rectifier is depicted in Figure 3.5.
The average output voltage of the rectifier based on (3.18) and Figure 3.5 can be formulated as below:

\[
V_d = \frac{3\sqrt{3}E_m}{\pi} - \frac{3\omega (L_s + L)}{\pi} I_d - 2(R + R_s) I_d
\]  

\[E_m = K_m \omega_m\]  

\[\omega = \frac{P}{2} \cdot \frac{2\pi}{60} \cdot \omega_m = \frac{P\pi}{60} \omega_m\]  

\[L_s = L_is + \frac{3}{2} L_{ms}\]

Where, \(\omega_m\) is the mechanical speed of the generator in rpm; \(E_m\) is the maximum of the phase voltage induced into the stator windings; and \(L_s\) is called the synchronous inductance of the generator.

Substituting from (3.21) and (3.22) into (3.20) and solve it for \(\omega_m\) results in:

\[\omega_m = \frac{V_d + 2(R + R_s) I_d}{\frac{3\sqrt{3}}{\pi} K_m - \frac{P}{20}(L_s + L) I_d}\]  

Equation (3.24) can be used to estimate the generator speed just by measuring the average output voltage and current of the diode rectifier. Simulation results for this case are given in section 3.5.1.

**3.3 Vector Control of a Single-Phase Voltage Source Inverter**

In this section independent control of active and reactive power using vector control method for a single-phase inverter will be explained. In the vector control
approach for three-phase inverters [11], time varying variable, such as phase voltages and currents will be transferred to the synchronous rotating d-q reference frame, which allows dealing with dc values instead of time varying variables. However, d-q transformations are defined for two-phase and three-phase systems [26]. Therefore, to use this method for a single-phase inverter we need to build a two-phase balance system. An imaginary phase, in which is orthogonal to the original system, can be considered such that, it has the same structure with the real circuit except that there is a 90° phase difference between voltages and currents of the real and imaginary circuits [42]. A full bridge single-phase inverter and its imaginary circuit are shown in Figure 3.6.

![Figure 3.6: Single-phase inverter and its imaginary circuit.](image-url)
3.3.1 Active and Reactive Power in the Synchronous Reference Frame

Figure 3.7 shows the transformation between a-b and d-q reference frames portrayed by trigonometric relations given in (3.25) and (3.26). In addition, voltage and current vectors of the real circuit in the rotating d-q reference frame are depicted in Figure 3.8.

\[
\begin{bmatrix}
  f_d \\
  f_q
\end{bmatrix} =
\begin{bmatrix}
  \cos \theta & \sin \theta \\
  \sin \theta & -\cos \theta
\end{bmatrix}
\begin{bmatrix}
  f_a \\
  f_b
\end{bmatrix}
\]  

(3.25)
\[
\begin{bmatrix}
  f_a \\
  f_b
\end{bmatrix} = \begin{bmatrix}
  \cos \theta & \sin \theta \\
  \sin \theta & -\cos \theta
\end{bmatrix} \begin{bmatrix}
  f_d \\
  f_q
\end{bmatrix}
\] (3.26)

Where the variable “f” can be define as a set of voltages or currents in the system. Based on Figure 3.8, active and reactive power equations in the synchronous frame can be written as follows:

\[ P = v_d i_d + v_q i_q \] (3.27)

\[ Q = v_d i_q - v_q i_d \] (3.28)

If the q-axis is chosen to be aligned with the phase voltage vector of the real circuit, which means \(v_d=0\) and \(v_q=|v|\), equations of active and reactive power can be simplified as:

\[ P = |v|i_q \] (3.29)

\[ Q = -|v|i_d \] (3.30)

Considering that the grid voltage, \(|v|\), is constant; by controlling \(i_q\) and \(i_d\), active and reactive power can be controlled, respectively.

### 3.3.2 Supply Side Converter Control Strategy

The voltage equations in Figure 3.6 can be written by using KVL law as:

\[
P \begin{bmatrix}
i_a \\
i_b
\end{bmatrix} = -\frac{R}{L} \begin{bmatrix} 1 & 0 \end{bmatrix} \begin{bmatrix} i_a \\
i_b
\end{bmatrix} + \frac{1}{L} \begin{bmatrix}
e_a - v_a \\
e_b - v_b
\end{bmatrix}
\] (3.31)
Transforming the voltage equations into the synchronous reference frame using (3.25) and (3.26), and considering \( v_d = 0 \) and \( v_q = |v| \) results in:

\[
P \begin{bmatrix} i_d \\ i_q \end{bmatrix} = \begin{bmatrix} -\frac{R}{L} & -\omega \\ \omega & -\frac{R}{L} \end{bmatrix} \begin{bmatrix} i_d \\ i_q \end{bmatrix} + \frac{1}{L} \begin{bmatrix} e_d \\ e_q - |v| \end{bmatrix}
\]

(3.32)

To provide decoupled control of active power, or \( i_q \), and reactive power, or \( i_d \), based on (3.32), the output voltages of the inverter in the synchronous reference frame should be chosen as:

\[
e_q = L(x_1 - \omega i_d) + |v|
\]

(3.33)

\[
e_d = L(x_2 + \omega i_q)
\]

(3.34)

By substituting (3.33) and (3.34) into (3.32), the decoupled equations of the system can be rewritten as follows:

\[
P \begin{bmatrix} i_d \\ i_q \end{bmatrix} = \frac{-R}{L} \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} \begin{bmatrix} i_d \\ i_q \end{bmatrix} + \begin{bmatrix} x_1 \\ x_2 \end{bmatrix}
\]

(3.35)

As can be seen from (3.27) and (3.28), the active and reactive power could be controlled through \( i_q \) and \( i_d \), respectively. Therefore, the control rules of (3.33) and (3.34) can be completed by defining current feedback loops as follows:

\[
x_1 = \left( k_1 + \frac{k_2}{s} \right) (i_q^* - i_q)
\]

(3.36)

\[
x_2 = \left( k_1 + \frac{k_2}{s} \right) (i_d^* - i_d)
\]

(3.37)
Figure 3.9 shows the control block diagram of the single-phase inverter based on the vector-control algorithm. To turn on and off the switches in the inverter a unipolar switching scheme is used for pulse-width modulation [43]. With the unipolar switching scheme introduced in Figure 3.9, harmonics in the output voltage of the inverter begins at around 2m_f, where m_f is the modulation frequency ratio. Moreover, based on this switching technique, the output voltage of the inverter can be V_d, 0, or –V_d which results in lower THD in the output voltage and current of inverter. It should be noted that, the commanded active and reactive power should be chosen as two times the desired values; because the imaginary circuit will not deliver (or absorb) any active and reactive power to (or from) the grid. Simulation results for independent control of active and reactive power are given in section 3.5.2.

![Diagram](image)

Figure 3.9: Vector control structure with unipolar switching scheme for single-phase inverter.
3.4 Wind Energy Conversion System

Figure 3.10 shows the schematic of a power circuit topology and control system of a variable speed wind turbine system that will be discussed in this section.

The simple maximum power tracker, which was discussed in chapter 2, is used to extract maximum power from the wind. Also, the speed estimator that was discussed in section 3.2.2 will be used to provide generator speed as input to the control system and maximum power tracker, as well. A step-up boost converter is used to control the speed of the permanent magnet generator, which is also the turbine speed, by balancing the input power to the generator from the wind turbine with the output power of the generator appearing at the output of the diode-rectifier. Detail operation of the ac-to-dc conversion system, including diode-rectifier and boost converter were discussed in chapter 2. Power extracted by the turbine from the wind is measured at the output of the diode-rectifier by measuring the variable dc-bus voltage, \( v_d \), and inductor current, \( i_L \). The calculated power is used as the second input signal to the maximum power tracking system.

As can be seen from Figure 3.10, the single-phase voltage source inverter, which was discussed in section 3.3.2, is employed as the grid-side converter. The main task of the front-end converter is to keep the dc-link voltage, \( V_{dc} \), constant at the commanded value. Neglecting harmonics due to switching and the losses in the inductor resistance and converter [24]:

\[
\begin{align*}
P_{inv} &= |v| i_q \\
v &\approx m_a V_{dc} \\
P_{inv} &= V_{dc} \times i_{dc} \\
\end{align*}
\]

\[ i_{dc} \approx m_a i_q \]  

\[ P_{inv} \approx |v| i_q \]  

\[ P_{inv} \approx m_a V_{dc} \times i_{dc} \]  

(3.38)
Figure 3.10: Power circuit topology and control structure for the wind energy conversion system.
Therefore, dynamics of the dc-link can be written as follows

$$C \frac{dV_{dc}}{dt} = I - i_{dc} \Rightarrow C \frac{dV_{dc}}{dt} = I - m_{d}i_{q}$$  \hspace{1cm} (3.39)

As can be seen from (3.39), the dc-link voltage can be controlled via $i_{q}$. Therefore, the control scheme can be developed for $i_{d}$ and $i_{q}$, with the $i_{q}$ command being derived from the dc-link voltage error through a PI controller, as shown in Figure 3.9 and Figure 3.10. The command $i_{d}$ determines the displacement factor on the grid-side of the inductor. Simulation results for maximum power tracking by the wind energy conversion system are given in section 3.5.3.

3.5 Simulation Results

The simulation results are categorized in three sections, which are speed estimation results, independent active and reactive power control, and finally maximum power tracking simulation results.

3.5.1 Speed Estimator

To run the simulation program for this case, a simple RL load is connected to the output of the diode-rectifier shown in Figure 3.4. The actual and estimated generator speeds are depicted in Figure 3.11-a. The estimated speed is calculated based on equation (3.24). After one second the mechanical input torque changes form 100N.m to 200N.m, which causes a corresponding change in the generator speed. As can be seen from Figure 3.11-a, the estimated speed correlates well with the actual speed of the generator.
Figure 3.11: a) Real and estimated speed b) Rectifier output voltage and generator output voltages c) Generator phase currents.

Variation of stator resistance with temperature can cause poor accuracy in the estimated results at low speeds. However, any wind conversion system has a minimum wind speed operation, which is named cut-in speed. Because of the cut-in speed, the system begins to generate power after the generator speed reaches a certain speed; therefore, the estimator does not have to estimate the generator speed for low speeds.

Figure 3.11-b shows the output voltage of the diode rectifier and absolute value of the line-to-line voltages induced into generator windings, $e_{ab}$, $e_{bc}$, and $e_{ca}$ before phase impedances, shown in Figure 3.5. The phase currents of the permanent magnet generator are plotted in Figure 3.11-c. Figure 3.12 shows an enlargement of Fig.11-b & c.
3.5.2 Independent Active and Reactive Power Control

Simulation results of independent active and reactive power control of the single-phase inverter based on the vector control method discussed in section 3.3.2 are shown in Figure 3.13. As mentioned previously, and as shown in Figure 3.13-a & b, active and reactive powers are controlled through the q and d-axis current components.

To examine the dynamics of the control algorithm, the input power to the dc-bus of the inverter is changed, as may occur due to wind speed variations in a real system. As can be seen from Figure 3.13-a & b, the controller changes the set value of the q-axis current component to maintain a fixed dc-link voltage of 420 volts based on equation (3.39), shown in Figure 3.13-c.
Furthermore, after 2 seconds the reactive power command changes from zero to 8 kvar; in other words, the commanded value of d-axis current changes from zero to –50 amps. Likewise, dynamic response of the d-axis current regulator is shown in Figure 3.13-a. An enlargement of grid voltage and current is depicted in Figure 3.14-b at the moment the reactive power changes. As can be seen, the power factor changes from unity to leading, indicating that the reactive power is injected into the grid by the inverter.
3.5.3 Maximum Power Tracking by Wind Energy Conversion

Figure 3.15 shows the maximum power tracking results using the speed estimator. The simulation program uses the typical wind turbine characteristics given in chapter 2, where the optimum operating points of the turbine are, (203r/min, 13kW), and (220r/min, 21kW) for two different wind speeds. As can be seen from Figure 3.15-a the generator speed starts from zero and reaches 203±2 r/min, relating to the maximum output power of 13kW. In 30 second, it is assumed that the wind speed increases; therefore, the control system changes commanded speed by using the maximum power tracking algorithm to capture maximum power from the wind at the current wind speed. Finally, the generator speed is adjusted to 220±2 r/min when generates 21kW power. Figure 3.15-c shows the locus of the output power of turbine verses generator speed.
3.6 Experimental Results

Figure 3.16 shows the experimental test setup which is used to verify the speed estimator. In the setup a dc motor is used instead of wind turbine. Furthermore, as shown in Figure 3.4, output of the PMG is connected to a three phase diode rectifier. Parameters of the PMG are given in Table 3.2.
Table 3.2: Parameters of PMG used in the test setup.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rated output power in W</td>
<td>746</td>
</tr>
<tr>
<td>Rated mechanical speed in rpm</td>
<td>1800</td>
</tr>
<tr>
<td>Number of poles</td>
<td>4</td>
</tr>
<tr>
<td>Peak line-to-neutral back emf in no-load in volt</td>
<td>212.3</td>
</tr>
<tr>
<td>Stator winding resistance in Ω</td>
<td>2.84</td>
</tr>
<tr>
<td>Synchronous inductance in mH</td>
<td>82</td>
</tr>
<tr>
<td>Peak line-to-neutral back emf constant in V/rpm</td>
<td>0.0965</td>
</tr>
</tbody>
</table>

Estimated speed and actual speed of the generator are shown in Figure 3.17. For better comparison, percentage of speed error between actual and estimated one is depicted in Figure 3.18. Speed error is defined as below:

\[
\text{Speed Error} = \left| \frac{\text{Estimated Speed} - \text{Actual Speed}}{\text{Actual Speed}} \right| \times 100
\]

As can be seen from the figure, estimator tracks generator speed with an error of less than %5, which is a very good estimation for wind turbine application.
Figure 3.17: Actual and estimated speed of the PMG.

Figure 3.18: Percentage of speed error using the speed estimator.
3.7 Stator Winding Condition Monitoring

System maintenance is one of the main concerns with wind power plants, more so since the wind turbines are not easily accessible. Maintenance schedules are provided to proactively reduce or prevent system failures. Nevertheless, the probability of a sudden system failure cannot be entirely ruled out.

Early detection of electrical component defect within an energy conversion system such as a permanent magnet generator can result in significant benefits:

1. Catastrophic failure can be prevented and consequently, potentially unsafe conditions can be avoided.
2. Damage to system components can be minimized.
3. Maintenance actions can be performed on a timely basis rather than unscheduled times.

An increase in the maintenance frequency will result in an increase in the maintenance downtime and consequently a decrease in the productivity of the system. Unfortunately, it is very difficult to determine exactly when maintenance action is needed for a permanent magnet generator in a wind energy system. Accordingly, an online condition monitoring system becomes a valuable tool to increase lifecycle, industrial efficiency, and reliability.

This section deals with the stator winding condition monitoring of the permanent magnet generator, used in variable speed wind turbine systems, which may help to increase the efficiency and reliability of the system [44, 45].
3.7.1 Machine Modeling

In the case of inter-turn faults, the number of stator phases (states) in a three-phase motor impacted by an inter-turn fault is increased to four, with the additional fourth phase representing the shorted portion of a phase winding. This fourth phase is mutually coupled to the original three phases. Assuming that an inter-turn fault occurs in phase-A, the state space representation is given by:

\[
E = V + (RL^{-1}) \Lambda + \dot{\Lambda}
\]  \hspace{1cm} (3.40)

where:

\[
E = \begin{bmatrix} e_{af} & e_{bf} & e_{cf} & e_{sc,f} \end{bmatrix}^T
\]  \hspace{1cm} (3.41)

\[
V = \begin{bmatrix} v_a & v_b & v_c & 0 \end{bmatrix}^T
\]  \hspace{1cm} (3.42)

\[
\Lambda = \begin{bmatrix} \lambda_a & \lambda_b & \lambda_c & \lambda_{sc} \end{bmatrix}^T
\]  \hspace{1cm} (3.43)

\[
\begin{bmatrix}
\lambda_a \\
\lambda_b \\
\lambda_c \\
\lambda_{sc}
\end{bmatrix} =
\begin{bmatrix}
L_{aa} & L_{ab} & L_{ac} & L_{a,sc} \\
L_{ba} & L_{bb} & L_{bc} & L_{b,sc} \\
L_{ca} & L_{cb} & L_{cc} & L_{c,sc} \\
L_{sc,a} & L_{sc,b} & L_{sc,c} & L_{sc,sc}
\end{bmatrix}
\begin{bmatrix}
i_a \\
i_b \\
i_c \\
i_{sc}
\end{bmatrix}
\]  \hspace{1cm} (3.44)

\[
\begin{bmatrix}
(1-\eta)e_{af} \\
e_{bf} \\
e_{cf} \\
\eta e_{af}'
\end{bmatrix} =
\begin{bmatrix}
v_a \\
v_b \\
v_c \\
0
\end{bmatrix}
\begin{bmatrix}
r_a & 0 & 0 & 0 \\
0 & r_b & 0 & 0 \\
0 & 0 & r_c & 0 \\
0 & 0 & 0 & r_{sc}
\end{bmatrix}
\begin{bmatrix}
i_a \\
i_b \\
i_c \\
i_{sc}
\end{bmatrix}
+ \begin{bmatrix}
\dot{\lambda}_a \\
\dot{\lambda}_b \\
\dot{\lambda}_c \\
\dot{\lambda}_{sc}
\end{bmatrix}
\]  \hspace{1cm} (3.45)

where, $\eta$ is the inter-turn shorted turns ratio.
In the case of cylindrical rotors:

\[
\begin{bmatrix}
\lambda_a \\
\lambda_b \\
\lambda_c \\
\lambda_{sc}
\end{bmatrix} =
\begin{bmatrix}
(1-\eta)^2(L_{sm} + L_{sl}) & (1-\eta)(-\frac{1}{2}L_{sm}) & (1-\eta)(-\frac{1}{2}L_{sm}) & \eta(1-\eta)L_{sm} \\
(1-\eta)(-\frac{1}{2}L_{sm}) & (L_{sm} + L_{sl}) & (-\frac{1}{2}L_{sm}) & \eta(-\frac{1}{2}L_{sm}) \\
(1-\eta)(-\frac{1}{2}L_{sm}) & (-\frac{1}{2}L_{sm}) & (L_{sm} + L_{sl}) & \eta(-\frac{1}{2}L_{sm}) \\
\eta(1-\eta)L_{sm} & \eta(-\frac{1}{2}L_{sm}) & \eta(-\frac{1}{2}L_{sm}) & \eta^2(L_{sm} + L_{sl})
\end{bmatrix}
\begin{bmatrix}
i_a \\
i_b \\
i_c \\
i_{sc}
\end{bmatrix}
\]

\[
\begin{bmatrix}
(1-\eta) e_{af} \\
e_{bf} \\
e_{cf} \\
\eta e_{af}
\end{bmatrix} =
\begin{bmatrix}
v_a \\
v_b \\
v_c \\
0
\end{bmatrix} +
\begin{bmatrix}
(1-\eta)r_a & 0 & 0 & 0 \\
0 & r_b & 0 & 0 \\
0 & 0 & r_c & 0 \\
0 & 0 & 0 & \eta r_a
\end{bmatrix}
\begin{bmatrix}
i_a \\
i_b \\
i_c \\
i_{sc}
\end{bmatrix} +
\begin{bmatrix}
\lambda_a \\
\lambda_b \\
\lambda_c \\
\lambda_{sc}
\end{bmatrix} +
\begin{bmatrix}
d \lambda_a \\
d \lambda_b \\
d \lambda_c \\
\lambda_{sc}
\end{bmatrix}
\]

\[
T_e = (e_{af}i_a + e_{bf}i_b + e_{cf}i_c)/\omega_{syn}
\]

\[
J \frac{d\omega_m}{dt} = T_m - T_e
\]

Above equations are used to model internal fault in the stator winding in the simulation program.

### 3.7.2 Condition Monitoring

The functional block diagram of an on-line condition monitoring is shown in Figure 3.19. In the block diagram, the generator terminal currents and voltages are
measured through current and voltage sensors and the outputs are digitized using an analog to digital (A/D) converter. The output signals of the A/D converter are further sampled and saved over a period equal to the period of the generator frequency, i.e. T=1/f, shown in Figure 3.19.

The sampled terminal voltages and currents are instantaneously multiplied by a set of sine and cosine signals as shown in Figure 3.19. Here, the summary of calculating fault signature (index) is given below:

\[
V_{xa} = 2.\text{ave}(v_a(t_k)) \cdot \cos(2\pi f_1 t) \quad (3.51)
\]

\[
V_{ya} = 2.\text{ave}(v_a(t_k)) \cdot \sin(2\pi f_1 t) \quad (3.52)
\]

\[
V_{ma} = \sqrt{V_{xa}^2 + V_{ya}^2} \quad (3.53)
\]

\[
\varphi_a = \tan(V_{ya}/V_{xa}) \quad (3.54)
\]
\[ V_a = V_{ma} e^{j\phi_a} \]  \hspace{1cm} (3.55)

Same procedures are performed for all the generator terminal voltages and currents in order to obtain phasor quantities of the generator quantities at the generator terminal. Accordingly, the voltage and current negative sequence components can be calculated as follows:

\[ V^- = (1/3) \left( V_a + \alpha V_b + \alpha^2 V_c \right) \]  \hspace{1cm} (3.56)

\[ I^- = (1/3) \left( I_a + \alpha I_b + \alpha^2 I_c \right) \]  \hspace{1cm} (3.57)

where: \( \alpha = \exp(j2\pi/3) \)

Meanwhile, the fault signature is defined as the following:

\[ Z_n = \left| \frac{I_n}{V_n} \right| \]  \hspace{1cm} (3.58)

### 3.7.3 Simulation Results

In this section an on-line trace of the fault signature \( Z_n \), given in (3.58), is shown in Figure 3.20, while the turbine-generator system works under 1%, 1.5%, 2%, 2.5%, and 3% inter-turn short circuits. Meanwhile, the mechanical speed of the turbine is shown in Figure 3.21. As can be seen from Figure 3.21, the control system keeps the average value of the shaft speed at the desired speed. However, as the percentage of the short circuit increases, the range of the speed oscillation around its desired (or commanded) value increases, shown in Figure 3.21.
Figure 3.20: The fault indicator (index).

Figure 3.21: Turbine mechanical speed in r/min
3.8 Summary

A simple speed estimator for a permanent magnet generator that could be used to implement maximum power tracking in wind turbine application was introduced. Furthermore, a vector control approach is used to control the output voltage and current of the single-phase voltage source inverter, such that the active and reactive power can be controlled independently.

Simulation results confirm that the speed estimator and vector control algorithm work efficiently in the closed loop control system to estimate generator speed for maximum power tracking from wind; and control active and reactive power independently.

Moreover, a new technique based on negative sequence component has been presented to monitor the stator winding condition of the permanent magnet generator in wind energy conversion systems. The simulation results confirm that the proposed fault indicator (index) can easily detect the fault even in the presence of a closed loop control system of a variable speed drive system. Use of this method could be a great help in maintenance of the permanent magnet generator to increase lifecycle of the generator and improve overall efficiency of the system.
CHAPTER 4

OPTIMAL DESIGN OF A HYBRID ENERGY SYSTEM

4.1 Introduction

The ever-increasing demand for conventional energy sources like coal, natural gas and crude oil is driving society towards the research and development of alternate energy sources. Many such energy sources like wind energy and photovoltaic are now well developed, cost effective and are being widely used, while some others like fuel cells are in their advanced developmental stage. These energy sources are preferred for being environmental-friendly. The integration of these energy sources to form a hybrid system is an excellent option for distributed energy production. Figure 4.1 shows a typical hybrid system that includes wind turbine, photovoltaic array, fuel cell stack, diesel generator, and battery module. Many such hybrid systems comprised of wind energy, photovoltaic and fuel cell have been extensively discussed in [46-48].

This chapter discusses a hybrid wind, photovoltaic and fuel cell generating system. The wind and photovoltaic are used as primary energy sources, while the fuel cell is used as secondary or back-up energy source. The system studied here is comprised of a
20 kW wind turbine generator (which was discussed in detail in chapters 2 and 3), a 15 kW photovoltaic array and a 10 kW fuel cell.

4.2 Photovoltaic Energy Source

The sun releases an enormous amount of energy in the universe. The amount of this energy which reaches the earth is defined as “solar energy constant”. The solar energy constant (S) is defined as the amount of solar radiation that reaches the earth’s upper atmosphere on a surface perpendicular to the sun’s rays [49]. A part of this incident solar energy is scattered and absorbed by the air molecules, cloud cover, atmosphere etc.
The remaining amount of radiation that is not scattered and absorbed and reaches the earth’s surface is estimated to be around 1000W/m$^2$ at high noon on a clear sky [49-50]. The radiation that comes directly from the sun without getting reflected or scattered is called direct radiation where as the radiation that is reflected and scattered is called diffused radiation. Global radiation is the term used to define total radiation (direct and diffused) [49, 51].

### 4.2.1 Working Principle and Equivalent Circuit

Solar cells are the most fundamental component of photovoltaic system, which converts the solar energy into electrical energy. They are very much similar to most of the commonly used solid-state electronic devices such as diodes, transistors etc. The solar cell essentially consists of a p-n junction formed by semiconductor material. When the sunlight falls on the solar cells an electron-hole pair is generated by the energy from the light (photons). The electrical field created at the junction causes the electron-hole pair to separate with the electrons drifting towards the n-region and the holes towards the p-region. Hence electrical voltage is generated at the output. The photocurrent ($I_{ph}$) will then flow through the load connected to the output terminals of a photovoltaic cell.

Ideal equivalent circuit of a solar cell is shown in Figure 4.2. It consists of a current source in parallel with a diode. In the ideal case the voltage-current equation of the solar cell is given by Equation (4.1).

$$I = I_{ph} - I_0 \left( e^{qV/kT} - 1 \right)$$  \hspace{1cm} (4.1)

where:
\( I_{ph} \): Photo current, \\
\( I_0 \): Diode reverse saturation current, \\
\( q \): Electron charge \((1.6 \times 10^{-19} \text{ C})\), \\
\( k \): Boltzman constant \((1.38 \times 10^{-23} \text{ J/K})\), \\
\( T \): Cell temperature in Kelvin.

![Solar cell equivalent circuit diagram](image)

Figure 4.2: Solar cell equivalent circuit diagram.

The solar cell is modeled and simulated using PSIM software. The simulation is based on the datasheet of Shell SQ160PC photovoltaic module. The parameters of this solar module are given in Table 4.1. The module is made of 72 solar cells connected in series to give a maximum power output of 160 W.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rated Power</td>
<td>( P_R )</td>
</tr>
<tr>
<td>Peak Power*</td>
<td>( P_{\text{MPP}}^* )</td>
</tr>
<tr>
<td>Peak Power Voltage</td>
<td>( V_{\text{MPP}} )</td>
</tr>
<tr>
<td>Peak Power Current</td>
<td>( I_{\text{MPP}} )</td>
</tr>
<tr>
<td>Open Circuit Voltage</td>
<td>( V_{\text{OC}} )</td>
</tr>
<tr>
<td>Short Circuit Current</td>
<td>( I_{\text{SC}} )</td>
</tr>
<tr>
<td>Minimum Peak Power</td>
<td>( P_{\text{MPP-Min}} )</td>
</tr>
<tr>
<td>Tolerance on Peak Power</td>
<td>( \pm 5% )</td>
</tr>
</tbody>
</table>

Table 4.1: Shell SQ160PC photovoltaic (PV) module.
4.2.2 Characteristics of the Photovoltaic Cells

The simulated Current-Voltage (I-V) characteristic of the PV Module is shown in Figure 4.3. The characteristic is obtained at a constant level of irradiance and by maintaining a constant cell temperature.

![Simulated I-V Characteristic](image)

Figure 4.3: Simulated current-voltage characteristic of Shell SQ160PC PV module.

The two most significant points on this characteristic plot are the short circuit current ($I_{SC}$) and the open circuit voltage ($V_{OC}$). The short circuit current ($I_{SC}$) is the maximum current produced when the cell is short-circuited and the terminal voltage is zero, corresponding to zero load. The open circuit voltage ($V_{OC}$) is the voltage across the cell terminals under open circuit conditions, when the current is zero, corresponding to a load resistance of infinity [49].

Figure 4.4 shows the simulated Power–Voltage (P-V) characteristics of the PV module. In order to extract the maximum efficiency from a solar cell it is necessary to
operate the cell at the point where the cell delivers maximum power. This operating work is known as the maximum power point (P_{MPP}).

![Power-voltage characteristic](image)

Figure 4.4: Simulated power-voltage characteristic of Shell SQ160PC PV module.

### 4.2.3 Variation of Characteristics

The V-I and P-V characteristics of the solar cell varies with the isolation levels. Isolation level is defined as the solar power density incident on the surface of a stated area and orientation and is expressed in W/m². The variation in both the I-V and P-V characteristics with isolation level are simulated and the results are shown in Figure 4.5 and Figure 4.6 respectively.

The photocurrent generated by the solar cell is proportional to the flux of the photons [52] and hence with increase in isolation level the photon flux increases and the hence the photocurrent also increases. The short circuit current (I_{SC}) increases as the isolation level increases. The open circuit voltage (V_{OC}) does not vary significantly with the change in isolation level.
Figure 4.5: Variation of I-V characteristic with isolation level.

Figure 4.6: Variation of P-V characteristic with isolation level.
The solar I-V characteristic is also temperature dependent. The simulated I-V and the P-V characteristics of the solar cell at different cell temperatures are shown in Figure 4.7 and Figure 4.8 respectively.

The open circuit voltage ($V_{OC}$) is directly proportional to the absolute cell temperature. The reverse saturation current ($I_0$) also depends on the cell temperature. For example, in a silicon PV cell, the open circuit voltage ($V_{OC}$) decreases by 2.3mV/°C with increase in temperature, which is about 0.5%/°C. Since the short circuit current remains unchanged, the cell power decreases by approx 0.5%/°C.

Figure 4.7: Variation of I-V characteristic with temperature.
4.3 Fuel Cells

4.3.1 Working Principle

A schematic representation of a fuel cell is shown in Figure 4.9. The fuel cell consists of an electrolytic layer and two catalyst-coated electrodes (cathode and anode) as shown in Figure 4.9. The electrodes are composed of porous material and located on either side of the electrolytic layer.

The gaseous fuels are fed continuously to the anode (negative electrode) and the oxidant (i.e. oxygen from air) is fed to the cathode (positive electrode). The gaseous fuel is usually hydrogen in most fuel cells. Thus, when hydrogen is fed to the anode, the
catalyst in the electrode separates the negatively charged electrons of the hydrogen from the positively charged ions. The anode reaction is as follows:

\[ 2H_2 \rightarrow 4H^+ + 4e^- \]  \hspace{1cm} (4.2)

The hydrogen ions pass through the electrolytic layer at the center of the fuel cell and combine with the oxygen and electrons at the cathode with the help of catalyst to form water. The cathode reaction is:

\[ 2H_2 + 4e^- + O_2 \rightarrow 2H_2O \]  \hspace{1cm} (4.3)

The overall equation is given by:

\[ 2H_2 + O_2 \rightarrow 2H_2O \]  \hspace{1cm} (4.4)
The electrons, which cannot pass through the electrolytic layer, flow from the anode to the cathode via the external circuit. This movement of the electrons gives rise to electric current.

The amount of power that is produced by a fuel cell depends on many factors, like the fuel cell type, the size of the fuel cell, the temperature and pressure at which it operates, the fuel supplied to the fuel cell, etc.

4.3.2 Equivalent Circuit

The main aim of creating a fuel cell model is to obtain the output voltage, power and efficiency of the fuel cell as a function of the actual load current. The output voltage of a single fuel cell is given by the (4.5) [54, 55]:

\[ V_{FC} = E_{Nernst} - V_{Act} - V_{Ohmic} - V_{Con} \]  \hspace{1cm} (4.5)

where:

\( E_{Nernst} \): Thermodynamic potential of the cell representing its reversible voltage.

\( V_{Act} \): Voltage drop due to the activation of the anode and cathode. It is a measure of the voltage drop associated with the electrodes.

\( V_{Ohmic} \): Ohmic voltage drop resulting from the resistances of the conduction of protons through the solid electrolyte and the electrons through its path.

\( V_{Con} \): Voltage drop resulting from the reduction in concentration of the reactants gases or, alternatively, from the transport of mass of oxygen and hydrogen.
The thermodynamic potential ($E_{\text{Nernst}}$) represents the fuel cell open circuit voltage and the other three voltages, activation voltage drop ($V_{\text{Act}}$), ohmic voltage drop ($V_{\text{Ohmic}}$), and concentration voltage drop ($V_{\text{Con}}$) represent reductions in this voltage to supply the useful voltage across the cell electrodes, $V_{\text{FC}}$, as a function of the operating current.

### 4.3.2.1 Thermodynamic Potential/ Cell Reversible Voltage

$E_{\text{Nernst}}$ is calculated starting from a modified version of Nernst equation, with an extra term to take into account changes in temperature with respect to new standard temperature [54, 56] and is given by (4.6).

$$E_{\text{Nernst}} = \frac{\Delta G}{2F} + \frac{\Delta S}{2F} \left( T - T_{\text{ref}} \right) + \frac{RT}{2F} \left[ \ln \left( \frac{P_{\text{H}_2}}{P_{\text{H}_2}^\text{ref}} \right) + \frac{1}{2} \ln \left( \frac{P_{\text{O}_2}}{P_{\text{O}_2}^\text{ref}} \right) \right]$$

(4.6)

where:

- $\Delta G$ : Change in the free Gibbs energy (J/mol)
- $F$ : Constant of Faraday (96.487 C)
- $\Delta S$ : Change of the entropy (J/mol)
- $R$ : Universal constant of the gases (8.314 J/Kmol)
- $P_{\text{H}_2}$ : Partial pressures of hydrogen (atm)
- $P_{\text{O}_2}$ : Partial pressures of oxygen (atm)
- $T$ : Cell operation temperature (K)
- $T_{\text{ref}}$ : Reference temperature (K)
Using the standard pressure and temperature (SPT) values for \( \Delta G, \Delta S \) and \( T_{\text{ref}} \), (4.6) can be simplified to (4.7) [54, 56].

\[
E_{\text{Nernst}} = 1.229 - 0.85 \times 10^{-5} (T - 298.15) + 4.31 \times 10^{-5} \left[ \ln \left( P_{H_2} \right) + \frac{1}{2} \ln \left( P_{O_2} \right) \right]
\]  

(4.7)

### 4.3.2.2 Activation Voltage Drop

The activation voltage drop, which takes into account both the anode, and the cathode over-voltage, is given by (4.8) [54, 55]:

\[
V_{\text{act}} = - \left[ \xi_1 + \xi_2 \times T + \xi_3 \times T \times \ln \left( C_{O_2} \right) + \xi_4 \times T \times \ln \left( i_{FC} \right) \right]
\]  

(4.8)

where:

- \( i_{FC} \): Cell operating current (A).
- \( \xi \): Parametric coefficient of each cell model, which is calculated based on theoretical equations with kinetic, thermodynamic and electrochemical foundations.
- \( C_{O_2} \): Concentration of oxygen in the catalytic interface of the cathode (mol/cm\(^3\)). \( C_{O_2} \) can be determined by the given (4.9).

\[
C_{O_2} = \frac{P_{O_2}}{5.08 \times 10^6 \times e^{-\frac{498}{T}}}
\]  

(4.9)

### 4.3.2.3 Ohmic Voltage Drop

The ohmic voltage drop results from resistance to electron transfer through the collecting plates and carbon electrodes plus the resistance to proton transfer in the solid...
polymer membrane [54, 55]. This voltage drop can be represented using Ohm’s law and is given by (4.10).

\[ V_{Ohmic} = i_{FC} \times (R_c + R_M) \]  

where:

\( R_c \): Resistance to electron flow, which is usually considered constant over a relatively narrow temperature range of Polymer Electrolytic Membrane (PEM) fuel cell operation [55].

\( R_M \): Resistance to the flow of protons, which is given by (4.11).

\[ R_M = \frac{\rho_m l}{A} \]

where:

\( \rho_m \): Membrane specific resistivity to the flow of hydrated protons (Ohm.cm),

\( l \): Thickness of the polymer membrane (cm),

\( A \): Cell active area (cm²).

In this particular PEMFC model, membranes of the type Nafion® is considered, which is a registered trademark of Dupont and broadly used in PEM fuel cell. The numeric expression for the resistivity of the membranes Nafion given by (4.12) is used [54, 55].

\[ \rho_m = \frac{181.6 \left[ 1 + 0.03 \left( \frac{i_{FC}}{A} \right)^2 + 0.062 \left( \frac{T}{303} \right)^2 \left( \frac{i_{FC}}{A} \right)^{2.5} \right]}{\left[ T - 0.634 - 3 \left( \frac{i_{FC}}{A} \right) \right]^{4.18} \left( \frac{T - 303}{T} \right)} \]  

(4.12)
where:

$$181.6/(ψ -0.634) : \text{Specific resistivity at no current and at } 30^\circ\text{C (Ω cm).}$$

$$\exp [4.18\{(T-303)/T\}] : \text{Correction factor if the cell temperature is not at } 30^\circ\text{C.}$$

$$ψ : \text{Adjustable parameter with value ranging from 14 at 100% relative humidity conditions and 22-23 under super saturated conditions.}$$

4.3.2.4 Concentration Voltage Drop [54]

The mass transport affects the concentrations of hydrogen and oxygen. This reduces the partial pressures of these gases. Reduction in the pressures of oxygen and hydrogen depends on the electrical current and on the physical characteristics of the system. To determine the concentration voltage drop, the maximum current density ($J_{\text{max}}$) is defined, under which the fuel is being used at the same rate of the maximum supply speed. The current density cannot surpass this limit because the fuel cannot be supplied at a larger rate. Typical values for $J_{\text{max}}$ are in the range of 500 to 1500 mA/cm². The concentration voltage drop is given by:

$$V_{\text{con}} = -B \ln \left(1 - \frac{J}{J_{\text{Max}}} \right)$$

(4.13)

where:

B : Parametric coefficient (V),

J : Actual current density (A/cm²),

$J_{\text{Max}} : \text{Maximum current density (A/cm²).}$
4.3.3 Fuel Cell Power and Efficiency

The instantaneous electric power and efficiency of each fuel cell are given by equations (4.14) and (4.15), respectively [54]:

\[ P_{FC} = V_{FC} \times i_{FC} \]  \hspace{2cm} (4.14)

where:

\[ i_{FC} : \text{Cell operating current (A)}, \]
\[ V_{FC} : \text{Output voltage of the fuel cell for a given operating condition (V)}, \]
\[ P_{FC} : \text{Output power of each fuel cell (W)}. \]

\[ \eta = \mu_f \frac{V_{FC}}{1.48} \]  \hspace{2cm} (4.15)

where:

\[ \mu_f : \text{Fuel utilization coefficient, generally in the range of 95\%}. \]
\[ 1.48 : \text{Maximum voltage that can be obtained using higher heating value (HHV) for hydrogen enthalpy}. \]

4.3.4 Fuel Cell Modeling and Characteristics

Using equations (4.5) to (4.14) and the data sheet of the BCS 500W stack fuel cell obtained from [9, 12] the fuel cell model is simulated. The fuel cell used in this simulation is the 500 W PEM fuel cell manufactured by BCS Technologies. The parameters for this fuel cell are given in Table 4.2.
### Table 4.2: Parameters of 500W BCS stack [9]

<table>
<thead>
<tr>
<th>Param.</th>
<th>Value</th>
<th>Param.</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>n</td>
<td>32</td>
<td>$\xi_1$</td>
<td>-0.984</td>
</tr>
<tr>
<td>T</td>
<td>333 K</td>
<td>$\xi_2$</td>
<td>$0.00286+0.0002\times\ln A+(4.3\times10^{-5})\times\ln C_{H_2}$</td>
</tr>
<tr>
<td>A</td>
<td>64 cm$^2$</td>
<td>$\xi_3$</td>
<td>$7.6\times10^{-5}$</td>
</tr>
<tr>
<td>l</td>
<td>178 μm</td>
<td>$\xi_4$</td>
<td>$-1.93\times10^{-4}$</td>
</tr>
<tr>
<td>$P_{H_2}$</td>
<td>1 atm</td>
<td>$\psi$</td>
<td>23</td>
</tr>
<tr>
<td>$P_{O_2}$</td>
<td>0.2095 atm</td>
<td>$J_{\text{max}}$</td>
<td>469 mA/cm$^2$</td>
</tr>
<tr>
<td>B</td>
<td>0.016 V</td>
<td>$J_n$</td>
<td>3 mA/cm$^2$</td>
</tr>
<tr>
<td>$R_C$</td>
<td>0.0003 Ω</td>
<td>$I_{\text{max}}$</td>
<td>30 A</td>
</tr>
</tbody>
</table>

### 4.3.4.1 Characteristics

The characteristics of this fuel cell obtained from the manufacturer is given in Figure 4.10 [57].

![Figure 4.10: Stack performance data of 500 W BCS stack [57]](image-url)
Voltage-Current (V-I) and Power-Current (P-I) characteristics of the fuel cell obtained from the simulation are shown in Figure 4.11 and Figure 4.12 respectively. As can be seen from Figure 4.11 and Figure 4.12, these characteristics match quite well with the manufacturer data for most part of the curve except at the end of the simulation. This is due to the lack of determining the right parameter set for the fuel cell stack. Since the end results, i.e. data obtained after the peak power of 500 W and maximum current of 30 A, were not important for further simulations, hence this model was considered acceptable for this study.

![Simulated voltage-current characteristics of 500 W BCS stack](image)

**Figure 4.11: Simulated voltage-current characteristics of 500 W BCS stack**

It can be seen from the characteristics that the fuel cell voltage and thus efficiency (efficiency is directly proportional to voltage referring to equation (4.15)) are higher for lower values of stack current and lower for higher values of stack current. Hence it is up
to the designer to choose the most appropriate operating point for the fuel cell. Operating the fuel cell at higher currents will allow smaller cell size and hence lower cost for the cell stack, but it will reduce the efficiency due to reduction in the voltage as stated before [53].

![Simulated power-current characteristics of 500 W BCS stack](image)

**Figure 4.12: Simulated power-current characteristics of 500 W BCS stack**

At the same time one cannot work with a very high voltage and thus at a very high efficiency since the output power of the fuel cell will be greatly reduced at such points. Although the most logical operating point would be at maximum power, which is obtained at very high stack current, it must be noted that operations at peak power will cause instability in control because the system will have a tendency to oscillate between higher and lower currents near the peak [53].
It is a usual practice to operate the fuel cell to the left of the peak power at a point that yields a compromise between low operating cost i.e. high efficiency that occurs at high voltage/low current and low capital cost i.e. less cell area that occurs at low voltage/high current [53].

4.4 Hybrid System Description

The proposed hybrid system studied here is comprised of a 20 kW wind turbine generator, a 15 kW photovoltaic array and a 10 kW fuel cell. Individual step-up dc-dc converter is used to control each of the three sources. The individual dc-dc converters are in turn connected to a single PWM voltage source inverter, which holds the output voltages of all the converters at a fixed value by balancing input and output power of the dc links. All the energy sources are modeled using PSIM® software tool to analyze their dynamic behavior. The complete hybrid system is simulated for different operating conditions of the energy sources.

4.4.1 Power Electronics and Control

The successful implementation of such a hybrid energy system is greatly dependent on the design of suitable power electronics and their control. Power electronics will help to improve the efficiency of the system and also help in making it more reliable. In the next sections the power circuit topology and the control of the individual energy sources are explained.
4.4.1.1 Power Circuit Topology

The configuration of the proposed hybrid system consisting of a wind turbine and photovoltaic array as primary energy sources and fuel cell as backup energy source is shown in Figure 4.13. All three energy sources are connected in parallel to a common PWM voltage source inverter through their individual dc-dc converters.

![Figure 4.13: Configuration of hybrid energy system.](image)

In this system each source has its individual control; meanwhile, from the inverter point of view, all the three generating units can be replaced by a single unit having a total current of $I_{D1} + I_{D2} + I_{D3}$. To explain the main advantage of this circuit topology, let us focus on Fig. 16. Diodes $D_1$, $D_2$, and $D_3$ play the key role in the system. The diodes allow only unidirectional power flow, i.e., from the sources to the dc-link or the utility grid.
Therefore, in the event of malfunctioning of any of the energy sources, the respective diode will automatically disconnect that source from the overall system [30].

### 4.4.1.2 DC-DC Boost Converters and their Control

The basic structure and control topology of the dc-dc Boost converter are shown in Figure 4.14 and Figure 4.15, which were discussed in detail in chapter 2. As indicated earlier the three energy sources are connected to individual dc-dc converters and the outputs of the three dc-dc converters are then connected to a single three-phase inverter. The dc-dc converters apart from boosting the input dc voltage of the energy sources also help in the control of the individual sources.

![Boost converter circuit topology](image)

**Figure 4.14**: Boost converter circuit topology.

![Control algorithm of boost converter](image)

**Figure 4.15**: Control algorithm of boost converter for wind and photovoltaic sources.
In wind turbine and photovoltaic array, the inductor current of the dc-dc converter is controlled based on the error signal. For the wind turbine the error signal is the difference between the reference turbine speed obtained from MPPT and the actual speed. Similarly for the photovoltaic array this error is the difference between the reference voltage set by the MPPT algorithm and the actual measured voltage. The error is fed into a proportional integrator (PI) type controller, which controls the duty cycle of the dc-dc converters.

For the fuel cell system, the inductor reference current is calculated using a look-up table. The input of the look-up table is the difference between required power and summation of the power generated by the turbine and photovoltaic array. The difference between this reference current and the measured inductor current is fed to the PI controller to minimize the error. The control topology of boost converter for fuel cell is shown in Figure 4.16.

![Figure 4.16: Boost converter control topology for fuel cell.](image)

Since this system does not allow reverse power flow, because of step-up boost chopper, many generating units can be connected in parallel to one smoothing unit and inverter. However, this gives rise to current distortion and a lagging power factor.
4.5 Simulation Results

To prove the proposed hybrid system design with individual control, the complete system is simulated using PSIM® software. As mentioned earlier the three energy sources are accurately modeled in PSIM® so as to predict their actual characteristics. Table 4.3, Table 4.4, and Table 4.5 gives the specifications of the wind turbine, photovoltaic and fuel cell respectively used for the modeling and simulation.

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rated Power Output</td>
<td>20 kW</td>
</tr>
<tr>
<td>Rated Speed</td>
<td>211 r/min</td>
</tr>
<tr>
<td>Stator Connection winding</td>
<td>Star</td>
</tr>
<tr>
<td>Number of Rotor poles</td>
<td>36</td>
</tr>
<tr>
<td>Stator Phase Resistor</td>
<td>0.1764 Ω</td>
</tr>
<tr>
<td>Synchronous Inductance</td>
<td>4.24 mH</td>
</tr>
<tr>
<td>Rated Phase Current</td>
<td>35 A</td>
</tr>
<tr>
<td>Rated Phase Voltage</td>
<td>205 V</td>
</tr>
</tbody>
</table>

Table 4.3: Permanent magnet generator specifications.

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Photovoltaic Module Manufacturer</td>
<td>Shell</td>
</tr>
<tr>
<td>Type No.</td>
<td>SQ160-PC</td>
</tr>
<tr>
<td>Standard Irradiance level</td>
<td>1000 W/m²</td>
</tr>
<tr>
<td>Standard Operating Temperature</td>
<td>25°C</td>
</tr>
<tr>
<td>Rated Power of Each Module</td>
<td>160 W</td>
</tr>
<tr>
<td>No. of Cells in Each Module</td>
<td>72</td>
</tr>
<tr>
<td>Open Circuit Voltage of Each Module</td>
<td>43.5 V</td>
</tr>
<tr>
<td>Short Circuit Current of Each Module</td>
<td>4.9 A</td>
</tr>
<tr>
<td>No. of Modules Connected in Series</td>
<td>8</td>
</tr>
<tr>
<td>No. of Modules Connected in Parallel</td>
<td>10</td>
</tr>
<tr>
<td>Total Rated Power of PV System</td>
<td>15 kW</td>
</tr>
</tbody>
</table>

Table 4.4: Photovoltaic array specifications.
<table>
<thead>
<tr>
<th>Fuel Cell Stack Manufacturer</th>
<th>BCS</th>
</tr>
</thead>
<tbody>
<tr>
<td>No. of Cells in Each Stack</td>
<td>32</td>
</tr>
<tr>
<td>Rated Power of Each Stack</td>
<td>500 W</td>
</tr>
<tr>
<td>No. of Stacks Connected in Series</td>
<td>20</td>
</tr>
<tr>
<td>Total Rated Power of Fuel Cell</td>
<td>10 kW</td>
</tr>
</tbody>
</table>

Table 4.5: Fuel cell specifications.

Figure 4.17 shows the variation of power output of the three sources. The wind turbine output is assumed to be 10 kW initially and then it increases to 15 kW, due to changes in the wind speed as seen in Figure 4.17-a. Similarly, Figure 4.17-b shows that the photovoltaic system is generating 14 kW initially and then its power level drops to 7.5 kW with decrease in the irradiance level. The reference fuel cell power is calculated as the difference between the demand (25 kW for this simulation case) and the summation of the wind and photovoltaic powers. This reference power serves as an input to a look-up table which calculates the reference current of the boost converter connected to the fuel cell. Figure 4.17-c is a plot of the fuel cell output power, which varies with changes in the wind and photovoltaic output powers. Figure 4.17-d gives the total power output of the hybrid system. It can be seen that this output power is always maintained constant at the demand in spite of the fluctuations in the wind and photovoltaic power generations.
Figure 4.17: Generated power by wind turbine, photovoltaic, and fuel cell.

Figure 4.18 proves the concept of individual control of the sources. Figure 4.18-a, shows that the wind turbine speed is controlled accurately to track the maximum power. Similarly, Figure 4.18-b shows the effective control of the photovoltaic output voltage to
track the maximum power. Finally, Figure 4.18-c illustrates current control of the fuel cell to generate the deficit power.

![Graphs showing speed, voltage, and current](image)

Figure 4.18: Control of wind turbine, photovoltaic, and fuel cell.

### 4.6 Summary

This chapter explained a wind, photovoltaic and fuel cell hybrid energy system, designed to generate a continuous power irrespective of the intermittent power outputs from the wind and photovoltaic energy sources. The wind and photovoltaic systems are controlled to operate at their point of maximum power under all operating conditions.
The fuel cell is controlled so as to maintain a minimum power level of 10 kW. The simulation results show that:

- The dc-dc converters are very effective in tracking the maximum power of the wind and photovoltaic sources.
- The fuel cell controller responds efficiently to the deficit power demands.
- With both wind and photovoltaic systems operating at their rated capacity, the system can generate power as high as 35 kW and the fuel cell does not need to be utilized in such cases.
- The system is capable of providing a minimum power of 10 kW to the load even under worst climatic conditions, when the wind and photovoltaic energies are completely absent.

In addition, full modeling and simulation of photovoltaic cell and fuel cell were presented in this chapter.
CHAPTER 5

A NEW POWER CONVERSION SYSTEM FOR DISTRIBUTED ENERGY RESOURCES

5.1 Introduction

This chapter discusses a new approach to developing a Power Conversion System (PCS) for Distributed Energy Resources (DER). Many DER require the use of a PCS to develop useable electricity from an energy source. By reducing the cost of the PCS, significant overall DER cost reduction occurs that can result in increased DER penetration. This chapter discusses various aspects of a PCS design including inverter topology, power, control and power supply circuit designs, switching and protection equipment and thermal considerations. The critical objective of this design is to reduce cost through modularity, new thermal and packaging concepts and use of a low loss inverter technology. The following sections deal with the system description, control strategy, power loss calculations, thermal analysis, and experimental results.
5.2 DER Requirements and Applications

DER are energy sources that are located near the load. DER has received significant attention as a means to improve the performance of the electrical power system, provide low cost energy, and increase overall energy efficiency. By locating sources near the load, transmission and distribution costs are decreased and delivery problems mitigated. DER applications can relieve transmission and distribution assets, reduce constraints, increase energy efficiency, and improve power quality and reliability. DER systems maybe either be connected to the local power grid, as shown in Figure 5.1, or isolated from the grid in stand alone operation. DER technologies include wind turbines, photovoltaics, fuel cells, microturbines, combustion turbines, cogeneration, and energy storage systems.

Figure 5.1: A grid-connected DER system.
Many DER require the use of PCS to convert the energy source into useful electricity and provide requirements for power grid interconnection. Some DER requiring PCS are fuel cells, microturbines, and energy storage devices. Typically these sources develop a DC voltage that is applied to an inverter, which technology also provides opportunity for enhanced protection and operation without significant cost increase. Some of PCS applications including peak shaving, UPS, power conditioning, and variable voltage source are illustrated in Figure 5.2 to Figure 5.5.

![Figure 5.2: Peak shaving concept using PCS.](image)

![Figure 5.3 Uninterruptible power supply as a backup power source.](image)
DER penetration has not met expected levels due to high initial costs. The approach taken with this PCS design is to reduce cost through modularity and new thermal and packaging concepts. The design requires the use of a low loss inverter and adequate means to dissipate heat generated by the inverter. The basic building block is a 100 kW module that can be paralleled to obtain higher power ratings.

Another important feature of the design is to match the DC bus voltage to the required AC output voltage. In this instance a nominal 1000 V dc bus was chosen and 480 V output voltage to match typical distribution class transformers. The selection eliminates the need for expensive DC/DC converters and custom transformers.
5.3 PCS Characteristics and Features [61, 62]

The main characteristics and features of this new PCS are:

- Low cost PCS for the DER applications
- Selectable output voltage (480V/240V/208V) depending on the input DC voltage
- DC bus voltage range from 800-1600 V
- AC output current of 120 Arms for 100 kW PCS
- Efficiency around 98%
- Capable of operating in parallel
- Inject and sink active and reactive power from the system
- Reliable for all power system operations
- Capable of both indoor and outdoor operations
- Modular device facilitating bench-top assembly

In order to accomplish the above characteristics for the PCS, some new concepts are introduced in the design. A low cost transformer tank is used for the packaging of this system. The tank is filled with transformer oil, for efficient cooling. Low cost ac/dc bushings are to be used in the PCS and also expensive circuit breakers are eliminated in the design, to reduce the overall cost of this unit. The entire PCS is designed with four basic building blocks namely the inverter unit, the control circuit, the protection and switching devices (contactors and fuses) and the power/control cables. These four
building blocks can be easily assembled to build the complete PCS unit, thus making it a one tool, one person assembled unit and in turn reducing the assembly cost. Also a smart design is incorporated in the auxiliary power to supply the control board to make the system more reliable in case of ac power outage.

5.4 System Description

The block diagram of the PCS is shown in Figure 5.6. The inverter is a diode-clamped three-level voltage source, current controlled inverter. As stated earlier any dc source, like supercapacitors, photovoltaics, fuel cells, and batteries capable of producing a dc voltage can be connected to the input of the PCS. For a 100 kW PCS, a minimum voltage of 800 V must be available at the dc bus to obtain an ac output voltage of 480 V. The block diagram shows all the major components of the PCS. The system hardware can be broken down into four major components, namely the power circuit, the control circuit, the system power supply units and the switching & protection equipment.

Figure 5.6: Power conversion system block diagram.
The power circuit of the PCS is laid out on the power circuit board (PCB). For a three-level inverter, the power circuit board consists of 12 IGBTs mounted on a heat sink. The heat sink is one of the most crucial components in an inverter design. The main function of the heat sink is to provide a medium of heat dissipation from the semiconductor devices. As mentioned before this PCS design has a new cooling and packaging scheme. Unlike conventional two-level inverters, which are either air-cooled or water-cooled, this inverter is oil-cooled; hence the power circuit, containing the IGBTs mounted on the heat sink is placed in a transformer tank filled with mineral oil. Natural convection of oil is used to cool the inverter, in a manner similar to most distribution transformer.

The control circuit is the brain of the PCS and contains all the control and data acquisition hardware. It houses the Digital Signal Processors (DSP) which performs all the switching algorithms and also provides the active and reactive power control. The third major hardware component of the PCS is the Main Power Supply Board (MPSB). The MPSB accepts a 24 V supply line from which it subdivides into the necessary voltages to run the system components. The voltages generated are ±5 V and ±15 V. This board is battery backed up in case of power failure of the supply voltage. The switching and protection equipment consist of the line side contactor and the fuses.

To facilitate the use of the new thermal and packaging scheme explained above, the inverter losses needed to be minimized and also the heat distribution inside the tank should be very uniform. As a result a three-level inverter configuration was chosen over two-level. A three-level inverter for high power applications has some major advantages,
which are listed in section 5.5.2, over its two level counterpart. So if a three-level topology is selected for the same system, then we can obtain a major reduction in the total losses seen by the system.

5.5 Three-Level Inverters

5.5.1 Circuit Topology and Switching Scheme

Figure 5.7 shows the circuit diagram of a diode-clamped three-level inverter. The switching states of each phase of the inverter are listed in Table 5.1. There are three types of switching states positive (P), zero (O), and negative (N) in each phase; therefore, the number of switching states for the inverter is $3^3 = 27$.

<table>
<thead>
<tr>
<th>Switching Symbols</th>
<th>Switching States</th>
<th>Phase Voltage</th>
</tr>
</thead>
<tbody>
<tr>
<td>S$_{1x}$</td>
<td>S$_{2x}$</td>
<td>S$_{3x}$</td>
</tr>
<tr>
<td>P</td>
<td>On</td>
<td>On</td>
</tr>
<tr>
<td>O</td>
<td>Off</td>
<td>On</td>
</tr>
<tr>
<td>N</td>
<td>Off</td>
<td>Off</td>
</tr>
</tbody>
</table>

Table 5.1: Switching states and phase-voltage of the inverter.

Figure 5.7: Circuit topology of the three-level inverter.
Like in Sine-Δ PWM technique for a 2-level inverter, three sinusoidal signals $V_{\text{control},A}$, $V_{\text{control},B}$, and $V_{\text{control},C}$ that are 120° out of phase will be chosen as control signals. These signals are compared with two triangular carrier signals $V_{\text{tri}1}$ and $V_{\text{tri}2}$ to generate switching functions for the 12 switches in the inverter. Referring to Figure 5.8, when $V_{\text{control},A} > V_{\text{tri}1}$, $S_{1A}$ is on and $S_{3A}$ is off, and when $V_{\text{control},A} < V_{\text{tri}1}$, $S_{1A}$ is off and $S_{3A}$ is on. Likewise, when $V_{\text{control},A} > V_{\text{tri}2}$, $S_{2A}$ is on and $S_{4A}$ is off, and when $V_{\text{control},A} < V_{\text{tri}2}$, $S_{2A}$ is off and $S_{4A}$ is on. The other two phases will work in the same way. Figure 5.8 shows the principal operation of a three-level inverter for a modulation frequency of 15 and modulation index of 0.8.

Features of Sine-Δ PWM technique for three-level inverters can be summarized as follows [50]:

- The best results are obtained if the carrier signals $V_{\text{tri}1}$ and $V_{\text{tri}2}$ are in-phase and frequency of the carrier signals is an odd multiplication of three.

- Magnitude of fundamental line-to-line rms voltage is given by: $V_{\text{LL-1}} = 0.612m_a V_{\text{dc}}$

- The inverter is a bidirectional inverter, which means the power flow could be from dc bus to ac source and vice versa. Simulation results for this concept are shown in Figure 5.9, where commanded active power changes from 15 kW for discharging operation to 10 kW for charging the dc bus.

- Line-to-line voltage includes some undesirable harmonics which are:

$$\begin{cases} h = lm_r + k & l = 1, 3, 5, \ldots \quad \text{and} \quad k = 2, 4, 6, \ldots \quad h: \text{Harmonic Number} \\ h = lm_r - k & l = 2, 4, 6, \ldots \quad \text{and} \quad k = 1, 5, 7, \ldots \end{cases}$$
Figure 5.8: Operation of three-level inverter using Sine-Δ-PWM technique [58].

Figure 5.9: Bidirectional power flow for charging and discharging the dc source.
5.5.2 Comparison of Two-Level and Three-Level Inverters

Results from theoretical analysis and laboratory prototyping in the last decade have proven that for an inverter rated above 100kw with dc bus around 1000 volts, a three-level inverter shows substantial advantages over its 2 level counterpart. The main advantages of three-level inverter include [59]:

- Much reduced actual switching frequency and, thus, switching losses of an inverter for the same level of PWM performance; for example, inverter structure changing from 2 level to 3 level, switching frequency can be reduced to one quarter of that used in a 2 level inverter while the PWM performance remains the same.

- The less switching loss the higher efficiency, which will increase the overall system life and improve the performance.

- In a three level inverter the losses are more evenly distributed in double the number of IGBTs. This distribution of losses helps in eliminating the hot spots, enhances heat dissipation from the IGBTs, reduces the thermal gradient between the IGBT and heat sink and thus adds to thermal robustness.

- Suitability for utility applications; a multilevel inverter inherently features a power structure that uses small rating IGBTs to configure inverters of large size. Power electronics inverters for utility applications require the modular flexibility and scalability to match system voltage and power requirements.
• The harmonic contents are less than a two-level inverter at the same switching frequency and the blocking voltage of the switching device is half of the dc link voltage. So the three-level inverter topology is generally used for high performance and high voltage ac drive systems.

• The main disadvantage of a three-level inverter is the need of double the number of IGBTs and added complexity to the control algorithm compared to a two-level inverter.

5.6 Power Loss Calculations

In a three-level inverter for each switch there are two types of power losses, namely conductive and switching losses. Switching loss itself includes turn-on and turn-off losses.

5.6.1 Conduction Loss Calculations

Based on the sign of output voltage and current in the inverter, the switching state of each switch can be recognized as “ON” or “OFF”. As can be seen from Figure 5.10-b, there are six different cases as follows:

1. \( V_{\text{out}} > 0 \) & \( i_a > 0 \) then \( T_1(\text{ON}), T_2(\text{ON}) \)

2. \( V_{\text{out}} > 0 \) & \( i_a < 0 \) then \( D_1(\text{ON}), D_2(\text{ON}) \)

3. \( V_{\text{out}} = 0 \) & \( i_a > 0 \) then \( T_2(\text{ON}), D_5(\text{ON}) \)

4. \( V_{\text{out}} < 0 \) & \( i_a > 0 \) then \( D_3(\text{ON}), D_4(\text{ON}) \)
5. \( V_{\text{out}} < 0 \) & \( i_a < 0 \) then \( T_3(\text{ON}), T_4(\text{ON}) \)

6. \( V_{\text{out}} = 0 \) & \( i_a < 0 \) then \( T_3(\text{ON}), D_6(\text{ON}) \)

Figure 5.10: a) Schematic of one leg of the inverter b) Phase voltage & current.

On-state models for each switch, either transistor or anti-parallel diode, are shown in Figure 5.11.

Figure 5.11: On-state model for transistors and diodes

The instantaneous conduction power loss for diodes and transistors can be calculated as:

\[
P_{\text{Con,D}}(t) = V_D(t) \times I_D(t) = (V_{DO} + R_D \times I_D(t)) \times I_D(t)
\]  

(5.1)
\[ P_{\text{Con,T}}(t) = V_T(t) \times I_T(t) = (V_{TO} + R_T \times I_T(t)) \times I_T(t) \] (5.2)

Therefore, the average value of conduction power loss for each switch is:

\[ P_{\text{Con,D}} = \frac{1}{T} \int_T P_{\text{Con,D}}(t) \, dt = \frac{1}{T} \int_T \left[ (V_{DO} + R_D \times I_D(t)) \times I_D(t) \right] \, dt \] (5.3)

Finally, the total conduction losses can be calculated as:

\[ P_{\text{Con}} = \sum_{i=1}^{6} P_{Di} + \sum_{i=1}^{4} P_{Ti} \] (5.4)

### 5.6.2 Switching Loss Calculations [60]

The total switching losses can be calculated as the integration of all turn-on and turn-off energies at the switching instants.

\[ P_{\text{Sw,T}} = \frac{f_{\text{Sw}}}{T} \int_0^{T/2} \left[ E_{\text{on}}(t, I_m) + E_{\text{off}}(t, I_m) \right] \, dt \] (5.5)

The turn-on and turn-off energy dissipation per switching pulse can be found from the IGBT data sheets and are specified at nominal current \( I_{\text{nom}} \). However, the applied dc link voltages in a particular application may differ from the nominal dc voltage used in the loss calculation. In practice a linear adjustment of losses in a certain limit of nominal voltage is permissible. Thus, we have:

\[ E_{\text{Sw,T}}(I) = (E_{\text{on,T}}(I_{\text{nom}}, V_{\text{nom}}) + E_{\text{off,T}}(I_{\text{nom}}, V_{\text{nom}})) \frac{I}{I_{\text{nom}}} \times \frac{V_{dc}}{V_{\text{nom}}} \] (5.6)
To calculate the total switching losses of the IGBT the switching energies needs
to be summed:

\[
P_{Sw,T} = \frac{1}{T} \sum_{n} E_{Sw,T}(I_{n}) \quad (5.7)
\]

The number of switching per period “T” is assumed to be “n”. An approximated solution
for the IGBT switching losses for a phase leg current can be found using:

\[
P_{Sw,T} = \frac{f_{Sw}}{\pi} \left( E_{on,T}(I_{nom}, V_{nom}) + E_{off,T}(I_{nom}, V_{nom}) \right) \frac{I_{m}}{I_{nom}} \times \frac{V_{dc}}{V_{nom}} \quad (5.8)
\]

The diode switching losses can then be calculated similar to the IGBT loss
calculations. The turn-on losses can be neglected in case of a diode, and hence
considering only the turn-off losses:

\[
P_{Sw,D} = \frac{f_{Sw}}{\pi} E_{off,D}(I_{nom}, V_{nom}) \frac{I_{m}}{I_{nom}} \times \frac{V_{dc}}{V_{nom}} \quad (5.9)
\]

5.6.3 Power Loss Simulation [61]

The total losses in the three-level inverter were simulated using Eupec’s
simulation software IPOSIM. The specifications used for this simulation are as below:

IGBT Specification:

Manufacturer: Eupec

Model No: FF400R17KE3_B2

Collector Emitter Voltage: 1700 V
DC Collector Current: 400 A

Maximum Junction Temperature: 125°C

100 kW PCS Specifications:

DC Link Voltage: 800-1600 V

Output ac Voltage: 480 V

RMS Current: 120 A

Frequency: 60 Hz

The total conduction and switching losses for the three-level inverter, i.e. for 12 IGBTs plus 18 diodes, for a given dc bus voltage range are tabulated in Table 5.2.

<table>
<thead>
<tr>
<th>DC Link Voltage (V)</th>
<th>800</th>
<th>900</th>
<th>1000</th>
<th>1100</th>
<th>1200</th>
<th>1300</th>
<th>1400</th>
<th>1500</th>
<th>1600</th>
</tr>
</thead>
<tbody>
<tr>
<td>IGBT Switching Losses [W]</td>
<td>194</td>
<td>219</td>
<td>243</td>
<td>264</td>
<td>288</td>
<td>312</td>
<td>336</td>
<td>360</td>
<td>384</td>
</tr>
<tr>
<td>Diode Switching Losses [W]</td>
<td>176</td>
<td>198</td>
<td>228</td>
<td>240</td>
<td>264</td>
<td>288</td>
<td>312</td>
<td>336</td>
<td>360</td>
</tr>
<tr>
<td>Total Conduction Losses [W]</td>
<td>924</td>
<td>924</td>
<td>924</td>
<td>924</td>
<td>924</td>
<td>924</td>
<td>924</td>
<td>924</td>
<td>924</td>
</tr>
<tr>
<td>Total Switching Losses [W]</td>
<td>371</td>
<td>417</td>
<td>471</td>
<td>504</td>
<td>552</td>
<td>600</td>
<td>648</td>
<td>696</td>
<td>744</td>
</tr>
<tr>
<td>Total Losses [W]</td>
<td>1294</td>
<td>1341</td>
<td>1395</td>
<td>1428</td>
<td>1476</td>
<td>1524</td>
<td>1572</td>
<td>1620</td>
<td>1668</td>
</tr>
</tbody>
</table>

Table 5.2: Simulation results for three-level inverter losses.

The total losses vary from 1.3 kW to 1.7 kW, where it varies from 2.4 kW to 3.2 kW for a two-level inverter [61]. Therefore, simulation results confirmed that the losses are reduced for the three-level inverter as discussed earlier. The dc bus voltage for the three-level inverter is 800-1600 V; hence an inductor of 1mH can be used to connect the
The inductor losses will be 700 W for worst case as before; therefore, the total losses in the three-level inverter varies from 2 kW to 2.4 kW.

The accuracy of the simulation results was verified using a 20 kW experimental set-up. The results obtained from this experiment are provided in Table 5.3 The total conduction and switching losses for the three-level inverter, i.e. for 12 IGBTs plus 18 diodes, for a given dc bus voltage of 600 V are tabulated in Table 5.3.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>(kHz)</td>
<td>(A)</td>
<td>(V)</td>
<td></td>
<td>(W)</td>
<td>(W)</td>
<td>(%)</td>
<td>(%)</td>
<td>(%)</td>
</tr>
<tr>
<td>10</td>
<td>33.3</td>
<td>603</td>
<td>0.8</td>
<td>441</td>
<td>444</td>
<td>97.8</td>
<td>97.8</td>
<td>0.68</td>
</tr>
<tr>
<td>4</td>
<td>9.52</td>
<td>581</td>
<td>0.8</td>
<td>89</td>
<td>96</td>
<td>98.6</td>
<td>98.35</td>
<td>7.87</td>
</tr>
<tr>
<td>2</td>
<td>9.35</td>
<td>562</td>
<td>0.8</td>
<td>66</td>
<td>61</td>
<td>98.9</td>
<td>99.01</td>
<td>7.58</td>
</tr>
<tr>
<td>1</td>
<td>9.11</td>
<td>537</td>
<td>0.8</td>
<td>51</td>
<td>48</td>
<td>99.1</td>
<td>99.12</td>
<td>5.88</td>
</tr>
</tbody>
</table>

Table 5.3: Simulation vs. experimental results.

As can be seen from Table 5.3, the experimental loss measurements correlate well with the simulated loss measurements. On an average, we were able to simulate the losses of the switches to within 7%, which is quite accurate.

5.7 Experimental Results

Having simulated the total losses for the PCS, a test set up was prepared to validate the new packaging and cooling scheme. 12 IGBTs were mounted on a heat sink as shown in Figure 5.12 and this assembly was immersed in a transformer tank filled with mineral oil. The test specifications are as below:
IGBTs:

Modules: Toshiba (MG150Q2YS51)

Collector Emitter Voltage: 1200 V

DC Collector Current: 200 A

Mineral Oil:

Dielectric Strength = 45 kV/cm

Flash Point = 147 deg C

Fire Point = 165 deg C

Transformer Tank:

Standard 300 KVA, 480 V / 12.47 kV transformer tank

Fins on Three Sides

Figure 5.12: IGBT-heatsink assembly for thee-level inverter.
The transformer tank used in this experiment is shown in Figure 5.13. From the loss simulation it was estimated that the total losses for the three-level inverter would be in the range of 2-2.4 kW, hence this amount of losses was generated in the set-up. Thermocouples were placed at different locations of the set up as shown in Figure 5.14.

Figure 5.13: Standard 300 kVA transformer tank.

Figure 5.14: Thermocouple locations for the test set-up.
Figure 5.15 shows the temperatures recorded by each of the thermocouples. The topmost plot is the temperature recorded at the base of the IGBTs, which is approximately 90°C. Adding another 17°C, for temperature gradient between the base and junction of IGBT, to calculate the temperature at the junction of the IGBTs, results in 107°C junction temperature. This temperature is much below the maximum allowable junction temperature of 125°C.

Figure 5.15: Temperature profile of the test set-up.

A thermal camera was used to study the temperature profile of the entire PCS assembly during the test. Figure 5.16 shows that the heat is very evenly distributed in the transformer tank. This proves the effectiveness of the cooling scheme in eliminating the hot spots and that natural convection is sufficient to cool the entire assembly.
5.8 Principal Operation of VSI’s Connected to Power System Grid

5.8.1 Limitation on Reactive Power Control

The output voltage of the voltage source inverter, shown in Figure 5.7, includes a fundamental component and a series of undesired harmonics. Let us assume that the output voltage is a pure sinusoidal waveform; in other words, ignore the harmonics. Therefore, the magnitude of the output voltage is equal to the magnitude of the fundamental component.

In the linear operation region, modulation index less than one \((0 < m_a \leq 1)\), the fundamental component of the inverter phase voltage satisfies [59]:

\[
V_{inv} = m_a \frac{V_{dc}}{2}
\]  

(5.10)
To further increase the amplitude of the output voltage, the over-modulation operation region can be used by increasing the modulation index to more than one, which results in (5.11), which indicates that the maximum of fundamental line-to-neutral output voltage is $2V_{dc}/\pi$.

$$\frac{V_{dc}}{2} < V_{inv} \leq \frac{4}{\pi} \times \frac{V_{dc}}{2}$$

(5.11)

Figure 5.17 shows a simplified equivalent circuit of grid connected voltage source inverter. As mentioned, “$V_{inv}$” is the fundamental component of the output phase-to-neutral voltage of the inverter. Moreover, phasor diagrams of the system for lagging and leading operation are given in Figure 5.18.

![Figure 5.17: Simple equivalent circuit of grid connected VSI.](image)

Figure 5.17: Simple equivalent circuit of grid connected VSI.

![Figure 5.18: Phasor diagram of system for (a) lagging operation, (b) leading operation.](image)

Figure 5.18: Phasor diagram of system for (a) lagging operation, (b) leading operation.
Based on Figure 5.17, the inverter can be treated as a synchronous machine: therefore, equations of active and reactive power in generation mode can be derived as follows [24-26, 66]:

\[ P_s = P_{\text{inv}} = \frac{V_s V_{\text{inv}}}{X_s} \sin \delta \] (5.12)

\[ Q_s = \frac{V_s V_{\text{inv}}}{X_s} \cos \delta - \frac{V_s^2}{X_s} \] (5.13)

\[ Q_{\text{inv}} = \frac{V_{\text{inv}}^2}{X_s} - \frac{V_s V_{\text{inv}}}{X_s} \cos \delta \] (5.14)

Eliminating “\( \delta \)” between (5.12) and (5.13), the locus of \( P_s - Q_s \) can be derived as follow:

\[ P_s^2 + \left( Q_s + \frac{V_s^2}{X_s} \right)^2 = \left( \frac{V_s V_{\text{inv}}}{X_s} \right)^2 \] (5.15)

Figure 5.19 shows the locus of \( P_s - Q_s \), which is a circle with the center of \( \left( 0, -\frac{V_s^2}{X_s} \right) \) and a radius of \( V_s V_{\text{inv}} / X_s \). As can be seen from the figure, the radius of the circle depends on \( V_{\text{inv}} \). Solving equation (5.15) for \( Q_s \) results in:

\[
Q_s = \begin{cases} 
Q_{S1} = \sqrt{\left( \frac{V_s V_{\text{inv}}}{X_s} \right)^2 - P_s^2 - \frac{V_s^2}{X_s}} \\
Q_{S2} = -\sqrt{\left( \frac{V_s V_{\text{inv}}}{X_s} \right)^2 - P_s^2 - \frac{V_s^2}{X_s}}
\end{cases}
\] (5.16)
Considering $V_S$ and $X_S$ are constant, for a given $P_S$ the maximum reactive power for lagging operation is $Q_{S1}$ when $V_{inv}$ has its maximum value, given in equation (5.11). Similarly, the maximum reactive power for leading operation is $Q_{S2}$. A special case is $P_S=0$, in this case points A and B in Figure 5.19 represent the maximum values of reactive power for lagging and leading operations, respectively.

To summarize the discussion, there are several limitations on reactive power control for both lagging and leading operations, which are:

- DC bus voltage size ($V_{inv}$ is a function of $V_{dc}$).
- The amount of active power injected to utility grid referring to (5.16).
- Current rating of switches used in the voltage source inverter, because by increasing reactive power the apparent power will increase, which causes phase current to increase.
5.8.2 Simulation Results

Let assume that the inverter is connected to a 480 volts grid through a 10 mH inductor. The injected power is set to \( P_S = 0 \) kW and dc-link voltage is 810 volts. To calculate the maximum limitation of \( Q_{S1} \) and \( Q_{S2} \), we need to calculate the maximum output phase voltage of the inverter:

\[
V_{inv} = \frac{\sqrt{2}}{\pi} V_{dc} = \frac{\sqrt{2}}{\pi} \times 810 = 364.6 \text{ volts}
\]

\[
X_S = \omega L = 2\pi \times 60 \times 0.01 = 3.77 \Omega
\]

\[
V_S = \frac{480}{\sqrt{3}} = 277.1 \text{ volts}
\]

\[
\begin{align*}
Q_{S1} &= 3 \times \left( \frac{V_S V_{inv}}{X_S} - \frac{V_S^2}{X_S} \right) = 3 \times \frac{V_S}{X_S} (V_{inv} - V_S) = 19.3 \text{ kvar} \\
Q_{S2} &= 3 \times \left( -\frac{V_S V_{inv}}{X_S} - \frac{V_S^2}{X_S} \right) = 3 \times \frac{V_S}{X_S} (-V_{inv} - V_S) = 141.5 \text{ kvar}
\end{align*}
\]

Based on above calculation, in lagging operation reactive power can be injected into the grid by the inverter up to 19.3 kvar, beyond that the inverter can no longer control active and reactive power. Simulation results for lagging operation are shown in Figure 5.20. As can be seen from the simulation results, when the commanded reactive power changes from 19 kvar to 23 kvar, the inverter looses control over active and reactive power injection. The same results are shown in Figure 5.21 for leading operation. In this case, there is no control on active and reactive power, when the commanded reactive power changes from 140 kvar to 145 kvar.
Figure 5.20: Lagging P.F. operation.

Figure 5.21: Leading P.F. operation.
5.8.2 Inverter’s Modes of Operation

Like in a synchronous machine, considering equations (5.12) and (5.13), the inverter can operate in four different operational modes which are:

- $P_{\text{inv}} > 0$ and $Q_{\text{inv}} > 0$, Generating mode of a synchronous machine operating at under excitation; in other words, operating in inverter mode with lagging power factor, which discharges the dc source.

- $P_{\text{inv}} > 0$ and $Q_{\text{inv}} < 0$, Generating mode of a synchronous machine operating at over excitation; in other words, operating in inverter mode with leading power factor, which discharges the dc source.

- $P_{\text{inv}} < 0$ and $Q_{\text{inv}} > 0$, Motoring mode of a synchronous machine operating at under excitation; in other words, operating in rectifier mode with lagging power factor, which charges the dc source.

- $P_{\text{inv}} < 0$ and $Q_{\text{inv}} < 0$, Motoring mode of a synchronous machine operating at over excitation; in other words, operating in rectifier mode with leading power factor, which charges the dc source.

5.9 Summary

From the simulations and thermal test carried out on the 100 kW, three-level PCS design it was concluded that:

- The 3-level PCS can be designed for a dc bus voltage range of 800-1600 V.
- Output AC voltage will be 480V and rms current 120 A.
• To dissipate a total loss of 2 kW a standard 300 kVA transformer tank with fins on three sides can be used.

• The estimated amount of oil required to cool such a system is less than 100 gallons.

Detail limitations on reactive power control and operation modes of inverter were discussed in this chapter.
CHAPTER 6

SUMMARY

This research presents important aspects of designing a power electronic interface for wind energy and hybrid generating systems. The specific goals of this study, based on chapters 2 to 5, can be summarized as follows:

- Developing accurate models for alternate energy sources, such as wind turbine, photovoltaic, and fuel cells to form a hybrid energy system.
- Offering a low cost wind energy system using permanent magnet generator and dc-dc boost converter.
- Introducing a simple generator speed control method using boost converter for maximum power tracking in wind turbine application.
- Suggesting a new speed estimator to eliminate speed sensor and so reducing cost which is very important in small size wind turbines.
- Investigation of a new vector control approach for a single phase voltage source inverter in wind energy applications.
- Proposing a new circuit topology for a hybrid energy system, including wind/photovoltaic/fuel cell, used in distributed energy application.

- Developing a new power conversion system to reduce the overall cost of hybrid energy systems.

The most significant accomplishments of this dissertation can be summarized as follow:

- Simulated characteristics of the photovoltaic module and fuel cell unit, based on the offered models, were in good agreement with manufacturer data sheet.

- The proposed power electronics interface and control algorithm for maximum power tracking was verified by simulation results in chapter 2. Using only one switching device in the dc-dc converter along with the fact that there is no copper loss in the stator of the permanent magnet generator, ensures higher efficiency and lower cost in the wind energy system.

- Accuracy and effectiveness of proposed speed estimator and vector control of single phase inverter were verified by simulation and experimental results in chapter 3.

- Simulation results in chapter 4 proved the operating principle, feasibility, and reliability of the proposed hybrid wind/photovoltaic/fuel cell energy system.

- Experimental and simulation results in chapter 5 validated the cooling and packaging concepts proposed by power conversion system.
Based on this dissertation, there are several topics for further investigation on design, control, and implementation of power electronic interface for small-scale wind turbine and hybrid systems, these include:

- Loss minimization of the permanent magnet generator by improving the power factor of machine, using a new control approach to manage the boost chopper for line current wave shaping.

- Usage of energy storage device, such as batteries or supercapacitors to improve dc-link performance and smooth out the variation of supply energy during calm periods in wind energy systems.

- As for new power conversion system, future work should be directed towards a more detailed cost analysis and developing IEEE 1547 and UL 1741 compliances for connecting the hybrid system to utility grid.

- Investigation of control algorithm for extending the constant power speed range for the permanent magnet generator in high power wind turbine.

- Investigation of active-damping concept in a wind turbine system based on power electronics interface.
APPENDIX A

A.1 Dynamic Modeling of Permanent Magnet Generator

The basic 2-pole permanent magnet machine model is shown as Figure A.1. The d-axis is aligned with the N-pole of the rotor and q-axis is 90 degree apart from d-axis. The flux linkage equations of the permanent magnet machine are [26] appendix:

\[
\begin{align*}
\left[ \lambda_{as}, \lambda_{bs}, \lambda_{cs} \right] &= \begin{bmatrix} L_{aa} & L_{ab} & L_{ac} \\ L_{ba} & L_{bb} & L_{bc} \\ L_{ca} & L_{cb} & L_{cc} \end{bmatrix} \begin{bmatrix} i_{as} \\ i_{bs} \\ i_{cs} \end{bmatrix} + \left[ \lambda_{asm}, \lambda_{bsm}, \lambda_{csm} \right] = \begin{bmatrix} L_{aa} & L_{ab} & L_{ac} \\ L_{ba} & L_{bb} & L_{bc} \\ L_{ca} & L_{cb} & L_{cc} \end{bmatrix} \begin{bmatrix} i_{as} \\ i_{bs} \\ i_{cs} \end{bmatrix} + \lambda_m \\
&= \begin{bmatrix} \cos \theta \\ \cos(\theta - \frac{2}{3} \pi) \\ \cos(\theta + \frac{2}{3} \pi) \end{bmatrix} \\
\end{align*}
\]  

(A.1)

Where the \( \lambda_{asm}, \lambda_{bsm} \) and \( \lambda_{csm} \) are flux linkages created by the permanent magnet.

As for the self-inductance,

\[
L_{aa} = L_{ls} + L_{qs} + L_{2s} \cos(2\theta) \quad \text{(A.2)}
\]

\[
L_{bb} = L_{ls} + L_{qs} + L_{2s} \cos(2\theta - \frac{2}{3} \pi) \quad \text{(A.3)}
\]

\[
L_{cc} = L_{ls} + L_{qs} + L_{2s} \cos(2\theta + \frac{2}{3} \pi) \quad \text{(A.4)}
\]
Where:

$L_{is}$ is the additional component due to the armature leakage flux;

$L_{0s}$ is self inductance due to the space fundamental air gap flux;

$L_{2s}$ is the component due to rotor position dependent flux.

When transferred from the abc reference frame to the dq frame, the d-axis and q-axis inductance are:

$$L_{md} = \frac{3}{2}(L_{0s} + L_{2s})$$  \hspace{1cm} (A.5)

$$L_{mq} = \frac{3}{2}(L_{0s} - L_{2s})$$  \hspace{1cm} (A.6)

$$L_{ds} = L_{is} + L_{md}$$  \hspace{1cm} (A.7)
In dq reference frame, the voltage equations can be written as [26]

\[
\begin{bmatrix}
V_{ds} \\
V_{qs}
\end{bmatrix} =
\begin{bmatrix}
R_s + pL_{sd} & -\omega L_{s}\omega \\
\omega L_{sd} & R_s + pL_{sq}
\end{bmatrix}
\begin{bmatrix}
i_{ds} \\
i_{qs}
\end{bmatrix} +
\begin{bmatrix}
0 \\
\omega \lambda_m
\end{bmatrix} \tag{A.9}
\]

The expression for electromagnetic torque in rotating dq reference frame may be written as [26]

\[
Te = \left( \frac{3}{2} \right) \left( \frac{P}{2} \right) \left[ \lambda_m^{*} i_q + \left( L_d - L_q \right) i_{d} i_{d}^{*} \right] \tag{A.10}
\]

Where, \( P \) is the number of magnetic poles of the permanent magnet machine.

For a nonsalient pole machine d-axis and q-axis inductance are equal, so if we assume \( L_d = L_q = L_{ss} \) the voltage and torque equations can be written as follows:

\[
\begin{bmatrix}
V_{ds} \\
V_{qs}
\end{bmatrix} =
\begin{bmatrix}
R_s + pL_{ss} & -\omega L_{ss} \\
\omega L_{ss} & R_s + pL_{ss}
\end{bmatrix}
\begin{bmatrix}
i_{ds} \\
i_{qs}
\end{bmatrix} +
\begin{bmatrix}
0 \\
\omega \lambda_m^{*}
\end{bmatrix} \tag{A.11}
\]

\[
Te = \left( \frac{3}{2} \right) \left( \frac{P}{2} \right) \left[ \lambda_m^{*} i_q \right] \tag{A.12}
\]
BIBLIOGRAPHY


[57] http://bcfuelcells.com


