Design and performance evaluation of a unity power factor converter for wind energy conversion systems

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TECHNOLOGICAL
UNIVERSITY**

**DESIGN AND PERFORMANCE EVALUATION OF A
UNITY POWER FACTOR CONVERTER FOR WIND
ENERGY CONVERSION SYSTEMS**

NIRNAYA SARANGAN

**SCHOOL OF ELECTRICAL AND ELECTRONIC
ENGINEERING**

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**DESIGN AND PERFORMANCE EVALUATION OF A
UNITY POWER FACTOR CONVERTER FOR WIND
ENERGY CONVERSION SYSTEMS**

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A thesis submitted to the Nanyang Technological University
in partial fulfillment of the requirement for the degree of
Master of Engineering

2012

STATEMENT OF ORIGINALITY

I hereby certify that the content of this thesis is the result of work done by me and has not been submitted for higher degree to any other university or institution.

NIRNAYA SARANGAN

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LIST OF SYMBOLS

P_m	Output mechanical power of the wind turbine (W)
ρ	Density of air (kg-m ³)
C_p	Power coefficient
A	Area swept by the wind turbine blades (m ²)
U_w	Wind speed (m/s)
λ	Tip speed ratio
β	Blade pitch angle (°)
r	Radius of wind turbine blade (m)
ω_m	Angular rotor speed of wind turbine (rad/s)
i_d, i_q	d-axis and q-axis current of generator (A)
L_d, L_q	d-axis and q-axis inductances of generator (H)
R_s	Generator stator resistance (Ω)
ω_e	Electrical rotor speed of generator (rad/s)
ψ_f	Permanent magnetic flux (Wb)
ω_g	Mechanical angular speed of generator (rad/s)
p	Number of generator pole pairs

T_e	Electromagnetic torque of rotor (N-m)
V_a, V_b, V_c	Three-phase voltages of generator (V)
L_a, L_b, L_c	Input inductors of the rectifier (H)
C_a, C_b	Identical DC link capacitances of three-phase rectifier (F)
S_a, S_b, S_c	Switching signals of the bidirectional switches
i_a, i_b, i_c	Inductor currents of the rectifier (A)

LIST OF ACRONYMS

AC	Alternating Current
ACC	Average Current Control
DC	Direct Current
DCM	Discontinuous Conduction Mode
DFIG	Doubly Fed Induction Generator
DG	Distributed Generation
DPF	Displacement Power Factor
EDCC	Equal Distance Current Control
FFT	Fast Fourier Transform
HAWT	Horizontal Axis Wind Turbine
HCC	Hysteresis Current Control
HVDC	High Voltage Direct Current
HTF	Harmonic Trap Filters
MPPT	Maximum Power Point Tracking
PF	Power Factor
PFC	Power Factor Correction

PI	Proportional Integral
PLL	Phase Locked Loop
PMSG	Permanent Magnet Synchronous Generator
PWM	Pulse Width Modulation
RMS	Root Mean Square
SCIG	Squirrel Cage Induction Generator
SPWM	Sinusoidal Pulse Width Modulation
THD	Total Harmonic Distortion
TSR	Tip Speed Ratio
UPF	Unity Power Factor
VAWT	Vertical Axis Wind Turbine
WECS	Wind Energy Conversion System
WT	Wind Turbine
WTG	Wind Turbine Generator

SUMMARY

We live in an era of globalization where the impending energy crisis and increasing levels of atmospheric pollution are the two chief reasons to invest more in renewable sources of energy. Solar, wind, tidal and geothermal energy are some of the important non-conventional sources that relieve our dependence on fossil fuels such as coal and natural gas. These renewable sources are available in abundance for free, offer unlimited potential for energy generation, and most importantly, are non-polluting in nature. More and more countries around the world choose to invest in research of such renewable energy systems.

A wind energy conversion system typically consists of three important components- the wind turbine, the electrical generator and the power electronic converter. Wind turbine driven Permanent Magnet Synchronous Generators (PMSG) find increasing applications due to their numerous advantages and represent a very important trend in the growth of variable wind speed conversion systems. A PMSG does not require an external excitation current and finds high popularity in low to medium power stand-alone systems due to its high efficiency and reliability. Small scale stand-alone wind energy systems are receiving considerable attention due to their importance in locations that are far flung and where conventional generation and grid interface may not be possible. With the growth of such systems, there is also equal advancement in the technology developed for them.

Wind is a highly stochastic source. Its fluctuating nature poses challenges in system design since the primary objective is to extract the maximum power from the wind. Such a system must be reliable in a wide range of operating conditions while maintaining

simplicity. However, it is highly difficult to obtain the highest power from the system during certain wind speed conditions. Such shortcomings should be considered while deciding on the control schemes and the overall system design.

Power electronic converters form an integral and important part of wind energy conversion systems. They are delegated the important task of maintaining good quality line currents to prevent efficiency reduction due to losses, to maintain high input power factor operation, while achieving extraction of the maximum possible power in the overall system. The system balance has to be ensured. Hence, the design of these converters merits careful study. In literature, one can see numerous front-end rectifiers and back-to-back converters proposed to achieve all the aforementioned aims. In this work, a three-phase high power factor front-end rectifier has been interfaced with a variable wind speed turbine generator system feeding a stand-alone load. This rectifier has been modeled based on the work done by Liu and Maswood.

This converter employs a current-controlled three-phase diode bridge rectifier employing three static bidirectional switches. The power devices used are inexpensive and offer less stress, thus eliminating the need for any clamping circuits to prevent excessive overvoltage. The significance of this converter lies in its ability to achieve its three-fold aim: to achieve very high input power factor operation, shape the line currents and minimize the harmonic levels in them as well as extract the maximum possible real power from the wind turbine-generator system under rated conditions of operation by means of different current control methods. An AC-DC-AC converter feeding a stand-alone load has been modeled to achieve its objectives satisfactorily.

CHAPTER 1

INTRODUCTION

1.1 Preamble

Power electronics is a multi-disciplinary field that encompasses power systems, solid state electronics, analog and digital systems, and electrical machines to name a few. With fast technological advancement and expansion in market demand, this field has proved itself to be indispensable in our everyday life. Power electronics finds applications in various fields, from electrical power transmission to transportation, from process control to electro-technical applications. These applications may be residential, industrial or commercial in nature [1].

Arguably, the most important application of this field is in the processing, control and flow of electric energy by supplying voltages and currents that are optimally suitable for user loads. When the transmission lines are quite long, transfer of power takes place typically over High Voltage DC (HVDC) lines. The conversion of AC power into DC takes place at the sending end and the conversion of DC back into AC power takes place at the receiving end, which is usually a residential or industrial load. The importance of power electronics is realized while trying to improve the efficiency of power transfer by utilizing the transmission network to the highest capacity.

The relevance of non-conventional sources of energy in the current scenario increases day by day. Renewable energy systems can be either employed as stand-alone systems or a large number of photovoltaic and wind based electric systems may be interconnected and connected to the utility grid. However, the stand-alone systems provide us with flexibility that utility based systems cannot. Power production closer to the load centers contributes to reduced costs and increased energy demand satisfaction. Therefore, there has been promising research happening in the study of wind energy as a principal source for isolated sites [2].

1.2 Motivation

Harmonic generation and poor input power factor are two pertinent problems in power systems. High levels of harmonic distortion in line currents and voltages not only reduce the overall system efficiency but also lead to interference with the interdependent components, equipment malfunction and high losses [3]. Consequently, a number of standards and regulations such as IEEE-519 and IEC 61000-3 have been introduced. They serve as guidelines in determining permissible levels of harmonic content in currents that are injected into the utility grid.

In systems with poor input power factor, the current drawn by the load is much higher than that drawn by a system with high power factor operation. Poor power factor leads to energy losses, requiring increased maintenance and higher costs for the system components. A number of control methods have been discussed in literature to enable

high power factor operation. These methods have been reviewed in detail in subsequent chapters of this thesis.

The issue of high power factor operation comes to prominence when conventional methods of AC-DC rectification are considered. Typically, diode bridge rectifiers find popularity in converting AC currents and voltages into DC. However, due to their inherent non-linearity they have poor input power factor and very high levels of harmonic content in their line currents and voltages. Therefore, it becomes imperative to employ some sort of power factor correction method to counterbalance this problem. This forms the basis of this work which is elaborated upon in the next section.

1.3 Objectives

The main objective of this work is to study the implementation of a suitable power converter topology with appropriate control methods for a stand-alone wind turbine generator (WTG) system. The aim is to achieve high input power factor operation while keeping the harmonic levels in the input currents and voltages as low as possible. There are many other challenges in such a system, ranging from the stochastic nature of wind which leads to a varying frequency of operation to the extraction of maximum real power from the incident wind for high efficiency. Other important considerations include the choice of control methods to maintain system simplicity and reliability.

The wind turbine in this study is used to drive a permanent magnet synchronous generator (PMSG). The topology considered is a three-phase diode bridge rectifier employing three static bidirectional switches. These switches are controlled by three

different current control methods with the purpose of achieving line current shaping and high power factor operation at the input side of the front-end rectifier. The rectifier is followed by a sinusoidal pulse width modulation (SPWM) inverter feeding a rated stand-alone load.

In this work, the system operation was studied for two constant wind speed conditions and a simple stepped wind speed profile. Three current control methods- the average current control (ACC), hysteresis current control (HCC) and equal distance current control (EDCC)- were used to determine the power factor operation of the front-end rectifier. These three control methods have been implemented in previous work by Liu and Maswood for a system with ideal sinusoidal voltage sources and their performance has been discussed showing very high input power factor operation while achieving low total harmonic distortion (THD) values in the line currents [4] [5] [6]. Therefore, it was of interest to see the behavior of these methods in a wind turbine driven system which has varying input conditions, which is the main contribution of this thesis. The performance of these methods as well as the challenges encountered in their implementation has been discussed in this work. Based on the challenges faced, potential research avenues in this topic of study have been highlighted in the end of the thesis.

1.4 Organization of the thesis

The thesis consists of seven chapters and is organized as follows:

1. Chapter 1 is a preamble of this work, providing an introduction of and the motivation behind the thesis, along with its objectives.

2. Chapter 2 presents an overview of a wind energy conversion system (WECS) with discussions on the general design and operating principles. Various generators popularly employed in WECS along with their merits and drawbacks are also presented.
3. Chapter 3 presents the literature survey performed on existing power factor correction techniques and the topologies adopted specifically for wind energy systems.
4. Chapter 4 discusses ACC method and its application in the wind energy system modeled in this work. Its performance is presented in the form of simulation waveforms and the operational parameters analyzed to determine its suitability in achieving the intended goals of low THD and high power factor while maintaining efficient power transfer.
5. Chapter 5 deals with the HCC method and its implementation in the proposed wind energy system. A detailed analysis of the performance parameters is presented in this chapter.
6. Chapter 6 discusses the behavior of the system for the EDCC method and is devoted to specific challenges and issues pertaining to employing these current control methods for a WECS.
7. Chapter 7 concludes the thesis with a summary of the results obtained and suggestions for future work.

CHAPTER 2

WIND ENERGY CONVERSION SYSTEMS

2.1 Wind as an energy source

Wind, as a source of energy, has been harnessed by man for many centuries now. The earliest records tell us that wind was the primary source powering ships till engines were invented. Wind turbines have been in existence in many countries as early as the 17th century. Their primary tasks were irrigation of land, along with the grinding and milling of grain and pumping of water from earth. The gigantic potential of wind for generation of electric power was realized in the 1800's. Denmark was the first country to employ a 23 m diameter wind turbine to generate electricity and by 1910, several hundred units with capacities of 5 to 25 kW were operational there [7].

The U.S Department of Energy through the International Energy Outlook 2006 (IEO) report of Energy Information Administration (EIA) stated that the global consumption of energy will grow at an annual average of 2% between the years 2003 and 2030. The forecast for the growth of electric energy generated by wind energy systems is greater, at 2.7% to a year. The generation of electric energy from wind systems has also grown very quickly- from a global installed power of 4.8 GW in 1995 to 58 GW in 2005, at an average annual growth rate of 24% [8]. According to the World Wind Energy Report

of 2010 released by World Wind Energy Association (WWEA), the highest nameplate capacity of a wind generator at the end of the year was 197 GW. As of 2011, it is estimated that 83 countries around the world use wind power on a commercial basis [9]. Considering this trend, it can be safely concluded that with increasing demand for electric energy generation, there will be a significant increase in the installation of wind energy systems globally.

Wind is a quiet alternative to traditional options such as diesel systems. They are economically viable and environmentally friendly, eliminating problems of pollution and the need for expensive maintenance. They offer the flexibility of distributed generation (DG) in remote locations that are not connected to the grid. Stand-alone wind energy systems, usually rated for low to medium power, find increasing preference in this aspect. In spite of all these advantages, wind offers a huge challenge in being harnessed as an energy source.

A WECS consists of three components – the wind turbine, the generator driven by the turbine and the power electronic converter interfaced between the generator and the grid or stand-alone load as shown in Fig.2.1.

Fig. 2.1. Block diagram of a typical WECS.

Two factors should be given consideration in the design of a WECS. One is the unpredictable, stochastic nature of wind. Depending on the geographical location and seasonal changes, the wind pattern changes globally. Some places may have abundant air motion while others have very poor winds. Thus, the challenge of utilizing the available wind to the maximum possible level emerges. The second issue is the strong interdependence between the aerodynamic characteristics of the wind turbine, the generator's rotor speed and the amount of power that can be extracted from the wind. Hence, it becomes necessary to implement a control method that will enable the extraction of the maximum power from the system under all possible operating conditions.

2.2 Wind turbines

The characterization of the wind turbine based on the amount of power it has to extract from the wind is highly important. The function of the wind turbine is to convert the kinetic energy of wind into rotational motion that will generate electrical power. This electrical power is then suitably conditioned depending on the load.

Typically wind turbines are classified based on the number of blades and the axis about which they are mounted. Two or three blade wind turbines are generally the most popular choices with the three blade turbine more preferred due to better performance as well as the even distribution of variations in wind speed from the rotors to the drive shaft. It is also capable of achieving better power coefficient. However, as the number of blades goes on increasing, the complexity of the system increases due to larger physical size and weight. Also, the turbulence of one blade will affect the efficiency of the other blades.

With fewer blades, the turbine can spin faster before this interference becomes excessive. The second classification is based on the axis about which the blades are assembled- vertical axis wind turbines (VAWT) and horizontal axis wind turbines as shown in Fig. 2.2 (a) and (b).

Fig. 2.2. Types of wind turbines (a) VAWT (b) HAWT [10].

In a VAWT, the blades are assembled about a vertical axis while in the HAWT, the blades are assembled and spin about a horizontal axis. The principal advantage of a VAWT is that the nacelle, which contains all the heavy machinery, can be located on the ground. This enables easy maintenance and servicing. Some drawbacks of VAWTs 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 and turbulence also poses a huge problem. Consequently, the HAWT is more popular.

2.3 Wind turbine characteristics

The linear motion of air is converted into rotational energy when it is incident on the wind turbine. This is converted into electrical energy by an electric generator. The conditioning of the electrical power is performed by the appropriate power electronic converter present at the generator output. The conditioned power is then fed to the load.

The output mechanical power of the wind turbine (*in W*) is given by the cube law equation,

$$P_m = 0.5\rho C_p A U_w^3 \quad (2.1)$$

where, ρ is the density of air ($kg-m^3$)

C_p is the power coefficient

A is the area swept by the wind turbine rotor (m^2)

U_w is the wind speed (m/s).

The power coefficient is a function of the tip speed ratio λ and the blade pitch angle β . It describes the efficiency of the wind turbine in converting the energy present in wind into mechanical power. The tip speed ratio λ may be defined as the ratio of the speed at which the outer tip of the turbine blade is moving to the wind speed. It is given by the equation,

$$\lambda = (r\omega_m) / U_w \quad (2.2)$$

The blade pitch angle β is defined as the angle at which the wind contacts the blade surface. The pitch angle may be changed to control the rotor torque and power. It also provides power and speed limitation at high wind velocities. This action called pitching will provide power limitation at tip-speed ratios that are higher than the predesigned values by turning the blades away, out of the wind.

The expression for power coefficient is given as [11],

$$C_p(\lambda, \beta) = C_1((C_2/\lambda_i) - C_3\beta - C_4)e^{(-C_5/\lambda_i)} + C_6\lambda \quad (2.3)$$

Here, the coefficients are:

$$C_1 = 0.5176$$

$$C_2 = 116$$

$$C_3 = 0.4$$

$$C_4 = 5$$

$$C_5 = 21$$

$$C_6 = 0.0068 \text{ and,}$$

$$(1/\lambda_i) = 1/(\lambda + 0.08\beta) - 0.035/(\beta^3 + 1) \quad (2.4)$$

It is valid to assume pitch angle to be zero for low to medium wind velocities [12]. Hence, in this work, $\beta=0^\circ$.

Wind energy conversion systems may be fixed speed or variable speed systems. There is a particular wind speed at which the wind turbine has the highest possible power coefficient. This becomes the optimum value. Maximum power extraction is ensured when the tip speed ratio and power coefficient are kept close to their optimum values at all possible modes of operation.

For the fixed wind speed system, the rotor speed will be maintained at a constant value even when the wind speed keeps varying. At all other wind speeds, the power coefficient is reduced. However, in variable wind speed operation, the rotational speed of the turbine is changed in response to the wind speed changes so that the power coefficient is maintained at its maximum value. Hence, the variable wind speed operation is capable of efficiently extracting more power from the wind than the constant wind speed mode [13]. Variable speed operation also offers reduced mechanical stress along with increased energy capture [14].

By considering optimum values of tip-speed ratio and power coefficient the expression for the maximum mechanical power (*in W*) at a specific wind speed can be given by [15],

$$P_{max} = (0.5\rho\pi r^5 C_{p,opt} \omega_m^3) / (\lambda_{opt}^3) \quad (2.5)$$

Fig. 2.3 shows the power coefficient values for various values of tip speed ratio and pitch angles. It is seen that the maximum power coefficient is achieved at 0° pitch

angle. The optimum values chosen for this work are 0.48 for the power coefficient and 8.1 for the tip speed ratio. This is explained in the appendix.

Fig. 2.3. Power coefficient versus tip speed ratio characteristics [16].

2.4 Choice of electrical generator

The penetration of a wind energy system in a power system needs to be studied carefully due to the effects it has on overall voltage and frequency balance. The interaction of wind turbines with different electrical generators is of high importance. There are many generator types which find application in a WECS. However, their applications are based on system dynamics and requirements. Some of the most commonly used generators in WECS are squirrel cage induction generator (SCIG), doubly fed induction generator (DFIG) and PMSG. These generators have been explained in [17] and an overview is presented with their schematic representations.

2.4.1 Squirrel Cage Induction Generator (SCIG)

Fig. 2.4 shows the wind turbine rotor coupled to the grid-connected SCIG. Due to the difference in the rotor and generator speeds, a gear box is essential. However, the rotor speed variations are very small and occur only due to changes in the rotor slip. Hence, the generator can be considered to be operating at constant speed. This generator consumes reactive power, because of which capacitors need to be added to facilitate power factor improvement. The rotor design is in such a way that the rotor efficiency will increase or decrease depending on the wind speed so that the generator is not damaged due to overloading at high wind speeds.

Fig. 2.4. Grid connected SCIG [17].

2.4.2 Doubly Fed Induction Generator (DFIG)

Fig. 2.5 shows the DFIG with gear box connected to the grid by means of a back-to-back voltage source converter. The stator windings of the DFIG are directly coupled to

the grid while the rotor windings are coupled to the voltage source converter. The other end of the converter is connected to the grid. The function of the back-to-back voltage source converter is to decouple the electrical grid frequency and the mechanical rotor frequency. This enables variable speed operation of the generator.

Fig. 2.5. DFIG with back-to-back voltage source converter feeding rotor winding [17].

2.4.3 Direct Drive Synchronous Generator

Fig. 2.6 shows a direct drive synchronous generator coupled to the grid through a back-to-back voltage source converter. This may be a diode rectifier and voltage source converter. The rotor is directly coupled to the generator, thus eliminating the need for a gear box. The back-to-back voltage source converter facilitates the control of the generator torque by changing the stator currents through the generator side converter voltage. A diode rectifier would result in an indirect control of the generator through control of the DC link voltage. In case of the grid connection, the reactive power and

active power are both generated and consumed at the grid side of the converter due to the self commutation of the voltage source converter. The current on the grid side is controlled in such a way that the real power is flowing to the grid and the terminal voltage is nearly equal to its reference value.

Fig. 2.6. Direct drive synchronous generator coupled to the grid through a back-to-back voltage source converter [17].

2.5 Permanent Magnet Synchronous Generator (PMSG)

The two prominent choices of generators in WECS are the DFIG and the PMSG. The DFIG offers the possibility of controlling the frequency and amplitude of the generated voltage through the excitation and independent of speed rotation. This makes it a good choice for directly grid-connected variable speed WECS of great size. However, it has some disadvantages. The major one among these is the need for a gear box when the number of poles is less. The use of a gear box implies increased weight, need for maintenance, higher costs, reduced efficiency and reliability. A feasible alternative to the

DFIG is the PMSG, which can be designed with higher number of poles and does not require a gear box.

The PMSG has numerous advantages [12]:

- Compact size
- Higher power density
- Reduced losses
- High reliability and robustness

The most important advantage is the elimination of the gear box. This translates to reduced maintenance needs due to the wear and tear occurring in brushes and the gear box. Thus, the wind turbine can be directly coupled to the generator. Such systems are called direct drive systems and are most suitable for low speed operating conditions.

A number of theoretical models have been developed in literature for the PMSG [18]. The mathematical model of the PMSG in the synchronous reference (d-q) frame (in the state equation form) is given by [19],

$$\begin{cases} di_d/dt = (1/L_{ds}+L_{ls}).(-R_s i_d + \omega_e(L_{qs}+L_{ls})i_q + u_d) \\ di_q/dt = (1/L_{qs}+L_{ls}).(-R_s i_q - \omega_e[(L_{ds}+L_{ls})i_d + \psi_f] + u_q) \end{cases} \quad (2.6)$$

Here, R_s is the stator resistance (Ω)

L_d is the direct axis inductance (H)

L_q is the quadrature axis inductance (H)

L_{ld} and L_{lq} are the leakage inductances of the generator on the d-axis and q-axis, respectively (H)

ψ_f is the permanent magnetic flux (Wb)

ω_e is the rotor speed of the generator (rad/s) and is defined by,

$$\omega_e = p \omega_g \quad (2.7)$$

Here, p is the number of pole pairs of the generator and ω_g is the mechanical angular speed of the generator (rad/s).

The equivalent circuit of the PMSG in the d-axis and q-axis is shown in Fig. 2.7.

(a) d-axis equivalent circuit.

(b) q-axis equivalent circuit.

Fig. 2.7. Equivalent circuit of the PMSG in the synchronous reference frame [19].

The electromagnetic torque in the rotor is written as,

$$T_e = (3/2) (P/2) [(L_d - L_q)i_q i_d + i_q \psi_f] \quad (2.8)$$

Where, P is the number of poles.

For a surface mounted cylindrical PMSG rotor, the effective air gap is large and hence, the d-axis and q-axis inductances are equal [20]. This is due to the relative permeability of the permanent magnet material being close to unity [21]. Therefore, the above equation reduces to

$$T_e = (3/2) (P/2) [i_q \psi_f] \quad (2.9)$$

In order to achieve maximum power from the incident wind, the WTG is operated in the variable speed, variable frequency mode. The rotor speed is varied in sync with the wind speed in order to maintain the tip speed ratio close to its optimum value. It is important that the PMSG load line be as close as possible to the maximum power line of the WTG at the optimum value of the power coefficient [22].

For the wind turbine driven PMSG, the operating DC link voltage of the diode bridge rectifier output will change with variation in wind speed. Thus, it is possible to predict the DC output voltage and DC output power of the system in order to obtain values that are significant of the maximum power operating points. By operating the WECS close to these values, it is possible to obtain maximum power extraction [23]. It is

not advisable to connect a wind generator to a constant DC voltage source such as a battery. This is because at low wind speeds, the induced voltage in the generator may not be high enough to overcome the reverse bias of the diode bridge rectifier. At high wind speeds, the impedance of the generator and the battery load will not match. This will limit the power that is transferred to the DC system from the AC side [24].

The parameters of the wind turbine and the direct driven permanent magnet synchronous generator employed [25] along with the circuit design are provided in the appendix.

CHAPTER 3

POWER FACTOR CORRECTION TOPOLOGIES AND TECHNIQUES

3.1 Basis

Typically in a wind energy conversion system, AC-DC-AC conversion is performed by a rectifier- inverter arrangement. The preferred method of rectification is the diode bridge rectifier. It is highly simple in nature, needs no elaborate control mechanisms and is inexpensive. However, it has its drawbacks.

- There is a large phase displacement between the fundamental components of current and voltage. Due to this, a large amount of reactive power is injected into the system. Hence, the source and distribution equipment need larger volt-ampere ratings to handle the increased reactive power.
- Input currents exhibit large harmonic components leading to very poor input power factor.
- The overall efficiency of the rectifier is reduced due to increased losses.

Poor power factor is of concern especially when loads such as variable speed AC motor drives, UPS systems, and induction heating systems are employed. Hence, literature

survey was performed to study different control methods for three-phase rectifiers that would help overcome these drawbacks.

3.2 Traditional power factor correction methods

Considering the importance of high input power factor, various methods have been explained in literature to perform active power factor correction (PFC). Three of these traditional methods are highlighted in this section to emphasize the need for a simpler yet robust correction technique to achieve the same objective.

3.2.1 Literature review of active PFC for three-phase diode rectifiers

Prasad, Ziogas and Manias [26] proposed a novel active power factor correction method for power supplies with three-phase front-end diode rectifiers. This method necessitates an additional single switch boost chopper. This combined front-end converter draws good quality sinusoidal AC currents while operating at high input power factor and a constant switching frequency. Fig. 3.1 shows the three-phase AC-DC converter employed in their work. It can be broadly classified into two parts-

- Three-phase AC-DC rectifier with input filter, boost inductor, an active power factor correction stage and a DC link filter capacitor.
- Load requiring a regulated or unregulated DC bus such as general purpose single-phase or three-phase inverters or DC-DC converters with high frequency isolation.

Fig. 3.1. Active PFC circuit for three-phase diode rectifiers [26].

Active input line current wave-shaping is performed by the input filter inductances L_{ia} , the boost switch Q_b , which operates at a constant frequency and diode D_b . When the boost switch is 'ON', all the three input phases are shorted through the input inductors and the line currents increase simultaneously in proportion to the input voltages, thus maintaining their sinusoidal nature. The authors state in their paper that "all three input ac currents consist of the fundamental (60 Hz) component and a band of high frequency unwanted components centered around the switching frequency (f_b) of the boost switch." However, the removal of these components is possible by the use of filters.

To summarize, the advantages achieved by this method are component count reduction, simplified input synchronization logic requirements and smaller reactive components. The disadvantages are increased current stresses on the switching devices

due to high switching frequencies (in the order of several tens of kHz) and high frequency ripple content of the pre-filtered AC input currents.

3.2.2 THD improvement and UPF operation using zig-zag transformer

Kim *et al.*, [27] proposed a new method to improve the performance of a three-phase diode bridge rectifier and achieve unity power factor for varying load conditions. The scheme employed consists of a zigzag transformer along with a current controlled PWM converter that ensures the circulation of the third harmonic current and the short circuiting of the zero sequence third harmonic current. Thus, the system shows good performance even in the discontinuous mode of operation of the diode bridge rectifier.

From Fig. 3.2, it is seen that the zigzag transformer is tapped to enable control of the voltage in the DC link. The two switches T_1 and T_2 are controlled to adjust the injection of the third harmonic current circulating between the AC and the DC sides. The amplitude of the injected current depends on the variation of the load current. The circulating harmonic current, which is injected, splits into three equal components in each branch of the zigzag transformer winding and suitably alters the shape of the input currents in each of the three phases.

Fig. 3.2. Active harmonic reduction scheme proposed by Kim *et al* [27].

In the input current analysis performed in this work, it was found that the variation of the injected harmonic current based on the load current led to significant reduction in the harmonic content. A proper choice of the RMS value of the circulating third harmonic current will lead to a reduction in the 5th, 7th, 11th and 13th harmonic components for a given load current.

3.2.3 Third harmonic current injection techniques

Pejovic implemented two methods of third harmonic current injection in his work [28] for three-phase rectifiers. One method of current injection involves simultaneous

current injection in all three phases while the other involves the injection of current to only one phase. A resistance emulator comprising a transformer, two diodes and a capacitor was also proposed in this work. In a three-phase diode bridge rectifier, two diodes will conduct during a cycle. The phase whose voltage is neither minimal nor maximal at the given conduction period will remain unconnected leading to discontinuities in the phase current. The aim of current injection is to patch these discontinuities. This method helps in reducing the input current harmonics and improving the power factor.

Conventionally, in this method, a part of the rectifier input power has to be taken by the current injection network and either dissipated in resistors or processed by proper switching topologies that will enable the recovery of the power taken, at the rectifier output. Fig. 3.3 shows the first type of current injection method employing a magnetic injection device.

Fig. 3.3. Current injection in all three phases employing magnetic injection device [28].

Here, current is injected simultaneously in all the three phases. This is achieved by injecting the third harmonic current in the neutral point of the input transformer secondary. The output current ' i_Y ' from the current injection network is divided into three equal components and then injected back at the rectifier input.

Fig. 3.4 shows the second type of third harmonic current injection employing static bidirectional switches. Instead of simultaneously injecting current into all the three phases, the output current from the current injection network is injected only into the phase whose voltage is neither maximal nor minimal, namely the one exhibiting discontinuities in the phase current. This is achieved by making use of three bidirectional switches. Only the switch which is connected to the phase with the discontinuities is turned on during that time period. Thus, the switch's operating frequency becomes double that of the line frequency.

Fig. 3.4. Current injection in all three phases employing static bidirectional switches [28].

A comparison of the two methods in terms of the voltage and current across the current injection network was performed in [24]. It was reported in the cited work that the current injection method ‘A’ involving all three phases and the magnetic injection device resulted in three times higher currents flowing through the current injection network. In the second method, involving bidirectional switches, the voltage across the current injection network was three times higher than the first method. Both of the methods however, required the same amount of power to be taken by the current injection network so as to provide the optimal third harmonic current injection.

3.3 An improved high power factor and low cost three-phase rectifier

Ewaldo Mehl and Ivo Barbi proposed a new method to improve the power factor of three-phase rectifiers by employing three active bidirectional switches rated at a small fraction of the total power that is processed while operating at the line frequency [29]. In their work, they reasoned that in the work done by Prasad *et al.* [26], the boost switch poses considerable challenges in high-power applications despite the high quality currents and near unity power factor operation.

The work done by Kim *et al.* [27] also poses problems in the form of utilization of special magnetic devices such as line interphase and zig-zag transformers. The major drawbacks of such a technique are increased weight, volume and costs while handling additional power losses in the magnetic components. To overcome these limitations, they proposed a control for the three-phase rectifier by employing three bidirectional switches. These switches would operate at line frequency and would be gated when the

corresponding phase voltage had crossed the zero-volt axis. Thus this converter would be of low cost, high reliability, good efficiency and increased simplicity.

Based on their earlier work [30], they made small changes in the converter topology to propose an improved high power factor three-phase rectifier to eliminate the neutral wire connection in the system and the resultant pulsed current. In the earlier topology, with a single load capacitor, it was observed that the energy stored in the input inductors contributed to high voltage stresses across the switching devices during the turn-off periods. The changes proposed also eliminated clamping circuits required to reduce voltage stresses across the switching devices. Fig. 3.5 shows the improved converter design by Mehl and Barbi.

Fig. 3.5. Improved high power factor front-end rectifier implemented by Mehl and Barbi.

V_a , V_b and V_c are the voltage sources of the three-phase AC system with input inductors L_a , L_b and L_c , respectively. D_1 to D_6 are low frequency diodes with two identical

filter capacitors C_a and C_b and load R_o . S_a , S_b and S_c are the three static bidirectional switches that are gated on at appropriate intervals to facilitate the input current shaping.

The advantages of this converter are:

- Elimination of neutral point connection for the AC system thus overcoming the problem of a pulsed current present on the neutral.
- Lower input currents, leading to lower harmonic distortion and good power factor.
- Elimination of a clamping circuit to prevent excessive overvoltage across the bidirectional switches during turn-off commutation.
- Two identical capacitors on the DC link instead of a single filter capacitance so that a balanced central node is created between the positive and negative output terminals.

The conduction angle of the switches is kept at $(1/12)$ of the voltage cycle or 30° which means that the switches operate with good efficiency at low frequencies. Thus, the power losses are less and low cost devices can be used. The input inductors used in the work cited are also of low cost ordinary core materials. Overall, this structure is quite reliable without presenting unnecessary complexities. The operation of this high power factor rectifier has been explained in detail in the subsequent chapters.

3.4 PFC converters in WECS

Typically wind energy conversion systems may be stand-alone or grid connected.

For grid connected AC-DC-AC systems, control may be achieved on the inverter side to

ensure a constant DC link voltage while achieving high power factor operation. It is also important to achieve a high power factor operation on the source side at the rectifier end. In this section, three methods have been discussed for achieving UPF operation while maintaining permissible harmonic content in the input line currents. There are many other techniques that achieve the same objective but for the sake of simplicity, this discussion has been kept concise.

3.4.1 UPF power conditioner for grid connected variable speed WECS

Raju *et al.* analyzed a UPF power conditioner for extracting maximum output power from a grid connected variable wind speed system [27]. This system consists of a variable wind speed turbine driving a PMSG through a gear box and two PWM converters. The first stage comprises a PWM rectifier that converts the AC voltages and currents from the PMSG to DC and the second stage a grid-connected PWM inverter that performs DC-AC conversion. The PWM rectifier is controlled to perform shaping of the input line currents in accordance with the phase voltages and the PWM inverter is controlled based on the hysteresis current control principle [31]. Fig. 3.6 shows the schematic of this converter.

Fig. 3.6. Schematic representation of the UPF power conditioner proposed by Raju *et al.*

The reference currents for the PWM inverter are generated by an independent controller in such a way that the inverter output power tracks the maximum power as calculated by the maximum power tracking algorithm and the reference currents are in phase with the reference voltages. Such a back-to-back converter employs extensive control as is clearly evident.

3.4.2 PFC for harmonic mitigation in WECS

Dos Reis *et al.*, proposed a single switch three-phase boost rectifier operating in the discontinuous conduction mode (DCM) in order to achieve harmonic mitigation and power factor improvement [14]. This topology is essentially the same as the one proposed

by Prasad *et al.*, described earlier in the same section. A sensor-less MPPT controller is employed to achieve maximum power tracking, harmonic mitigation and output voltage control. To avoid redundancy, the schematic is not shown here.

In their later paper, the authors also explored the use of Passive Harmonic Trap Filters (HTF) to achieve harmonic mitigation [32]. However, they reasoned that it will not prove to be a viable solution. This is because with variations in wind speed, the frequency and amplitude of the generator voltages and currents will also change. In such a situation, a large number of trap filters will be needed for each condition of operation making it a highly bulky and practically infeasible system. Thus, a more active approach of solving this problem was advocated.

3.4.3 Three-phase high-frequency semi-controlled rectifier for PM WECS

A three-phase semi-controlled rectifier employing three diodes and three switches was proposed by Oliveira *et al.*, for grid connected PMSG based wind energy systems. The DC-AC stage of the system is a single-phase full-bridge inverter employing four IGBTs and unipolar modulation. DC link voltage regulation is performed by controlling the current that is injected into the grid.

The rectifier control system is based on the hysteresis control principle. Here, the input currents are measured and compared with the reference values. The reference current shapes are obtained from the respective input voltages and their peak values are given by the maximum power point tracking algorithm [33]. This algorithm makes use of

the generator voltage frequency to obtain the peak values of current from a pre-programmed table. Fig. 3.7 shows the schematic of the WECS proposed [29].

Fig. 3.7. Three-phase semi-controlled rectifier-inverter topology for the WECS [33].

The advantages of this system are:

- Simple topological construction
- Robustness
- High efficiency due to reduced number of elements

The disadvantage is the high harmonic distortion of the generator currents, which the authors defend to be within acceptable limits.

3.5 Foundation for this work

In this thesis, the front-end rectifier based on the topology proposed by Mehl and Barbi [29] and later modified by Liu and Maswood [6] has been considered to achieve high power factor operation while maintaining acceptable values of line current THD for a stand-alone wind energy conversion system. PSIM[®] has been used to model the system. The in-built tools in the software have been used to calculate the Total Harmonic Distortion (THD) and the input power factor. The details of the proposed system with its control methods are presented in the next chapter.

CHAPTER 4

AVERAGE CURRENT CONTROL METHOD IN UPF RECTIFIERS

4.1 Conventional diode bridge rectifier

The conventional topology employed to perform AC-DC conversion is a diode bridge rectifier. It employs no control, is highly simple but has certain drawbacks due to its non-linear nature. Fig. 4.1 shows the circuit diagram of a traditional three-phase diode bridge rectifier. The system employing a fixed pitch wind turbine driving a PMSG is interfaced to this conventional diode bridge rectifier and its performance discussed in this section. The rated wind speed 12 m/s is considered. The output of the diode bridge rectifier is connected to a simple resistive load.

Fig, 4.1. Conventional three-phase diode bridge rectifier.

Fig. 4.2 shows the performance coefficient of the wind turbine value is very low, averaging 0.055 in the steady state, when ideally the optimum value is 0.48. The mechanical power produced by the wind turbine is 1.055 kW as seen in Fig. 4.3. Ideally, the mechanical power produced in this condition should be 2.53 kW. Thus, it is seen that only 42% of the total mechanical power is converted into available mechanical power for the system. The efficiency of the PMSG is reduced to 92% implying large losses in power.

Fig. 4.2. Power coefficient of the wind turbine with a traditional diode bridge rectifier.

Fig. 4.3. Wind turbine mechanical and PMSG electrical power for the traditional diode bridge rectifier.

Fig. 4.4 shows the phase ‘a’ current to the diode bridge rectifier without current control. It is evident that the levels of harmonic distortion are very high. The THD is calculated as 22.99% which is unacceptable. With such high harmonic levels, the losses occurring due to heating will be of very large proportions leading to equipment malfunction and higher costs for maintenance.

Fig. 4.4. Input line current in phase ‘a’ of the diode bridge rectifier without power factor and current control.

Thus, it is essential that some form of current control is employed to reduce the line current harmonic levels while maintaining high power factor operation.

4.2 Three-phase three-level rectifier

A three-phase three-level rectifier is used in the study of control methods for maintaining operation at unity power factor and reducing the harmonic content [6]. This type of rectifier is suitable for high power applications due to low blocking voltages across the power switches during operation. The performance parameters under study for

this converter are the input power factor and the total harmonic distortion in the input phase currents. Fig. 4.5 shows the front end converter for achieving high power factor. In this converter there is a single bidirectional switch for every phase. Each of these switches operates at a maximum of twice the line frequency. Hence, the voltage stresses are quite low resulting in low losses.

Fig. 4.5. Front-end rectifier with three static bidirectional switches [6].

The three static bidirectional switches are controlled by selected methods in order to achieve line current shaping. The DC link has two identical capacitors with a mid-point connection to the current control circuit. It is important to maintain the voltage balance across the two capacitors. This is because a large asymmetry in the voltage across the two capacitors will cause higher voltage stress on them. This will lead to an increased blocking voltage stress on the converter power semiconductor devices [34].

The bidirectional switches are typically assembled using four diodes and a power MOSFET. MOSFETs are used in the construction of these switches for the front-end

rectifier because the power requirement of these switches is only a small fraction of the rectifier's total power rating during the converter operation. This keeps the stresses on the switches low and enables the usage of low-power devices leading to a significant reduction in cost [35]. This assembly is shown in Fig. 4.6.

Fig. 4.6. Bidirectional switch assembly [6].

4.3 Average current control method

Referring to Fig. 4.5, the following equations are given,

$$\left\{ \begin{array}{l} L(di_a/dt) = v_a - (v_{AM} + v_{MO}) \\ L(di_b/dt) = v_b - (v_{BM} + v_{MO}) \\ L(di_c/dt) = v_c - (v_{CM} + v_{MO}) \end{array} \right. \quad (4.1)$$

where, i_a , i_b and i_c are inductor currents,

v_a, v_b and v_c are source voltages from the PMSG,

v_{MO} is the voltage of mode M in reference to the neutral point N and,

v_{AM} , v_{BM} and v_{CM} are voltages at nodes A,B and C referring to node M.

These voltages can be expressed as follows where, $sign(i_a)$, $sign(i_b)$, $sign(i_c)$ depend on the polarity of inductor currents,

$$\left\{ \begin{array}{l} v_{AM} = sign(i_a) (1-s_a) (V_{dc}/2) \\ v_{BM} = sign(i_b) (1-s_b) (V_{dc}/2) \\ v_{CM} = sign(i_c) (1-s_c) (V_{dc}/2) \end{array} \right. \quad (4.2)$$

$$\left\{ \begin{array}{l} sign(i_a) = 1 \quad \text{if } i_a \geq 0 \\ -1 \quad \text{if } i_a < 0 \end{array} \right. \quad (4.3)$$

Here, s_a , s_b and s_c are the switching states for the three bidirectional switches S_a , S_b and S_c . 1 is for switch-on and 0 for switch-off. The formula used for calculating the input power factor is [36],

$$Input PF = (I_{L,rms}/I_{s,rms})*DPF \quad (4.4)$$

Where, $I_{L,rms}$ is the RMS value of the fundamental current component,

$I_{s,rms}$ is the RMS value of the total line current,

DPF is the displacement power factor between the source voltage and the corresponding line current in the specified phase.

4.4 Schematic of the UPF converter employing ACC method

Fig. 4.7 shows the schematic of the ACC method employed for the high power factor front-end rectifier. In our system, the pitch angle is taken as 0° and hence, only the wind speed is of significance in mathematically modeling the wind turbine by using the prescribed equations as explained before.

Fig. 4.7. Schematic of the UPF converter in the wind generator system employing ACC method.

The mechanical torque T_m calculated from the wind turbine block is the input to the PMSG. The stator voltages of the generator are represented by V_a , V_b and V_c . i_a , i_b and i_c are the generator currents which are the input line currents to the front-end rectifier. An outer DC voltage regulator is implemented to keep the DC link voltage close to the prescribed value. From this control, the unity sine current templates are generated which are compared with the actual line currents to get the error. This instantaneous error is fed to the PI regulator whose parameters need to be chosen carefully. The ramp comparison method is performed to generate the gating signals S_a , S_b and S_c for the switches.

The instantaneous current error is calculated and fed to a PI regulator as shown in Fig. 4.8. This is fed to a comparator along with a saw-tooth carrier. If intersections are obtained, the error is forced to remain within the band specified by the carrier waveform. The carrier signal is common to all the three phases. The integral term is useful in reducing the error between the reference and actual currents.

Fig. 4.8. Average current controller.

The converter's average input current ripples can be calculated from,

$$\Delta i = (V_{in}/L) \cdot \alpha \cdot T_s \quad (4.5)$$

Here, V_{in} is the single phase boost rectifier average input voltage

α is the average duty ratio and,

T_s is the switching period.

4.5 Performance investigation

4.5.1 Operation at rated wind speed - 12 m/s

The performance of the converter employing ACC is studied for the rated wind speed 12 m/s first. Fig. 4.9 shows the performance coefficient C_p of the wind turbine at a value 0.472. It is slightly lower than the optimum value of 0.48.

Fig. 4.9. Power coefficient of the wind turbine for ACC at rated wind speed 12 m/s.

Fig. 4.10 shows the mechanical power obtained from wind to be 2.49 kW. This falls short of the ideal maximum value of 2.533 kW. However, 98% of the wind power has been converted into mechanical power by the turbine. 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.

Fig. 4.10. Mechanical, generator and DC link output power of the system for ACC at rated wind speed 12 m/s.

The harmonic spectrum of the line current in phase 'a' to the front-end rectifier is shown in Fig. 4.11. The fundamental frequency is at 34 Hz. The most dominant harmonic frequencies are highlighted in the figure along with their magnitudes. The peak of the fundamental component is 8.02 A. It is observed that these dominant harmonic components are much lower than 10% of the fundamental magnitude. The THD of the line current in phase 'a' is 7.31%, which is acceptable in this system since it is at the front-end rectifier end, away from the point of common coupling.

Fig. 4.11. FFT spectrum of input phase 'a' current to front-end rectifier for ACC at rated wind speed 12 m/s.

Fig. 4.12 shows the input power factor to the front-end rectifier to be 0.996.

Fig. 4.12. Input power factor to the front-end rectifier for ACC at rated wind speed 12 m/s.

The voltage at the DC link output of the rectifier is 306 V. This is lower than the maximum possible DC link voltage of 312.6 V at 12 m/s. However, the control system demonstrates its ability to maintain the DC link voltage balance across the load capacitances in this case as seen in Fig. 4.13. The voltage across capacitor C_a is 153.37 V while the voltage across the second capacitance is 153.35 V.

Fig. 4.13. Voltage across the DC link capacitors at the front-end rectifier output for ACC at rated wind speed 12 m/s.

4.5.2 Operation above rated wind speed - 14 m/s

The wind speed is now increased to 14 m/s from the rated value of 12 m/s and the performance of the system analyzed. The parameters considered are the same as before and the results are shown below.

The front-end rectifier with ACC control displays very good performance with the power coefficient at 0.479, which is closer to the optimum value of 0.48, as seen in Fig. 4.14.

Fig. 4.14. Power coefficient of the wind turbine for ACC at higher wind speed 14 m/s.

The mechanical power produced is 4015 W which is close to the rated maximum value as shown in Fig. 4.15. 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%.

Fig. 4.15. Mechanical, generator and DC link output power of the system for ACC at higher wind speed 14 m/s.

Fig. 4.16 shows the FFT spectrum of the phase 'a' current of the front-end rectifier. The 7th harmonic falls well below 10% of the fundamental's magnitude. The magnitude of the other harmonics is negligible. The THD of this input current is 5.953%.

Fig. 4.16. FFT spectrum of input phase 'a' current to front-end rectifier for ACC at higher wind speed 14 m/s.

Fig. 4.17 shows the input power factor to the rectifier to be 0.997.

Fig. 4.17. Input power factor to the front-end rectifier for ACC at higher wind speed 14 m/s.

Fig. 4.18 shows the voltages across the two DC link capacitors. The voltage across capacitor C_a is 193.48 V while across capacitor C_b it is 196.17 V.

Fig. 4.18. Voltage across DC link capacitors at the front-end rectifier output for ACC at higher wind speed 14 m/s.

4.6 Analysis of results for ACC method

Table 4.1 shows the performance parameters of the UPF converter with ACC. A comparison has been drawn for the two wind speed conditions to determine the efficacy of the control employed. It is seen that the average current control method consistently maintains high input power factor, greater than 0.995. The THD values of the line currents are also acceptable, with much better values at the higher wind speed operation. Real power extracted from the system is 97.7 % of the available mechanical power. The rectifier has excellent power balance at the input and output. For the rated load condition, considering the two wind speed conditions, the ACC works quite satisfactorily.

Table 4.1 Performance parameters of the UPF converter for ACC method.

	Rated wind speed 12 m/s	Higher wind speed 14 m/s
Power coefficient C_p	0.472	0.479
Mechanical power P_m (kW)	2.49 kW	4.015 kW
Input and output power of the front-end rectifier $P_e = P_{dc}$ (kW)	2.43 kW	3.923 kW
THD of phase current i_a (%)	7.31%	5.95%
Input power factor	0.996	0.997

CHAPTER 5

HYSTERESIS CURRENT CONTROL METHOD IN UPF RECTIFIERS

5.1 Types of HCC methods in literature

In their earliest work, Maswood and Liu proposed a simple hysteresis current controller which employs high switching frequencies. This reduces the size of the input inductors. The switching losses resulting due to the switching frequencies can be kept within permissible limits because the system that has been considered in this work is of low power rating. In this method, the phase current was controlled to track a reference value that would fall within a specific window width [5].

In [37], a modified current control with variable hysteresis band was proposed. Accordingly, with variations in the input voltage and load, the hysteresis band would also change, thus retaining a constant switching frequency. In conventional HCC with a fixed band, the switching frequency is highly random. This implies that the supply current harmonics would range across the entire frequency spectrum. However, with this modification, with a constant switching frequency, the supply current harmonics can also be centered on that value, thus adding to converter reliability. Later, they proposed a

synchronous reference frame based HCC method [38]. Fig. 5.1 shows the control used for this topology.

Fig. 5.1. Synchronous reference frame based HCC [38].

In this method, Park's transformation was used to obtain the three reference phase currents. The PLL circuit is used to obtain ωt , the angular position of the AC supply voltage. The DC link voltage control is achieved by controlling the Park's active current i_d and the unity power factor operation is ensured by keeping the Park's reactive current $i_q = 0$.

5.2 HCC method in the WTG system with UPF rectifier

The conventional HCC method is based on the random frequency method of control and is appropriate in many applications due to certain advantages such as easy implementation, good accuracy and high robustness. The only drawback is the random

switching frequency. Fig. 5.2 shows the schematic of the UPF converter employing conventional HCC method.

Fig. 5.2. Schematic of the UPF converter in the wind generator system employing HCC method.

The bidirectional switches are controlled based on the current error in each phase falling within the hysteresis band. The choice of the hysteresis band is critical in determining the switching states of these switches and thus, the current shaping of the rectifier currents. The switching states are determined based on the current error calculated for each phase [5].

The purpose of the outer DC link voltage control is to provide the three-phase input voltages with synchronized input reference currents. The unity sine current

reference templates are then sent to the hysteresis current controller along with the actual phase currents to generate switching signals for the three switches. Fig. 5.3 shows the switching operation for phase ‘a’ of the UPF converter employing HCC.

Fig. 5.3. Switching operation for phase a: Sa is bidirectional switch for phase a and D1 and D4 are diodes in the upper and lower bridge, respectively.

The switching signals for the bidirectional switches are given by where h is the hysteresis band.

$$S_x = \begin{cases} 1 & \text{if } (i_x > 0 \text{ and } i_x < i_x^* - h) \text{ or } (i_x < 0 \text{ and } i_x > i_x^* + h) \\ 0 & \text{if } (i_x > 0 \text{ and } i_x > i_x^* + h) \text{ or } (i_x < 0 \text{ and } i_x < i_x^* - h) \end{cases} \quad (5.1)$$

Using this control method, the phase currents can be made to fall within a particular band. However, there is a condition which states that when half of the DC link voltage is lesser than the phase voltage, the high power factor condition is not achieved [37].

5.3 Performance investigation

5.3.1 Operation at rated wind speed - 12 m/s

Fig. 5.4 shows the performance coefficient C_p of the wind turbine for HCC at a value of 0.479 for the steady state.

Fig. 5.4. Power coefficient of the wind turbine for HCC at rated wind speed 12 m/s.

The rated mechanical power for 12 m/s is 2.53 kW and the actual mechanical power generated by the wind turbine is 2.525 kW. The front-end rectifier transfers the generator power of 2.469 kW entirely to the DC link output, as seen in Fig. 5.5. Fig. 5.6 shows the magnitude of the dominant components is well below 10% of the fundamental's magnitude. The THD of this current is 8.26%. Similar to the operation with ACC for 12 m/s, since this harmonic level is not at the point of common coupling, by

virtue of being able to achieve high input power factor and extraction of maximum possible real power, it is acceptable.

Fig. 5.5. Mechanical, generator and DC link output power of the system for HCC at rated wind speed 12 m/s.

Fig. 5.6. FFT spectrum of input phase 'a' current to front-end rectifier for HCC at rated wind speed 12 m/s.

Fig. 5.7 shows that the input power factor is 0.994. Fig. 5.8 shows the DC link voltage obtained is 309 V while the ideal DC link voltage for 12 m/s at the maximum power operation is 313 V, which is acceptable.

Fig. 5.7. Input power factor to the front-end rectifier for HCC at rated wind speed 12 m/s.

Fig. 5.8. Voltage across the DC link capacitors at the front-end rectifier output for HCC at rated wind speed 12 m/s.

5.3.2 Operation above rated wind speed - 14 m/s

Fig. 5.9 shows the performance coefficient drop to 0.476. This reflects a corresponding marginal reduction in the mechanical power extracted by the wind turbine.

Fig. 5.9. Power coefficient of the wind turbine for HCC at higher wind speed 14 m/s.

Fig. 5.10 shows the powers produced for this higher wind speed condition. The maximum mechanical power for 14 m/s is 4.01 kW and the turbine produces 3.99 kW. Thus, the system shows its capacity of extracting 99% of the maximum 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.

Fig. 5.10. Mechanical, generator and DC link output power of the system for HCC at higher wind speed 14 m/s.

Fig. 5.11 displays the FFT spectrum of the phase ‘a’ current to the front-end rectifier. The fundamental frequency is 45 Hz. The dominant harmonics are 225 Hz and 315 Hz whose magnitudes are lower than 10 % of the fundamental’s magnitude. THD is calculated as 5.85%.

Fig. 5.11. FFT spectrum of input phase ‘a’ current to front-end rectifier for HCC at higher wind speed 14 m/s.

Fig. 5.12 shows that the input power factor is 0.994.

Fig. 5.12. Input power factor to the front-end rectifier for HCC at higher wind speed 14 m/s.

Fig. 5.13 shows that 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 theoretical maximum of 394.8 V.

Fig. 5.13. Voltage across DC link capacitors at the front-end rectifier output for HCC at higher wind speed 14 m/s.

5.4 Analysis of results for HCC method

The HCC has excellent capacity of maintaining the input power factor of the front-end rectifier close to unity. In both the wind speeds, it maintains a value of 0.994. The THD value falls within acceptable limits in both the operating speeds, thus realizing the second major objective of the current control. Real power extracted from the system is 97.8 % of the available mechanical power. The rectifier maintains 100% power transfer with the entire input power being available at the DC link output, thus showing very minimal losses at this conversion stage. For the rated load condition, considering the two wind speed conditions, the hysteresis current control works quite satisfactorily as shown in Table 5.1.

Table 5.1. Performance parameters of the UPF converter for HCC method.

	Rated wind speed 12 m/s	Higher wind speed 14 m/s
Power coefficient C_p	0.479	0.476
Mechanical power P_m (kW)	2.525 kW	3.99 kW
Input and output power of the front-end rectifier $P_e = P_{dc}$ (kW)	2.469 kW	3.902 kW
THD of phase current i_a (%)	8.26%	5.85%
Input power factor	0.994	0.994

CHAPTER 6

CHALLENGES FACED

6.1 Equal distance current control (EDCC) method

Liu and Maswood discussed a third current control method called the equal distance current control (EDCC) method employed for systems with ideal three-phase sinusoidal voltage sources [6]. The main objective of this method, like the ACC and HCC is to achieve high input power factor operation with low THD values of the input line current and the outer DC link voltage control. Fig. 6.1 shows the control diagram of this method.

Fig. 6.1. Control block diagram for the bidirectional switches employing EDCC method.

When the input phase voltage crosses the zero-volt axis, the corresponding bidirectional switch is ON. Each of the switches, thus, conducts twice in each cycle. I_{dc} is the DC link current and it is responsible for determining the pulse width. This current is measured and used to calculate the normalized DC link current value 'k'. This determines the value of the conduction angle ' α ' based on the mode of operation. When the converter operates below the rated power, the conduction angle $\alpha = 14.9 + 15.1k$. When the converter operates above its rated power, the value of the conduction angle is $\alpha = 30k$. The DC link voltage V_{dc} is measured and compared with the reference value V_{ref} to obtain the voltage compensation for the conduction angle. The optimum value of K_p for the voltage compensation block is chosen in the paper as 0.5 after an in-depth analysis.

Some important assumptions made in this current control method are that:

- The rated output voltage of the converter can be calculated by assuming that the phase current is zero when $\omega t = 180^\circ$.
- It is assumed that the input current supplies the load during the 90° to 120° interval and this condition is used to determine the critical input inductance.

Thus, this control method requires the calculation of a critical input inductance (H), whose value is given as [6],

$$L_{critical} = (3.8489 * 10^{-2} * V_i^2) / fP_o \quad (6.1)$$

where, V_i is the line RMS voltage,

f is the system frequency and,

P_o is the rated output power.

The rated DC link output voltage V_o is calculated based on the assumption mentioned which is given by [6],

$$V_o = 1.3366 V_i \quad (6.2)$$

6.2 Challenges in implementing EDCC in WECS

For the rated wind speed of 12 m/s, based on the performance results of the other two current control methods, the fundamental frequency of operation is taken as 35 Hz. Based on equations (6.1) and (6.2), the critical input inductance is calculated as 23.57 mH by taking the rated output power as 2500 W. The rated output voltage is calculated as 310 V for a line-to-line input voltage of 231.5 V_{rms}.

6.2.1 Operation at rated wind speed - 12 m/s

Fig. 6.2 shows that the power coefficient obtained at this mode of operation is 0.463, which is well below the optimum value of 0.48. Fig. 6.3 shows the mechanical power produced by the wind turbine to be 2.446 kW, which is lesser than the maximum rated value of 2.53 kW. The efficiency of conversion is, thus, restricted to 96.7%. The electrical power produced by the PMSG is 2.389 kW which is transferred without losses to the DC bus output. However, the efficiency of conversion from mechanical to electrical power is also lower.

Fig. 6.2. Power coefficient of wind turbine for EDCC at rated wind speed 12 m/s.

Fig. 6.3. Mechanical, generator and DC link output power of the system for EDCC at rated wind speed 12 m/s.

Fig. 6.4 shows the input phase voltage and current in phase ‘a’ of the front-end rectifier. It is seen that the input power factor is quite low at 0.862.

Fig. 6.4. Input power factor to the front-end rectifier for EDCC at rated wind speed 12 m/s.

The wind speed was increased to 14 m/s and the performance of the system studied for the same parameters. For this condition of operation, the input inductance was calculated as 18.35 mH and the rated output voltage of the system was computed as 390.78 V.

However, the performance of the system was unsatisfactory with high THD values of the line current and very poor input power factor. The study was repeated for the rated wind speed 12 m/s and then 14 m/s with higher input inductance of 30 mH. There was a significant improvement in the quality of the line currents and the input power factor. However, the real power extracted was much lower than the rated values, with efficiency

of conversion at 85.6%. Taking into view such poor performance, the results have not been shown here.

6.2.2 Limitations and possible remedies for EDCC Method

The major drawback of this method is the requirement of bulky input inductances. For low to medium power systems, employing line inductances of 30 mH or 40 mH is not practically feasible due to the low efficiency. Though this system presents close to unity power factor operation and minimal THD values of line currents while employed for utility-based systems, it offers considerable challenges while employed in WECS. The operation of this current control is predominantly based on the calculation of the line inductance and the rated output voltage.

In a WECS, the frequency of operation keeps varying. For low wind speed conditions, the fundamental frequency of operation is lower, while it increases with higher wind speeds. Thus, this would necessitate a variation in the input line inductance. Also, re-computation of the rated output voltage will have to be performed. Hence, this method needs to be re-analyzed to accommodate these operating conditions. The EDCC method would prove to be of much use in high power systems, where the requirement of higher line inductances could be justified. However, in the current work, due to these disadvantages, its importance and efficacy could not be validated.

6.3 Variable wind speed operation

The advantages of variable wind speed systems have been discussed in the earlier chapters and the important conditions that need to be realized to achieve maximum power extraction have been enumerated. It is essential to maintain the tip speed ratio and power coefficient values of the system close to their optimum values to enable the maximum power tracking.

In this work, ACC and HCC were employed for the rated load with a step change in wind speed to see how much real power was extracted from the system. The primary objectives are to maintain close to unity power factor operation while maintaining permissible levels of harmonics in the line currents.

6.3.1 ACC with variable wind input

The performance of the UPF rectifier with average current control is studied for a variable wind speed input. Fig. 6.5 shows the variation in wind speed. The initial speed is the rated speed of 12 m/s. At 0.5 s, it is increased by 2 m/s to 14 m/s and the corresponding variation in the power coefficient C_p is observed. 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.

Fig. 6.6 shows that the input power factor achieved by the system is 0.996. There is a slight variation in current when the wind speed changes at 0.5 s but the overall power

factor at the input of the rectifier is still higher than 0.99 which shows the efficacy of the control method employed.

Fig. 6.5. Wind speed variation and performance coefficient of wind turbine system with ACC.

Fig. 6.6. Determination of input PF of the front-end rectifier employing ACC at variable wind speed.

With change in wind speed, there is a corresponding change in the mechanical and the electrical input and output powers of the converter. This is shown in Fig. 6.7. 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. At this increased wind speed, maximum power achieved is exactly equal to its ideal value. The electrical input and output power of the rectifier are equal, implying complete real power transfer.

Fig.6.7. Mechanical, generator and DC link output power of the system for ACC at variable wind speed.

The input line currents to the front-end rectifier are shown in the Fig. 6.8. With an increase in wind speed, the line currents also increase in magnitude. This signifies a variation in the fundamental frequency as well. It is seen that the currents retain the same magnitudes as in the case of the individual wind speed operation conditions. Thus, the controller is able to handle a variation in the input operating conditions. However, analysis of the THD and the FFT spectrum could not be done in this case because of the

obscurity in the fundamental frequency due to the presence of multiple harmonic components from both the wind speeds. This is an area that needs to be devoted sufficient attention.

Fig. 6.8. Input line currents to the front-end rectifier with ACC for variable wind speed operation.

Fig. 6.9 shows that the DC link voltage reaches 312.73 V for 12 m/s which is lesser than the ideal value of 313 V while for 14 m/s, the rated DC link voltage of close to 395 V is reached. Capacitor voltage balance is achieved for the initial condition, but with an increase in wind speed, the balance seems to be disturbed as the simulation time progresses. The remedy for this problem is to use a bigger capacitance at the DC link. This ensures voltage balance across the DC link, while keeping the output voltage ripple to a much lower value than before. Hence, two capacitors of the value 4000 μ are used at

the DC link to ensure satisfactory operation during the variable wind speed condition. This is shown in Fig. 6.10.

Fig. 6.9. Voltage across the DC link capacitors at the front-end rectifier output for ACC at variable wind speed.

Fig. 6.10. Voltage across the DC link capacitors at the front-end rectifier output for ACC at variable wind speed with a higher capacitance value.

6.3.2 HCC with variable wind input

With a change in wind speed, the performance coefficient reaches 0.479 and 0.474 for 12 m/s and 14 m/s, respectively as seen in Fig. 6.11. Fig. 6.12 shows the input power factor as 0.994.

Fig. 6.11. Wind speed variation and performance coefficient of wind turbine for system with HCC.

Fig. 6.12. Determination of input PF of the front-end rectifier employing HCC at variable wind speed.

Fig. 6.13 shows that the mechanical power is 2.53 kW for 12 m/s which is at its rated value. For 14 m/s, the mechanical power is 3.98 kW with efficiency of conversion at 99%. Fig. 6.14 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 operation conditions.

Fig. 6.13. Mechanical, generator and DC link output power of the system for HCC at variable wind speed.

Fig. 6.14. Input line currents to the front-end rectifier with HCC for variable wind speed operation.

Fig. 6.15 shows the DC voltages across the two capacitors at the output of the front-end rectifier. It measures 313.6 V for 12 m/s which is equal to the ideal value while for 14 m/s, the voltage 394.47 V, again close to the ideal value of 394.8 V is reached. The balance in the voltages across the capacitors is satisfactory throughout the simulation period.

Fig. 6.15. Voltage across the DC link capacitors at the front-end rectifier output for HCC at variable wind speed.

6.4 Summary of current control methods for variable wind speed operation

For rated load conditions without any additional control mechanism, it is seen that the controller is capable of almost extracting the maximum possible real power with an efficiency of 97%-99%. Efficiency of power transfer is satisfactory at the input and output

of the front-end rectifier. However, it is important to minimize even the small differences in C_p values for the change in wind speed. This will ensure that the maximum possible power at specific operating conditions will be extracted completely without much loss.

The HCC method shows better performance in maintaining the DC link voltage balance and achieving slightly better power coefficient value at the two wind speed conditions. However, the ACC method achieves a better power factor of 0.996 in comparison to the input power factor of 0.994 for the hysteresis current control method. Thus, it is seen that both the current control methods are extremely well suited for the operation of this system with rated load and variation in wind speed.

CHAPTER 7

CONCLUSION

7.1 Summary and discussion of results

In this work, a WECS interfaced with an AC-AC converter feeding a stand-alone load has been 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. ACC and HCC have been employed to perform active input line current shaping, while the behaviour of the EDCC has been discussed. Their performances have been compared for two different cases of wind speeds, as well as varying wind speed profile.

The aim of controlling this wind turbine based system is to extract the maximum possible power from the PMSG and also to maintain the maximum real power flow from the PMSG to the converter system. It is observed that the AC electric power that is available at the input of the front-end UPF rectifier is transferred to the output DC link without much loss. This power is transmitted to an SPWM inverter feeding a standalone load. The quality of the line currents at the input of the converter is good and the harmonic distortions are within acceptable limits for the front-end rectifier in a stand-alone system. High power factor is achieved at the input of the converter and the voltage

maintained at the DC link output is close to the reference value specified for particular operating conditions. Table 7.1 shows the system performance for the two current control methods during the fixed wind speed condition.

Table 7.1 Performance parameters of the WTG system with UPF converter for fixed wind speed conditions.

WIND SPEED	12 m/s		14 m/s	
Current Control Method	ACC	HCC	ACC	HCC
Power Coefficient C_p	0.472	0.479	0.479	0.476
Mechanical Power P_m (kW)	2.49 kW	2.525 kW	4.015 kW	3.99 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

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 THD values of the line current for phase 'a' of the converter have been compared. While the

ACC method achieves THD values around 6% and 7%, the HCC achieves THD values around 6% and 8%. The proposed method was compared with a traditional diode bridge rectifier without any control methods, which is typically employed in a majority of rectification systems. It shows a vast degradation in performance under similar conditions of the wind turbine and PMSG operations. The line current at the input of the traditional rectifier exhibits very high harmonic distortion, contributing to increased losses and poor power factor at the rectifier input. The generator electric power extracted by the traditional AC-DC rectifier is also considerably lower than the rated power of the wind turbine- PMSG system.

The ability of the system to extract maximum possible real power with minimal values of reactive power at the converter input is 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, signifying very low losses and very high efficiency. The DC link voltage balance is also satisfactory.

In terms of simplicity of system, the HCC would be preferable. In contrast to the average current controller, it employs minimum PI controllers. It would be of special significance in high power applications for the proposed rectifier because of lower switching stresses and consequent losses in comparison to the average current control method. Even though the HCC has random switching frequencies, they are still lesser in magnitude in comparison to the switching frequency required by the ACC.

However, both these controllers play an equal role in maintaining overall system simplicity and reduced maintenance with minimal costs. The importance of a current control method to ensure good power extraction and satisfactory efficiency in current and voltage quality is substantiated. Thus, the converter employing the said current control methods would prove to be very efficient in extracting the maximum generator real power for implementation in a standalone wind based system.

7.2 Scope for future work

In this work, the system employs a fixed pitch wind turbine operating at two fixed wind speed conditions. Simple operating conditions have been assumed with the view of implementing and justifying the application of this converter for a wind energy system. For a rated load, irrespective of changes in wind speed, the controllers have performed well in ensuring near unity power factor operation, reasonable THD content in line currents and satisfactory extraction of maximum possible real power. A very significant advantage of this system is the absence of reactive power at the PMSG-front-end rectifier coupling side. This eliminates the need of additional reactive power compensation circuits. Thus, the entire system is simple in its construction and offers good reliability.

There are many avenues that can be explored to continue in this line of work. The first important consideration is that of maximum power tracking. The controller design can be modified into a more advanced version to consider the varying operating characteristics of the wind turbine with different wind speed conditions. The main aim is to eliminate the need of an additional controller to perform Maximum Power Point Tracking (MPPT). By

incorporating a speed control mechanism and interrelating the speed, torque and current quantities, a novel control method that will suitably alter the switching of the rectifier based on different loading conditions can be realized.

The outer DC link voltage mechanism currently employed has a limitation in the values that it can achieve. This can be further perfected by adding a controller to enable voltage balancing. The operating range fixed for this controller falls beyond the low wind speed conditions. This is because the power generated by the generator is insufficient to drive the load during such low wind speed conditions. The remedy for this problem is the addition of a battery – ultra capacitor system which will help in generating the deficit power along with the generator to supply the load. Such low speed conditions can be investigated in deeper detail.

The EDCC method is another area of interest. If the limitations posed by the critical input inductance requirement as well as the need for a rated output voltage can be overcome or remedied by altering the constraints in controller design, it can prove to be of much use in high power systems.

The most important application that can be looked into for this WECS is a specific residential/commercial load. This can be realized by designing a suitable storage system to enable reliable transfer of power, irrespective of source or load disturbances.

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Appendix A

A.1 Wind Turbine Specifications

Radius of wind turbine = 1.26 m

Base wind speed = 12 m/s

Base rotational speed = 741.98 rpm

Optimal Power Coefficient = 0.48

Optimal tip speed ratio = 8.1

A.2 Constants for the Power coefficient Calculation

Coefficients in C_p calculation	Value
C_1	0.5176
C_2	116
C_3	0.4
C_4	5
C_5	21
C_6	0.0068
C_7	0.08
C_8	0.035

A.3 Permanent Magnet Synchronous Generator Specifications

Rated power = 3 kW for 12 m/s

Stator resistance = 0.49Ω

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

Number of poles = 6

A.4 Near UPF Converter Specifications

Line inductance = 10 mH for average current control and 15 mH for hysteresis current control

DC link capacitance ($C_1=C_2$) = 1000 μ F

Switching frequency for ACC = 20 kHz

Hysteresis band for HCC = 0.2

Appendix B

Fig. B.1. PSIM schematic for Average Current Control Method.

Fig. B.3. PSIM schematic for Equal Distance Current Control Method.

Appendix C

Wind Turbine Model

The wind turbine model was constructed taking a rated wind speed of 12 m/s and using the established mathematical equations to calculate the tip speed ratio and the power coefficient. Different values of rotor speed in rad/s were considered to calculate the corresponding values of these two quantities.

Fig.C.1 shows the wind turbine model used to calculate the TSR_{opt} and $C_{p opt}$.

Fig. C.1. Wind turbine model to calculate optimum tip speed ratio and power coefficient.

Using this model, for varying rotor speed conditions, different values of the tip speed ratio and power coefficient were obtained. For optimum operation of the system, it is essential to keep these two quantities close to their maximum values. Hence, a plot of power coefficient versus the tip speed ratio was obtained to determine the optimum values for the rated operation. This is shown in Fig. C.2.

Fig. C.2. Optimum Power coefficient vs. Tip Speed ratio for the system presented.

From Fig. C.2 it is seen that the optimum power coefficient is 0.48 for a corresponding optimum tip speed ratio of 8.1. These values have been taken as reference while discussing the performance of the system.

Appendix D

Wind Turbine Generator model

The wind turbine model is interfaced with a Permanent Magnet Synchronous Machine in the Motor Drive Module of PSIM[®] which runs in the generator mode as shown in Fig. D.1.

Fig. D.1. Wind turbine generator interfaced to an uncontrolled diode bridge rectifier.

For an uncontrolled diode bridge rectifier, the equation for output DC voltage can be obtained by ignoring the overlap due to the PMSG inductance as,

$$V_{dc} = (3\sqrt{2} V_{ll,rms}) / \pi \quad (\text{V}) \quad (\text{D1})$$

For 12 m/s, the RMS line to line voltage is 231.5 V. Using equation (D1), the output DC voltage of the rectifier is calculated as 312.6 V.

For 14 m/s, the RMS line to line voltage is 292.4 V. Using equation (D1), the output DC voltage of the rectifier is calculated as 394.8 V.

These values are used to cross examine the DC bus link output voltage obtained with the current control methods in the results section.