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**Analysis of Current Control of a Unity Power Factor Rectifier in a
Standalone Wind Energy Conversion System feeding a DC Bus**

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A thesis submitted to the Nanyang Technological University in partial
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*Dedicated to my father R.Venkataraman, mother Jayanthi Venkataraman, sister
Neeraja Venkataraman and grandmother Kachi.*

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Abbreviations

WECS	Wind Energy Conversion System
MPPT	Maximum Power Point Tracking
PMSG	Permanent Magnet Synchronous Generator
PSO	Particle Swarm Optimization
ENB	Energy Neutral Building
ACC	Average Current Control
HCC	Hysteresis Current Control
WBCSD	World Business Council for Sustainable Development
IEA	International Energy Agency
ASD	Adjustable Speed Drive
PF	Power Factor
EMF	Electromotive force
UPF	Unity Power Factor
THD	Total Harmonic Distortion
TDD	Total Demand Distortion
PFC	Power Factor Correction
TSR	Tip Speed Ratio
OTC	Optimum Torque Controller
PSF	Power Signal Feedback
P&O	Perturb and Observe
HCS	Hill Climbing Search

Notations

I. Notations used in PMSG d-q model (Figure 2.05)

e_a, e_b, e_c	Phase to neutral electromotive force of the PMSG generator machine (V)
V_{an}, V_{bn}, V_{cn}	Phase to neutral terminal voltage of PMSG (V)
i_a, i_b, i_c	Phase currents of PMSG (A)
R_s	Stator resistance of the PMSG (Ω)
L_a	Phase inductance of the PMSG (mH)
Ψ_{pm}	Magnetic flux produced by the magnets of the PMSG (Wb)
Ψ_{sd}, Ψ_{sq}	d and q components of PMSG stator induced flux
u_{sd}, u_{sq}	PMSG stator terminal d-q voltages (V)
i_{sd}, i_{sq}	PMSG stator d-q currents (A)
L_d, L_q	PMSG stator d-q inductances (mH)

II. Notations used in lead-acid battery model (Figure 2.11)

Q_{bat}	Lead acid battery charge (C)
SOC	State of Charge of the lead-acid battery (%)
R_{sd}	Self-discharge resistance of the lead-acid battery (Ω)
$I_{peak, DCDC}$	Peak-current of solid-state switch in bidirectional DC-DC converter (A)
$V_{peak, DCDC}$	Peak-voltage of solid-state switch in bidirectional DC-DC converter (V)

III. Notations used in Unity Power Factor UPF Rectifier (Chapter 3)

T_s	Time period of ramp signal in Average Current Control (ms)
A	Mean duty cycle of the Average Current Control

S_x	Bidirectional switch switching signal
i_x^*	Reference current signal sine template (A)
h	Hysteresis bandwidth (A)

IV. Notations used for dynamic performance analysis of UPF converter (Chapter 4)

I_s	RMS current (A)
I_{dis}	Distortion current component (A)
I_{s1}	Fundamental rms component (A)
I_{sh}	Rms h order harmonic component (A)
THD	Total Harmonic Distortion (%)
TDD	Total Demand Distortion of line currents

V. Notations used in simulation model of wind energy conversion system

1) Wind Turbine Simulation model

C_p	Coefficient of performance of the wind turbine
λ	Tip-speed ratio of wind turbine
TSR	Tip-speed ratio of wind turbine
λ_{opt}	Optimum tip-speed ratio of wind turbine
$C_{p,max}$	Maximum coefficient of performance of wind turbine
ρ	Air density (kg/m^3)
ω_m	Rotor mechanical speed (rad/s)
R	Radius of wind turbine (m)
T_m	Wind turbine torque (N-m)

V	Wind linear velocity (m/s)
V_{rated}	Base wind speed (m/s)
P_m	Mechanical wind turbine power (kW)

2) Permanent Magnet Synchronous Generator Simulation Model

P_o	Nominal output power (kW)
ω_{rated}	Base rotational speed (rpm)
P	Number of poles
R_a	Armature resistance (Ω)
$V_{\text{pk}}/\text{krpm}$	Peak voltage per 1000 rpm (V/krpm)

3) Lead acid battery bank simulation Model

C_{bat}	Open circuit battery capacitance (F)
R_{sd}	Self-discharge resistance of battery ($k\Omega$)
$R_{\text{ic}}, R_{\text{id}}$	Charging and discharging resistance of battery ($m\Omega$)
$R_{\text{oc}}, R_{\text{od}}$	Over-charging and over-discharging resistance of battery ($m\Omega$)
C_o	Over-charging/discharging capacitance (F)

4) UPF converter simulation model

G	Virtual conductance (Ω^{-1})
V_{dc}	Dc-link voltage (V) of the wind energy conversion system
P_e	PMSG electrical power (kW)
P_{dc}	DC link electrical power (kW)
P_{bat}	Battery power (kW)

C_a, C_b UPF rectifier dc-link capacitance (F)

5) Static and Dynamic Particle Swarm Optimization simulation model

$\vec{x}$ Particle position for the PSO method

$\vec{v}$ Particle velocity for the PSO method

P_{best} Local best particle position of PSO algorithm

G_{best} Global best particle position of PSO algorithm

c_1, c_2 Cognitive and social coefficients of PSO algorithm

ω Weightage of the PSO algorithm

n_{max} Maximum number of iterations

Abstract

A stand-alone isolated wind energy conversion system (WECS) is comprised of a wind turbine, a mechanically coupled generator, a power electronic converter, a battery system and the electric load. Such a system does not have a connection to the utility grid. Traditionally, a diode rectifier is used to convert the generator AC output voltage to a DC voltage in order to connect to a DC-bus, which is interfaced with DC loads and the battery system. However, owing to their nonlinear switching nature, diode-bridge rectifiers inject harmonic components into the system, at the interface point, leading to an increased total harmonic distortion (THD) of generator current, which leads to increased AC side losses leading to heating, equipment malfunction and reduced utilization efficiency of the WECS system. To mitigate these power quality issues, a unity power factor (UPF) rectifier scheme is explored as a suitable alternative in place of the fixed diode rectifier structure, as the front end AC-DC converter for the wind energy conversion system.

In this thesis, the focus is on developing a novel current control strategy for the modified Unity Power Factor Rectifier in a standalone wind energy conversion system, that ensures high-power factor operation and low current harmonics at the rectifier AC side, as well as the extraction of maximum mechanical power from the wind turbine (maximum power point tracking). The parameters under study are the input Power Factor (PF), Total Harmonic Distortion (THD) of the AC input currents to the AC-DC converter and the coefficient of performance (C_p) for the wind turbine. A wind-turbine interfaced permanent magnet synchronous generator (PMSG) and a unity power factor current-controlled rectifier are modelled in the PSIM[®] software environment, to validate the performance of the proposed new WECS topology using the UPF AC-DC rectifier converter.

Firstly, two current control methods were tested, the Average Current Control and Hysteresis Current Control, are employed using the UPF rectifier as the front end converter, to test their effectiveness in meeting the system objectives. A traditional diode bridge rectifier without the current control is used as the base case front-end converter to compare the performance with the UPF rectifier AC-DC converter. The performance of the UPF rectifier AC-DC converter is tested for constant wind speed conditions as well as for varying wind speed profile under rated load.

In addition to high power factor operation, the power electronic converter must also maximize the power extracted from the wind turbine. A maximum power point tracking (MPPT) algorithm, based on Perturb and Observe and a modified Hill Climbing Search technique, is included in the current control to facilitate maximum power tracking. Rotor-speed control of the wind-turbine is performed using a unique combination of maximum power tracking using Particle Swarm Optimization (PSO) technique and power factor correction. Dynamic and steady state operations are investigated in PSIM[®] software environment which validates the performance of the current-controlled Unity Power Factor Rectifier Converter.

Finally, the performance of the MPPT is further improved by utilizing the PSO algorithm approach using a static PSO algorithm for constant wind speeds and dynamic PSO algorithm for varying wind speeds operations. The combined current control algorithm with Hysteresis Current Control and PSO is validated for excellent dynamic performance in meeting the operational system objectives, viz. maximum power point tracking, Unity Power Factor Control and reduced total harmonic distortion of input line AC side currents.

The UPF rectifier AC-DC converter is therefore capable of maximum power extraction from the wind turbine system for a wide range of wind speed variations while maintaining higher

power factor operation at AC side, good voltage reference tracking and reduced switching voltage stress. It is proposed as an efficient AC-DC converter for operation in a stand-alone WECS.

Chapter 1 Introduction

1.1 Motivation

World Business Council for Sustainable Development (WBCSD) foresees building energy as one of the areas where major changes were needed to transform energy efficiency. According to the International Energy Agency (IEA) the avenue of energy demand in buildings will represent up to 50% of the energy-related investments by the year 2030 [1]. If recommended energy efficiency measures are incorporated at the building-design stage, energy savings can range between 40 to 50%. For existing buildings, the potential can be as high as 20-25% which can be achieved by implementing demand control and retrofitting measures [2].

One key aspect of modern-day renewable and alternate energy emphasis is the concept of an Energy Neutral Building (ENB). Such a building will meet its regulated energy demand from alternative and renewable sources, except for some large loads such as pump/lift motors. Hence, its major power consumptions from the electric utility can be reduced through efficiency enhancement measures so that power saved from the alternatives can be returned to the electric utility when possible.

In comparison to the other renewable energy sources, the yearly installed capacity of wind energy is fast growing. According to the Renewables 2011 global report, eighty three nations commercially employed wind power [3]. By 2012, several countries had already achieved relatively high levels of wind energy penetration, such as Denmark with 34%, Portugal, Spain and Ireland with a 20% each and the USA with only 4.5 % penetration [4]. In 2014, a record high wind penetration level of 39.2 % was set at Denmark at the Anholt wind farm [5].

The energy required to operate the electric motors, compressors and lifts that employ AC type motors, form about 62% of the electric energy requirements of a building, according to a

recent survey. Three phase motors employed for low to medium power applications constitute 85% of all motors. Each of these AC motors employs an adjustable speed drive (ASD) to control the speed of the motor, which is a power electronic converter. Most commercially available ASDs have about 85% efficiency and a source power factor (PF) of about 0.72. In this work, a stand-alone wind energy conversion system is studied, with a view of application for the energy-neutral building environment. Since most wind-turbines already operate with a low coefficient of performance, the design of the power electronic converter used in such a system is of great importance.

This work investigates the design and development of a high efficiency, high input power-factor power AC-DC converter for a stand-alone wind energy conversion system driving standalone electric loads. Since wind energy is stochastic and varying, there is a need to ensure power conditioning before it is fed to the sensitive AC and DC loads. If the wind turbine-generator is connected directly to the load, there will be energy fluctuations, as well as, voltage and current distortions as the wind speed changes, and this is undesirable. Apart from this, the wind turbine will have no form of speed-control, and this will lead to inefficient operation as explained in Chapter 3. Thus, there is a need to interface the wind-turbine generator and the stand-alone load by means of an AC-DC power converter interface.

1.2 Research objectives

The objective of this work is to design a new topological structure and power controller for a stand-alone wind energy conversion system, with special emphasis on maintaining enhanced power quality. A wind energy conversion system typically consists of a wind-turbine, mechanically coupled with the permanent magnet synchronous generator. The generator is interfaced with the electric load (which represents the Energy Neutral Building) through the designed power electronic AC-DC rectifier converter.

At the onset of the work, it is useful to determine the main requirements in a stand-alone wind energy system, and design the power converter based on these objectives.

1. Maximum Power Point Tracking

The power characteristics of a wind-turbine system are bell-shaped and the mechanical power captured is highly dependent on the wind velocity and turbine-generator rotor speed. Hence, the power converter used in a wind-energy conversion system must be capable of regulating the generator rotor shaft speed in order to achieve maximum power tracking for a range of wind speeds (Variable speed operation). The converter achieves this by changing the electrical loading on the generator, thus improving the coefficient of performance of the wind-turbine, as will be explained in Chapter 4.

2. Unity Power Factor Operation

The designed converter must be capable of operating near unity power factor operation at the stator terminals of the wind-turbine generator. In UPF operation, the AC-DC rectifier converter and load appear as a resistive load to the generator. The advantage of achieving this is that for a given voltage and required power rating, the current drawn is less, when current and voltage waveforms are in phase. This results in maximum real energy transfer, implying maximum efficiency.

3. High quality of input current

The converter must ensure high quality near sinusoidal line current from the generator with low harmonic content, measured by the Total Harmonic Distortion value (THD). The THD of the line currents must comply with the requirements of the IEEE 519 standard. A high value of THD implies the presence of significant low and high-frequency harmonic content and indicates increased losses and reduced efficiency.

4. Dc-link Voltage stabilization / Power Balance

The stand-alone WECS system must be designed with a constant dc-bus output voltage value for a specified range of wind speed fluctuation and electric load variations. This is important because the dc-bus voltage will affect the performance of electric loads connected at the dc-bus. In a stand-alone system scenario these loads could be dc Loads (Battery loads, LED systems, dc motors) or AC loads interfaced to the dc-bus through an inverter.

This research work validates the use of a Unity Power Factor Rectifier, consisting of a traditional diode bridge configuration with a parallel bank of bi-directional switches, as the front-end converter in a WECS. This AC-DC converter is based on Vienna Topology that is very popular in the Telecommunication industry because it leads to high power density of

three-phase AC supplies [6]. The use of a Vienna rectifier in a stand-alone wind energy conversion system WECS scenario is not previously investigated. Additional controllers are included to this structure to include features such as maximum power operation of the turbine and the stabilization of dc-link voltage.

The purpose of this work is to study the feasibility of using these features for maximum power and maintaining unity power factor in a wind-energy conversion system scenario and study the effect on dynamic system performance in terms of current quality, wind-turbine efficiency and other significant parameters.

1.3 Major Thesis Contribution

The following contributions have been made in the thesis

1. In this work, the use of a new AC-DC Unity Power Factor Topology in a wind energy conversion system is explored. The concept of this topology proposed in [7], was developed for the Telecommunication industry due to the high density of three-phase power supplies. The application of the UPF rectifier in a standalone wind energy conversion system has not been explored in detail in the literature. The UPF rectifier offers advantages such as full current-control ability of the wind turbine-generator, unity power factor operation at the generator stator terminals (improving generator utilization efficiency), reduced harmonic distortion in the current waveform of the PMSG and cost-reduction compared to the PWM rectifier because of lesser number of switches. With these characteristics, the proposed AC-DC converter makes an excellent front-end rectifier interface in a standalone wind energy conversion system, when compared to the traditionally employed diode bridge rectifier.
2. An open loop Maximum Power Tracking MPPT feature was tested specifically for the Unity Power Factor Rectifier Converter in a standalone wind energy conversion system,

based on the perturbation of the virtual system conductance. Detailed analysis has been provided for the feasibility of this approach. By incorporating the conductance concept into the current control, the Unity Power Factor Rectifier is capable of simultaneously achieving high power factor operation, high quality currents at the wind-turbine generator stator terminals and maximum power tracking of the wind turbine.

3. Finally, a Particle-Swarm Optimization PSO method is used in the current control for the unity power factor. Two versions of this algorithm were proposed and developed. The first is a static PSO MPPT, which was used to test the feasibility of utilizing this current control to meet the system objectives. The algorithm is extended to a dynamic PSO algorithm, which is capable of detecting the optimum virtual conductance during fluctuating wind speeds with a very high speed of convergence. This technique requires minimal knowledge about the wind turbine characteristics, and shows excellent dynamic performance when utilized to control a UPF rectifier in a standalone wind energy conversion system, feeding a dc resistive standalone load.

1.4 Organization of thesis

The research work presented in this thesis is organized in the following manner;

Chapter 1 - the research motivation, research objectives, summary of this research work have been highlighted.

Chapter 2 - the literature review has been presented and the concepts pertaining to a standalone wind energy conversion system have been discussed viz. wind turbine, electrical generators, energy storage system. The proposed AC-DC converter (Unity Power Factor rectifier converter) topology has also been presented.

Chapter 3 – In this chapter the detailed description of the design and analysis of a Unity Power Factor Rectifier Interface for interfacing PMSG to DC bus in a Standalone wind energy system is presented. Firstly, two current control methods for a three-phase three-level Unity Power Factor Rectifier Converter topology viz. Average Current Control (ACC) and Hysteresis Current Control (HCC) have been briefly explained. Secondly, the performance and effectiveness of Average Current Control and Hysteresis Current Control have been compared and contrasted for a standalone wind energy conversion system through simulation and experimental results. Finally, the use of a battery storage element in the standalone wind energy system has been studied. The dynamic performance of Hysteresis Current Control has been validated for a standalone wind energy conversion system employing a lead acid battery bank model as a low cost energy storage component.

Chapter 4 – In this chapter, the necessity for maximum power tracking of the wind turbine is investigated and the relevant literature survey of the common Maximum Power Point Tracking (MPPT) techniques used in wind energy systems has been presented. A perturb and observe maximum power point tracking technique has been developed for the front end UPF AC-DC rectifier. The performance of a standalone wind energy conversion system employing a UPF rectifier has been studied with the designed current control for constant and variable wind speeds.

Chapter 5 –A novel current control employing Particle Swarm Optimization for maximum power point tracking and Hysteresis Current Control for unity power factor operation has been developed. The results of utilizing the designed control in a Unity Power Factor Rectifier in a standalone wind energy conversion system have been discussed. A comparison between the Perturb and Observe MPPT (presented in Chapter 4) and Particle Swarm Optimization MPPT (presented in Chapter 5) is also included here.

Chapter 6 – In this chapter, the contributions of this research work are summarized. A list of recommended research directions for future researchers is also presented.

Appendix– Additional details relevant to the simulation results presented in Chapters 3, 4 and 5 are presented in Appendix. A brief note has also been made on the limitations and strengths of the PSIM[®] simulation environment which has been extensively used in this research work.

Chapter 2 Overview of wind energy conversion systems

A wind energy conversion system (WECS) typically consists of a wind turbine, a gearbox, a mechanically coupled generator, a power electronic interface for power conditioning the wind turbine energy to be compatible with the electric load requirements and an additional energy storage system, such as lead-acid battery bank, to supply and store deficit or surplus energy.

The first stage of a WECS is the wind turbine system. The function of the turbine is to transform the wind kinetic energy into rotational motion that will produce the driving mechanical torque to the electrical generator shaft to produce electrical power. This power from the generator is fed to a power electronic AC-DC converter (rectifier) which ensures load matching.

Two major issues are of great importance in the design of the standalone wind energy conversion system. The first issue is the varying stochastic nature of wind. Considering this issue, it becomes mandatory to ensure maximum utilisation of wind energy under varying wind speed conditions. The second issue is the relationship between aerodynamic characteristics of the wind turbine, rotor speed of the generator and the amount of energy extracted from the wind. The power electronic converter must be capable of adjusting the rotor speed of the generator effectively, in order to ensure maximum power utilization operation over an extensive-range of wind speeds and load conditions.

In this work, a dc-load consisting of a rectifier-battery system driving a resistive load is used to model the stand-alone load. In this chapter, the four major components of a WECS will be discussed in brief and the relevant literature review will be presented.

2.1 Wind turbine

A wind turbine is a prime mover device that transforms the wind kinetic input energy available in wind into usable rotational energy. This rotational energy is then transferred to the electric generator shaft to generate output electrical energy.

Wind turbines are classified popularly based on the turbine axis about which the blades are assembled as Vertical axis wind turbines or VAWTs and Horizontal axis wind turbines or HAWTs. In vertical axis wind turbines, the blades are assembled about a vertical axis while in the latter, the blades are assembled and spin about a horizontal axis. Horizontal axis wind turbines are more used and popular than the vertical axis turbine. The principal advantage of a vertical axis wind turbine is that the nacelle unit can be located on the ground level, which contains all the heavy and complex machinery. This enables easy maintenance and servicing when needed. Some drawbacks of vertical axis wind turbines are that the blades are quite close to the ground where wind speeds are lower. Due to this proximity the stresses on the blades are more. Turbulence also becomes a huge problem [8].

2.1.1 Wind turbine characteristics

The linear velocity and motion of air is converted into rotational energy when incident on the wind turbine. This is then converted into electrical energy by the electric generator. The power conditioning of this electrical power is performed by the interface AC-DC, DC-DC and DC-AC power electronic converters at the generator output. The conditioned power is then fed to the load.

The potential power that can be harnessed from the wind striking a turbine is,

$$P_v = (0.5) \cdot \rho_a \cdot A \cdot v^3 \quad (2.01)$$

where, ρ_a is the density of air in kg/m^3

A is the area swept by the turbine blade in m^2

v is the wind speed in m/s

The relationship between the potential power available to the wind turbine, P_v and the actual mechanical power harnessed by the turbine P_m is based on the coefficient of performance C_p as:

$$P_m = C_p (\lambda, \beta) \cdot P_v \quad (2.02)$$

This highlights that the mechanical power harnessed by the wind turbine is dependent upon a parameter known as the coefficient of performance of the wind turbine. The value of the coefficient of performance, C_p is determined by two variables viz. Tip-Speed Ratio (λ) and Pitch Angle (β). Tip-Speed Ratio (λ) for a wind turbine is the ratio between the tangential speed of the tip of a blade and the actual velocity of the wind. Pitch angle (β) refers to the angle of attack of the blades of wind turbine into or out of the wind.

The expression for the coefficient of performance C_p is given by [9],

$$C_p (\lambda, \beta) = C_1 \cdot [(C_2 / \lambda_i) - (C_3 \cdot \beta) - C_4] \cdot e^{-(C_5 / \lambda_i)} + C_6 \cdot \lambda \quad (2.03)$$

where,

$$\lambda = (r \cdot \omega_m) / v \quad (2.04)$$

$$(1 / \lambda_i) = (\lambda + 0.08 \beta)^{-1} - 0.035(\beta^3 + 1)^{-1} \quad (2.05)$$

Where, r is the radius of the wind turbine blade (m) and ω_m is the angular rotor speed (radians per second). Coefficients C_1 to C_6 are constants a function of the characteristics of the wind

turbine chosen. The values of C_1 to C_6 for the chosen turbine described in [9] shown in Table 2.1.

Table 2.1 Wind turbine model coefficients C_1 to C_6

<i>Coefficient</i>	<i>Value</i>
C_1	0.5176
C_2	116
C_3	0.4
C_4	5
C_5	21
C_6	0.0068

Since wind is a stochastic source of energy, it is very important to design the conversion system to extract the maximum power from the wind under all possible operating conditions. Wind energy systems may be constant wind speed systems or variable wind speed systems. Variable wind speed systems find increased preference over fixed wind speed systems.

Figure 2.01 Power coefficients vs. Tip Speed Ratio characteristics [10]

This is because they provide optimum energy extraction, as well as, reduced mechanical stress on the drive. Typically for low power, fixed pitch WECS, the wind turbine generator is made to operate in the variable frequency mode. In variable speed operation, the aim of the controller is to maintain the tip speed ratio of the wind turbine close to the optimum value regardless of wind speed. This means the rotor speed is adjusted as the wind speed varies, to obtain maximum efficiency of the wind turbine.

As seen from Figure 2.1, it is essential to operate the wind turbine close to the optimum TSR in order to attain maximum coefficient of performance. The TSR can be varied by adjusting the rotor speed of the generator. This action is performed by the power electronic converter, by adjusting the electrical torque.

From (2.02), we can derive

$$C_p (\lambda, \beta) = P_v / P_m \quad (2.06)$$

The PSIM® model of the wind turbine and choice of wind turbine parameters is described in Appendix A.

2.2 Standard electrical Generator employed in Wind Energy Conversion Systems

To produce electrical energy from the rotational energy, the shaft of the wind turbine is coupled with an electrical generator with or without the aid of a gear-box. The output of the generator is usually three-phase alternating current, the frequency of which is highly dependent on the wind speed. Wind turbine efficiency known as the turbine co-efficient of performance, is typically in the range of 30%-50%. Due to the low efficiency, a power electronic converter that facilitates maximum power tracking of the wind turbine is absolutely essential.

Traditionally wind energy systems employ one of the following types of electrical generators - Permanent Magnet Synchronous Generator, Doubly Fed Induction Generator (DFIG) and the Squirrel Cage Induction Generator (SCIG) [11]. The reasons for choosing a Permanent Magnet Synchronous Generator as the wind-turbine generator, in this work are described in Section 2.2.3.

2.2.1 DFIG based wind energy conversion system

DFIG based wind turbines account for nearly half the market share of commercially available wind turbine-generators [12]-[13].

Figure 2.02 Configuration of DFIG generator with back-to-back converter

The typical topology of a DFIG generator power electronic converter is shown in Figure 2.02. In a DFIG system, the stator is directly connected to the load bus while a back-to-back converter is used to connect the rotor side to the load bus, for a reduced speed operation [14]. The power flow direction in the stator side is unidirectional, while the rotor power flow direction depends upon the rotor speed. In the event that the rotor speed is below synchronous speed, the rotor power is negative (draws power), and when the rotor speed exceeds the synchronous speed, the rotor power is positive (delivers power).

The back-to-back converter consists of a rotor side converter and a load-side converter. The speed of the converter is controlled by the rotor side converter [14], while the load side converter regulates the dc-bus voltage [15].

Since the rotor is capable of operating up to 30% above the synchronous speed, the rotor converter is rated at one-third the stator rated power [16], offering a reduction in cost and device ratings of the rotor-side power electronic converter. This economic advantage makes the DFIG generator a favored choice for high power grid-connected wind energy conversion systems [17]. However, for a stand-alone wind turbine system, where the power range is less than a few hundred kilowatts, the economic gain is marginal. Another advantage of a DFIG converter is the ability to energize the stator from the rotor circuit, eliminating the necessity of external reactive power compensation.

Extensive work has been done in the DFIG rotor converter control system [17]-[20] demonstrating the significant benefits of this configuration, particularly in the control of the dc-bus voltage.

The DFIG generator configuration, however, does have several limitations, as listed below:

1. The rotor power may be very high during transient starting of the generator, and could damage the reduced power rotor converters [21].
2. The use of slip-rings and brushes is unavoidable, affecting the system reliability and maintenance requirements.
3. Since a multi-pole low-speed DFIG is not technically feasible [22], a gear box system is mandatory in this type of generator, negatively impacting the system cost and reliability.

2.2.2 SCIG based wind energy conversion system

The squirrel-cage IG (SCIG) is another potential candidate for a wind turbine generator owing to its simple yet robust construction [23].

Figure 2.03 Configuration of SCIG generator with back-to-back converter

The typical topology of a SCIG generator power electronic converter is shown in Figure 2.03. SCIG has a rotor composed of longitudinal conductive bars set into grooves and short circuited by shorting rings. The SCIG was widely used in fixed-speed WECS [23] (first Danish wind turbines), and it is still used for variable-speed wind-energy generation. The IG with a frequency converter is completely decoupled from the grid; hence this system has a complete grid connection capacity.

The advantage of the SCIG over the DFIG is two-fold. Brushes are not required for the machine operation and (excluding lubrication) requirement for maintenance is minimal.

The limitations of SCIG machines in a wind energy conversion system are as follows:

1. Two full-rated power converters are required for operation, making the system cost higher compared with the DFIG generator.
2. Multi-pole direct drive is not feasible and a gear box is necessary for proper operation, reducing the reliability in comparison with PMSG direct-drive generators [23].

SCIG-based wind turbine systems are a very mature research topic and the topics of research include simulation design, configuration of emulator, design of novel power converter topology and control schemes [24]-[29], and self-excitation and voltage build up techniques in stand-alone and hybrid micro-grids [30]-[32].

2.2.3 Permanent Magnet Synchronous Generator based wind energy conversion system

A. Advantages of using a Permanent Magnet Synchronous Generator

The primary reason for using PMSG is that, it can be used for gearless operation for sufficiently high number of pole pairs. This elimination of the gear system promises to make the PMSG system more robust, compact (in terms of weight and dimensions), fewer maintenance requirements, reduced turbine blade size and high efficiency. The disadvantages is the high cost of the PM material and power converter. The significant advantages of a permanent magnet synchronous generator are listed below [33]:

- Highly efficient in terms of energy output
- Does not employ external power source for the field excitation
- Robustness and more reliable
- Due to the elimination of gear-box, the system reliability will increase and mechanical losses will decrease. For a similar rating the cost of a PMSG is much more than a DFIG or SCIG, due to the cost of the permanent magnet material. Offers a lighter solution and improved power per unit weight
- The cost consideration is offset to some extent by eliminating the excitation losses in the other generators, improving the overall system efficiency.

Thus a PMSG is an excellent choice for a low power WECS (power < 100 kW). The small signal modelling of a permanent magnet synchronous generator has been explained in [11] and is highlighted in the following section.

B. Reason for selection of Permanent Magnet Synchronous Generator from a research perspective

Many papers have focused on the performance of the direct-drive PMSG systems, due to the reasons mentioned above. However, most of these systems are applied in grid-connected wind energy systems [34] - [37] and do not discuss the research challenges in a stand-alone wind energy systems.

A stand-alone wind energy conversion system employing a direct drive PMSG has been discussed in [38]. The paper discussed a control strategy for maximum power point tracking of the wind turbine by control of the turbine-side generator. Another stand-alone wind energy conversion system utilizing a direct-drive PMSG and rectifier-inverter configuration is presented in [39]. This paper discusses the regulation of the dc-link voltage and the output ac voltage of an inverter irrespective of variations in the wind speed and load.

However, neither of these papers studies the power factor performance of the generator which is an important characteristic of the wind energy conversion system.

To the best of the author's knowledge, there is a gap in the existing literature on the study of power factor improvement and maximum power tracking in a stand-alone wind energy conversion system. This work studies the feasibility of obtaining maximum power tracking, as well as high power factor operation in a stand-alone wind energy system.

Three potential candidates for a wind turbine generator have been discussed in the previous section. After considering the advantages and limitations of the generators, it is found that the direct-drive permanent magnet generator indicate the future trend of wind turbine generators.

C. Small-signal modelling of the PMSG

The PMSG modelling can be a complex task when considering the dynamics of operation of the machine and the machine characteristics. Within the scope of the work presented in this thesis, the PMSG modelling is based on the following assumptions [40].

1. The stator windings are sinusoidally distributed along the air-gap.
2. The rotor inductance values are assumed to be constant i.e. independent of rotor position
3. The effects of hysteresis and magnetic saturation are assumed to be negligible
4. The stator windings are assumed to be perfectly symmetrical.
5. The power losses are assumed to be fixed since the capacitance of the windings is neglected and the resistance is assumed to constant.

Figure 2.04 Equivalent circuit of a PMSG in stationary three-phase reference frame [11]

With these assumptions, the operation of a PMSG can be studied by means of its equivalent circuit diagram in the stationary three-phase reference frame and the synchronous reference frame. Figure 2.04 shows the equivalent circuit diagram in the three-phase reference frame.

In Figure 2.04, R_s is per phase resistance of the stator and L is per phase inductance of the PMSG. u_{sa} , u_{sb} , u_{sc} represent the phase to neutral terminal voltage, e_a , e_b and e_c are the phase to neutral electromotive force (EMF) and i_a , i_b and i_c are the stator phase currents of the PMSG. The corresponding equations have been obtained from [11] as follows,

$$\frac{d}{dt} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} = -\frac{R_s}{L} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \frac{1}{L} \begin{bmatrix} e_a \\ e_b \\ e_c \end{bmatrix} - \frac{1}{L} \begin{bmatrix} u_{sa} \\ u_{sb} \\ u_{sc} \end{bmatrix} + \frac{V_n}{L} \quad (2.07)$$

Utilizing Park's transformation to (2.07), the equations can be converted to the d-q reference frame as follows,

$$u_{sd} = -R_s i_{sd} + \omega_e \psi_{sq} - \dot{\psi}_{sd} \quad (2.08)$$

$$u_{sq} = -R_s i_{sq} + \omega_e \psi_{sd} - \dot{\psi}_{sq} \quad (2.09)$$

$$\text{Where, } \psi_{sd} = L_d i_{sd} - \psi_{pm} \quad (2.10)$$

$$\psi_{sq} = L_q i_{sq} \quad (2.11)$$

In these equations u_{sd} and u_{sq} represent the terminal voltages at the Permanent Magnet Synchronous Generator stator, i_{sd} and i_{sq} are the PMSG generator d-q axis currents, ψ_{pm} is the magnetic flux produced by the magnets of the PMSG, L_d and L_q represent the inductance of the stator referred to the d-q reference system. The corresponding equivalent circuit of the PMSG in the d-q reference frame is shown in Figure 2.05.

Figure 2.05 Equivalent circuit of a PMSG in d-q reference frame [11]

The PMSG is considered to have a non-salient rotor configuration i.e. the d and q axis inductances are assumed to be equivalent. Assuming ‘P’ poles of the PMSG, the following equation can be obtained for electrical torque applied to the PMSG rotor,

$$T_e = \frac{P}{2} [\psi_{pm} i_{sq}] \quad (2.12)$$

A 3kW rated PMSG, was used as the electrical generator in the system and its modelling parameters were adopted from [41] and are given in Table 3.2.

2.3 Power Conditioning Interface Topologies Applied to PMSG stand-alone systems

As mentioned earlier, low to medium power wind turbine are coupled with a 3-phase electrical generator (in this case Permanent Magnet Synchronous Generator), in order to supply a three phase AC where the frequency varies with the speed of the wind. The generator is interface with the stand-alone load through a power electronic converter. Several topologies are possible in a stand-alone PMSG wind energy conversion system, and the common topologies [42] are presented here.

The simplest topology is shown in Figure 2.06. The constant voltage dc-link could be interfaced to battery storage via charging circuit, or converted to AC voltage in the case of grid-based systems [43]. The only component in this topology is a diode bridge rectifier. The simple 6-pulse diode rectifier system presents benefits of low cost and simple construction. However, the interfacing of the diode rectifier poses several challenges. Firstly, a diode rectifier based WECS cannot be controlled, therefore variable speed operation is not possible. Owing to the uncontrollable nature of the rectifier, the PMSG load line cannot be matched with the maximum power line of the turbine, which implies that maximum power point tracking is not possible, which is very important for the practical WECS systems to maintain efficient power generating conditions irrespective of the deviation in the wind speed conditions.

Secondly, it is established that a diode bridge rectifier injects relatively large magnitude of 5th, 7th, 11th and 13th order harmonics into the supply waveform. The presence of these high harmonics cause several issues [44]:

- Heating of the generator and decrease in generator output efficiency caused by increase in both copper and iron losses due to significant harmonic content in the stator currents.
 - Reduced output power due to ripple content and negative sequence stator currents
- Mechanical oscillations due to torque pulsations due to ripple content introduced by high frequency harmonics.

Figure 2.06 WECS without power factor correction in the PMSG side and fixed DC load

These issues can be addressed by achieving near unity power factor. This is done by emulating a resistive load at the stator terminal of the generator. This can be done in either of the following topologies – employing an interfacing DC-DC converter (Figure 2.07) or utilizing pulse width modulation techniques with 6-switch rectifiers (Figure 2.08).

Figure 2.07 WECS utilising Diode Bridge Rectifier and DC-DC converter

In systems shown in Figure 2.07 above, the DC/DC converter is often a boost converter, and the entire power has to be transmitted across a single switch, thereby causing high stress levels across the switch.

Figure 2.08 Wind energy conversion system utilising PWM Rectifier

Figure 2.08 shows another common topology used in WECS. Utilizing a 6-switch rectifier, a greater degree of control over the PMSG can be attained but the increased switch count leads to an increase in the converter cost.

2.3.1 Proposed Topology

The Unity Power Factor Rectifier Converter is based on the Vienna topology that is very popular in the telecommunication industry because it leads to high power density of three-phase AC supplies [6]. In the proposed system, a three-phase three-level Unity Power Factor Rectifier [45] is used as the front-end converter as shown in Figure 2.09. The topology and current control of the Three-Phase Three level Rectifier has been discussed in Section 3.2 and Section 3.3.

The predominant features of the topology shown in Figure 2.09 are:

- Ability to achieve current control of generator.
- Maintain unity power factor at the generator stator terminals, thereby improving
- Generator efficiency.
- Reduced harmonic distortion in the current waveform of the PMSG.
- Lower cost compared to the PWM rectifier because of lesser number of switches (3 as opposed to 6).

Figure 2.09 WECS with front-end Unity Power Factor Rectifier Converter

2.4 Energy Storage System

Energy storage devices are capable of being topped up during periods of low demand and drained during periods of high demand and enormously aid the voltage control problem in renewable energy systems.

Since fluctuating wind speed conditions are common, storage devices such as batteries and super-capacitors are essential in wind-energy systems. In this work a lead-acid battery based system has been chosen as the energy storage element. A comprehensive comparison of

Lead-acid, Nickel–cadmium (NiCd), Nickel-metal hydride (NiMH), Lithium Ion (Li-ion), Sodium–Sulphur (Na S) and Metal Air batteries is provided in [46].

Figure 2.10 Configuration of energy storage system used in the standalone WECS system

The lead-acid battery is among the most mature battery technologies available today. Despite their shorter life-cycle and lower energy density, they are considered a very good option for WECS, because of low cost and higher energy efficiency.

A battery-storage system consists of the batteries, DC-DC converter and a control module for generating appropriate control signals for the DC-DC converter. Dump loads, are sometimes used to dissipate excess energy [46]-[47].

Figure 2.10 shows a simple configuration of a battery energy storage system as used in a wind energy conversion system. The number of battery cells to be connected in series is decided by the required battery bank voltage and the number of strings connected in parallel is dependent upon the rated battery bank current. A bi-directional DC-DC converter, which allows charging and discharging of the batteries, employing proper battery control strategy is needed in order to be compatible with the system.

2.4.1 Lead-Acid Battery Model

Figure 2.11 Lead acid battery model [48]

The dynamic model of a lead-acid battery was adopted from [48] and the calculations for modelling the battery are (2.13) - (2.17). The battery model used in this project is PS 1208, a 12V 0.8 Ah battery. In order to obtain a nominal voltage of 300V, 25 batteries were connected in series, and two such strings were connected in parallel to limit the discharge current to 4.5 A.

When completely charged, the charge available in a 12 V 0.8 Ah battery (Q) is determined by,

$$Q = 0.8 \times 3600 = 2880 \quad (2.13)$$

The capacitance of the battery (C_{bat}) is a representation of the battery capacity (which is caused by the flow of electrons) and given by,

$$C_{\text{bat}} = \frac{Q}{V} = \frac{2880}{12} = 240 \text{ F} \quad (2.14)$$

The self-discharge phenomenon of the lead-acid battery is modelled using R_{sd} . Self-discharge is a process in batteries in which the storage capacity of a battery is reduced because of internal chemical reactions, when the battery electrodes are not connected. Based on the capacity retention ratio chart from the lead acid battery datasheet it is known that at 30°C, the state of charge of the battery drops to 83% in six months. The discharge in 6 months is given as

$$Q(\text{discharged}) = 2880 \times 0.17 = 489.6 \text{ C} \quad (2.15)$$

$$\text{Current through } R_{\text{sd}} = \frac{489.6}{6 \times 30 \times 24 \times 60 \times 60} = 3.148 \times 10^{-5} \text{ A} \quad (2.16)$$

$$R_{\text{sd}} = \frac{14.5}{3.148 \times 10^{-5}} = 460.6 \text{ k}\Omega \quad (2.17)$$

To simplify the modelling the internal resistance of the battery at the rated load is considered to be equal for both charging and discharging modes, denoted by R_{sd} . Ideally, the overvoltage capacitance C_o and charging and discharging overvoltage resistances R_{oc} and R_{od} are measured experimentally from the battery but in this case, values have been adopted from published data on similar battery modelling and are presented in Table A2 in Appendix A. Additional details regarding the sizing of the battery depending upon types of loads are

provided in the “IEEE Recommended Practice for Sizing Lead-Acid Batteries for Stationary Applications” [49]. Detailed description of these practices is out of the scope of this thesis.

2.4.2 DC-DC converter for battery interface

Figure 2.12 Half-bridge bidirectional DC-DC converter

The function of the battery bank is to provide an auxiliary source of power to maintain the dc-link voltage in the scenario of low wind speeds. A half-bridge dc-dc buck boost converter (presented in Figure 2.12) is chosen as the dc-dc converter to connect the battery bank to the dc-link, due to the versatility of the converter to aid in both charging and discharging. The above circuit can be made to work in buck or boost mode depending on the switching of the switches S_{upper} and S_{lower} . The switching signals of the switches S_{upper} and S_{lower} enable the converter to operate in one of four modalities, illustrated in Figure 2.13.

- Modality I ($S_{upper} = \text{OFF}$, $S_{lower} = \text{ON}$) – This is a discharging mode of the battery. The diodes are both reverse biased and block any current. The path of the battery current is

shown in Figure 2.13. In this mode the battery discharges and the inductor current increases, therefore the converter operates in boost mode.

- Modality II ($S_{upper} = \text{OFF}$, $S_{lower} = \text{OFF}$, D_{upper} conducting) – This is also a discharging mode of the battery. When the battery operation in modality I and the lower switch S_{lower} is turned OFF, the inductor forces the current to flow in the same direction. The diode D_{upper} starts conducting, and the dc-dc converter transfers power to the dc-link.

Figure 2.13 Four modalities of operation of the battery buck-boost converter

- Modality III ($S_{upper} = \text{ON}$, $S_{lower} = \text{OFF}$) – This is a charging mode of the battery. In this modality, the upper switch is turned on and the lower switch is turned off. Both the diodes, D_{upper} and D_{lower} are reverse biased and in current blocking mode. During this mode, the converter is in buck mode and the power from the dc-link is transferred to the battery bank to charge it.

- Modality IV ($S_{upper} = \text{OFF}$, $S_{lower} = \text{OFF}$, D_{lower} conducting) – This is a charging mode of the battery. When the converter is functioning in modality III and the upper switch is turned off, the inductor forces the current direction to remain the same. As a result, the lower diode, D_{lower} starts free-wheeling and the battery continues charging, till the inductor current drops to zero.

Figure 2.14 Control signals for the bidirectional dc-dc converter

The current and voltage ratings of the switching devices can be determined based on the rated output power and range of input voltage ($V_{bat, \min}$ to $V_{bat, \max}$) as described in [50]:

$$I_{peak, DCDC} \geq \frac{2P_{load}}{\eta V_{bat, \min}} \quad (2.18)$$

$$V_{peak, DCDC} \geq V_{bat, \max} \quad (2.19)$$

The control of the bidirectional power converter is shown in Figure 2.14. The dc-link voltage of the system is compared with the reference dc-link voltage and the error is fed to a PI controller. The controller output is limited to the maximum battery charging/discharging current. The limiter output is compared with the actual battery current and the difference is fed to a second PI controller. The limited version of this signal is fed to a comparator along with a triangular signal to produce the switching signal for the upper switch, S_{upper} . The switching signal of the lower switch is obtained by complementing the S_{upper} signal with a NOT gate.

Chapter 3 Design and Analysis of Unity Power Factor Rectifier Interface for interfacing PMSG to DC bus in a Standalone wind energy system

3.1 Degradation of Permanent Magnet Synchronous Generator performance with uncontrolled rectifier

In electromechanical systems with variable angular speed of permanent-magnet synchronous generator (PMSG), such as wind turbine systems, harmonic components of generator voltages and currents in transient and steady state have an adverse impact on energy efficiency [51]. This occurs due to low power production and internal resistance of the machine.

Undesired harmonic current existing in stator windings increase extra core losses, induce excessive heating in generator and torque ripple. Moreover, the harmonic components decrease the lifetime of the generator and drive train [52].

The use of rectifiers introduces a high intensity of current harmonic content into the PMSG [53]. The flow of these harmonic currents induces further losses to the generator, thereby producing more heat in the generator. This leads to reduction in efficiency in WECS and also decreases the life span of the generator. The power extracted and transmitted by the traditional AC-DC-AC converter is also considerably lower than the rated power of the wind turbine- PMSG system.

Besides the issue of harmonic content, low power factor operation can also affect the PMSG performance negatively in the following manner [54].

- A low power factor leads to a higher internal current and the excessive heat generated will damage or shorten generator life-span

- Increased reactive loads can reduce output voltage and damage equipment sensitive to reduced voltage
- Low power factor operation requires equipment to be constructed heavier to absorb internal energy requirements
- Low power factor operation will result in a more expensive system with equipment capable of absorbing internal loads and larger load requirements

Thus, it is important to utilize current control techniques at the front-end rectifier to ensure low harmonic content in current and voltage waveforms, as well as a high power factor operation. Thus, in this work, the diode rectifier is replaced with a front-end converter employing current control methods for efficient real power extraction.

Figure 3.01 Front-end high power factor rectifier in a 3-phase AC supply system

A three-phase three-level rectifier is used as the front-end converter in the wind energy system. By providing current control, this converter fulfils the dual roles of maintaining high power factor operation and reduction of the harmonic distortion of the line current. Another advantage of the UPF rectifier topology is the minimum blocking voltages across the power switches, which lends itself well to high power rating operation. The important parameters of the system include the PMSG power factor and the quality of the stator currents, indicated by the total harmonic distortion.

Figure 3.01 shows the front end converter for achieving high power factor when used in a utility grid scenario. In this converter there is a single bidirectional switch for every phase, leading to reduced voltage stress across the switches, and minimizing the losses. It is possible to change the electrical load as seen by the source (wind-turbine – generator) by performing current control of the three-phase three level rectifier. By changing the load as seen by the generator, the rotor speed of the generator can be varied, and hence maximum power point tracking can be performed.

The two current control methods used in this work are Average current control (section 3.2) and Hysteresis current control (section 3.2) [55].

3.2 Average current control method

The three-phase three-level Unity Power Factor Rectifier shown in Figure 3.01 is retained to study this control method. As explained before, it utilizes a bidirectional switch for each phase, named S_a , S_b and S_c . The bidirectional switches are responsible for shaping the input current and also regulating the output dc voltage of the rectifier.

Referring to Figure 3.01, the following equations can be formulated,

$$\begin{cases} Ri_a + L \frac{di_a}{dt} = V_a - (V_{am} + V_{mn}) \\ Ri_b + L \frac{di_b}{dt} = V_b - (V_{bm} + V_{mn}) \\ Ri_c + L \frac{di_c}{dt} = V_c - (V_{cm} + V_{mn}) \end{cases} \quad (3.01)$$

where, i_a , i_b and i_c are inductor currents

V_a , V_b and V_c are the source voltages

V_{mn} is the voltage of mode M in reference to the neutral point N

V_{am} , V_{bm} and V_{cm} are voltages at nodes A,B and C referring to node M.

$$\begin{cases} V_{am} = \text{sign}(i_a)(1 - s_a) \frac{V_{dc}}{2} \\ V_{bm} = \text{sign}(i_b)(1 - s_b) \frac{V_{dc}}{2} \\ V_{cm} = \text{sign}(i_c)(1 - s_c) \frac{V_{dc}}{2} \end{cases} \quad (3.02)$$

Where $\text{sign}(i_a)$, $\text{sign}(i_b)$ and $\text{sign}(i_c)$ depend on the polarity of inductor currents i.e.

$$\text{sign}(i_a) = \begin{cases} 1 & \text{if } i_a \geq 0 \\ 0 & \text{if } i_a \leq 0 \end{cases} \quad (3.03)$$

Where, s_a , s_b and s_c are the switching states for the three bidirectional switches S_a , S_b and S_c .

The ON-state is represented as a '1', and the off state is represented as the '0'. The control diagram for the Average Current Control method is shown below. The switching criterion of the average current controller is the intersection between the carrier ramp signal and the error signal.

Figure 3.02 illustrates the Average Current Control diagram for a Unity Power Factor Rectifier. There are two loops present in this control. The outer loop, which is the voltage loop, ensures the constancy of the dc link voltage and is also responsible for tracking the

reference input. The voltage difference between the two capacitors at the dc link has to be controlled to ensure voltage balance.

Figure 3.02 Average current control in a three-phase three-level UPF rectifier

The outer loop is utilized to calculate the reference current waveform. The difference in the reference current and line current determines the output of a PI controller. The Average Current Control utilizes the PI controller signal in comparison with a periodic ramp signal i.e. the carrier waveform to determine the switching positions of the bidirectional switches. The controller schematic is presented in Figure 3.3.

Figure 3.03 Generating switching signals – Average Current Controller

The frequency of the carrier waveform dictates the frequency of the control signal for Average Current Control and is selected as 20 kHz. The converter's average input current ripples can be calculated from (3.04)

$$\Delta i = \frac{V_{in}}{L} \alpha T_s \quad (3.04)$$

Where, V_{in} is the mean voltage of the single phase boost rectifier

α is the mean duty ratio

T_s is time period of the ramp signal

The switching losses are higher in the Average Current Control method due to the high frequency of operation. Due to this limitation, the application of this control is limited to lower power application only. The schematic of a wind turbine driven PMSG interfaced with the near UPF rectifier AC-DC converter employing ACC method is shown in Figure 3.4.

Figure 3.04 Schematic of the UPF rectifier AC-DC converter in the wind generator system employing Average Current Control Method.

3.3 Hysteresis current control method

The conventional Hysteresis Current Control method is based on the random frequency method of control. This method is appropriate in many applications due to advantages such as implementation ease, robustness and high levels of accuracy. The only shortcoming is the erratic frequency of bidirectional switching signals.

Figure 3.05 shows the complete Hysteresis Current Control method adopted for a three-phase three-level Unity Power Factor Rectifier. In the proposed rectifier, Hysteresis Current Control method is employed to control the switching period of the bidirectional switches. Independent controllers are used for each phase. The switching signals for the bidirectional switches are given by (3.05).

Figure 3.05 Control diagram for three-phase three-level Unity Power Factor Rectifier
employing Hysteresis Current Control method

$$S_x = \begin{cases} 1 & \text{if } (i_x > 0 \text{ and } i_x < i_x^* - h) \text{ or } (i_x < 0 \text{ and } i_x > i_x^* + h) \\ 0 & \text{if } (i_x > 0 \text{ and } i_x > i_x^* + h) \text{ or } (i_x < 0 \text{ and } i_x < i_x^* - h) \end{cases} \quad (3.05)$$

where, h is the hysteresis band-width, i_x is the instantaneous current of phase 'x' and i_x^* is the ideal sine wave reference current of phase 'x'. The hysteresis current control technique controls the switching of the bidirectional switches in order to maintain the actual current within the hysteresis limits i.e. $(i_x^* - h)$ to $(i_x^* + h)$. An example of phase 'a' bidirectional switch is shown in Figure 3.06 . When the bidirectional switch S_a is on, the current through phase 'a' increases as expressed in (3.06)

Figure 3.06 Switching operation for phase a: S_a is bidirectional switch for phase a and D1 and D4 are diodes in the upper and lower bridge, respectively.

$$i_a R + L \frac{di_a}{dt} = V_a \quad (3.06)$$

Where, i_a and V_a represent phase 'a' voltage and current and L is the phase 'a' inductance.

When the bidirectional switch S_a is off, the current through phase 'a' increases as expressed in (3.07)

$$i_a R + L \frac{di_a}{dt} = V_a - 0.5 V_{dc} \quad (3.07)$$

Therefore, by turning the bidirectional switch on and off, the pulsing operation can maintain the phase current of phase 'a' within the required limits. The hysteresis bandwidth (h) is determined by trial and error method in simulation environment.

Figure 3.07 Schematic of the UPF rectifier AC-DC converter in the wind generator system employing Hysteresis Current Control Method.

In the Average Current Control method, a mathematical expression was given to calculate the ripple in the line current. To ease comparison, the Hysteresis Current Controller boundary is chosen to be the same value, that is, $2h = \text{input current ripple computed}$, from which the hysteresis band value h is obtained. The schematic employed for the HCC is shown in Figure 3.07 where the unity sine references are then sent to the Hysteresis Current Controller along with the actual phase currents to generate switching signals for the three switches.

3.4 Comparative study of Average Current and Hysteresis Current Control

The results of the comparative study of the stand-alone wind energy conversion system in the PSIM[®] simulation environment employing average current control and hysteresis current control are documented in Sections 3.5 and 3.6. In Section 3.5, the performance of a stand-alone wind energy conversion system without an energy storage system is studied, focussing on the comparison between the average current controller and hysteresis current controller. In Section 3.6, the necessity of a battery storage system has been presented and a battery model has been added to the system and its performance is studied. The components making up the wind energy conversion system are the wind turbine, permanent magnet synchronous generator, a Unity Power Factor Rectifier Converter and the stand-alone load [56].

The calculation of the primary performance parameters in the simulation study of the stand-alone WECS are explained briefly below:

- i. Coefficient of performance of the wind turbine (C_p)

The coefficient of performance of a wind-turbine was explained in Section 2.1, and the importance of operating the wind-turbine at the optimum C_p was discussed.

In the simulation study that follows, C_p , for the various cases is calculated based on equation (2.02) in Chapter 2, is repeated here for reference.

$$C_p(\lambda, \beta) = P_u / P_m \quad (2.02)$$

where P_u is the total kinetic power available in the wind given by (2.01), and P_m is the power extracted from the wind by the wind-turbine (given by the product of wind turbine-torque and turbine speed).

ii. Power Factor, Pf.

In following simulations, power factor is calculated as the ratio of real power to apparent power as shown in (3.08). In the special case that the signals are sinusoidal, the power factor may be determined by taking the cosine function of the phase different between the waveforms. In a 3-phase system the power factor [57] is expressed as

$$PF = \text{Total three-phase real power} / 3 * (\text{RMS phase voltage} * \text{RMS phase current}) \quad (3.08)$$

According to the IEEE 519 standard for medium power drives (as used in this work), the minimum stipulated power factor is 0.94. Details regarding the application of IEEE 519 standard at the design stage, when the precise demand current is unknown are prescribed in [58].

iii. Total Harmonic Distortion of line currents, THD

The amount of distortion in the line current waveform is quantified by means of an index called Total Harmonic Distortion (THD) expressed in (3.09)

$$THD = 100 * \frac{I_{dis}}{I_{s1}} = 100 * \frac{\sqrt{I_s^2 - I_{s1}^2}}{I_{s1}} = 100 * \frac{\sqrt{\sum_{h=2}^{\infty} I_{sh}^2}}{I_{s1}} \quad (3.09)$$

where $I_s, I_{s1}, I_{sh}, I_{dis}$ are the net rms current, fundamental rms component, h order rms harmonic component and distortion component respectively.

iv. Total Demand Distortion of line currents, TDD

This parameter is related to the frequency components of the line currents as expressed in (3.10)

$$TDD = 100 * \frac{\sqrt{\sum_{h=2}^{\infty} I_{sh}^2}}{I_L} \quad (3.10)$$

where I_{sh} represents the harmonic stator current component and I_L represents the maximum load current demand.

THD is a measure of the effective value of the harmonic components of a distorted waveform. TDD is a measure of the effective value of the harmonic components of a distorted waveform, taking into account the loading (relative to maximum load current demand). For the maximum load demand, TDD is equal to the THD of the current, and as the loading changes, the TDD becomes lower than THD.

The IEEE 519 does not give a fixed definition for the maximum load current demand used in equation (3.10). It is recommended to be the mean value of the peak demand for each month of the previous year. Being an experimentally measured value dependent upon various parameters and system conditions (loading factor, operation parameters), choosing the design value becomes tricky. It has been suggested therefore to employ the rated value of the load and utilize a method whose performance stays stable under lighter condition of loading. Since the full load condition leads to the maximum contribution to the distortion index, and drops as the loading decreases [59]. If the conditions to the IEEE 519 standard are being satisfied at full load operating conditions, then the V and I distortion requirements will be satisfied at all load levels. At full-load operating conditions, the TDD is equal to the THD. Due to these reasons, the Total Harmonic Distortion (THD) will be used to assess the dynamic performance of the wind energy conversion system, in this work.

Table 3.1 Current Distortion Limits set by IEEE 519 standard (I_{sc}/I_L)

I_{sc}/I_L	<i>Individual Harmonic Order (Odd Harmonics)</i>					
	$h < 11$	$11 \leq h < 17$	$17 \leq h < 23$	$23 \leq h < 35$	$35 \leq h$	<i>TDD</i>
<20	4.0	2.0	1.5	0.6	0.3	5.0
20-50	7.0	3.5	2.5	1.0	0.5	8.0
50-100	10.0	4.5	4.0	1.5	0.7	12.0
100-1000	12.0	5.5	5.0	2.0	1.0	15.0
>1000	15.0	7.0	6.0	2.5	1.4	20.0

Where, I_{sc} = maximum short circuit current at point of connection

I_L = fundamental component of maximum load current at point of connection

The requirements set by the IEEE 519 standard on the current distortion is reproduced from the original publication, in Table 3.1.

The limitation set on the current quality by the IEEE 519 standard from Table 3.1 is based upon the TDD of the current waveform. When the peak load current is the rated load capacity of the non-linear load [59], the total harmonic distortion becomes equal to the total demand distortion and can be used to check if the system is compatible with the IEEE 519 standard. For a wind turbine driven generator, the value of I_{sc}/I_L is typically in the range of the 20-50 range. The maximum THD requirement set by the IEEE 519 standard for the wind turbine generator from Table 3.1 is 8 %.

3.5 Variable speed wind energy conversion system (WECS) without battery

The design parameters of the wind energy conversion system are documented in Appendix A.

The relevant data is presented here again for the clarity of the reader.

Table 3.2 Wind turbine parameters

<i>Term</i>	<i>Units</i>	<i>Value</i>
P_o	Nominal output power (kW)	4
V_{rated}	Base wind speed (m/s)	12
ω_{rated}	Base rotational speed (rpm)	741.98
TSR_{opt}	Optimal tip speed ratio	8.1

At the onset, the performance of the wind energy conversion system using an uncontrolled diode bridge rectifier was studied as the base case for comparison. It is seen that there was a vast deterioration in terms of the quality of currents as well as the real power extracted from the system. The THD levels of the input currents reached values as high as 25.82%, which is unacceptable by the IEEE 519 standards. The mechanical power produced by the wind turbine reduces to 2.255 kW for 12 m/s in comparison to the maximum rated value of 2.53 kW. Hence, there is a necessity for utilizing a front-end converter with effective current control. By utilizing current control, it is possible to control the electrical speed of the generator, and thus, variable speed operation is possible, thus it is possible to achieve a high coefficient of performance from the wind turbine.

Table 3.3 PMSG system parameters [41]

<i>Term</i>	<i>Units</i>	<i>Value</i>
P	Number of poles	6
R_a	Armature resistance (Ω)	0.49
L	Armature d-q inductances (mH)	5.35
$V_{pk}/krpm$	Peak voltage in V per 1000 rpm	450

The Unity Power Factor Rectifier is used as the front end converter in the designed wind-energy conversion system. In the following sections, the performance of the two different current control strategies of the Unity Power Factor Rectifier Converter to deliver power to a stand-alone load are studied, viz. Hysteresis Current Control and Average Current Control techniques. A comparison is then made between the two current control methods, in order to select the most suitable control technique for the next stage of the work.

3.5.1 Performance of the UPF rectifier AC-DC converter scheme with Average Current Control

In this section, Average Current Control technique is employed to switch the bi-directional switches in the unity Power Factor rectifier, and the results are presented below. Figure 3.08 (a) shows the input phase voltage V_{an} and the corresponding current I_a . The input power factor is high at 0.996. Figure 3.08 (b) shows the harmonic spectrum of the phase ‘a’ current with dominant harmonic components at 170 Hz and 238 Hz. However, their peak magnitudes are lesser than 5% of the fundamental component’s magnitude. The FFT spectrum is also restricted to 1 kHz because of the negligible harmonics beyond this range. From the FFT, the PMSG stator current fundamental component (peak) is determined as 8.95 A. The THD of this current is 7.95%. From Figure 3.08 (c), the mechanical power obtained from wind is 2.49 kW. The electrical power produced by the PMSG is 2.43 kW which is transferred entirely to the dc link output of the front-end rectifier. The control system demonstrates its ability to maintain the dc link voltage balance across the load capacitances in this case as seen in Figure 3.08 (d). The voltage across capacitor C_a is 153.37 V while the voltage across the second capacitance is 153.35 V.

(a) Input Voltage/ Current waveforms of the front-end UPF

(b) FFT of phase current I_a of the front-end UPF rectifier

(c) Wind turbine mechanical power, PMSG electrical power and dc output power

(d) Dc bus capacitor voltages

Figure 3.08 Performance of the UPF rectifier with ACC at the rated wind speed 12 m/s.

Figure 3.09 (a) shows the input power factor of the UPF rectifier for the higher wind speed condition, at 0.997. Figure 3.09 (b) shows the harmonic component at 307 Hz which falls well below 10% of the fundamental's magnitude and is within acceptable limits. The other components are at 218 Hz and 481 Hz, but their magnitudes are quite negligible. From the FFT, the PMSG stator current fundamental component (peak) is determined as 11.29 A. The THD of this input current is 5.95%. The mechanical power produced is 4015 W which is close to the rated maximum value as shown in Figure 3.09 (c). The electrical input power to the rectifier is 3.923 kW which is transferred to the dc link output entirely. Thus, the efficiency of power conversion from mechanical to electrical is 97.7%. The voltage across capacitor C_a is 193.48 V while across capacitor C_b it is 196.17 V. The overall dc link voltage is higher than the previous case and measures 389.64 V. It is lesser than the ideal value of 395 V. However, this difference is still acceptable. To avoid redundancy, the voltage balance is not shown for above the rated wind speed condition.

(a) Input Voltage/ Current waveforms of the front-end UPF

(b) FFT of phase current I_a of the front-end UPF rectifier

(c) Wind turbine mechanical power, PMSG electrical power and dc output power

Figure 3.09 Performance of the UPF rectifier with ACC at the higher wind speed 14 m/s.

Figure 3.10 (a) shows the variation in wind speed from 12 m/s to 14m/s and the corresponding variation in the power coefficient C_p . It is seen that initially the C_p value is 0.474 and after the step change in wind speed, it increases to 0.479 which is closer to the optimum value of 0.48. Figure 3.10 (b) shows that the input power factor achieved by the system is 0.996. With change in wind speed, there is a corresponding change in the mechanical and the electrical input and output powers of the converter as seen in Figure 3.10 (c).

(a) Wind speed variation and coefficient of performance of wind turbine

The mechanical power is 2.5 kW for 12 m/s which is a little lesser than its rated value while it increases to 4.013 kW at 14 m/s. The electrical input and output power of the rectifier are equal, implying complete real power transfer. The input line currents to the front-end rectifier are shown in Figure 3.10 (b). With an increase in wind speed, the line currents also increase in magnitude.

(b) Phase 'a' voltage and current waveforms of the front-end rectifier

(c) Wind turbine mechanical power, PMSG electrical power and dc output power

Figure 3.10 Performance parameters of the UPF rectifier with ACC with varying wind speed profile

3.5.2 Performance of the system with Hysteresis Current Control

Figure 3.11 (a) illustrates the phase ‘a’ input voltage and current of the UPF rectifier. The quality of current and voltage is good and the input power factor is high (0.994). Figure 3.11 (b) shows the FFT spectrum of phase ‘a’ current. The fundamental frequency is at 36 Hz. The dominant components are close to 180 Hz and 250 Hz and their magnitudes are well below 10% of the fundamental current component’s magnitude. From the FFT, the PMSG stator current fundamental component (peak) is determined as 8.71 A. The THD of this current is 8.26%.

(a) Input Voltage/ Current waveforms of the front-end UPF

(b) FFT of phase current I_a of the front-end UPF rectifier

The wind turbine mechanical power produced is 2.525 kW. The PMSG produces 2.47 kW which is transferred entirely to the dc link output, as seen in Figure 3.11 (c). Figure 3.11 (d) shows the voltages across the two output dc link capacitors.

(c) Wind turbine mechanical power, PMSG electrical power and dc output power

(d) Dc bus capacitor voltages

Figure 3.11 Performance of the UPF rectifier with HCC at the rated wind speed 12 m/s.

The wind speed is increased to 14 m/s and Figure 3.12 (a) shows that the input power factor of the UPF rectifier is 0.994. Figure 3.12 (b) shows dominant harmonics at 225 Hz and 315 Hz. But, their magnitudes are lower than 10 % of the fundamental component magnitude. From the FFT, the PMSG stator current fundamental component (peak) is determined as 10.97 A. THD is calculated as 5.85%.

(a) Phase 'a' voltage and current waveforms of the front-end rectifier

(b) FFT of phase current I_a of the front-end UPF rectifier

(c) Wind turbine mechanical power, PMSG electrical power and dc output power

Figure 3.12 Performance parameters of the UPF rectifier with HCC at wind speed 14 m/s.

Figure 3.12 (c) shows the system's capability of extracting 99% of the available wind-turbine power. The PMSG generates 3.9 kW which is the input power available at the front-end rectifier. This power is transferred entirely to the dc link output of the rectifier, thus achieving high efficiency operation. While the voltage across the first capacitor is 195.4 V, the second capacitor has 193.3 V across it. The dc link voltage achieved is 388.6 V in comparison to the reference value of 395 V.

(a) Wind speed variation and coefficient of performance of wind turbine

(b) Phase 'a' voltage and current waveforms of the front-end rectifier

With a change in wind speed, the performance coefficient reaches a value of 0.479 and 0.474 for 12 m/s and 14 m/s, respectively as seen in Figure 3.13 (a). Figure 3.13 (b) shows the input power factor achieved by the system to be 0.994. Figure 3.13 (c) shows that the mechanical power is 2.53 kW (for 12 m/s), which is close to the rated value. For 14 m/s, the mechanical power is 3.98 kW with efficiency of conversion at 99%. The simulated wind turbine power increases rapidly because the effect of machine inertia is not considered in this work. Figure

3.13 (d) shows the input line currents to the front-end rectifier. The currents retain the same quality as in the case of the individual wind speed operating conditions.

(c) Wind turbine mechanical power, PMSG electrical power and dc output power

Figure 3.13 Performance of the UPF rectifier with HCC with varying wind speed profile

3.5.3 Experimental Results

A 1.5kW laboratory prototype configurable to utilize either Hysteresis Current Control or Average Current Control was developed to validate the simulation results. The source voltage waveforms were obtained using a regulated 3-phase Ac-supply, in place of the PMSG output voltage waveforms.

Table 3.4 Comparative performance parameters of the wind energy system employing
Average Current Control and Hysteresis Current Control

<i>Wind speed</i>	<i>12 m/s (rated speed)</i>		<i>14 m/s (> rated speed)</i>	
Current Control Method	ACC	HCC	ACC	HCC
Mechanical Power P_m (kW)	2.49 kW	2.525 kW	4.015 kW	3.990 kW
Generator Power and dc link output power $P_e = P_{dc}$ (kW)	2.43 kW	2.469 kW	3.923 kW	3.902 kW
THD of phase 'a' input current (%)	7.31 %	8.26%	5.95%	5.85%
Input power factor	0.996	0.994	0.997	0.994

Figure 3.14 Laboratory prototype of Unity Power Factor Rectifier Converter used to compare
the average and Hysteresis Current Control methods.

In order to implement a prototype, a DS1103 Dspace controller and the MATLAB- Simulink Real-Time workshop (RTW) provided by Math Works environment were employed to generate the switching signals for the UPF rectifier. The prototype is shown in Figure 3.14 and the key components used are given in Table 3.5. In the table, y represents the phase (a, b

or c). In order to implement each of the bidirectional switches required in the Unity Power Factor converter, a total of 4 diodes and a solid state IGBT are utilized, as shown in Figure 3.15.

Figure 3.15 Implementation of a bidirectional switch utilizing 4 diodes and IGBT

Table 3.5 Unity power factor parameters used in experimental prototype

<i>Unity Power Factor Drive parameters</i>		
IXYS MDD26	Diode rectifier	D_1 - D_6
BYT200PIV	Bi-directional diode	D_y^+ , D_y^-
IRG4PH50UPbF	Bidirectional switch IGBT	S_{upf}
AC choke inductor	L_y	5mH
Dc-Link Capacitor	C_a , C_b	1200uF

A. Experimental results with Average Current Control

The prototype obtained voltage and current waveforms of the Unity Power Factor Rectifier employing Average Current Control technique are shown in Figure 3.16 (a)-(c). Figure 3.16 (a) shows the ability of the system to maintain near unity power factor at the input terminals (0.994). However, as Figure 3.16 (c) shows, the voltage tracking is not perfectly achieved and there is some ripple in the dc-link voltage. This leads to a higher THD (15%) than the values obtained in the simulations; however a slight degradation in the hardware prototype is expected.

(a) Input phase voltage V_{an} and current I_a

(b) Harmonic spectrum for input phase current I_a

(c) Dc link voltage V_{dc}

Figure 3.16 Results obtained from Unity power factor rectifier employing Average Current Control method.

B. Experimental Results with Hysteresis Current Control

The hardware results of the Unity Power Factor Rectifier employing Hysteresis Current Control technique are shown in Figure 3.17 (a) - Figure 3.17 (c). Figure 3.17 (a) shows the ability of the system to maintain near unity power factor at the input terminals.

The converter input current, shown in Figure 3.17 (b) is practically sinusoidal, in phase with the input voltage and only has a THD of 6%. This leads to high power factor (0.996). The dc-link voltage tracking is accurately achieved using Hysteresis current control

The test shows that while both the Hysteresis Current control method and the Average current control method are capable of achieving unity power factor at the input terminals, the HCC is easier to implement and is capable of tracking the reference dc-link voltage more accurately compared to ACC. The key difference in the results of the laboratory prototype employing Average current control and Hysteresis current control are summarized in Table 3.6.

(a) Input phase voltage V_{an} and current I_a

(b) Harmonic spectrum for input phase current I

(c) Dc link voltage V_{dc}

Figure 3.17 Results obtained from Unity power factor rectifier employing Hysteresis Current Control method.

Table 3.6 Comparative performance parameters of the UPF Rectifier laboratory prototype
employing Average Current Control and Hysteresis Current Control

<i>Parameter</i>	<i>Average Current Control</i>	<i>Hysteresis Current Control</i>
Input current THD (%)	15%	6%
Input power factor	0.9940	0.9960

3.5.4 Conclusion from comparative performance study of the UPF Rectifier employing Average Current Control and Hysteresis Current Control

A traditional AC-AC converter in WECS with diode bridge front-end rectifier without any control methods delivers much lower real power than the rated power of the generator. The qualities of the source voltages and currents do not conform to acceptable limits of IEEE 519 standard. Replacing the front end diode bridge rectifier with a current controlled Unity Power Factor Rectifier improves the line current quality and increases the real power extracted from the PMSG. Table 3.4 lists the key performance parameters of the system for the two different wind speed conditions with two current control methods.

The comparison yields that while both the current control methods are excellent in transferring all the generator power to the load, the ACC method is more effective in achieving high power factor, consistently above 0.995, while the HCC method achieves an input power factor of 0.994. The THDs of the line current for phase ‘a’ of the converter have been compared. While the ACC method achieves THD around 7% and 6%, the HCC achieves values around 8% and 6%.

The ability of the system to extract maximum possible real power with minimal reactive power at the converter input is particularly demonstrated. The efficiency of mechanical power to electrical power conversion is maintained between 97% and 99%. The power that is

available at the input of the front-end rectifier is transferred entirely to the dc link output, indicating low converter losses and high efficiency. The dc link voltage balance is also excellent.

For rated load conditions in the variable wind speed operation, the controller is capable of extracting the maximum possible real power with an efficiency of 97%-99%. Efficiency of power transfer is excellent at the input and output of the front-end rectifier. The ACC achieves a superior power factor of 0.996 in comparison to the input power factor of 0.994 for the HCC. Thus, it is seen that both the current control methods are extremely well suited for robust dynamic operation of this system under both rated load and variation in wind speed.

Finally, a 1.5kW laboratory prototype was developed to validate the simulation results. The experimental test shows that while both the Hysteresis Current control method and the Average current control method are capable of achieving unity power factor at the input terminals, the HCC is easier to implement and is capable of tracking the reference dc-link voltage more accurately compared to ACC.

3.6 Preliminary Conductance based Maximum Power Point Tracking (MPPT) Technique

The control techniques described in Section 3.5 are used when the front-end AC-DC UPF converter is fed from the utility-grid i.e. system with a strong regulated frequency and magnitude of input voltage. The purpose of utilising a unity power rectifier as the front-end AC-DC converter in the standalone wind energy conversion systems is to ensure that the load (rectifier-load system) sensed at the generator stator terminals is nearly resistive.

The power factor correction algorithm described in Section 3.5 does not perform maximum power point tracking, which is one of the desired features required. In order to integrate the maximum power tracking feature into the current control technique, the concept of conductance needs to be introduced to the algorithm.

Conductance (G) is defined as the inverse of the resistance (R). The modified control design used in this work, is similar to the control developed in [60]-[61], and is illustrated in Figure 3.18. The controller is shown only for a single phase; the same control algorithm is applied on each of the three phases. The reference current is determined by taking the product of the input voltage and conductance (G). After this reference current is calculated, it is then fed directly into an Average Current Control (ACC) or a Hysteresis Current Control (HCC) algorithm as mentioned earlier.

The controller regulates the phase difference between the generator three phase stator current and voltage waveforms to zero (unity power factor operation). We define a factor ' G ', which is the system virtual conductance. The virtual conductance of the system is regulated by the maximum power tracking controller. For a fixed input voltage, a larger conductance G , implies an increased current magnitude and vice versa.

The major advantage of a near Unity Power Factor Rectifier Converter is that the energy loss due to the machine resistance is least when the external load is nearly resistive. On the contrary, when a diode-rectifier is used, the power factor is not unity and the current waveform shows large peaks, leading to reduced efficiency and increased power losses.

Figure 3.18 Conductance (G) PFC Algorithm

3.7 Variable speed wind energy conversion system with battery storage

The stand-alone wind energy conversion system employing a front-end unity power factor, discussed in Section 3.5, shows an improved performance over the traditional system employing a front-end diode rectifier as explained earlier [56]. The losses due to higher harmonic current components are reduced because of the improvement in the total harmonic distortion of the input current.

However, there are two limitations in the system described in Section 3.5, when used in a stand-alone wind energy conversion system. Firstly, although the converter is capable of effectively regulating the dc-bus voltage for the rated wind speed, it alone cannot maintain the bus voltage at a constant value for varying wind speeds. This would lead to problems if dc loads (such as lighting loads or motors) were connected to the dc bus or if the dc bus was

interfaced with AC loads through an inverter. Another limitation of the system described is that while it shows excellent dynamic performance at the rated speed and above the rated speed, it does not satisfy the system objectives, at wind lower wind speeds, as explained below.

Consider the stand-alone system schematic feeding AC-loads as shown in Figure 3.19. The relationship between system dc-link voltage and power balance can be given as (3.11).

$$V_{dc} = \sqrt{\frac{2}{C} \int (P_w \pm P_b - P_{inv}) dt} \quad (3.11)$$

where V_{dc} is the dc link voltage, C is the system capacitance, P_w is wind power output from PMSG, P_b is the battery power and P_{inv} is the inverter power output. (Since there is no battery in this system, $P_b = 0$).

As mentioned earlier, the Unity Power Factor Rectifier shows excellent dynamic performance when the dc link voltage satisfies the requirement given by (3.12).

$$V_{dc} \geq \frac{3\sqrt{3}}{\pi} V_m \quad (3.12)$$

where, V_m is the peak value of the phase to neutral voltage. When the dc link voltage drops below the value mentioned in (3.12), it leads to poor power factor and increased line current harmonics.

At rated wind speeds, the value of V_{dc} is sufficient to satisfy the condition for optimum performance of UPF rectifier AC-DC converter. However, when the wind speed drops below rated value, P_w decreases and the value of V_{dc} drops below the rated value, and the UPF rectifier AC-DC converter is not capable to function effectively. In order to maintain V_{dc} at a sufficient value, a battery system can be used to supplement the power from the PMSG. In

such a scenario, the battery power $P_b > 0$ and thus, the value of V_{dc} can be sustained above the value needed for robust dynamic performance of the UPF rectifier AC-DC converter.

Figure 3.19 Stand-alone wind energy conversion system schematic

This makes the case for the use of additional energy sources, and a battery system for use in the stand-alone wind energy conversion system environment. A battery energy storage system based on lead-acid battery was modelled in the PSIM[®] software environment, as presented in Section 2.4.1. The purpose of the battery is to supplement the power provided by the wind turbine in the case of low wind speeds, thereby maintaining robust dynamic operation for this case. The system schematic is shown in Figure 3.20.

3.7.1 Operation at rated wind speed condition

The following section presents the preliminary digital simulation results of the WECS, equipped with a battery storage system. The Unity Power Factor Control performance has been tested only for the Hysteresis current control at this stage.

Figure 3.20 Schematic of the UPF rectifier AC-DC converter in the wind generator system employing battery storage

The performance of the system explained in [56] and highlighted in Section 3.5 is unsatisfactory below rated speed because the system is not able to maintain dc-link voltage at a sufficiently high value. This leads to poor power factor and increased THD of the line-currents. The system performance can be improved considerably when a battery system is integrated into the stand-alone wind energy system. The battery provides the additional energy during times of low wind speed, enabling the stabilization of the dc-link voltage around the rated value of 400 V.

To test the feasibility of operating simultaneously in unity power factor mode and maximum power mode, an open-loop form of maximum power point tracking was implemented in the PSIM[®] simulation environment with a parameter sweep function. The control shows good performance when applied to the Unity Power Factor Rectifier in a wind energy conversion system, as explained in the following section. The performance of the control was tested for two conditions— performance below rated wind speed and at rated wind speed condition.

In order to determine the value of the virtual conductance used in the MPPT, the parameter sweep option available in PSIM[®] software environment was utilized. The parameter sweep allows the user to simulate a system with one (or more) parameters varying incrementally while the rest of the system parameters are kept constant. For each step of the parameter sweep, the system was simulated for 0.7 seconds. This is to ensure the stabilization of the electrical power, P_e and allow the system to attain a steady state condition. The value of conductance that led to the highest wind turbine coefficient of power, C_p was chosen as the virtual conductance for that wind speed. The parameter sweeps have not been shown in the following sections; the optimum conductance determined has been mentioned.

3.7.2 Operation below rated wind speed condition

To test the performance of the system with the inclusion of a battery system, the following simulations have been performed in a PSIM[®] software environment for a wind speed of 10m/s. (Rated wind speed is 12 m/s) and the results have been illustrated in Figure 3.21 (a) through Figure 3.21 (e). For the wind speed of 10 m/s, the parameter sweep of the virtual conductance in the open loop MPPT determined the value of conductance as $G = 10$. Therefore, in the following section, a virtual conductance of 10 is used to determine the efficacy of the Unity Power Factor Rectifier Converter.

(a) Current and Voltage waveforms of the front-end rectifier

The PMSG output phase current and voltage waveforms for a wind speed of 10 m/s are shown in Figure 3.21 (a). The rms values of phase voltage and phase current are 109.3 V and 4.41 A respectively. The converter input power factor is found to be 0.9989.

(b) FFT of phase current I_a of the front-end UPF rectifier

From the FFT in Figure 3.21 (b), the PMSG stator current fundamental component (peak) is determined as 6.23 A. The input current THD is calculated as 1.82%.

The coefficient of performance is determined by taking the ratio of wind-turbine mechanical power to the power available in the wind, and is found to have an average value of 0.479, as shown in Figure 3.21 (d), which indicates excellent dynamic performance of the power converter. Thus, the addition of the battery system, leads to increased range of operation of the wind-energy conversion system.

(c) Wind turbine mechanical power, PMSG electrical power, battery power and dc output power

The average wind turbine mechanical power, PMSG electrical power, battery power and dc-link power are found to be 1.46 kW, 1.43 kW, 1 kW and 2.46 kW respectively, as illustrated in Figure 3.21 (c).

(d) Wind turbine coefficient of performance

The dc-link voltage stabilization is shown in Figure 3.21 (e). The dc-link voltage value is maintained at 400V. This implies that the dc-link voltage is stabilized effectively at lower wind speeds, and the UPF rectifier AC-DC converter can fulfil the system objectives, in terms of input power factor, high coefficient of performance and input current THD.

(e) Dc-link voltage

Figure 3.21 Performance parameters of the UPF rectifier with HCC at wind speed of 10 m/s
in wind energy conversion system employing energy storage

3.7.3 Operation at rated wind speed condition

As explained in Section 3.7.2, the system shows a marked improvement in dynamic performance at lower wind speeds, in terms of dc-link voltage stabilization, coefficient of performance and unity power factor at the generator stator terminals. In this section, the performance of the system at rated wind speeds is illustrated by presenting the key waveforms. For the wind speed of 12 m/s, the parameter sweep of the virtual conductance in the open loop MPPT determined the value of conductance as $G = 11.5$. Therefore, a virtual conductance of 11.5 is used to determine the efficacy of the Unity Power Factor Rectifier Converter.

(a) Current and Voltage waveforms of the front-end UPF rectifier

The PMSG output phase current and voltage waveforms for a wind speed of 12 m/s are shown in Figure 3.22 (a). The rms values of phase voltage and phase current are 133.3 V and 6.19 A respectively. The converter input power factor is found to be 0.9943. From the FFT shown in Figure 3.22 (b), the PMSG stator current fundamental component (peak) is determined as 8.77 A and the input current THD is calculated as 1.33 %.

(b) FFT of phase current I_a of the front-end UPF rectifier

The average wind turbine mechanical power, PMSG electrical power, battery power and dc-link power are found to be 2.53 kW, 2.49 kW, 26.14 W and 2.5 kW respectively, as illustrated in Figure 3.22 (c).

(c) Wind turbine mechanical power, PMSG electrical power, battery power and dc output power

(a) Wind turbine coefficient of performance

(b) Dc-link voltage

Figure 3.22 Performance parameters of the UPF rectifier with HCC at rated wind speed (12 m/s) in wind energy conversion system employing energy storage

The coefficient of performance for rated wind speed operation is determined as 0.4798, as shown in Figure 3.22 (d), which indicates excellent dynamic performance of the power converter. This indicates that the open-loop maximum power point tracking is working in tandem with the Unity Power Factor Rectifier Converter. Thus, the addition of the battery

system, does not affect the operation of the wind-energy conversion system at rated wind speed (12 m/s).

The dc-link voltage stabilization of the system is shown in Figure 3.22 (e). The dc-link voltage value attains a steady state value of 400V after the initial dip. This implies that the dc-link voltage is stabilized effectively at rated wind speed, and thus UPF rectifier AC-DC converter can satisfy the system objectives, in terms of input power factor, high coefficient of performance and input current THD.

3.7.4 Discussion of results with integration of battery in stand-alone wind energy conversion system

- The performance parameters of the wind-energy conversion system with battery system included is summarized in Table 3.6. The power converter shows excellent dynamic performance and meets the system objectives for an extensive range of wind speeds.
- Dc-link Voltage stabilization is excellent for variable wind speeds and the dc- bus voltage is maintained at 400V for a wind speed of 12 m/s (rated wind speed) as well as for a wind speed of 10 m/s (below rated speed). This is a significant improvement over the system presented in [56], where the dc-bus voltage was not stabilized across wind speeds. In this system, the dc-bus can drive dc-loads, or feed an inverter connected to stand-alone Ac-loads.
- Unity power factor operation is excellent for wind speed conditions below rated wind speed, as well as at rated wind speed.
- The co-efficient of performance of the wind-turbine is improved significantly for operation below rated wind speed.

Table 3.6 Performance of Wind-energy conversion system with battery

<i>Windspeed</i>	<i>10 m/s (below rated speed)</i>	<i>12 m/s (rated speed)</i>
Virtual Conductance (Ω^{-1})	10	11.5
PMSG stator power factor	0.9989	0.9943
THD of phase ‘a’ output current (%)	1.82	1.33
C_p of wind-turbine	0.479	0.4798
Dc-link voltage (V)	400	400

3.8 Contributions of Chapter 3 “Design and Analysis of Unity Power Factor Rectifier Interface for interfacing PMSG to DC bus in a Standalone wind energy system”

This work aims at proposing and validating a unity power factor three-phase three-level rectifier as a possible front-end converter for a standalone WECS feeding a dc bus. While this topology is very popular in the telecommunication industry because of increased power density of three-phase AC supplies, its use in a stand-alone wind energy conversion system scenario has still not been fully explored.

In this work, a stand-alone wind energy system interfaced employing a front end Unity Power Factor Rectifier is being investigated. A simple topology (consisting of a parallel bank of bidirectional switches in the three-phase converter) aids the converter in achieving near UPF operation. The wind energy conversion system is connected to a standalone DC load. Two current control methods, i.e. Average Current Control and Hysteresis Current Control have been employed to perform active input line current shaping and their performances have been compared for different wind speed conditions.

A laboratory prototype of the Unity Power Factor Rectifier Converter driving a stand-alone load is studied, and the ACC and HCC current control methods were tested for comparison.

The HCC current control technique was found to be superior and shows better voltage balance across the dc-link capacitors. A Unity Power Factor Rectifier employing HCC (to control the bi-directional switches) can thus serve as an excellent front end converter in wind energy conversion system driving stand-alone loads.

The research objectives were defined in Section 1.2, and simulations were performed to test the validity of the designed converter in fulfilling the objectives viz. maximum power point tracking, unity power factor operation, High quality of input line currents and dc-link voltage stabilization. The designed system works very well in a stand-alone wind energy system especially at rated wind speeds and above rated wind speed, compared to a traditional, uncontrolled diode bridge rectifier system, typically employed in wind systems as the front-end converter.

The unity power factor ensures that all the power produced at the generator is real power and shows high-efficiency operation, as seen from the generator ac-power and dc-bus power waveforms shown in Section 3.5. The UPF rectifier maintains high quality of the line currents at the input of the converter and satisfies the requirements of IEEE standard 519 for a stand-alone system. With the addition of the MPPT feature, to the UPF operation, the co-efficient of performance of the wind-turbine is also maintained at a high value. Thus, the Unity Power Factor Rectifier serves as an excellent choice for a front-end converter in a stand-alone wind energy system.

While the basic system shows excellent dynamic performance at and above rated wind speed, it is unable to satisfy the system requirements below the rated wind speeds (Voltage stabilization, unity power factor operation). Thus, the addition of an energy storage system is proposed to complement the reduced wind-energy, in the lesser wind speed scenario. A battery energy storage system based on lead-acid battery and bi-directional power converter

was modelled and used to achieve dc-bus voltage stabilization. A preliminary open-loop maximum power point tracking feature was also tested, and was capable of achieving a high wind-turbine co-efficient of performance. The addition of energy storage lends itself to an increased range of performance of the stand-alone system, i.e. the system shows excellent voltage stabilization and high co-efficient of performance even below rated wind speeds.

Chapter 4 Perturbation and Observation Maximum Power Point Tracking in Wind Energy Conversion Systems

The objectives of current control in a stand-alone wind energy conversion system were discussed in Section 1.2. Chapter 3 detailed the two current control methods utilized in the unity power factor operation of the front end rectifier used in the wind energy conversion system i.e. Average Current Control and Hysteresis Current Control. The necessity of maximum power point tracking was already established in Section 2.1.1. This chapter presents the literature survey of the common maximum power tracking techniques (MPPT) available for wind energy systems and discusses the implementation of the MPPT feature in the standalone wind energy conversion system.

4.1 Common maximum power point tracking techniques in wind energy systems

Maximum power point tracking of the wind turbine is an essential feature that must be performed by the converter utilized in a wind energy conversion system [62]-[64]. The commonly cited methods of maximum power point tracking and their advantages and drawbacks are presented Section 4.1.1- Section 4.1.5.

4.1.1 Tip speed ratio (TSR) control

The optimum power curves of a wind turbine for four different wind speeds is shown in Figure 4.01. The tip speed ratio (λ) is defined as the ratio of between the velocity of the end-point of the turbine blade to the wind speed velocity.

$$\lambda = \frac{R\omega_m}{v} \quad (4.01)$$

where, v is the wind speed, R is the wind turbine radius and ω_m is the mechanical rotor speed of the wind turbine.

Figure 4.01 Wind turbine power characteristic curves for various wind velocities

Figure 4.02 Control scheme of tip-speed ratio controller

Despite optimum rotor speed changing with wind speed, the optimum tip-speed ratio is constant for a given wind turbine. In the TSR method, the generator mechanical rotor speed is controlled to maintain the optimum tip speed ratio. If TSR is stabilized at the optimum value, the energy drawn from the wind turbine will be maximized. The operating TSR is continually measured and the difference between the optimum value and the operating value is fed to the

controller, which uses the error to drive the rotor speed change of the turbine. This method is easy in theory, however requires very accurate mechanical sensors and has high cost and possibility of error [65]. The tip speed ratio control scheme is illustrated in Figure 4.02.

4.1.2 Optimal torque (OT) control

The wind energy system can be made to operate at maximum power coefficient by maintaining the tip-speed ratio close to the optimum value as mentioned in Section 6.1.1. In this method of control, the PMSG electrical torque is used to stabilize the TSR at its optimum value.

(4.01) can be re-written as

$$v = \frac{R\omega}{\lambda} \quad (4.02)$$

Using (4.02) in the wind turbine mechanical power equation, we get

$$P_m = \frac{1}{2} \rho \pi R^5 \frac{\omega_m^3}{\lambda^3} C_p \quad (4.03)$$

where, P_m is the wind turbine mechanical power, ρ is the air density and C_p is the coefficient of performance of the wind turbine.

If the wind turbine is made to operate at a Tip Speed Ratio (λ_{opt}), it will also operate at maximum coefficient of performance ($C_{p,max}$).

Using these values in (4.03), we get

$$P_m = \frac{1}{2} \rho \pi R^5 \frac{\omega_m^3}{\lambda_{opt}^3} C_{p,max} \quad (4.04)$$

The wind turbine torque T_m can be obtained by dividing (4.04) by mechanical rotor speed

$$T_m = \frac{1}{2} \rho \pi R^5 \frac{\omega_m^2}{\lambda_{opt}^3} C_{p,max} \quad (4.05)$$

Since ρ , R , λ_{opt} and $C_{p,max}$ are constants for the wind turbine, (4.05) can be rewritten as

$$T_m = K \omega_m^2 \quad (4.06)$$

The optimum torque curve for various wind speeds is shown in Figure 4.03.

By maintaining the torque close to the value obtained in (4.06), the tip-speed ratio of the wind turbine will stay close to the optimum value and the wind turbine will operate near maximum coefficient of performance. The schematic of the optimum torque controller is shown in Figure 4.04.

Figure 4.03 Control schematic of the optimum torque-based controller

Figure 4.04 Control schematic of the optimum torque-based controller

The advantage of this method is that it is simple, fast and efficient and does not require wind speed detection. However, as a trade-off, the lack of wind speed detection means that the

optimum torque calculation will not be accurate for fast changing wind speed conditions, and the wind turbine may not operate at optimum tip speed ratio [65]. The second restraint is that the value of K_{opt} is highly sensitive to the wind turbine characteristics, preventing the application of the algorithm to all turbines (with different characteristics).

4.1.3 Power signal feedback (PSF) control

A schematic representation of this type of control method is shown in Figure 4.05. In this method, the optimum power for various rotor speeds must be determined experimentally and programmed into a lookup table [66]-[68]. The controller then uses the difference between power and actual turbine power to affect the rotor mechanical speed and drives the wind turbine towards optimum tip-speed ratio. Some systems use the maximum dc output power vs. dc-link voltage to program the look up table, instead of the wind turbine maximum power vs. rotor speed curve [46].

Figure 4.05 Control schematic of the power signal feedback-based controller

4.1.4 Perturbation and observation (P&O) control / Hill Climbing Search (HCS)

Perturb and Observe is a mathematical search function, where the control variable is subjected to small changes (perturb) and the monitoring the effect of this perturbation on a target function (observe) until the rate of change of the target function becomes close to zero. This technique has been commonly applied in maximum power tracking of solar panel systems [69]. P&O or Hill Climbing Search (HCS) affects the tip-speed ratio (and therefore, the C_p of the wind turbine) by altering the rotor speed of the generator, based upon the direction of observed variation in power. This eliminates the requirement of prior information about the turbine characteristics or speed of the wind [63], [70].

The hill climbing of the P&O function is shown in Figure 4.06. Depending upon which side of the optimum point the current point of operation lies, the controller shifts it to the other side. Common perturbed and observed functions from literature are tabulated in Table 4.1.

Table 4.1 Significant Literature Review

<i>Perturbed parameter</i>	<i>Observed parameter</i>	<i>Reference</i>
Rotor speed	Wind turbine power	[71]
Inverter input voltage	Generator output power	[46]
Converter duty cycle	Generator output power	[72]-[73]
Input current	Generator output power	[74]
Input voltage	Generator output power	[75]

Figure 4.06 Hill Climbing Search Algorithm explained for a wind turbine power characteristic

The major challenge in this system is determining the step-size of the perturbation. A larger step size improves the response time, but leads to more oscillations about the maximum power point, leading to reduced efficiency; a smaller step-size shows fewer oscillations but significantly affects the convergence speed [76]. This is further highlighted in Figure 4.07. One method to solve the problem of step-size is to use an adaptive step-size approach, where the step-size is large at the start of the search and made smaller as the search progresses and fine-tuning is required [76], [73]. This minimizes the search time, as well as the oscillations about the maximum power point.

Figure 4.07 Effect on perturbation step-size on the maximum power point tracking operation

4.1.5 Other methods

According to the literature, fuzzy logic control can be used to determine the best perturbation size for the hill-climb method [77]. The benefits include obtain rapid convergence and immunity to noise and system parameters [78]–[81]. The major drawback of the FLC method is the apparent complexity in implementation.

The summary of the MPPT techniques is presented in [82] and is reproduced as Table 4.2, to summarize the pros and cons of the techniques discussed.

Table 4.2 Comparison of Maximum Power Point Tracking Techniques [82]

<i>Technique</i>	<i>Complexity</i>	<i>Convergence Speed</i>	<i>Prior Knowledge</i>	<i>Memory Requirement</i>	<i>Wind speed measurement</i>	<i>Dynamic Performance</i>
TSR	Simple	Fast	No	No	Yes	Very good
OTC	Simple	Fast	Yes	No	No	Very good
PSF	Simple	Fast	Yes	Yes	Yes	Good
P&O	Simple	Depends	No	No	No	Good
Other Methods	High	Medium	Yes	Yes	No	Good

4.2 Maximum power tracking in UPF Rectifier

4.2.1 Modifying the current control design to implement maximum power point tracking

The control techniques described in Chapter 3 can be employed when the front-end converter is fed from the utility-grid i.e. constant voltage, constant frequency AC system. The purpose of utilising the unity power rectifier as the front-end converter in the wind energy conversion systems is to make the entire system appear as a resistive load to the primary input source (generator).

The current control algorithm described in Chapter 3 aids the high power factor operation of the PMSG, but does not enable effective power extraction from the wind turbine. To enable the optimal power point operation of the wind turbine into the current control technique described above, the concept of conductance was introduced to the algorithm.

An open loop maximum power point tracking was implemented with a simple parameter sweep in the Chapter 3, as shown in Figure 4.08. This setup was successful in demonstrating the basic premise of maximum power point tracking in a Unity Power Factor Rectifier i.e. varying the electrical power obtained from the Permanent Magnet Synchronous Generator by controlling the virtual conductance. In this chapter, the algorithm is improved upon so that it is capable of guessing an initial estimate of virtual conductance, and then tuning the virtual conductance to its optimum value. This is done by observing the change in coefficient of performance C_p with a change in guessed conductance value (perturb and observe). C_p is estimated using the electrical power produced with the calculated wind power. Using this information, the optimum conductance value is obtained for various wind speeds, as the optimum conductance is unique for different wind speeds. With the integration of MPPT, the validity of integrating unity power factor operation and maximum power point tracking is studied.

Figure 4.08 Conductance (G) PFC Algorithm

The complete current-control of the front-end rectifier is a combination of the MPP and the PFC algorithm, shown in Figure 4.10. The MPP algorithm first determines the magnitude of phase current which leads to the highest value of co-efficient of performance (C_p). This current magnitude is then multiplied by a sine template to generate the reference phase

Figure 4.09 Overall schematic of Wind Energy Conversion system with PFC and MPPT

current waveform, i_a^* , which is used by the PFC algorithm to control the switching signal of the bi-directional switches of the Unity Power Factor Rectifier Converter.

The sine template is generated by normalizing the phase voltage, i.e. dividing the phase voltage by its peak value. The peak voltage, V_{peak} is calculated utilizing the instantaneous peak detector [83], which uses instantaneous phase voltages V_{an} , V_{bn} and V_{cn} using (4.07). The entire schematic of the wind energy conversion system along with the topology and current control is shown in Figure 4.09.

$$V_{peak} = \left(\left[\frac{2}{3} V_{an}(t) - \frac{1}{3} V_{bn}(t) - \frac{1}{3} V_{cn}(t) \right]^2 + \left[\frac{1}{\sqrt{3}} V_{bn}(t) - \frac{1}{\sqrt{3}} V_{cn}(t) \right]^2 \right)^{\frac{1}{2}} \quad (4.07)$$

Figure 4.10 Designed control schematic showing PFC and MPPT control.

4.2.2 Challenges of implementing MPPT in a Unity Power Factor (UPF) converter based wind energy conversion system

The implementation of the maximum power tracking feature for the unity power factor wind energy conversion system (UPF WECS) presented a few challenges. This section deals with these issues and their resolution.

A. Presence of local maxima in the power curve

When local maxima exist in the power curve of a WECS, the traditional Hill Climbing Search (HCS) algorithm is not effective because it is incapable of distinguishing between local and global maxima. From system simulations, it is observed that a UPF WECS shows the existence of local maxima, when the loading is varied. Figure 4.11 shows maxima for a parameter sweep of I_{ref} (independent variable) for the WECS for a wind speed of 9 m/s. Thus, the traditional HCS will not work effectively in this system unless it is modified.

Figure 4.11 Presence of local and global maxima in the power curve of a UPF WECS for a parameter sweep of I_{ref} for a wind speed of 9 m/s.

This issue was resolved by utilizing the value of co-efficient of performance i.e. C_p in the algorithm. The algorithm verifies the value of C_p whenever a maximum point is reached. If a maxima has been reached but the corresponding C_p is not the optimum value (>0.47 in this case from the wind-turbine parameters), the modified HCS confirms that the point is only a local maxima, and continues searching for MPP. If the C_p target is achieved for a particular point, then it is confirmed as a global maximum point.

B. Oscillations about the maximum power point

Even when the MPP has been reached, the system might oscillate around the MPP, causing a reduction in turbine-efficiency. The problem of oscillations was addressed and resolved in the designed MPP algorithm by stopping the algorithm once the global MPP was found. This decision was based on the value of C_p as explained in Section 4.1.4 and required a minimum C_p to stop searching. The speed of the search is considerably high, with a settling time of 0.1s

4.3 Maximum Power Point Tracking Algorithm

The MPPT algorithm can operate in three regions of operation. When the turbine operates on the left-hand side of the MPP, as shown in Figure 4.12 (a), the algorithm is in region one. Region two represents the up-hill climb when the operating point is to the right of the MPP, shown in Figure 4.12 (b). Region three deals with the stabilization of the operating point at the maximum power point. The third region of operation helps prevent oscillations about the maximum power point and is triggered by the current C_p being greater than 0.47. This strongly indicates that the MPP has been reached (the theoretical limit is 0.48). If the MPP has been reached, the algorithm commands a 'stop'. The flowcharts in Figure 4.13 and Figure 4.14 summarize the important aspects of the MPPT algorithm in region one and region two of operation.

Step 1- Check for wind speed change, or if operating point is on the left side of hill

In the first step, the algorithm collects the inputs, viz. coefficient of performance, C_p , conductance G , and wind speed V_w . It monitors if the wind speed has changed, in which case, the algorithm resets, clearing the stored maximum values. If not, it proceeds to check if the current value of electrical power, P_e is more than the value obtained at the previous iteration and if the current conductance, G is more when compared to the previous iteration. This determines that the current operating point is on the left of the maximum power point, as

shown in Figure 4.12 (a). The algorithm also keeps note of the maximum electrical power, P_e obtained thus far, for any given speed.

Step 2 - Check if operating point is on the right side of the hill

If the current P_e is instead less than the previous P_e , it means the operating point is on the left side of the hill relative to the current operating point, and so, in order to climb back up, the algorithm sends a $-0.1V I_{ref}$ signal. This should cause an increase in P_e because the system had previously overshoot the MPP, as shown in Figure 4.12 (b).

Sometimes, performing Step 2 as shown in Figure 4.12 (b) does not lead to an increase in P_e as would be expected. This was observed on an infrequent number of occasions during multiple simulation runs in PSIM[®]. The reason for this behaviour is because the operating point is stuck in a local maximum. To counter this behaviour, if the algorithm detects that this erratic behaviour occurs three times in succession, the algorithm causes an increased perturbation ($+0.3V I_{ref}$ signal) which will move the operating point out of the local maxima and then resume normal functioning.

Step 3 - Determining the maximum power point

The algorithm steps 1 and 2 cover the scenario when the operating point is either on the left or the right of the maximum power point. In the third step, the coefficient of performance of the wind turbine is checked to see if it is close to the maximum value (rated for the wind turbine). In this case, the algorithm notes that that the maximum power tracking algorithm has been determined for the given wind speed, and terminates the algorithm, until it detects a variation in the incident wind velocity. In the event of a change in wind velocity, the algorithm returns to step one. The entire code for the maximum power point tracking algorithm has been reproduced in Appendix B.

(a) Region 1 –Up-hill climb from left of MPP

(b) Region 2 – Up-hill climb from right of MPP

Figure 4.12 Hill-Climbing maximum power point tracking technique

Figure 4.13 Step one - MPP algorithm flowchart

Figure 4.14 Step two - MPP algorithm flowchart

4.4 Simulation Results

The simulation results of the described current control algorithm applied to the wind energy conversion system are presented in this section. The relevant parameters of the wind-turbine and PMSG used in the system are provided in Appendix A. The effectiveness of the algorithm is determined by the resulting coefficient of power (C_p) of the turbine and the 3-phase PMSG electrical power, P_e . The optimum achievable C_p for the chosen wind turbine is 0.48 [84].

4.4.1 Front end converter - Diode-bridge rectifier

In order to highlight the effect of current control on the system performance, simulation results are obtained for rated wind speed operation of the wind energy conversion system without current control. The front-end converter without current control (3-phase diode bridge rectifier) is interfaced with the PMSG. Figure 4.15 (a) and Figure 4.15 (b) show the values of the electrical power of the generator (P_e) and the coefficient of power (C_p) without current control method for the rated wind speed of 12 m/s.

Figure 4.15 (a) shows the oscillations and the average value of the C_p obtained by this method (0.36), which is far less than the optimum efficiency level (0.48). The effect of a low C_p , can be observed on the resulting electrical power developed by the PMSG P_e , averaging 1.848 kW (The rated mechanical power of the wind-turbine is 2.5 kW). There is also an overall reduction in the system efficiency because utilizing a diode bridge rectifier as the front-end converter leads to poor quality line current from the PMSG. The THD of the line current is very high, which leads to increased losses and heating of the PMSG. These results establish the necessity of utilizing some form of current-control in the front-end rectifier.

(a) Coefficient of performance of wind turbine, C_p

(b) Generator electrical power, P_e

Figure 4.15 Performance of the UPF rectifier without MPPT at the rated wind speed 12 m/s.

4.4.2 Front end converter – Unity power factor rectifier converter

In order to test the performance of the system with current controlled front end rectifier, the simulation was carried out for the same system parameters when a Unity Power Factor

Rectifier Converter was used as the front-end rectifier in place of a traditional diode bridge converter.

The performance of the system was tested in two cases. In the first case, the wind speed input to the system was maintained at 12 m/s, to test the performance of the system at rated wind speed. In the second case, a variable wind speed profile was chosen as the input to the system to determine the dynamic performance of the Unity Power Factor Rectifier Converter with the designed current control.

i. Constant wind speed profile (12 m/s)

Figure 4.16 (a) and Figure 4.16 (b) highlight the electrical power drawn from the PMSG (P_e) and the coefficient of power (C_p) for the unity power factor wind energy conversion system for the rated wind speed (12 m/s). It is observed that the time taken to reach steady state is around 0.1s. The observed waveforms of C_p and P_e indicate minimal oscillations. The C_p recorded in this case is 0.4793, which is close to the optimum efficiency of 0.48, and higher than the average C_p obtained when the system is operated with a diode bridge rectifier. The electrical power P_e obtained is higher (2.39 kW) when compared to the system performance with a diode bridge rectifier and closer to the rated value of 2.5 kW.

Figure 4.16 (c) shows the phase voltage and current waveforms of the wind-turbine coupled PMSG. The UPF rectifier AC-DC converter maintains the power factor at the stator terminals at 0.9931. The phase voltage and current (rms) are 134.57 V and 6.16 A respectively. The current waveform has been scaled by a factor of 5 to show the high power factor operation clearly. It is seen that the current waveform is nearly sinusoidal indicating low harmonic distortion. From the FFT in Figure 4.16 (d), the PMSG stator current fundamental component (peak) is determined as 8.67 A and the THD is calculated as 4.37%. The near UPF operation

indicates that the entire converter and load appears as a resistive load to the PMSG source, and thus enabling maximum transfer of real power.

(a) Generator electrical power P_e

(b) Coefficient of performance of wind turbine, C_p

(c) PMSG Voltage/Current waveforms for a UPF rectifier

(d) FFT of phase 'a' current of the front-end UPF rectifier

The average wind turbine mechanical power, PMSG electrical power and dc-link power are found to be 2.53 kW, 2.46 kW and 2.46 kW respectively, as illustrated in Figure 4.16 (e). The battery power was found to be negligible, since the wind turbine is operating at the rated wind

speed conditions and does not require the auxiliary power source to meet the load demand.

The dc-link voltage is stabilized at 400 V, as seen in Figure 4.16 (h).

(e) Mechanical, Generator and dc link output powers

(f) Conductance perturbation by the maximum power point tracking algorithm

The virtual system conductance (G) determined by the MPPT algorithm is shown in Figure 4.16 (f). It is seen that the conductance is progressively increased in steps of 0.1. The region highlighted in Figure 4.16 (f) as 'Region A' has been expanded upon in Figure 4.16 (g) below.

(g) Decrease in conductance by the maximum power point tracking algorithm

Figure 4.16 (g) illustrates the region of the perturbation where a negative perturbation in conductance causes a decrease in observed electric power, P_e . The MPPT algorithm notes that a negative perturbation of the conductance leads to a reduction in electrical power, three consecutive times; it perturbs the conductance by an increased value and re-initializes the maximum power point search feature. This prevents it from getting stuck in a loop.

'Region A' highlights the operation of the maximum power point tracking algorithm when a negative perturbation in conductance consecutively three times does not cause the electrical power (observed parameter) to increase. This could be because the algorithm is stuck around a local maximum point. In this scenario, as seen in Figure 4.16 (g), the algorithm perturbs the conductance (perturbed parameter) by a larger positive quantity, and re-initializes the maximum power point search.

(h) dc-link voltage

Figure 4.16 Performance parameters of the UPF rectifier with the maximum power point tracking algorithm in a stand-alone wind energy conversion system at rated wind speed.

To test the performance of the designed current control over a range of wind speeds, the MPPT algorithm was tested over a range of wind speeds from 8 m/s to 12 m/s. The important system parameters obtained with the optimized conductance values for various wind speeds is presented in Table 4.3.

As seen from the (near maximum) coefficient of performance of the wind turbine and the high output power factor of the PMSG, the designed control using modified HCS and Hysteresis current control is extremely effective at maintaining near unity power factor and high coefficient of performance simultaneously, over a range of wind speeds.

ii. Varying wind speed profile – (10-13 m/s)

In this scenario, a variable wind speed profile was used as an input to the wind energy system, to test the dynamic performance of MPPT algorithm. As shown in Figure 4.17 (a) the wind speed was changed five times in 2.5 seconds. A stepped wind speed profile was deliberately chosen to test the speed of the maximum power point tracking feature. It is seen from the response that the current control algorithm is capable of quickly re-finding the MPP, in the event of rapid change in velocity of the incident wind. The tracking ability of the MPPT feature is illustrated in Figure 4.17 (b). This figure shows that the co-efficient of performance of the wind-turbine is maintained close to the optimum value despite rapid wind speed changes.

Table 4.3 MPPT obtained Optimal Conductance Values and WECS performance parameters
for various wind speeds

<i>Wind speed(m/s)</i>	<i>Optimum conductance (Ω^{-1})</i>	<i>Coefficient of performance</i>	<i>PMSG electrical power(W)</i>	<i>PF</i>	<i>I_{THD} (%)</i>
8	7.60	0.4731	722.93	0.9817	7.24
9	8.20	0.4701	1022.8	0.9855	7.43
10	9.20	0.4624	1380.05	0.9878	6.22
11	10.10	0.4651	1847.57	0.991	4.85
12	10.80	0.4793	2469.69	0.9931	4.37

The range of wind speed variation in this simulation study was chosen as 3 m/s. The reason for the choice of a 3 m/s variation is that a variation of 6m/s represents a power change of 57% to 157%, according to equation (2.01). At each instant of wind speed change, the C_p

drops quickly but recovers within 0.1s. This is the time taken for the generator rotor-speed to reach the optimum speed for maximum power tracking.

(a) Varying wind speed profile for testing dynamic performance

(b) Coefficient of performance of turbine with varying wind speed profile

Figure 4.17 Performance parameters of the UPF rectifier with the maximum power point tracking algorithm with varying wind speed profile

This implies that the wind-energy system is tracking effectively tracking the optimum rotor-speed for each wind speed successfully. In this study, the machine inertia has been considered negligible, as seen from the system parameters in Appendix B.

4.5 Contributions of Chapter 4 “Perturbation and Observation Maximum Power Point Tracking in Wind Energy Conversion Systems”

In this chapter, the maximum power tracking feature of the Unity Power Factor Rectifier used as the front end rectifier in a stand-alone wind energy conversion system was explored in detail. A sophisticated control strategy was developed, based on the open-loop conductance control, presented in Section 3.6. The control strategy uses a variation of the Perturb and Observe strategy to determine the optimum conductance for a given wind speed. The conductance determined was used to obtain the reference current to be used in the Hysteresis Current Control algorithm, for ensuring high power factor operation (near unity power factor). The developed algorithm was tested and contrasted with a diode rectifier (without current control) to show the effect of current control on the electrical power (P_e) and co-efficient of performance.

In order to test the effectiveness of the maximum power tracking feature at constant wind speeds, the system was simulated for a range of various wind speeds (from 8 m/s to 12 m/s) and the optimum conductance was determined for each of these wind speeds. For the rated wind speeds, the coefficient of performance of the wind turbine with the determined value of conductance (10.8) was found to be tending to the maximum coefficient of performance for the chosen wind turbine (0.4793). The power factor at the stator terminals of the PMSG was found to be near unity (0.9932). Additionally, the Total Harmonic Distortion of the line currents (4.37%), which was well within the limits prescribed by the IEEE 519 standard.

Table 4.3 highlights the important performance parameters of the current control algorithm over range of wind speeds (8 m/s to 12 m/s).

Finally, the designed algorithm was tested for performance under fluctuating wind speed conditions. It shows excellent dynamic performance and is able to simultaneously track the maximum power point of the wind turbine (as indicated by a very high co-efficient of performance) and maintain near unity power factor effectively for rated wind speed (12 m/s) as well as for varying wind speed profiles.

Thus, the developed current control technique, combining maximum power point tracking and Hysteresis Current Control shows excellent dynamic performance when applied to a Unity Power Factor Rectifier in a standalone wind energy conversion system. The control is capable of simultaneously maintaining near- unity power factor at the stator terminals, high quality of PMSG line currents and effectively tracking the maximum power point of the wind-turbine for a range of wind speeds. It can thus be a very attractive alternative to a diode bridge rectifier in a wind energy conversion system feeding static dc loads.

Chapter 5 Particle Swarm Optimization (PSO) based Maximum Power Point Tracking

Particle Swarm Optimization (PSO) is a random search technique developed by Kennedy and Eberhardt in 1995 [85]. It was inspired by the random search technique found in bees and birds to quickly locate food. Each bird adapts its flying positional course based upon the movement of the other surrounding birds in the flock, to converge quickly and accurately to the neighbourhood optimal point of interest. The birds represent the multiple search agents travelling in the specified search space, and the location of the food represents the global location optimum point in the search hyperspace domain.

The PSO random search algorithm has been universally applied in various global search and optimization problem domains to determine the near optimal solutions [86].

- Antenna design
- Communications networks
- Function selection optimization
- Control and adaptive gain scheduling
- Modelling and optimization of electric grid networks
- Artificial neural network ANN training
- Other search and optimization areas where GA also can be utilized.

The salient features of the PSO algorithm are [87]

- Computationally efficient and fast optimization search method
- It can be used to effectively solve a number of non-linear discontinuous optimization problems

- Individuals follow a very simple search algorithm; emulate the success of neighbouring agents or individuals within the flock
- Discovery of near optimal regions in a complex N-dimensional search hyper-space

The PSO search and optimization is a cooperative random search algorithm, so the agents aid and collaborate with each other to converge to the global optimum point. The number of agents within the flock stays constant in the PSO algorithm. This separates the PSO from techniques such as Genetic Algorithm (GA), which is a competitive and selective algorithm where the number of agents diminishes at each cycle based on the tactic of the survival of the Fittest. Compared to Generic Algorithm, PSO is computationally easy to implement and there are only few parameters to adjust and it shows competitive performance when compared to the complex GA.

The PSO search algorithm consists of multiple agents that each have a particle position 'x' and velocity 'v'. The quality of any reached solution is determined by a specified fitness function J_0 for the particles. Typically, the aim of the algorithm is to find the optimal solution that offers the lowest value of fitness function, J_0 . Multiple solutions may exist in the case of complex hyper-surface search space.

Each particle or agent in a particle swarm represents a possible solution to the optimization problem. As the flock travels through the specified search space, the agents/particles store the individual best position (based on the fitness function) and best position among all agents. The individual best position of a particle is referred to as its local best solution (P_{best}) and the best position among all particles is called the global best solution (G_{best}). As explained in Section 5.1, the agents update their velocity and position iteratively to converge towards the globally best position (G_{best}) that minimizes a selected objective optimization function.

5.1 Structure of a particle

Each particle or agent in a particle swarm represents a possible solution to the optimization problem. Typically each agents consists of the following information

1. Particle 'i' position ($\vec{x}$) - This is the vector containing the co-ordinates of the agent in the solution space. 'i' varies from 1,2,3...N. The dimensions of the search hyperspace are used to establish the size of the vector, $\vec{x}$.
2. Particle velocity ($\vec{v}$) - This is the velocity vector of $\vec{x}$. The dimensions of the hyperspace search space are used to establish the size of $\vec{v}$. The velocity vector determines the direction and resolution of the PSO search algorithm.
3. The fitness function, J_0 which is dependent on the particle position ($\vec{x}$) and determines the quality of a potential solution.
4. P_{best} is the localized fitness function of the best solution yet found by a particular particle.
5. The value of the best fitness function found by a particular solution is termed P_{best} .
6. The value of the best fitness function amongst all solutions is termed G_{best} .

5.2 Basic Principle of Particle Swarm Optimization

The velocity and position of the N-dimensional agents are updated every iteration according the following equations [88].

$$V_i^{k+1} = \omega V_i^k + c_1 r_1 (P_{best} - x_i^k) + c_2 r_2 (G_{best} - x_i^k) \quad (5.01)$$

$$x_i^{k+1} = x_i^k + V_i^{k+1} \quad (5.02)$$

where x_i is the position of particle i; V_i is the velocity of particle i; k denotes the iteration number; ω is the specified inertia weight; r_1 and r_2 are random variables uniformly distributed such that ($0 < r_1 < 1$ and $0 < r_2 < 1$); and c_1 , c_2 are the cognitive and social coefficient, respectively.

As seen in equations (5.01) and (5.02), the velocity of an agent is influenced by three impulses. This is depicted in Figure 5.01.

- Inertia component – This component of velocity causes the particle to continue travelling along its current path.
- Cognitive component – This component of velocity causes the particle to move towards its local best position (P_{best}) in its history.
- Social component - This component of velocity causes the particle to move towards the global best (G_{best}) i.e. the best position achieved among all the particles.

Figure 5.01 Explanation of velocity update equation in vector form

5.3 PSO Procedure

The flowchart of a basic PSO algorithm is illustrated in Figure 5.02. The operating principles of a basic PSO method can be described as follows:

- Step 1 (PSO Initialize) - The N-particles are initialized at random positions ($x_1, x_2 \dots x_n$) within the search space. Any prior information available about the neighbourhood of the maximum and constraints of the system are included in this initialization phase. The particles are initialized with random velocity vectors.
- Step 2 (PSO Evaluation) - The fitness function J_0 of all the particles in the swarm are calculated based on their current positions. This is performed by using the particle information in the system objective function.
- Step 3 (Particle Information) - Based on the fitness calculations, the individual best solution of the particles (P_{best}) and global best fitness (G_{best}) of the swarm are updated.
- Step 4 (Particle Update) - Based on equations (5.01) and (5.02), the particle position (x) and velocity (v) are updated
- Step 5 (Convergence Check) - The convergence criterion of the search is checked to see if the particles have converged. If the maximum number of iterations has been reached or if all the particles have velocities lower than a threshold, the process is terminated. If the convergence criterion is not met, the number of iterations is incremented by one, and the algorithm resumes from Step 2.

Figure 5.02 Flowchart of the Particle Swarm Optimization (PSO) Algorithm

5.4 Implementation of PSO algorithm in a Wind Energy Conversion System

While PSO based maximum power tracking has been applied to solar PV systems [89], its application in wind energy systems has been limited to improving the learning rate in a neural network-based MPPT [90]. A maximum power tracking control using Particle Swarm Optimization for a wind energy system was proposed by the authors in [91] but the power factor of the generator and the generator current harmonics, which are important objectives in a standalone wind energy system, have not been discussed.

Figure 5.03 Current control diagram for the Unity Power Factor Rectifier highlighting the maximum power tracking control and Unity Power Factor Control (for phase 'a')

As explained in Section 3.6, the selection of conductance can affect the coefficient of performance of the wind turbine. The PSO is therefore suitable for solving the maximum power point tracking function of the Unity Power Factor Rectifier Converter.

The schematic of the complete current control, combining the PSO for maximum power point tracking and Hysteresis Current Control for near unity power factor operation, in a Unity Power Factor Rectifier Converter is shown in Figure 5.03.

The MPPT circuit in Figure 5.03 is implemented using Particle Swarm Optimization. The objective of the Particle Swarm Optimization in this work is to determine the optimum conductance (G) that will maximize the coefficient of performance of the wind-turbine for a particular wind speed. The results of the PSO algorithm are presented in two sections. In Section 5.4.1, a static PSO approach is adapted to the wind energy conversion system. In the static PSO approach, the wind speed is maintained constant for the duration of the simulation (fixed wind speed) to test the convergence of PSO algorithm. Next, in Section 5.4.3, a real-time dynamic PSO algorithm (including sampling) is developed, which works under fluctuating wind speed conditions. The details of the static and dynamic PSO algorithms are explained in Section 5.4.1 and Section 5.4.2.

5.4.1 Static Particle Swarm Optimization method (SPSO)

In the static Particle Swarm Optimization, the PSO algorithm was applied to the wind energy conversion system with fixed wind speeds.

- The number of agents for the static PSO was chosen as 3, for the ease of implementation and testing.
- Since the independent variable in the case of maximum power tracking is the virtual conductance (G), it is chosen as the particle position
- The step-size (ΔG) is chosen as the particle velocity for the algorithm
- Since a large step size implies a large change in conductance, the maximum step size (velocity) is clamped to avoid a sudden and abrupt change in the system conductance.

The SimCoupler[®] module in PSIM[®] was utilized in order to implement a static PSO algorithm in a unity power factor wind energy conversion system. Figure 5.04 shows the co-simulation set up of the wind energy conversion system topology (modelled in PSIM[®]) and the current control system (modelled in MATLAB). Each PSIM[®] simulation represents an agent in the PSO algorithm and the conductance value (G) represents the agent position.

Figure 5.04 Setup of co-simulation between PSIM[®] and MATLAB for implementation of Particle Swarm Optimization implementation in a wind energy conversion system

The outputs of the Particle Swarm Optimization system are the 3 particle position (G , conductance) which act as the input to the PSIM[®] system. Each agent is initialized with a random position (G) and velocity (ΔG), and simulated for a time of 0.3s. This permits the wind energy system to reach its steady state. The steady state generator power, P_e from each agent is sent to the MATLAB environment, which computes the fitness value for each agent ($3000 - P_e$) and calculates the new position and velocity of the agents using equations (5.01)

and (5.02). The updated values of G and velocity are sent back to the PSIM[®] simulation and this loop repeats till the maximum number of iterations has been performed.

(a) Features of the Static PSO

i) Balance between exploitation and exploration

In the stand-alone wind energy conversion system, there is a possibility of multiple peaks; the weight ω must be chosen very carefully to avoid convergence failure.

A low value of ω on the other hand will lead to smaller particle velocity (step-size) and consequently, smaller changes in particle position. This is suitable for the exploitation feature of the search when a fine-tuning in the particle position is required. The drawback with a low weight ω is that the particles might not find the global maximum if they are stuck near a local maxima and convergence might take a very long time, since the step-size is quite small [92].

A higher value of ω will lead to higher values of particle velocity and consequently, larger changes in particle position. This is suitable for the exploration feature of the search when a large part of the search space has to be covered. The drawback with a high weight ω is that the obtained solution may not be fine-tuned, since the step-size is quite large. Based on these criteria, ω was chosen as 0.4.

ii) Choice of cognitive and social coefficients (c_1, c_2)

The PSO coefficients are weighted equally in the static PSO, implying that the particle velocity is equally affected by the particle's best position and the best position achieved by the flock.

(b) Results of the Static PSO utilized in the wind energy conversion system

Figure 5.05 Particle swarm optimization of the conductance (agent position) of the wind energy conversion system for the rated wind speed of 12 m/s

As the optimum value of 'G' differs for different wind speeds, the PSO simulation was run for wind speed variation from 8 m/s to 12 m/s, and the optimal value of 'G' for these wind speeds is tabulated in Table 5.1. Figure 5.05 shows the performance of the PSO algorithm for a fixed wind speed of 12 m/s. At the start of the simulation, the agents start off with random values of conductance but after 12 iterations, they all converge to a value of 8.13.

Table 5.1 PSO Optimized Conductance for various wind speeds

<i>Wind speed (m/s)</i>	<i>Optimum Conductance (Ω^{-1})</i>
8	3.66
9	4.60
10	5.75
11	6.86
12	8.13

As seen from Figure 5.05, the convergence of particles occurs after 9 iterations, in the case of static PSO. This shows that the PSO can be applied to the wind energy conversion system. In order to test the other parameters of the system with the optimized conductance value, the main parameters have been highlighted below, for a wind speed of 12 m/s. The code used for testing and implementing the static PSO is described in Appendix C.

(c) Simulation Results of the optimized conductance utilized in the wind energy conversion system for rated wind speed (12 m/s)

In order to test the Particle Swarm Optimization, Table 5.1 was used to determine the optimal conductance of the system for a corresponding wind speed. In this the performance of the static Particle Swarm Optimization algorithm when applied to the wind energy conversion system at rated wind speed (12 m/s) is discussed by presenting the key waveforms.

The PMSG output phase current and voltage waveforms for a wind speed of 12 m/s are shown in Figure 5.06 (a). The rms values of phase voltage and phase current are 137.44 V and 6.21 A respectively. The converter input power factor is found to be 0.9818 (nearly unity power factor). From the FFT in Figure 5.06 (b), the PMSG stator current fundamental

component (peak) is determined as 8.72 A and the input current THD is calculated as 4.46 %, which is well within the limits set by the IEEE 519 standard.

(a) Input Voltage/Current waveforms of the front-end rectifier

(b) FFT of phase 'a' current of the front-end rectifier

(c) Mechanical, Generator and dc link output powers of the system

The average wind turbine mechanical power, PMSG electrical power, battery power and dc-link power are found to be 2.53 kW, 2.47 kW, 4.9 mW and 2.46 kW respectively, as illustrated in Figure 5.06 (c).

(d) Coefficient of performance of wind turbine

The coefficient of performance for rated wind speed operation is determined as 0.4797, as shown in Figure 5.06 (d), which indicates maximum power point tracking by the wind turbine. This indicates that the Particle Swarm Optimization algorithm is extremely effective in determining the optimal conductance at the rated wind speed of 12 m/s.

The dc-link voltage stabilization of the system is shown in Figure 5.06 (e). The dc-link voltage value attains a steady state value of 400V.

(e) dc-link voltage

Figure 5.06 Performance parameters of the UPF rectifier with HCC and Static PSO algorithm for wind speed of 12 m/s.

After testing the performance of the algorithm at rated wind speed, the simulation was performed at a range of wind speeds to test the performance of the designed control over a range of wind speeds. The PSO algorithm was used to obtain the optimal conductance for wind speeds ranging from 8 m/s to 12 m/s. The important system parameters obtained with the optimized conductance values for various wind speeds is presented in Table 5.2.

Table 5.2 PSO optimized conductance and performance of system for various wind speeds

<i>Wind speed (m/s)</i>	<i>Optimum conductance (Ω^{-1})</i>	<i>Coefficient of performance</i>	<i>PMSG electrical power (W)</i>	<i>PF</i>	<i>I_{THD} (%)</i>
8	3.66	0.4751	725.99	0.9761	8.11
9	4.60	0.4691	1020.63	0.9819	7.12
10	5.75	0.4791	1429.89	0.9852	6.15
11	6.86	0.4702	1867.83	0.9892	4.75
12	8.13	0.4797	2471.1	0.9922	4.43

As seen from the (near maximum) coefficient of performance of the wind turbine and the high output power factor of the PMSG, the designed control using PSO and Hysteresis current control is extremely effective at maintaining near unity power factor and high coefficient of performance simultaneously, over a range of wind speeds.

(d) Limitations of the Static PSO algorithm in a wind energy conversion system

These simulations were performed with a static PSO approach. In the static PSO system, the wind speed to the wind energy conversion system was kept constant throughout. The system was only tested for a constant wind speed. The reason behind this approach was to test whether the particles achieve convergence in this system. In an actual wind energy conversion system, the wind speed is stochastic, and can constantly vary. This was tested in the second phase, dynamic PSO. The relevant parameters used in the Particle Swarm Optimization algorithm are presented in Table 5.3.

Table 5.3 Static Particle Swarm Optimization Parameters

<i>PSO Parameter</i>	<i>Units</i>	<i>Value</i>	<i>Comments</i>
Objective function, J_0	W	3000- P_e	P_e = PMSG electrical power
Agent position	Ω^{-1}	G	G = System virtual conductance
Number of iterations	-	12	-
Number of agents	-	3	-
Simulation time per agent	s	0.3	In order to reach steady state
c_1 , c_2	-	2	Equal weights to global and local bests
Ω	-	0.4	Kept constant
$v_{\max}$	Ω^{-1}	3	Maximum step size limit

5.4.2 Dynamic Particle Swarm Optimization method (DPSO)

In this section, the approach of utilizing PSO to perform MPPT was adopted into a wind energy conversion system, with fluctuating wind speed, to test whether the system is capable of attaining the optimum conductance quickly in the case of varying wind speed. In the dynamic Particle Swarm Optimization, the algorithm was executed in real-time with the wind energy system simulation. A sampling time of 0.1 seconds was chosen for this system [93]. This ensures that the wind energy conversion system has reached the steady state of fitness function with a chosen particle position, which is essential for the PSO algorithm to function accurately. The setup of the system has been illustrated in Figure 5.07.

(a) Flowchart of the dynamic Particle Swarm Optimization algorithm

The flowchart of the dynamic PSO algorithm, employed in the designed wind energy conversion system is depicted in Figure 5.08.

Figure 5.07 Setup of co-simulation between PSIM[®] and MATLAB for implementation of static Particle Swarm Optimization

(b) Features of Dynamic Particle Swarm Optimization algorithm

i) Particle Information

- The system virtual conductance, G is chosen as the particle position (p)
- The step-size (ΔG) is chosen as the particle velocity (v)
- The PMSG electrical power, P_e was chosen as the fitness function, J_0
- Sampling Time (T_s)

Figure 5.08 Flowchart of the Particle Swarm Optimization (PSO) Algorithm in a Wind Energy Conversion system

The sampling time plays an important role in the convergence of the dynamic PSO algorithm. In order to accurately function, the sampling time of the dynamic PSO algorithm must ensure that the wind energy conversion system reaches a steady state with a given agent position (conductance). If the sampling time is not chosen carefully, and the system is in a transient state when the fitness value is sampled, the optimized conductance value will not be accurate. Through trial and error, the best value of sampling time was found to be 0.1 seconds.

ii) Linearly changing weight, ω

In this work, a linearly changing weight ω is adopted and is shown in Figure 5.09. This model of ω , allows the system to be in ‘exploration’ mode in the initial phase of the algorithm and switch to fine tuning, or ‘exploitation’ in the later stage of the algorithm. This allows the particles to converge faster and closer to the optimum conductance, when compared with a constant weight ω [94].

Figure 5.09 Linear model of ω used in modified Particle Swarm Optimization

The equation used to model the linearly decreasing model of ω shown in Figure 5.09 is given by equation (5.03)

$$\omega = \omega_{max} - \frac{n}{n_{max}}(\omega_{max} - \omega_{min}) \quad (5.03)$$

where, ω is the weight, ω_{min} and ω_{max} represent the minimum and maximum weights, n represents the current iteration number (1,2,3... n_{max}) and n_{max} represents the maximum number of iterations. Choice of cognitive and social coefficients (c_1, c_2)

The PSO coefficients are weighted in the favour of the social coefficient, c_2 ($c_2 > c_1$). This implies that the particle velocity is affected predominantly by the best position achieved by the flock.

iii) Distinguishing between wind speed change and change in particle position

In the wind energy conversion system, the fitness function J_0 (a function of the electrical power, P_e) could suddenly vary due to fluctuating wind speed power, as well. Equation (5.04) is used in order to distinguish the change in electrical power due to wind speed change from the change in fitness function due to the particle position.

$$\Delta P_e(k) = \left| \frac{P_e(k) - P_e(k-1)}{P_e(k)} \right| \times 100\% \quad (5.04)$$

The value calculated in (5.04) determines the ratio of change in electrical power. If the ratio is more than 25%, it implies that the change in power has occurred due to a change in wind speed, as a particle position change is not capable of producing a high change in electrical power.

iv)Standard deviation

The standard deviation of the agent position (conductance) was used in order to test the convergence of the algorithm in the wind energy conversion system. The criterion for convergence is given by (5.05).

$$\text{Standard Deviation (SD)} = \sqrt{\frac{(g_1 - g_{mean})^2 + (g_2 - g_{mean})^2 + (g_3 - g_{mean})^2}{3}} \quad (5.05)$$

where, g_{mean} is the average of the conductance values and is given by (5.06).

$$g_{mean} = \frac{g_1 + g_2 + g_3}{3} \quad (5.06)$$

Table 5.4 Dynamic Particle Swarm Optimization Parameters

<i>PSO Parameter</i>	<i>Units</i>	<i>Value</i>	<i>Explanation</i>
Fitness function, J_0	W	P_e	PMSG electrical power
Agent position	Ω^{-1}	G	System virtual conductance
Number of iterations	-	100	-
Number of agents	-	3	-
Sampling time	s	0.1s	In order to reach steady state
c_1, c_2	-	0.8, 1.2	Search is weighted towards global best
$\omega_{max}, \omega_{min}$	-	0.4, 0.05	PSO initialized, final weight
PSO reset criterion	-	$\Delta P_e(k) > 25\%$	From equation (5.04)
v_{max}	Ω^{-1}	1.5	Maximum step size limit

The important parameters of the dynamic Particle Swarm Optimization system are highlighted in Table 5.4. The code used for testing and implementing the dynamic PSO is described in Appendix D.

(c) Dynamic Particle Swarm Optimization - Analysis Result

In order to test the performance of the dynamic Particle Swarm Optimization, a variable stepped wind speed profile was applied to the wind energy conversion system, and the key waveforms are presented.

(a) Agent positions and the standard deviation for agents 1, 2, 3

(b) Coefficient of performance (C_p) of wind turbine and dc-link voltage of Agent 1

The applied wind speed profile is a stepped profile described by (5.07) and is shown in Figure 5.10 (a).

$$\text{Wind speed} = \begin{cases} 9 \text{ m/s for } t = (0 - 2.2)\text{s} \\ 10 \text{ m/s for } t = (2.2 - 4.4)\text{s} \\ 12 \text{ m/s for } t = (4.4 - 6.6)\text{s} \\ 11 \text{ m/s for } t = (6.6 - 8.8)\text{s} \end{cases} \quad (5.07)$$

The convergence of the particles or agents is illustrated in Figure 5.10 (a). The three agents are initialized at random positions at the start of the PSO algorithm, but as the number of iterations increase, they converge to the optimal position for the particular wind speed. The

lowest part of the figure highlights the standard deviation of the particle position, and it is seen that the particles converge successfully in all cases. The standard deviation in all cases (except region 2) is less than 0.001. The optimum conductance at which the dynamic PSO converges is 4.54, 6.01, 8.47 and 6.53 for regions 1, 2, 3 and 4 respectively.

The PSO reset function causes the particles to re-initialize at 2.2, 4.4 s and 6.6 s, when the wind speed changes, as illustrated by the agent positions in Figure 5.10 (a).

The coefficient of performance (C_p) of the wind turbine for a particular agent with the stepped-wind speed profile is shown in Figure 5.10 (b). The dynamic PSO maintains the coefficient of performance is maintained at 0.4753, 0.4795, 0.4797 and 0.4701 for regions 1, 2, 3 and 4. This validates the excellent maximum power point tracking ability of the dynamic PSO algorithm.

The dc-link voltages for the varying wind speed are also shown in Figure 5.10 (b). The battery is capable of maintaining the dc-link voltage at (nearly) 400 V for wind speeds of 10-12 m/s. In the case of wind speed 9 m/s, the dc-link voltage drops to 375.52 V. This is because the additional battery power is not sufficient to hold the dc-link voltage at 400 V. The dc-link voltage problem can be resolved by utilizing additional sources such as fuel cells (or extra battery bank) to increase the power at the dc-link and maintain the voltage at the rated level.

The voltage and current waveforms of the PMSG for a particular agent are shown in Figure 5.10 (c). Since it is difficult to determine the power factor and current harmonics distortion from this figure, it has been divided into the 4 regions mentioned earlier and the magnified waveforms at steady-state are illustrated in Figures 5.10 (d) – 5.10 (k).

(c) PMSG voltage and current waveforms for varying wind speed profile (complete response)

(d) PMSG voltage and current waveforms for varying wind speed profile for $v = 9 \text{ m/s}$ (region 1)

(e) PMSG stator current harmonics for $v=9$ m/s (region 1)

The stator PMSG voltage and current waveforms for $v=9$ m/s, i.e. region 1, are shown in Figure 5.10 (d). The rms values of phase voltage and phase current are 106.31 V and 3.9 A respectively. The converter input power factor is found to be 0.9891 (nearly unity power factor). From the FFT in Figure 5.10 (e), the PMSG stator current fundamental component (peak) is determined as 4.67 A and the stator current THD is calculated as 6.62 %, which is well within the limits set by the IEEE 519 standard.

The stator PMSG voltage and current waveforms for $v=10$ m/s, i.e. region 2, are shown in Figure 5.10 (f). The rms values of phase voltage and phase current are 109.17 V and 4.42 A respectively. The converter input power factor is found to be 0.9908 (nearly unity power factor). From the FFT in Figure 5.10 (g), the PMSG stator current fundamental component (peak) is determined as 6.22 A and the stator current THD is calculated as 6.62 %, which is well within the limits set by the IEEE 519 standard.

(f) PMSG voltage and current waveforms for varying wind speed profile for $v = 10 \text{ m/s}$ (region 2)

(g) PMSG stator current harmonics for $v = 10 \text{ m/s}$ (region 2)

The stator PMSG voltage and current waveforms for $v = 12 \text{ m/s}$, i.e. region 3, are shown in Figure 5.10 (h). The rms values of phase voltage and phase current are 133.57 V and 6.21 A respectively. The converter input power factor is found to be 0.9938 (nearly unity power factor). From the FFT in Figure 5.10 (i), the PMSG stator current fundamental component

(peak) is determined as 8.73 A and the stator current THD is calculated as 4.51 %, which is well within the limits set by the IEEE 519 standard.

(h) PMSG voltage and current waveforms for varying wind speed profile for $v = 12 \text{ m/s}$ (region 3)

(i) PMSG stator current harmonics for $v = 12 \text{ m/s}$ (region 3)

(j) PMSG voltage and current waveforms for varying wind speed profile for $v = 11$ m/s (region 4)

(k) PMSG stator current harmonics for $v = 11$ m/s (region 4)

Figure 5.10 Performance parameters of the UPF rectifier with HCC and Dynamic PSO algorithm for varying wind speed profile

The stator PMSG voltage and current waveforms for $v = 11$ m/s, i.e. region 4, are shown in Figure 5.10 (j). The rms values of phase voltage and phase current are 132.61 V and 4.74 A respectively. The converter input power factor is found to be 0.9925 (nearly unity power

factor). From the FFT in Figure 5.10 (i), the PMSG stator current fundamental component (peak) is determined as 6.68 A and the stator current THD is calculated as 4.71 %, which is well within the limits set by the IEEE 519 standard.

The figures above illustrate the performance of a single agent. In order to obtain the optimal conductance value for various wind speeds, the average value of agent 1, agent 2 and agent 3 is utilized (when the dynamic PSO is employed) are highlighted in Table 5.5.

Table 5.5 Dynamic PSO optimized conductance utilizing average conductance for various wind speeds

<i>Wind speed(m/s)</i>	<i>G_{mean} (Ω^{-1})</i>	<i>Coefficient of performance</i>	<i>PMSG electrical power(W)</i>	<i>PF</i>	<i>$I_{THD}(\%)$</i>
8	4.13	0.4771	729.05	0.9885	6.75
9	4.54	0.4753	1037.37	0.9891	6.62
10	6.01	0.4795	1431.03	0.9908	6.06
11	6.53	0.4797	1873.02	0.9925	4.71
12	8.47	0.4701	2471.47	0.9938	4.31

5.5 Comparison between HCS, Static PSO and Dynamic PSO performance

In order to present a comparison between the performances of the Hill-climb search MPPT, Static PSO and Dynamic PSO, the results have been compiled and summarized in Table 5.6 below.

In terms of maximum power point tracking, (which is determined by the coefficient of performance of the wind turbine), the dynamic PSO shows the best performance for a range of wind speeds. The Hill Climbing Search and Static PSO show similar performance with respect to the maximum power point tracking. All other factors remaining equal, the electrical power extracted from the PMSG is highest in the dynamic PSO due to the higher coefficient of performance obtained.

When the comparison of the three techniques is compared for the power factor performance, the dynamic PSO shows the power factor closest to unity, followed by the hill climb search PSO and the static PSO.

Finally, the dynamic PSO produces lower harmonic content in the PMSG stator current, compared to the static PSO and hill climbing search MPPT. At lower wind speeds HCS shows better performance when compared with static PSO, but at higher wind speeds, the static PSO performs better.

There are a few limitations of the HCS algorithm, compared with the PSO techniques. Firstly, the accurate wind velocity is expected to be known for the HCS MPPT algorithm. Secondly, the maximum co-efficient of performance of the wind turbine, and the current co-efficient of performance of the wind turbine need to be calculated for the algorithm, based on the rotor speed and the wind speed. The advantage of the PSO techniques (both static and dynamic) that needs to be highlighted is that accurate knowledge of the wind speed and co-efficient of

performance is not required for the good performance of these algorithms. However, in the case of HCS MPPT, these two parameters must either be accurately measured or calculated, as they are needed for the algorithm.

Table 5.6: Comparison of Perturb and Observe, Static and Dynamic PSO Control techniques

<i>Wind speed(m/s)</i>	<i>MPPT Technique</i>	<i>Coefficient of performance</i>	<i>PMSG electrical power(W)</i>	<i>PF</i>	<i>I_{THD}(%)</i>
8	HCS	0.4731	722.93	0.9817	7.24
	SPSO	0.4751	725.99	0.9761	8.11
	DPSO	0.4771	729.05	0.9885	6.75
9	HCS	0.4701	1022.8	0.9855	7.43
	SPSO	0.4691	1020.63	0.9819	7.12
	DPSO	0.4753	1037.37	0.9891	6.62
10	HCS	0.4624	1380.05	0.9878	6.22
	SPSO	0.4791	1429.89	0.9852	6.15
	DPSO	0.4795	1431.03	0.9908	6.06
11	HCS	0.4651	1847.57	0.991	4.85
	SPSO	0.4702	1867.83	0.9892	4.75
	DPSO	0.4797	1873.02	0.9925	4.71
12	HCS	0.4793	2469.69	0.9931	4.37
	SPSO	0.4797	2471.1	0.9922	4.43
	DPSO	0.4797	2471.47	0.9938	4.31

Taking into account the three factors viz. maximum power tracking, high power factor operation and harmonic content analysis, the dynamic PSO shows superior performance compared to the other two techniques. A summary of the comparison between the HCS and Dynamic PSO has been presented in Table 5.7 for the readers.

Table 5.7: Comparison between HCS and PSO MPPT techniques

Parameter	Hill Climbing Search MPPT	Dynamic PSO
Performance parameters	Shows good performance in terms of maximum power point tracking, high power factor operation and current harmonic spectrum.	Dynamic PSO shows superior performance in terms of maximum power point tracking, high power factor operation and current harmonic spectrum.
Knowledge of system parameters	Requires knowledge of wind speed and coefficient of performance of wind turbine	Requires only the electrical power extracted from the PMSG.
Tuning of parameters	Requires proper selection of ΔI_{ref}	Requires the proper selection of weight ω , cognitive and social coefficients ($c1, c2$)

5.6 Conclusions and contributions

In this chapter, an improved current control system for a Unity Power Factor Rectifier Converter in a standalone wind energy conversion system has been proposed and discussed. The control utilizes a combination of Particle Swarm Optimization (PSO) and Hysteresis Current Control (HCC) to perform dual roles i.e. high power factor operation, as well as, maximum power tracking of the wind turbine.

In order to test the concept and convergence ability of the Particle Swarm Optimization in a wind energy conversion system, a static PSO algorithm for constant wind speed operation was designed and implemented. This static PSO algorithm utilized the system conductance as

the particle position and a function of PMSG power, P_e as its fitness function J_0 . It shows convergence for a range of wind speeds (from 8 m/s to 12 m/s). The optimized conductance obtained from the PSO for 12 m/s (rated wind speed) was used to simulate the wind energy conversion system and the important parameters of the WECS were observed. The coefficient of performance of the wind turbine with the determined optimum conductance was found to be close to the maximum coefficient of performance for the chosen wind turbine (0.4797). The power factor at the stator terminals of the PMSG was found to be near unity (0.9922). Additionally, the Total Harmonic Distortion of the line currents (4.43%) was well within the limits prescribed by the IEEE 519 standard.

As shown from the parameters in Table 5.2, the algorithm shows excellent performance over a range of wind speeds, indicating that the designed control using PSO and Hysteresis current control is applicable to the Unity Power Factor Rectifier Converter in a standalone wind energy conversion system.

Finally, a dynamic version of the PSO algorithm was designed to operate under varying wind speed condition. This was achieved by introducing the ability to detect change in wind speed, which would allow the algorithm to reset. The dynamic PSO was tested by subjecting the wind energy conversion system to a varying wind speed profile. The algorithm showed excellent convergence for a range of wind speeds from 9 m/s to 12 m/s, as indicated by the standard deviation of the algorithm. The dc-link voltage was stabilized at 400V, in all cases except for the wind speed of 9m/s. Table 5.5 tabulates the performance criteria of the dynamic PSO algorithm with a varying wind speed profile, and it is observed that for the entire range of wind speeds, the algorithm is capable of determining the optimal conductance that leads to a very high co-efficient of performance, as well as, near unity power factor. The

quality of the line currents at the input of converter is also well within the limits prescribed by the IEEE 519 standards.

Thus, the developed current control technique, combining Particle Swarm Optimization and Hysteresis Current Control shows excellent dynamic performance in the application of a Unity Power Factor Rectifier Converter to a standalone wind energy conversion system. The control is capable of simultaneously maintaining near-unity power factor at the stator terminals, high quality of PMSG line currents and effectively tracking the maximum power point of the wind-turbine for a range of wind speeds. It can thus be a very attractive alternative for a front-end rectifier in a wind energy conversion system.

Chapter 6 Conclusions and recommendations

6.1 Contribution and Conclusion

The aim of this work was to propose and validate a unity power factor three-phase three-level rectifier as an attractive front-end converter in a wind energy conversion system consisting of a PMSG, unity power factor rectifier converter feeding standalone dc-resistive loads. While this topology is very popular in the telecommunication industry because of the possibility of increased power density in three-phase AC supplies, its use in a standalone energy system involving renewable energy sources has not been explored in the literature.

A wind energy conversion system utilizing a Unity Power Factor Rectifier Converter feeding a stand-alone dc resistive load is being thoroughly investigated. The use of simple bidirectional switches in the three-phase converter results in near unity power factor operation. Two current control methods, i.e. Average Current Control and Hysteresis Current Control have been employed to perform active input line current shaping and their performances have been compared for various wind speed conditions.

A laboratory prototype of the Unity Power Factor Rectifier Converter feeding a stand-alone load is built and tested, and the popular ACC and HCC current control methods were tested for comparison. The HCC current control technique was found to be superior and provides better voltage balance across the dc-link capacitors. A Unity Power Factor Rectifier employing HCC (to control the bi-directional switches) can thus serve as an excellent front end converter in wind energy conversion system driving stand-alone dc resistive loads.

The objectives of the thesis were established in Section 1.2, and simulations were performed to test the validity of the designed converter in fulfilling the objectives viz. maximum power point tracking, unity power factor operation, high quality of input line currents and dc-link

voltage stabilization. The designed system works very well in a stand-alone wind energy system especially at rated wind speeds and above rated wind speed, compared to a traditional, uncontrolled diode bridge rectifier system, typically employed in wind systems as the front-end converter.

The unity power factor ensures that all the power produced at the generator stays as real power and ensures high-efficiency operation, as seen from the generator ac-power and dc-bus power waveforms shown in Section 3.5. The UPF rectifier maintains high quality line currents at the input of the converter and satisfies the requirements of IEEE standard 519 for a stand-alone system. With the addition of the MPPT feature, to the UPF operation, the coefficient of performance of the wind-turbine is also maintained at a high value. Thus, the Unity Power Factor Rectifier serves as an excellent choice for a front-end converter in a stand-alone wind energy system.

While the basic system shows excellent dynamic performance at and above rated wind speed, it is unable to satisfy the system requirements below the rated wind speeds (Voltage stabilization, unity power factor operation). Thus, the addition of an energy storage system is proposed to complement the reduced wind-energy, at lower wind speeds. A battery energy storage system based on lead-acid battery and bi-directional power converter was modelled and used to achieve dc-bus voltage stabilization. A preliminary open-loop maximum power point tracking feature was also tested, and was able to achieve high coefficient of performance. The addition of energy storage lends itself to an increased range of performance of the stand-alone system, i.e. the system shows excellent voltage stabilization and high coefficient of performance even below rated wind speeds.

Extending the open loop maximum power point design, the current control algorithm was modified for the rotor speed control of the turbine in a stand-alone wind energy conversion

system. The control strategy uniquely combines unity power factor operation and maximum power tracking MPPT features, for a stand-alone wind energy conversion system utilizing a Unity Power Factor Rectifier Converter. The performance of the wind energy conversion system utilizing a base-case conventional diode bridge front-end rectifier and the Unity Power Factor Rectifier Converter were evaluated under the system conditions. The UPF rectifier AC-DC converter shows superior performance in terms of the power drawn from the generator as well as the co-efficient of performance. For the rated wind speed of 12 m/s, the diode bridge rectifier system only showed real-power transfer of 1.8 kW, whereas the UPF rectifier AC-DC converter system with the MPPT algorithm showed an increase in the real power transfer of 2.39 kW, which is much closer to the rated power (2.5 kW).

The performance of the current control system was validated in two cases, i.e. for a constant wind speed profile and a varying wind speed profile. In both cases, the algorithm effectively achieves the maximum C_p (0.479) with a convergence time of 0.1s, showcasing the ability of the MPP to function successfully for a range of input wind speeds. The power factor at the generator stator bus is nearly unity, leading to higher real power transfer from the AC PMSG generator to the dc-bus loads.

Thus, the combined current control algorithm with incremental conductance algorithm shows excellent dynamic performance, in terms of maximum power tracking and unity power factor operation for an extended range of wind speeds, in the case of a standalone wind energy system feeding to static dc resistive loads.

6.2 Recommendations for further research

The objective of this work was to develop and validate new controllers for the Unity Power Factor Rectifier for use in a standalone wind energy conversion system. While some areas were explored in detail, others have been out of scope for this work, and are recommended for further research and investigative studies.

Even though a UPF rectifier topology and its controller has been developed for the WECS, there is room for improvement.

- AC Loads – Since the focus of this work was mainly on the AC-DC Unity Power Factor rectifier, only the dc-loads were considered in the analysis. In order to obtain a comprehensive picture for energy analysis, ac-side loads such as induction motors could be considered in the load study. In order to feed AC-loads and local generator bus loads, an inverter needs be to be incorporated into the topology. The primary objective of the voltage source converter VSC inverter controller in the stand-alone set-up would be for regulating the voltage frequency and magnitude at a constant value. The WECS system could be considered to feed hybrid buses (AC-DC-AC), which are connected at different buses with loads and the performance of the MPPT and current control could be studied.
- Motor Loads – The proposed PSO current control method was validated for static resistive and RL loads. In further research, the analysis could be extended to dynamic loads such as motor loads, to test the optimum conductance technique for the inrush current period.

$$G_{opt}(k) = G_1 + k \cdot G_2 \quad (6.01)$$

where G_{opt} represents the dynamic conductance, G_1 and G_2 represent the steady state conductance and inrush optimum conductance and k is a random constant from 0 (for maximum inrush current) to 1 (steady state).

The optimization must be capable of calculating G_1 and G_2 , such that the G_{opt} optimum can guarantee maximum power performance of the wind turbine for multiple values of k .

- Hybrid system design - Since the energy from a wind-energy conversion system alone is in the small power range of 2-4 kW only, additional energy sources, such as solar panels, fuel cells and battery banks can be included in the hybrid system. For the energy storage system, a dynamic model incorporating features such as state of charge (SOC) could be developed. The state of charge SOC could be used to determine whether the excessive power from the hybrid system is used to charge the battery or is dissipated across a dump load. If the SOC is below the rated minimum level, the battery charging would be given top priority, and if above a rated maximum, the dump loads would be activated. The dynamic performance of the standalone hybrid micro-grid could be analysed and load studies could be performed. The aim will be to connect the sources in such a way that maximum power transfer is being ensured from all the sources, whilst maintaining the power requirement of the load and the dc-link voltage requirement.
- Grid-interconnected system - This work deals with a stand-alone system, where there is little to no possibility of grid connection. In order to address grid connection, the analysis would be different and more work would be needed to synchronize the system with the utility grid. The major concern would be the synchronization of the voltage magnitude and frequency with the grid. It would be of interest to study the performance of the system in a grid-connected scenario.

Author publications

Journal Publications

1. Venkataraman, A.; Maswood, A.I.; Sarangan, N.; Gabriel, O.H.P., "An Efficient UPF Rectifier for a Stand-Alone Wind Energy Conversion System," in *Industry Applications*, IEEE Transactions on , vol.50, no.2, pp.1421-1431, March-April 2014

Conference Proceedings (Arranged by relevance)

1. Venkataraman, A; Maswood, AI; Rahman, S.N.; Gabriel, O.H.P., "A novel maximum power point tracking algorithm for a stand-alone unity power factor wind energy conversion system," *Renewable Energy Research and Applications (ICRERA), 2013 International Conference on* , vol., no., pp.109,114, 20-23 Oct. 2013.

2. Maswood, A.I.; Sarangan, N.; Venkataraman, A.; , "Comparison of current control methods for a near Unity Power Factor Rectifier Converter in a wind generator system feeding stand-alone loads," *Industry Applications Society Annual Meeting (IAS), 2011 IEEE* , vol., no., pp.1-8, 2011.

3. Pinkymol, H.R.; Maswood, A.I.; Venkataraman, A., "Space vector based field oriented control of Permanent Magnet Synchronous Motor with a 3-level inverter scheme," *Transportation Electrification Conference and Expo (ITEC), 2013 IEEE* , vol., no., pp.1,6, 16-19 June 2013

4. Ooi H. P. Gabriel, Ali I. Maswood, Aditya Venkataraman, Multiple-Poles Multilevel Diode-Clamped Inverter (M2DCI) Topology for Alternative Multilevel Converter” – Accepted for presentation at International Power and Energy Conference (IPEC), 2012.

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Appendix

Appendix A - Wind Energy Conversion System Parameters

i) Wind turbine specifications

The wind turbine torque is modelled as a current controlled voltage source driving a PMSG in the PSIM[®] environment, using the wind turbine equations described in Chapter 2. The input for the wind turbine block is the wind velocity V and output of the wind turbine block is the torque of the turbine, which can be connected to the PMSG block available in the PSIM environment.

Figure A.1 The PSIM[®] simulation model of the wind turbine

Rated wind speed = 12 m/s

Optimal tip speed ratio = 8.1, C_p (max) = 0.48 (selected on the basis of [95], which compares the coefficient of performance of 10 commercially available wind turbine (most wind turbines are capable of producing a maximum C_p value of 0.479-0.5). The simulation model is based on the E101 turbine which has a maximum coefficient of performance of 0.48)

Radius = 1.26 m

Density of air = 1.225 kg/m³

Rated mechanical power (for 12m/s) = 2.5 kW

ii) PMSG specifications

Rated power = 3 kW

Stator resistance = 0.49Ω

Stator inductances ($L_d = L_q$) = 5.35mH

Number of poles = 6 poles

iii) Unity power factor rectifier converter specifications

Per phase inductance = 15 mH

DC link capacitance ($C_a = C_b$) = 1000 μF, $V_{DC} = 400$ V

Hysteresis band = 0.2 A,

Load = 65 Ω

iv) Reference dc-link voltage calculation

For an uncontrolled diode bridge rectifier, the equation used for calculating the reference dc-link voltage (ignoring the overlap due to the PMSG inductance) is given as (A1)

$$V_{dc,ref} = (V_{ll,rms}) \frac{3\sqrt{2}}{\pi} \quad (A1)$$

where $V_{ll,rms}$ is the input line to line rms voltage. The value of $V_{dc,ref}$ calculated from equation (A1) is used as the reference voltage in the average current and Hysteresis Current Control in

Chapters 4 and 5. When the DC link voltage drops below the value mentioned in (A1), it leads to poor power factor and increased line current harmonics.

Table A1 Reference dc-link voltage calculation

<i>Wind speed (m/s)</i>	<i>V_{ll,rms} (V)</i>	<i>V_{dc,ref} (V)</i>
8	166.9	225.6
10	192.8	260.5
12	231.5	312.6
14	292.4	394.8

v) Rating of bidirectional switches in Unity Power Factor Rectifier

The peak and RMS ratings of the bidirectional switch current can be calculated using (1) and (2) to determine the ratings of the switches [21].

$$I_{sw(avg)} = \frac{2}{3} \frac{P_{dc}}{V_p} \left(\frac{2}{\pi} - \frac{V_p}{V_{dc}} \right) \quad (1)$$

$$I_{sw(rms)} = \frac{1}{3} \frac{P_{dc}}{V_p} \left(1 - \frac{32\sqrt{2}}{3\pi} \left(\frac{V_p}{V_{dc}} \right) + 6 \left(\frac{V_p}{V_{dc}} \right)^2 \right)^{\frac{1}{2}} \quad (2)$$

Where, P_{dc} represents the dc-link rated power, V_p represents the amplitude of the supply voltage (calculated at rated wind speed), V_{dc} represents the rated dc-link voltage.

vi) Lead Acid Battery Bank Model Parameters

The model of a lead-acid battery adopted in this research work is presented in Section 2.4.1.

The battery parameters used in simulation are presented in Table A2 below.

Table A2 Lead-acid battery parameters

<i>Term</i>	<i>Units</i>	<i>Value</i>
C_{bat}	Open circuit battery capacitance in Farads	240
R_{sd}	Self-discharge resistance of battery in $k\Omega$	460.6
$R_{ic} = R_{id}$	Charging and discharging resistance of battery in $m\Omega$	8.9
$R_{oc} = R_{od}$	Over-charging and over-discharging resistance of battery in $m\Omega$	100
C_o	Over-charging/discharging capacitance in Farad	200

Appendix B – C-Code used for the Maximum Power Point Tracking in Chapter 4

```
#include <math.h>
```

```
#include "PsimBlock.h"
```

```
#include "stdafx.h"
```

```
#include <stdlib.h>
```

```
#include <stdio.h>
```

```
#include <assert.h>
```

```
#include <String.h>
```

```
int i, j, k, q, down, step, flag, flag2, flag3; //iteration variables
```

```
double Pe, Iref, IrefMax, PeMax, Cp, upCp, downCp, MPPCp, Wspeed, currWspeed,  
CpMax; //Pe=input, Iref=output
```

```
double m, n, o, p, s, r;
```

```
double arrayPe[250000]; //declare arrays to allocate memory
```

```
double arrayIref[250000];
```

```
__declspec(dllexport) void OPENSIMUSER(const char *szId, const char * szNetlist, void **  
ptrUserData, int *pnError, LPSTR szErrorMsg, void * pPsimParams)
```

```
{  
  
m=n=o=p=0;  
  
q=0;  
  
Iref=0;  
  
Cp=0;  
  
j=1;  
  
i=0;  
  
flag=0;  
  
flag2=0;  
  
flag3=0;  
  
currWspeed=0;  
  
Wspeed=567; //random initialization  
  
IrefMax=0;  
  
PeMax=0;  
  
CpMax=0;  
  
arrayPe[0]=0;  
  
arrayIref[0]=0;  
  
//Define iteration & customization parameters here
```

```

step=50;

}

__declspec(dllexport) void RUNSIMUSER(double t, double delt, double *in, double *out,
void ** ptrUserData, int *pnError, LPSTR szErrorMsg)

{

//Empty the arrays if allocated memory limit is reached

if (i>245000)

{

        i=0;

        j=1;

}

i++;

Pe=in[0];

Cp=in[2];

Wspeed=in[1];

arrayPe[i]=Pe;

flag2=0;

//In the event of wind velocity change, restart search

```

```

if (i>2 && abs(Wspeed-currWspeed)>=0.5)

{

    i=1;

    j=1;

    PeMax=0;

    CpMax=0;

    IrefMax=0;

    Iref=0;

    flag=0;

    flag2=0;

    flag3=0;

}

//Reduces the number of iterations; in this case, the algo runs every 50 time steps

k=j*step;

if (k==i) //Start this loop only every (step) iterations; in this case step=50

{

    //Increase Iref by +0.1 if the current Pe is greater than the previous Pe

    //Increase Iref for as long as max. Cp and max. Pe has not been reached

```

```

if (arrayPe[i]>arrayPe[i-step] && arrayPe[i]>PeMax && Cp<0.479)

{

    Iref=Iref+0.1;

    arrayIref[i]=Iref;

    j++;

    flag=1; //Flags to keep track of which statements are being used for later

}

//Decrease Iref for as long as max Cp and max Pe has not been reached

//Don't enter this statement if MPP has been reached previously (by setting
requirement flag3==0)

else if (arrayPe[i]<=arrayPe[i-step] && flag3==0 && Cp<0.479)

{

    if (down<4)

    {

        Iref=Iref-0.1;

        if (Iref<0)

        {

            Iref=abs(Iref); //ensures Iref never becomes negative

```



```

        }

        down++;

    }

    //Fixes the erratic response:

    //If decrease in Iref causes a decrease

    else if (down==4)

    {

        Iref=Iref+0.3;

        down=0;

    }

    arrayIref[i]=Iref;

    j++;

    flag=1;

}

else //MPP has been found

{

    flag3=1;

```

//Only enter this if statements for inc. or dec. Iref have been entered previously
(by setting flag==1)

```
if (flag==1 && arrayIref[i-step]!=0)
```

```
{
```

```
    Iref=arrayIref[i-step];
```

```
    out[0]=Iref;
```

```
    flag=0;
```

```
}
```

```
else
```

```
{
```

```
    Iref=IrefMax; //Store previous max Iref value as current max value
```

```
}
```

```
IrefMax=Iref;
```

```
if (Pe>PeMax && Cp>upCp)
```

```
{
```

```
    PeMax=Pe; //update max Pe if available
```

```
}
```

```
Iref=IrefMax;
```

```

out[0]=Iref; //send updated Iref to output signal

if (Cp>CpMax)

{

    CpMax=Cp; //update max Cp if available

}

p=IrefMax; //for storage in text file

s=PeMax;

r=CpMax;

//record MPP for this wind speed

if (m!=p || n!=s || o!=r)

{

    FILE * data2=fopen("D:\\academics\\3.2\\FYP\\run    psim\\Max
values.txt", "a+");

    fprintf(data2, "%i %f %f %f %f\n", i, IrefMax, PeMax, CpMax,
Wspeed);

    fclose(data2);

}

j++;

```

```

        flag2=1;

    }

}

m=IrefMax; //for storage of max values in text file

n=PeMax;

o=CpMax;

if(flag2==0) //if the previous statement wasn't entered, send previous Iref as output

{

    out[0]=Iref;

}

currWspeed=Wspeed; //check for change in windspeed

}

```

Appendix C - MATLAB Code used for the Static PSO Maximum Power Point Tracking in Chapter 5

```
function [iref1n,Pb4,VPb1,iref2n,Pb5,VPb2,iref3n,Pb6,VPb3,Gb1,VGb,v1,v2,v3] =  
fcn(Pe1,iref1o,Pb1,Vm1,Pe2,iref2o,Pb2,Vm2,Pe3,iref3o,Pb3,Vm3,Gb,GObjmin,V1,V2,V3)  
  
x = [iref1o iref2o iref3o];  
  
y = [Pe1 Pe2 Pe3];  
  
vel = [V1 V2 V3];  
  
Pbest=[Pb1 Pb2 Pb3];  
  
particle=3;  
  
Gbest=Gb;  
  
Objmin=[Vm1 Vm2 Vm3];  
  
Obj=Objmin;  
  
for j=1:particle  
  
Obj(j)= 4000-y(j);  
  
if Obj(j) < Objmin(j)  
  
Pbest(j)= x(j);  
  
Objmin(j)= Obj(j);  
  
end
```

Figure C.1 Structural Schematic of the Particle Swarm Optimization co-simulation (Simulink and PSIM)

if Objmin(j) < GObjmin

Gbest= Pbest (j) ;

GObjmin=Objmin(j);

end

vel(j)=0.4*vel(j)-2*rand(1,1)*(x(j)-Pbest(j))-2*rand(1,1)*(x(j)-Gbest);

if vel(j)>3

vel(j)=3;

end

```
if vel(j)<-3

vel(j)=-3;

end

x(j)=x(j)+vel(j);

end

iref1n=x(1);

Pb4=Pbest(1);

VPb1=Obj(1);

iref2n=x(2);

Pb5=Pbest(2);

VPb2=Obj(2);

iref3n=x(3);

Pb6=Pbest(3);

VPb3=Obj(3);

v1=v(1);

v2=v(2);

v3=v(3);

Gb1=Gbest;
```

VGb=GObjmin;

MATLAB Code

simulink

for k=1:15

sim(Simulink File.slx')

K1=sum(Iref1)/6000;

K2=sum(Iref2)/6000;

K3=sum(Iref3)/6000;

Q(k,1)=K1;

Q(k,2)=K2;

Q(k,3)=K3;

meanQ=(Q(k,1)+Q(k,2)+Q(k,3))/3;

sdq=sqrt((((Q(k,1) - meanQ)*(Q(k,1) - meanQ) +(Q(k,2) - meanQ)*(Q(k,2) - meanQ)+(Q(k,3) - meanQ)*(Q(k,3) - meanQ))/3);

standdev(k)=sdq;

end

Appendix D – C-Code used for the Dynamic PSO Maximum Power Point Tracking in Chapter 5

```
#include <Stdlib.h>
```

```
#include <String.h>
```

```
#include <math.h>
```

```
#include <Psim.h>
```

```
// PLACE GLOBAL VARIABLES OR USER FUNCTIONS HERE...
```

```
float
```

```
sd,mean,vmax,vmin,wmax,wmin,x1,x2,x3,g1,g2,g3,v1,v2,v3,pb1,pb2,pb3,gb,o1,o2,o3,o1o,o
```

```
2o,o3o,o1m,o2m,o3m,ogm,r1,r2,r3,r4,r5,r6,w;
```

```
int j,p,flag,itn;
```

```
////////////////////////////////////
```

```
// FUNCTION: SimulationStep
```

```
// This function runs at every time step.
```

```
//double t: (read only) time
```

```
//double delt: (read only) time step as in Simulation control
```

```
//double *in: (read only) zero based array of input values. in[0] is the first node, in[1] second  
input...
```

```
//double *out: (write only) zero based array of output values. out[0] is the first node, out[1]  
second output...
```

```
//int *pnError: (write only) assign *pnError = 1; if there is an error and set the error  
message in szErrorMsg
```

```
// strcpy(szErrorMsg, "Error message here...");
```

```
// DO NOT CHANGE THE NAME OR PARAMETERS OF THIS FUNCTION
```

```
void SimulationStep(
```

```
    double t, double delt, double *in, double *out,
```

```
    int *pnError, char * szErrorMsg,
```

```
    void ** reserved_UserData, int reserved_ThreadIndex, void *  
reserved_AppPtr)
```

```
{
```

```
if (j%5000==0)
```

```
{
```

```
p=p+1;
```

```
// ENTER YOUR CODE HERE...
```

```
r1 = float (rand())/float(RAND_MAX);
```

```
r2 = float(rand())/float(RAND_MAX);
```

```
r3= float (rand())/float(RAND_MAX);
```

```
r4= float(rand())/float(RAND_MAX);
```

```
r5= float(rand())/float(RAND_MAX);
```

```
r6= float(rand())/float(RAND_MAX);
```

```
o1=in[0];
```

```
o2=in[1];
```

```
o3=in[2];
```

```
out[42]=o1;
```

```
out[43]=o2;
```

```
out[44]=o3;
```

```
out[45]=o1o;
```

```
out[46]=o2o;
```

```
out[47]=o3o;
```

```
if (p>4)
```

```
{
```

```
if((abs(o1o-o1)/(o1o)>0.25)){
```

```
flag=1;
```

```
j=0;
```

```
p=-1;
```

w=0.4;

g3=6;

g1=3.5;

g2=9;

v3=0.2;

v1=0.3;

v2=-0.4;

pb3=6;

pb1=3.5;

pb2=9;

gb=2;

o1o=0.05;

o2o=0.05;

o3o=0.05;

o1m=0.05;

o2m=0.05;

o3m=0.05;

ogm=0.05;

```
vmax=1.5;
```

```
vmin=0.15;
```

```
wmax=0.4;
```

```
wmin=0.05;
```

```
itn=100;
```

```
goto label;
```

```
}
```

```
}
```

```
if ( o1>o1m ) {
```

```
    pb1=g1;
```

```
        o1m=o1;
```

```
}
```

```
if ( o2>o2m ) {
```

```
    pb2=g2;
```

```
        o2m=o2;
```

```
}
```

```
if ( o3>o3m ) {
```

```
    pb3=g3;
```

```

        o3m=o3;

    }

    if ( o1m>ogm ) {

        ogm=o1m;

        gb=pb1;

    }

    if ( o2m>ogm ) {

        ogm=o2m;

        gb=pb2;

    }

    if ( o3m>ogm ) {

        ogm=o3m;

        gb=pb3;

    }

    w=wmax-((wmax-wmin)*p/itn);

    if (p>itn) {

        w=wmin;

    }

```

```
v1=(w*v1)-(0.8*r1*(g1-pb1))-(1.2*r2*(g1-gb));
```

```
v2=(w*v2)-(0.8*r3*(g2-pb2))-(1.2*r4*(g2-gb));
```

```
v3=(w*v3)-(0.8*r5*(g3-pb3))-(1.2*r6*(g3-gb));
```

```
if (v1>vmax) {
```

```
v1=vmax;
```

```
}
```

```
if (v1<=-vmax) {
```

```
v1=-vmax;
```

```
}
```

```
if (v2>vmax) {
```

```
v2=vmax;
```

```
}
```

```
if (v2<=-vmax) {
```

```
v2=-vmax;
```

```
}
```

```
if (v3>vmax) {
```

```
v3=vmax;
```

```
}
```

```

if (v3<-vmax) {

v3=-vmax;

}

g1=g1+v1;

g2=g2+v2;

g3=g3+v3;

mean=(g1+g2+g3)/3;

sd=sqrt(((g1 - mean)*(g1 - mean) +(g2 - mean)*(g2 - mean)+(g3 - mean)*(g3 - mean))/3);

}

label:

o1o=o1;

o2o=o2;

o3o=o3;

out[0]=g1;

out[1]=g2;

out[2]=g3;

out[3]=pb1;

out[4]=pb2;

```



```

out[5]=pb3;

out[6]=gb;

out[7]=sd;

out[8]=v1;

out[9]=v2;

out[10]=v3;

out[11]=flag;

out[33]=p;

out[41]=mean;

label2:

j=j+1;

}

////////////////////////////////////

// FUNCTION: SimulationBegin

// Initialization function. This function runs once at the beginning of simulation

// For parameter sweep or AC sweep simulation, this function runs at the beginning of each
simulation cycle.

// Use this function to initialize static or global variables.

```

```

//const char *szId: (read only) Name of the C-block

//int nInputCount: (read only) Number of input nodes

//int nOutputCount: (read only) Number of output nodes

//int nParameterCount: (read only) Number of parameters is always zero for C-Blocks.
Ignore nParameterCount and pszParameters

//int *pnError: (write only) assign *pnError = 1; if there is an error and set the error
message in szErrorMsg

// strcpy(szErrorMsg, "Error message here...");

// DO NOT CHANGE THE NAME OR PARAMETERS OF THIS FUNCTION

void SimulationBegin(const char *szId, int nInputCount, int nOutputCount,

                    int nParameterCount, const char ** pszParameters,

                    int *pnError, char * szErrorMsg, void ** reserved_UserData, int
reserved_ThreadIndex, void * reserved_AppPtr)

{

// ENTER INITIALIZATION CODE HERE...

j=0;

p=-1;

sd=45;

w=0.4;

```

g3=6;

g1=3.5;

g2=9;

v3=0.2;

v1=0.3;

v2=-0.4;

pb3=6;

pb1=3.5;

pb2=9;

gb=2;

o1o=0.05;

o2o=0.05;

o3o=0.05;

o1m=0.05;

o2m=0.05;

o3m=0.05;

ogm=0.05;

vmax=1.5;

```

vmin=0.15;

wmax=0.4;

wmin=0.05;

itn=100;

flag=0;

srand(time(NULL));

}

////////////////////////////////////

// FUNCTION: SimulationEnd

// Termination function. This function runs once at the end of simulation

// Use this function to de-allocate any allocated memory or to save the result of simulation in
an alternate file.

// Ignore all parameters for C-block

// DO NOT CHANGE THE NAME OR PARAMETERS OF THIS FUNCTION

void SimulationEnd(const char *szId, void ** reserved_UserData, int reserved_ThreadIndex,
void * reserved_AppPtr)

{

}

```

Appendix E – A note on the strengths and limitations of PSIM[®] computer simulation platform

Computer based simulations are used to verify the power electronics control and topology proposed in this thesis. In the simulation, certain assumptions are made to model a system, as close to reality as possible, so that the performance of the system can be studied. By careful selection of variables, it is possible to test the performance of the system for a wide-range of conditions, such as different wind speeds, conditions of loading, sudden changes in environmental conditions etc. In this work, the PSIM[®] simulation environment has been used extensively to test, validate and verify the performance of the proposed unity power factor converter controller. A note is made here on the strengths and limitations of the PSIM[®] simulation environment for the benefit of the reader.

PSIM[®] is an electronic circuit simulation software package, designed specifically for use in power electronics and motor drive simulations but can be used to simulate any electronic circuit. PSIM[®] uses a strong algorithm dedicated to electrical circuits (piecewise method, generic models and a fixed time-step) that enables a fast and accurate simulation. The software is used widely in industrial research and development, as well as in academia for research and tutorial purposes.

The following points make PSIM[®] an ideal candidate for the design and simulation of the power electronics converter topology and control proposed in this thesis.

1. The first reason for using PSIM[®] is the co-simulation feature, SimCoupler. This tool facilitates the user to design the power circuits in PSIM[®] and the control system in Simulink and perform co-simulation. MATLAB has a diverse control systems toolbox and PSIM[®] has an extensive power device library, making this a very useful feature.

This was utilized in the development of the Particle Swarm Optimization based current control in Chapter 5.

2. In PSIM® it is easy to selectively introduce parasitic interactions and non-ideal conditions. This feature enables the user to introduce near real-world conditions to the simulation problem, to obtain practically relevant simulation results. This allows designers to simulate their designs with high accuracy. Actual test results are found to be closely matching with simulated results [96].
3. The fast simulation allows repetitive simulation runs and significantly shortens the design cycle. The outstanding processing speed of PSIM® is also very useful in cases when both line-frequency and high-frequency components are present, for example, power factor correctors or inverters [E.2].
4. PSIM® has a built-in C-compiler which allows the user to develop the C-code into PSIM® without compiling [97]. This feature enables easy and flexible implementation of user-defined function or control methods. The user-defined function block was used in this thesis to model the hysteresis current control block in Chapter 3, as well as the maximum power point tracking feature in Chapter 4 and 5.

There are a few limitations of the PSIM® simulation environment.

1. In-depth knowledge of power electronics subject is necessary to interpret the obviously incorrect results.
2. The complexity of the block diagram used to simulate the power circuit can increase drastically with the number of semiconductors in the circuit.

Due to the advantages mentioned above PSIM® software has been used for testing and developing accurate power electronic and control circuits, such as three-phase diode

rectifiers, thyristor based converters and three phase PWM rectifiers is discussed in [97]. In this thesis, PSIM® is used to validate the proposed current control technique in Chapter 4 and 5.