TJ
828
-P76
2006

FLEXIBLE POWER FLOW CONTROL FOR BRUSHLESS DOUBLY FED INDUCTION GENERATOR

by

KOSTYANTYN PROTSENKO B.ENG.

Ryerson University
Toronto, 2003

A thesis

presented to Ryerson University

in partial fulfillment of the
requirements for the degree of

Master of Applied Science

in the Program of
Electrical Engineering

UMI Number: EC53576

INFORMATION TO USERS

The quality of this reproduction is dependent upon the quality of the copy submitted. Broken or indistinct print, colored or poor quality illustrations and photographs, print bleed-through, substandard margins, and improper alignment can adversely affect reproduction.

In the unlikely event that the author did not send a complete manuscript and there are missing pages, these will be noted. Also, if unauthorized copyright material had to be removed, a note will indicate the deletion.

UMI[®]

UMI Microform EC53576
Copyright 2009 by ProQuest LLC
All rights reserved. This microform edition is protected against
unauthorized copying under Title 17, United States Code.

ProQuest LLC
789 East Eisenhower Parkway
P.O. Box 1346
Ann Arbor, MI 48106-1346

I hereby declare that I am the sole author of this thesis or dissertation.

I authorize Ryerson University to lend this thesis or dissertation to other institutions or individuals for the purpose of scholarly research.

n

—
— / .
(Signature)

I further authorize Ryerson University to reproduce this thesis or dissertation by photocopying or by other means, in total or in part, at the request of other institutions or individuals for the purpose of scholarly research.

—
(Signature)

BORROWER’S PAGE

Ryerson University requires the signature of all persons using or photocopying this thesis.

Please sign bellow.

Name	Address	Date	Signature

ABSTRACT

Kostyantyn Protsenko

Flexible Power Flow Control for Brushless Doubly Fed Induction Generator

Electrical and Computer Engineering

Ryerson University

Toronto 2007

This thesis presents the brushless doubly fed induction generator (BDFIG) system for the wind energy conversion. The system is proposed as an advanced solution to the traditional doubly fed induction generator (DFIG) to reduce the maintenance cost and improve the system reliability of the wind turbine system. The proposed BDFIG employs two cascaded induction machines to eliminate the brushes and copper rings in DFIG. The dynamic model of BDFIG with two machines' rotors electromechanically coupled in the back-to-back configuration is developed and implemented using Matlab/Simulink. Based on the model, the control scheme for flexible power flow control in BDFIG with back-to-back converter is developed. The independent control of the active and reactive power flow is achieved by means of a four-quadrant power converter under the closed-loop stator flux oriented control scheme. In the proposed control strategy, the generator speed tracks well the reference speed, thus the maximum power extraction is achieved. The experiment was done on a 2kW BDFIG system. Simulations and experimental results from the experimental system verify the proposed system model and control design.

ACKNOWLEDGMENTS

I wish to express my deep gratitude to my supervisor, Professor Dewei Xu for his support and the knowledge he shared during my graduate studies at Ryerson University.

I would also like to thank the fellow students in LEDAR: Anita, Behrang, Kristian, Moya and Bing for all their invaluable help.

With a great pleasure I share my achievements with my parents Viktor and Lyuba whose presence, constant support and understanding made all this work possible. And I specially thank Yulia for the inspiration that she gave when going was tough.

TO MY GRANDPARENTS

TABLE OF CONTENTS

CHAPTER 1 INTRODUCTION	1
1.1 Background of Wind Energy Applications.....	1
1.2 Classification of Wind Turbines and Generators.....	3
1.3 Most Popular Generator Topologies for Wind Applications	6
1.3.1 Squirrel Cage Induction Generators.....	7
1.3.2 Doubly-Fed Induction Generators	9
1.3.3 Synchronous Generators	12
1.4 Motivation and Objective	14
1.5 Thesis Outline	15
CHAPTER 2 BDFIG MODEL DEVELOPMENT	17
2.1 General Structure of BDFIG.....	17
2.2 BDFIG Mathematical Modeling	20
2.2.1 Power Machine Modeling.....	22
2.2.2 Control Machine Modeling.....	25
2.2.3 Complete BDFIG Model.....	27
2.3 Model Simulation Results.....	29
2.3 Conclusion.....	33
CHAPTER 3 CONTROLLER DESIGN	34
3.1 Wind Turbine Operation.....	34
3.1.1 Variable Speed Operation	34
3.1.2 Reactive Power Regulation.....	36
3.1.3 Requirements for Controller Design of BDFIG.....	36
3.2 Stator Flux Based FOC.....	37
3.3 BDFIG Controller Design.....	40
3.3.1 Grid-Side Power Converter Control	41
3.3.2 Generator-Side Power Converter Control.....	45
3.4 Conclusion.....	52

CHAPTER 4 BDFIG CONTROLLER MODELING AND SIMULATION	54
4.1 Wind Turbine System in Simulink	54
4.1.1 Turbine Aeromechanical Model	55
4.1.2 Controller Models	56
4.2 BDFIG System Simulation Results.....	60
4.4 Conclusion.....	66
CHAPTER 5 EXPERIMENTAL TESTING AND RESULTS.....	68
5.1 Experimental Setup.....	68
5.1.1 Formation of the BDFIG.....	68
5.1.2 Controller Implementation.....	70
5.1.3 Wind Drive Implementation	73
5.2 Testing Results and Analysis.....	74
5.2.1 No Load Tests	74
5.2.2 Low Power Tests.....	78
5.2.3 Medium Power Tests	83
5.2.4 Speed Tracking.....	86
5.3 Conclusion.....	88
CHAPTER 6 CONCLUSIONS.....	89
6.1 Conclusions	89
6.2 Major Contributions	90
6.3 Further Research.....	90
APPENDICES	93
Appendix A	93
Appendix B.....	93
Appendix C	95
Appendix D	96
Appendix E.....	96
REFERENCES.....	107

LIST OF TABLES

Table 3-1: Grid-side Controller Gains.....	44
Table 3-2: Ziegler-Nichols PI Gains for Generator-side Converter	52
Table 5-1: Power and Control Machine Parameters.....	69
Table 5-2: BDFIG Power Flow	87

LIST OF FIGURES

Figure 1-1: Total Global Wind Energy Capacity	1
Figure 1-2: Installed Global Capacity Breakdown	2
Figure 1-3: Typical Turbine C_p Curve for 0° Blade Pitch	4
Figure 1-4: Geared-drive Turbine Configurations	7
Figure 1-5: Direct-in-line ASG Wind Turbine	9
Figure 1-6: DFIG Wind Turbine	11
Figure 1-7: Typical BDFIG Configuration Based on Cascaded Rotor	15
Figure 2-1: Typical BDFIG Stator Arrangement	18
Figure 2-2: BDFIG Back-to-Back Configuration	20
Figure 2-3: Power Machine D-Q Transformation	23
Figure 2-4: Power Machine D-Q Equivalent Circuits	24
Figure 2-5: Control Machine D-Q Transformation	25
Figure 2-6: Control Machine D-Q Equivalent Circuits	26
Figure 2-7: BDFIG D-Q Equivalent Circuits	28
Figure 2-8: BDFIG Model in Simulink	30
Figure 2-9: Speed-Torque Curve of BDFIG	31
Figure 2-10: No-load Control Machine Current	31
Figure 2-11: Generation Mode of BDFIG	32
Figure 2-12: Generation Mode Control Current	32
Figure 2-13: Control Machine Excitation Voltage	32
Figure 2-14: Control Machine Excitation Current	32
Figure 2-15: BDFIG Response to Control Excitation	32
Figure 2-16: BDFIG Torques Over the Tested Range	32
Figure 3-1: Typical Turbine Characteristic Curves	35
Figure 3-2: Turbine Power Curves	36
Figure 3-3: Voltage Vector Position	38
Figure 3-4: Flux Vector Position	39
Figure 3-5: Voltage and Flux Vectors	40
Figure 3-6: VSR Circuit Model	41
Figure 3-7: Grid-side Controller Structure	43
Figure 3-8: D - Q Frame Alignment	46
Figure 3-9: Generator-side VSI FOC	51
Figure 3-10: Full BDFIG Controller	53
Figure 4-1: Wind Turbine System Model	55
Figure 4-2: Wind Turbine Model	56
Figure 4-3: VSR Controller Block	57
Figure 4-4: VSI Controller Block	58
Figure 4-5: VSI Flux Estimation Block	58
Figure 4-6: VSI PI Controllers	59
Figure 4-7: VSI Decoupling Block	59
Figure 4-8: Speed Demand Profile	60
Figure 4-9: DC Link Voltage of the VSR	61
Figure 4-10 a, b: BDFIG Speed Tracking Performance	62
Figure 4-11 a, b: Active/Reactive Power Flow in Control Machine	63
Figure 4-12 a, b: Active Power Decoupling	64
Figure 4-13 a, b: Reactive Power Decoupling	64

Figure 4-14 a, b: Control Machine Current	65
Figure 4-15: Torque Distribution in BDFIG	66
Figure 5-1: Turbine Generator Setup	68
Figure 5-2: Bidirectional Converter	69
Figure 5-3: Controller Structure	71
Figure 5-4: BDFIG Wind Turbine System Diagram	73
Figure 5-5: VSR Waveforms at $\omega_m=900$ rpm, $Q_p=3800$ VA, $P_p=0$ W	74
Figure 5-6: System Waveforms at $\omega_m=710$ rpm, $Q_p=3800$ VA, $P_p=0$ W	76
Figure 5-7: System Waveforms at $\omega_m=710$ rpm, $Q_p=1260$ VA, $P_p=0$ W	77
Figure 5-8: Power Machine Waveforms at $\omega_m=930$ rpm, $Q_p=3850$ VA, $P_p=-390$ W	79
Figure 5-9: BDFIG Waveforms at $\omega_m=810$ rpm, $Q_p=3850$ VA, $P_p=-397$ W	80
Figure 5-10: BDFIG Waveforms at $\omega_m=810$ rpm, $Q_p=1280$ VA, $P_p=-401$	81
Figure 5-11: BDFIG Waveforms at $\omega_m=810$ rpm, $Q_p=1285$ VA, $P_p=-592$ W	83
Figure 5-12: VSR Waveforms at $\omega_m=810$ rpm, $Q_p=1285$ VA, $P_p=-592$ W	84
Figure 5-13: System Waveforms at $\omega_m=1000$ rpm, $Q_p=3800$ VA, $P_p=-585$ W	85
Figure 5-14: BDFIG Speed Tracking Experimental Result	86
Figure 5-15: BDFIG Speed Tracking Simulation Result	87
Figure 5-16: BDFIG Power Flow Comparison Chart	88

LIST OF PRINCIPAL SYMBOLS

1. General Variables

v^α, v^β	Variables in α - β reference frame
v^d, v^q	Variables in d-q reference frame
s	Derivative operator

2. BDFIG Quantities

1.1 Power Machine

ω_p / f_p	Power machine electrical frequencies
θ_p	Power machine angle
P_p	Power machine pole pairs
V_{sp}, V_{rp}	Stator and rotor voltages respectively
I_{sp}, I_{rp}	Stator and rotor currents respectively
R_{sp}, R_{rp}	Stator and rotor resistances respectively
L_{sp}, L_{rp}, L_{mp}	Stator, rotor and mutual inductances respectively
Φ_{sp}, Φ_{rp}	Stator and rotor fluxes respectively
T_e^p	Power machine electrical torque
F_F^p, J_p	Friction and inertia respectively

2.2 Control Machine

ω_c / f_c	Control machine electrical frequencies
θ_c	Control machine angle
P_c	Control machine pole pairs
V_{sc}, V_{rc}	Stator and rotor voltages respectively
I_{sc}, I_{rc}	Stator and rotor currents respectively

R_{sc}, R_{rc}	Stator and rotor resistances respectively
L_{sc}, L_{rc}, L_{mc}	Stator, rotor, and mutual inductances respectively
Φ_{sc}, Φ_{rc}	Stator and rotor fluxes respectively
T_e^c	Control machine electrical torque
F_F^c, J_c	Friction and inertia respectively

2.3 Common Quantities

ω_m, ω_n	BDFIG mechanical and natural speeds respectively
ω_r, ω_e	BDFIG rotor and synchronous electrical speeds
θ_m	BDFIG mechanical angle
L_r, R_r	BDFIG rotor inductance and resistance respectively
I_r	BDFIG total rotor current
Φ_r	BDFIG total rotor flux
T_L, T_e	Load and electrical torques respectively

2.4 Turbine Parameters

β	Blade pitch angle
λ	Tip to Speed Ratio (TSR)
C_p	Power Coefficient
ρ	Air density

2.5 Controller Parameters

δ	Leakage constant
K_i	Integral gain of PI controller
K_p	Proportional gain of PI controller

Chapter 1 Introduction

1.1 Background of Wind Energy Applications

Over the last twenty years, the wind energy generation industry has experienced rapid and successful growth. It has received much attention that brought it to the forefront as the leading form of renewable energy production. Even before Kyoto protocols, which promote the use of clean energy sources and limit the use of fossil fuel-based systems, came into effect, the total wind power generation capacity of the world has been growing by more than 30 percent annually since 1995 as shown Figure 1-1 [1].

Figure 1-1: Total Global Wind Energy Capacity

The first largest wind energy market appeared in the beginning of 1980's in California and its appearance was caused by the oil and energy crisis at the time. However, wind energy generation was only a temporary attempt for the USA. Remarkably, most of the turbines installed at that time were designed and produced by European manufacturers and California became a testing ground for the new technology. As the energy crisis subsided and the oil prices fell, Californian market began to collapse which forced upstart manufacturers out of the business.

However, the idea of wind power generation became very appealing to the environmentally conscious European society. The technologies that were used in the USA took their hold in the countries of Western Europe and began growing rapidly. The pace of that development was so staggering, that within several years Europe overtook the whole of North America in the number of the wind turbines installed annually. As a consequence, the present European wind-power generation capacity represents two thirds of the global total, with North America lagging far behind with mere 18 percent as shown in Figure 1-2 [1].

Figure 1-2: Installed Global Capacity Breakdown

Currently, the wind energy generation sector is enjoying unprecedented growth rates of up to 40 percent in some European countries with the projected rates of up to 16 percent annually until at least 2012. With these rates of development wind energy generation becomes the leading alternative solution to fossil-fuel based systems and comes to the forefront of much research activity [2, 3].

However, before the full discussion of this research and its results can be presented, a brief introduction to the various types of wind turbines and power generators is very crucial in order to facilitate the main concepts discussed in the work.

1.2 Classification of Wind Turbines and Generators

The operation of a wind turbine is based on the behavior of a simple windmill. Like the windmill, the propeller of the turbine captures the energy available in the wind and converts it into the rotational energy of the shaft. However, unlike the windmill, this energy is converted into electricity by means of electromechanical machinery. The electromechanical converter usually consists of the generator, a power electronic interface to the grid and some mechanical accessories with or without a gear-box.

Generally, the wind turbine systems can be classified according to their aerodynamic configuration, transmission design and their operational speed range. Further classification can be performed based on the power output, the generator type, grid connection, etc.

The aerodynamic configuration divides the wind turbines in two main categories: the horizontal axis wind turbines (HAWT) and vertical axis wind turbines (VAWT). Due to reasons of mechanical resonance, efficiency and size more than 95 percent of the currently operating wind turbine designs are HAWT. The choice of this configuration has one major disadvantage that the main components of the energy conversion system such as generator, gearbox, pitch control mechanism, the power converter and grid-interface device, have to be located in the nacelle of the turbine. This leads to the increased demands on the stability, strength and cost of the support structure.

Regardless of the aerodynamic configuration of the wind turbine, its absolute maximum power extraction efficiency is restricted by the Betz limit of 59.3 percent. Recent studies by Dr. Gorlov [4] showed that the maximum efficiency of the two-dimensional propellers is actually

only 30.1 percent. However, no turbine can ever operates at its maximum efficiency all the time. Instead, its operation is built around the performance coefficient (C_p) of its propeller. This is an aerodynamic characteristic of the propeller that determines the amount of energy extracted from the airflow at a given speed [5]. The performance coefficient, which is determined the turbine blade design, can be considered as a function of the tip speed ratio and the blade pitch. Tip speed ratio (TSR) is in turn the function of the wind speed (v_w), rotor speed (ω_r) and propeller radius (R_r), given as:

$$\lambda = \frac{\omega_r R_r}{v_w} \quad (1.1)$$

A typical coefficient of the wind turbine at a given pitch (0°) is shown in Figure 1-3. The optimal C_p is only possible at certain tip speed ratio.

Figure 1-3: Typical Turbine C_p Curve for 0° Blade Pitch

For the curve given in Figure 1-3, the optimal C_p occurs at tip speed ratio of around 6.5, therefore, the absolute maximum power will only be delivered to the grid under these conditions. Yet, it is not always possible to maintain zero blade pitch, because it would create unwanted output fluctuations as well as greatly increase the electrical and mechanical load on the whole system when the wind is too strong. To partially cure this problem, the pitch control mechanisms (or stall control) are installed to regulate the position of the blades and maintain the highest possible power the system can be deliver to the grid.

Nevertheless, not all of the mechanical energy captured by the wind turbine is converted into the electric power supplied to the grid. To reduce the losses of the power conversion process, various types of the generators are used in the wind turbines and will be briefly discussed in Section 1.3.

One of the classifications of the generators is based on the configuration of the coupling between the propeller shaft and the generator rotor. Thus, the geared-drive concept refers to the arrangement under which the propeller shaft and the rotor are coupled through the step-up gearbox; the direct-drive concept refers to the wind turbine in which the propeller is directly connected to the shaft of the rotor of the generator.

The need for the gear box arises from the fact that even under the best circumstances, the propeller of the turbine will not rotate faster than several dozen revolutions per minute. The generator, however, needs to rotate at several hundreds or thousands revolutions to produce current of the standard 50 or 60 hertz. Therefore, the easiest way to increase the speed of the generator is to include a step-up gear box. The main advantage of the geared-drive technology is the relative simplicity of the generator design. It allows the use of the very robust induction generators directly connected to the grid. In this case, the power converter is optional and can be installed only if variable speed operation is desired. On the other hand, the considerable drawbacks of the geared-drive are the necessity of the regular maintenance and gearbox losses.

The direct-drive concept appears to eliminate the shortcomings of the geared-drive turbines. Since the generator synchronous speed is inversely proportional to the number of its poles, as shown in (1.2), there exists a way of increasing the number of poles as to bring the synchronous speed down to several dozens revolutions per minute. The absence of the high-maintenance gearbox makes the direct-drive turbines well suited for the offshore operation. However, this technology has a couple of very serious drawbacks that cannot be ignored: direct drive turbines require a complex power conditioning block and a large-diameter heavy generator. Unfortunately, the current technologies do not always provide economical solutions to these challenges, and it

remains to be seen if direct-drive units can form economically viable alternative to the geared-drive turbines.

$$\omega_{sync} = \frac{120f_e}{P} \quad (1.2)$$

Finally, the generators are distinguished by their operational modes, fixed-speed or variable-speed operation. As the name implies, fixed-speed generators operate at a constant speed regardless of the wind conditions. The speed is restricted by the amount of the slip available in the generator and the pitch control is used to limit the maximum power. The fixed-speed approach has several important implications such as low efficiency at low wind speed, power fluctuation, high noise levels at low speeds and increased mechanical loads on the whole system. The main advantage of such a system, however, is the absence of any expensive power converter and the losses associated with it.

Under the variable-speed operation mode, the rotational speed of the rotor is changed to extract more power at low or medium wind speeds. This approach solves the problems of the fixed-speed turbine, but requires more advanced power conversion mechanisms, some of which may not guarantee flicker-free power output. The variable speed operation is also more efficient as it allows implementation of the maximum power point tracking (MPPT) schemes to improve the system utility.

The current tendency is to use variable-speed turbines so that the total generation capacity can be increased and more importantly the power fluctuations problems associated with the fixed-speed turbines can be partially solved.

1.3 Most Popular Generator Topologies for Wind Applications

From the very inception, wind turbine research and development was concentrated heavily on the design of the geared-drive generators. The field of renewable energy production is still domi-

nated by this concept and a considerable number of various topologies have been developed for this purpose.

Induction generators are the dominant in wind energy applications. The choice of this type of the generators is dictated by the fact that the rotational speed of its rotor can be controlled through the slip, which is the percentage difference between the synchronous speed of the generator and the actual speed of the rotor. The variable-speed operation can be best accomplished with wound type rotor, while fixed speed configuration relies on the squirrel-cage rotor design because of its robustness low manufacturing and maintenance cost. The following diagram shows the various configurations of the geared-drive wind turbines [6].

Figure 1-4: Geared-drive Turbine Configurations

1.3.1 Squirrel Cage Induction Generators

The earliest and most popular concept used for wind power generation was a fixed speed induction generator (FISG) design. Wind turbines based on this topology (also known as “Danish” concept) utilize the squirrel-cage rotor arrangement. This approach was chosen because of the versatility of the cage rotor concept: cheapness of manufacturing and remarkable reliability. The most important limitation of this design, however, is relatively constant slip of around one percent. That is, the design of the turbine allowed only fixed operational speed.

Most of the currently operational FSIG wind turbines have the sophisticated blade pitch control to adjust the propeller in such a way as to limit the maximum power. However, the response

times of the mechanical components often prevent the system from timely responding to the gusts of wind. This characteristic of the FSIG wind turbine is the major cause of the output power instability and requires a very strong grid to allow for uninterrupted operation [8].

The FSIG wind turbines have one weakness that becomes increasingly detrimental as the wind power generators are called upon to play larger role in the power market. The main issue is the quality of the power supplied to the grid, in other words the combination of active and reactive power delivered to the customer. The problem is twofold – not only an induction generator cannot produce any reactive power, but it actually consumes it for a proper operation. As long as such generator plays a supplemental role in the grid connected to the conventional (synchronous generator) source of electric power, this problem remains of little importance. Currently, reactive power generation and power factor correction is achieved on a small scale by the addition a bank of static capacitors of various denominations and switching them on and off to satisfy the grid demand. However, if induction generator wind turbines were to completely replace the conventional sources, the problem of the reactive power generation could not be solved with this temporary fix. In 2003, a new solution was proposed by the utility giant PacifiCorp, which includes a new system called D-VAR that would be able to provide continuously up to ± 8 MVARs of power [8]. It remains to be seen if this system, based entirely on IGBT technology, can provide an adequate reactive power generation capacity for induction generator-based wind turbines.

Another shortcoming of the FSIG wind turbines is the noisiness of their operation. The problem lies in the fact that there is a direct relation between the rotational speed of the propeller and the noise level produced by the air friction with the blades. Since the turbine operates at a constant speed, the noise produced by it would be of the same intensity in any wind conditions. That implies that even on a relatively calm day, the turbine would be as noisy as during the high-wind periods.

To eliminate the some of the shortcomings of the FSIG wind turbines, the most obvious solution is to allow the variable-speed operation of the wind turbine. Thus, the easiest way to allow variable speed operation of the generator with the squirrel-cage rotor is to add a power converter

between the turbine and the grid. Such a converter includes the AC/DC and DC/AC sub-converters, with the latter being connected to the grid (the arrangement, shown in Figure 1-5, is called Direct-in-line ASG). This configuration allows the generator to run at the speed proportional to the wind speed, regardless of the grid frequency. In this mode, the power capture is maximized through the continuous operation over the wide range of the wind speeds.

Figure 1-5: Direct-in-line ASG Wind Turbine

The common approach is to use a controlled AC/DC converter, such as PWM rectifier in line with the generator. This provides the flow of the reactive power to the stator winding. However, the conventional converter needs to be oversized to handle the reactive power needs of the generator and exhibits poor efficiency at the low wind speeds.

In order to convert the DC link voltage back to the AC with appropriate frequency Voltage Source Inverters are used most often. These are based on IGBT switching devices and can be controlled to provide required frequency and amplitude, depending on the load conditions. The typical operation of the VSI will be discussed in Chapter 3.

1.3.2 Doubly-Fed Induction Generators

The alternative solution to the squirrel-cage rotor generator is a doubly-fed induction generator (DFIG) based on the wound rotor machine. These appear to be very useful when employed as electromechanical converters in the variable-speed turbines, because their rotational speed can be controlled through the rotor slip. In general, if an AC source is connected to the stator winding of

induction machine, it will produce a rotating magnetic flux. This in turn will create an emf in the rotor, which depends on the number of windings in both stator and rotor. Thus, rotor emf can be expressed as:

$$E_{rotor} = E_{stator} \frac{N_{rotor}}{N_{stator}} s \quad (1.3)$$

The rotational speed of the motor is given as:

$$\omega_{rotor} = \omega_{sync} (1 - s) \quad (1.4)$$

Therefore, it can be shown that the slip can be controlled through the power dissipation in the rotor windings:

$$s = \frac{P_{rotor, copper}}{P_{airgap}} \quad (1.5)$$

The above equation forms the basis of the variable speed control of the wound rotor induction generator.

In order to control the amount of slip, it is necessary to be able to manage the amount of energy dissipated in the rotor. This is achieved by providing the separate feed to the rotor winding through the slip rings. The rotor winding can be connected to either a resistive load or the grid through a separate converter. In both cases, the rotor slip recovery performs the role of the speed controller by recycling the amount of slip energy. By withdrawing more slip energy (like more rotor copper loss), the speed can be decreased. Doubly-fed arrangement provides several advantages over the direct-in-line ASG: flexible power quality control, relatively small converter size with fractional rating and improved efficiency. Most importantly, DFIGs permit frequency regulation, which is essential if wind turbines are to become a sole source of electricity in the future.

A simplified schematic of the DFIG wind turbine is shown in Figure 1-6. To allow variable speed operation current is ejected into the rotor windings through the slip rings. The power for rotor windings is generated by the turbine itself and then fed back through bi-directional converter block. Since it is the converter block that controls the amount of power ejected into the

rotor, its rating determines the speed range of the wind turbine. Most of the DFIG wind turbine designs allow only around 30 percent of the variable speed range. This limitation allows reducing the size of the inverter and keeping its rating as low as 25 percent of the rated power of the turbine.

Figure 1-6: DFIG Wind Turbine

The doubly-fed configuration allows very flexible control of the generator. For instance, it is possible to decouple the speed control from the power quality control using the field oriented control approach. Thus, depending on the conditions the speed or the power quality can be controlled independently [7, 10, 11, 12].

Since their emergence, DFIG wind turbines proved to be a very popular alternative to the FSIG configurations and much research has been done on the optimization of their performance. As discussed previously, the output power of the wind turbine is above all the function of the tip speed ratio. However, as shown in Figure 1-3, the absolute maximum power can be extracted only at a certain value of λ ; for any other value of the tip speed ratio, the maximum power is only available when the rotor is free to rotate proportionally to the wind speed. Therefore, the operation of the DFIG can be broken down into two ranges: below and above λ_{opt} . To achieve the optimal operation, DFIG wind turbine requires both the blade pitch control and rotor speed control.

In general, the frequency of the output voltage from the stator side is given as:

$$\omega_s = \omega_m \pm \omega_r \quad (1.6)$$

When the wind is low, the blades are fixed at a constant pitch and the rotor is turning proportionally to the wind speed to maintain the λ_{opt} . Under this condition the stator frequency is fixed to the grid frequency and rotor frequency is adjusted to increase or decrease the speed, which optimizes the tip-speed-ratio. However, once the wind picks up, the pitch of the blades is constantly adjusted to limit the maximum power and the rotor frequency is adjusted accordingly to the maximum power limit [13].

There are numerous control schemes proposed for the output power optimization of the DFIG wind turbines. Most of them are centered on the decoupled control of the speed and power quality. In [14], a new method of decoupled torque and power quality control is discussed. The authors point out that their approach allows minimizing the losses in the converter. At the same time, they argue that it is essential to have highly precise estimate of the stator flux leakage, which might not always be available.

1.3.3 Synchronous Generators

The alternative to the induction generator wind turbines is presented by the use of the synchronous generators for the power conversion. In their operation, synchronous machines rely on the rotating magnetic field created by the direct-current in the rotor windings, or by the permanent magnets. Due to the unique flux generation, the frequency of the induced voltage in the stator winding always matches the synchronous speed defined in (1.2), hence the name – synchronous machine.

Synchronous generators are much better suited for direct drive operation than the induction generators, due to their construction and synchronous operation. For years the rotors for these

machines were mainly based on the electric magnets, because these were relatively cheap and were not subject to demagnetization over their useful life. However, new technologies help to stretch the operational life of permanent magnets, making the rotors more compact and removing the reliance on the DC power sources for rotor magnetization. All this helps to increase the number of poles, making for more robust direct drive wind turbines based on permanent magnet synchronous generators (PMSG).

Currently there are several PMSG topologies being used in the industry or under investigation by the researches. These include radial-flux, axial-flux and transverse-flux synchronous generators. As their names imply, these generators are differentiated by orientation of the magnetic field created inside the machine and have various advantages that can be utilized in different situations. It appears that the axial-flux synchronous machines offer greater benefits of smaller size and improved power-to-weight ratio, however, their suitability for high power operation requires further study [15, 16, 17].

Regardless of the topology, the greatest benefit of the synchronous generator wind turbines is the removal of the gearbox and their ability to output the reactive power to the grid. This comes at a price of the inclusion of the power conditioning block. The reason for this requirement is the simple fact that the AC voltage frequency of these generators is merely a function of the wind speed and the blade pitch of the turbine. To achieve appropriate output frequency regulation it is essential to introduce a power converter unit between the generator and the grid. Therefore, the typical configuration of the synchronous generator in the wind turbines is similar to the one depicted in Figure 1-6. Needless to say, that the power converter in this case must be rated for the full power of the generator, which increases the size and cost of the whole system.

1.4 Motivation and Objective

Based on the analysis of the available systems presented in the previous sections, most of the current wind turbine manufacturers rely on the DFIGs as the generator of choice for their production, however, the traditional DFIG based wind energy conversion systems have the disadvantages that cannot be overlooked. In order to recovery the slip energy from rotor to the grid, it is necessary to use a wound type rotor with slip rings and commutation brushes. Their presence increases the maintenance costs significantly. Currently, the average life of the brushes used in the DFIG turbines is between 6 and 12 month, which necessitates regular maintenance. Under the current conditions, when most of the turbines are organized into the wind parks and are located on land, the maintenance cost may still be kept within reasonable limits, but in the future this will not be possible. As envisaged by the leading utility companies, and as driven by the market demand, most of the future wind power generation will be moved to the offshore locations, where the wind parks comprising dozens of turbines will be created. Depending on the wind climate of the given area, these parks may be built as far as 30 kilometers away from the cost line. Clearly, such an arrangement will favor the turbine design that requires the least frequent inspection and maintenance. Under the new conditions cost of maintenance of the DFIG turbines will increase significantly – a simple replacement of the brushes involves considerable logistical effort of bringing technicians and spare parts to offshore location [18].

The possible solution for these shortcomings is the introduction of the gearless drive, however, that would lead to the increased size, higher manufacturing and installation costs. The other solution may present itself in the form of the Brushless Doubly Fed Induction Generator (BDFIG), which can be seen as an advanced version of the DFIG, because it is based on the same principle of the slip energy recovery used for the output control. There are several advantages to the new topology that consist of the two induction machines connected in cascade with a common rotor, as shown in Figure 1-7. The first one is the absence of the commutation brushes since the slip energy is exchanged through the second stator winding with the purpose of creating

an additive torque – similar to the function performed by the rotor in the DFIG. The absence of the physical connection to the rotor not only eliminates brushes and slip rings, but also removes the necessity of the wound type rotor. Thus, the second advantage of the design is the possibility to implement the generator using the very reliable and cost effective squirrel-cage rotor. The freedom to use the cage rotor is very significant, as it has the potential of simplifying the generator design, bringing the initial cost and the maintenance expenses down.

Figure 1-7: Typical BDFIG Configuration Based on Cascaded Rotor

Therefore, the main objectives of this thesis were to: 1) develop a mathematical dynamic model for the BDFIG with cascaded rotor. The model would be used in the simulation and controller design; 2) design a suitable controller for BDFIG that would ensure stability and optimal operation of a variable speed wind turbine for any operating condition. To simplify the design and for the economical reason the present research has been carried out using the brushless doubly fed induction generator consisting of the two cascaded wound-rotor induction machines.

1.5 Thesis Outline

This thesis is organized to provide the detailed information about the research work on BDFIG in five chapters.

Chapter Two presents the work involved in creating the appropriate mathematical model of the BDFIG. The chapter gives the step by step development of the dynamic model in the D-Q reference frame and its implementation using Matlab/Simulink package. The simulation results that verify the proposed model are also presented in this chapter.

Chapter Three presents the flexible power controller design for the BDFIG. First, it introduces the basic theory of the variable speed wind turbine operation, reactive power regulation and the requirements for the effective controller. The structure of the typical field oriented control (FOC) is discussed and the proposed controller scheme for both the grid-side and generator-side controllers is presented.

Chapter Four provides all the models for different components of the BDFIG wind turbine system, their integration and use in Matlab/Simulink. The simulation results for the complete system are also given in this chapter.

In Chapter Five, the experimental platform is introduced, including the wind turbine emulator. The experimental results for the testing system are provided, compared to the simulation data and analyzed.

Finally, Chapter Six concludes the research in this thesis and list the major contributions and other issues that require further research.

Chapter 2 BDFIG Model Development

2.1 General Structure of BDFIG

To eliminate the shortcomings of the DFIG associated with the inclusion of brushes and wound type rotor in the wind turbine generator, a different approach can be taken by using a brushless generator to perform all the functions of the DFIG. The brushless operation is achieved through the addition of the second stator winding and connecting it to the slip power recovery loop. The simplest way to introduce the second stator winding is to connect two induction machines in cascade, as shown in Figure 2-1. Under such an arrangement the generator has two separate stator windings that are magnetically coupled through the common rotor. Therefore, it is possible to produce two electro-magnetic torques acting on the shaft of the generator. To allow variable speed operation, however, these torques need to be variable quantities. This is achieved by inserting an AC-AC power converter block between one of the machines forming the BDFIG and connecting the other one directly to the grid. By managing the frequency and magnitude of the voltage applied across the winding of the second stator the magnitude of the total torque of the generator is adjusted to control the required operational speed.

It must be noted, that it is not necessary to connect the machines of equal rating to form the BDFIG. It is sufficient to construct the generator from the main induction machine of the desired power rating (referred to as a power machine) and a smaller generator with roughly 25 percent capacity (referred to as a control machine). The reduced ratings of the control machine are justified by the fact that this portion of the BDFIG performs only regulatory functions and handles a fraction of power that flows through the power machine.

Figure 2-1: Typical BDFIG Stator Arrangement

From the above discussion, an important conclusion regarding the operational speed of the BDFIG can be drawn. It is clear that normal operational conditions there exist two excitation voltages applied to the stator windings of the BDFIG. Furthermore, these voltages generally have different frequencies. Therefore, the mechanical speed of the BDFIG is both the function of the power machines and control machine excitation voltages. The general expression for the mechanical speed of the BDFIG is given in (2.1). Whether the two frequencies combine in additive or subtractive manner is determined by the rotor interconnection in the BDFIG, however, in the generation mode it is preferable that the control machine frequency carries a positive sign.

$$\omega_m = \frac{120(f_p \pm f_c)}{(P_p + P_c)} \quad (2.1)$$

Since the control machine in BDFIG only performs the function of the regulator, then the natural state of the generator can be defined as an operation when the control windings are shorted. Therefore, the synchronous speed (equivalent of IM synchronous speed) of the generator is given as:

$$\omega_n = \frac{120f_p}{(P_p + P_c)} \quad (2.2)$$

This speed definition in (2.2) offers an immediate insight into the advantages of BDFIG operation in the wind turbine. It demonstrates that the rotational speed of the generator can be greatly reduced by the inclusion of the control machine with high number of poles. What makes this task easier is the fact that the control machine only handles a fraction of the total generator power, thus its size is still relatively small compared to the power machine. Nevertheless, the combination of the number of poles of the BDFIG must not be assigned randomly. To achieve optimal performance, especially with the squirrel cage rotor design, the number of poles should be selected according to the outline proposed in [19, 20]. These papers offer a precise relation between the numbers of poles in the two machines, which is governed by the need to avoid magnetic coupling between the two windings and prevent any unbalanced electromagnetic pull. It states that number of poles in both machines must satisfy the Maximum Common Divisor (MCD) constraints in (2.3) and that their difference must comply with (2.4).

$$\frac{P_p}{MCD} = 2n, \quad \frac{P_c}{MCD} = 2n-1, \quad n = 2, 3, 4, \text{etc.} \quad (2.3)$$

$$|P_p - P_c| > 1 \quad (2.4)$$

Once the BDFIG has been formed using the cascaded inductions machines, its operation remains essentially the same as that of the DFIG. Here the principle of the slip recovery is used once again to increase the variable speed operational range. Through the use of the bidirectional power converter the active and reactive power flows are directly controlled as necessary, allowing manipulating the amount of slip or reactive power in the BDFIG system. The purpose of the BDFIG controller therefore is to allow a flexible regulation of the power flow to the control machine, creating the necessary conditions for independent control of the speed and power factor in the generator.

Before such a controller can be designed, it is imperative to produce a comprehensive mathematical model of the BDFIG that can be used in simulation as well as in the future research. The

following sections provide complete information regarding the physical and mathematical modeling of the BDFIG and reproduce the results of the model testing and verification.

2.2 BDFIG Mathematical Modeling

The BDFIG consists of two induction machines and the behavior of the individual machines is governed by the set of first order differential equations associated with the simple induction machine as shown in (2.5):

$$\begin{bmatrix} \mathbf{V}_s \\ \mathbf{V}_r \end{bmatrix} = \begin{bmatrix} R_s & 0 \\ 0 & R_r \end{bmatrix} \begin{bmatrix} \mathbf{I}_s \\ \mathbf{I}_r \end{bmatrix} + \frac{d}{dt} \begin{bmatrix} \Phi_s \\ \Phi_r \end{bmatrix} + j \begin{bmatrix} \omega_e & 0 \\ 0 & \omega_r \end{bmatrix} \begin{bmatrix} \Phi_s \\ \Phi_r \end{bmatrix} \quad (2.5)$$

To establish the complete mathematical representation of the dynamic behavior of the BDFIG it is first necessary to clarify the kind of the electromechanical interconnection that exists between the cascaded machines. A thorough analysis of all the possible configurations was performed in [21]. One of the simplest ways to connect these two machines is in the back-to-back fashion with no phase inversion on the rotor side, as shown Figure 2-2.

Figure 2-2: BDFIG Back-to-Back Configuration

With this connection the rotor currents contributed by the two machines combine in the subtractive fashion and the rotor voltages have the same signs, i.e. $I_{rp} = -I_{rc}$ and $V_{rp} = V_{rc}$. The chosen connection greatly affects the distribution of the magnetic fields inside the BDFIG, producing the two counter-rotating torques as will be discussed in the following sections.

Regardless of the chosen connection the general equations describing the dynamic behavior of the BDFIG system are given in (2.6):

$$\begin{bmatrix} \mathbf{V}_{sp} \\ \mathbf{V}_{rp} \\ \mathbf{V}_{rc} \\ \mathbf{V}_{sc} \end{bmatrix} = \begin{bmatrix} R_{sp} & 0 & 0 & 0 \\ 0 & R_{rp} & 0 & 0 \\ 0 & 0 & R_{rc} & 0 \\ 0 & 0 & 0 & R_{sc} \end{bmatrix} \begin{bmatrix} \mathbf{I}_{sp} \\ \mathbf{I}_{rp} \\ \mathbf{I}_{rc} \\ \mathbf{I}_{sc} \end{bmatrix} + \frac{d}{dt} \begin{bmatrix} \Phi_{sp} \\ \Phi_{rp} \\ \Phi_{rc} \\ \Phi_{sc} \end{bmatrix} + j \begin{bmatrix} \omega_p & 0 & 0 & 0 \\ 0 & \omega_r & 0 & 0 \\ 0 & 0 & \omega_r & 0 \\ 0 & 0 & 0 & \omega_c \end{bmatrix} \begin{bmatrix} \Phi_{sp} \\ \Phi_{rp} \\ \Phi_{rc} \\ \Phi_{sc} \end{bmatrix} \quad (2.6)$$

The expanded flux vector matrix for the general system in (2.6) is defined as:

$$\begin{bmatrix} \Phi_{sp} \\ \Phi_{rp} \\ \Phi_{rc} \\ \Phi_{sc} \end{bmatrix} = \begin{bmatrix} L_{sp} & L_{mp} & 0 & 0 \\ L_{mp} & L_r & 0 & 0 \\ 0 & 0 & L_r & L_{mc} \\ 0 & 0 & L_{mc} & L_{sc} \end{bmatrix} \begin{bmatrix} \mathbf{I}_{sp} \\ \mathbf{I}_{rp} \\ \mathbf{I}_{rc} \\ \mathbf{I}_{sc} \end{bmatrix} \quad (2.7)$$

For the back-to-back configuration with no phase inversion the rotor currents of the individual machines have the opposite signs, the fluxes inside the rotor combine to produce the virtual rotor flux, as shown in (2.8):

$$\Phi_r = \Phi_{rp} - \Phi_{rc} \quad (2.8)$$

Combining the rotor voltage equations under the constraints of the back-to-back configuration and noting that all the rotor parameters combine in the additive manner produces (2.9). The new flux expressions that account for the common rotor flux are defined in (2.10).

$$\begin{bmatrix} \mathbf{V}_{sp} \\ 0_r \\ \mathbf{V}_{sc} \end{bmatrix} = \begin{bmatrix} R_{sp} & 0 & 0 \\ 0 & R_r & 0 \\ 0 & 0 & R_{sc} \end{bmatrix} \begin{bmatrix} \mathbf{I}_{sp} \\ \mathbf{I}_r \\ \mathbf{I}_{sc} \end{bmatrix} + \frac{d}{dt} \begin{bmatrix} \Phi_{sp} \\ \Phi_r \\ \Phi_{sc} \end{bmatrix} + j \begin{bmatrix} \omega_p & 0 & 0 \\ 0 & \omega_r & 0 \\ 0 & 0 & \omega_c \end{bmatrix} \begin{bmatrix} \Phi_{sp} \\ \Phi_r \\ \Phi_{sc} \end{bmatrix} \quad (2.9)$$

$$\begin{bmatrix} \Phi_{sp} \\ \Phi_r \\ \Phi_{sc} \end{bmatrix} = \begin{bmatrix} L_{sp} & L_{mp} & 0 \\ L_{mp} & L_r & -L_{mc} \\ 0 & -L_{mc} & L_{sc} \end{bmatrix} \begin{bmatrix} \mathbf{I}_{sp} \\ \mathbf{I}_r \\ \mathbf{I}_{sc} \end{bmatrix} \quad (2.10)$$

Following the standard procedure, the dynamic equations in (2.9) and (2.10) need to be represented in a selected direct-quadrature reference frame. The structure of the BDFIG offers the choice of three reference frames attached to the power machine stator, to the rotor or to the control machine stator. The most obvious solution would be to attach the reference frame to the rotor as its rotational speed is the same for both of the machines forming the BDFIG. However, this is not a suitable choice because that frame does not rotate at constant speed, moreover, when transformed to this frame, the currents and voltages would retain their sinusoidal nature, presenting a considerable challenge for controller design [21]. The best choice that allows transformation all the voltages and currents into DC values under steady state operation therefore lies in selecting the synchronously rotation frame attached to the power machine stator as a reference for the future model development.

2.2.1 Power Machine Modeling

The d-q transformation of the power machine voltages and currents follows the outline presented in [22]. The purpose of the transformation is to remove as many time-varying parameters from the system as possible. By converting the three-phase machine to its two-phase equivalent and selecting the appropriate reference frame, all the time-varying inductances in both the stator and the rotor are eliminated, allowing for a simple yet complete dynamic model of the electric machine. When the reference frame is attached to the voltage vector of the power machine stator, the graphical representation of the transformations is given in Figure 2-3. In the figure D_s^P/Q_s^P denote the stationary reference frame attached to the power machine stator while D_e/Q_e is the

synchronous reference frame rotation at ω_e . The transformation angle for the stator quantities is the synchronous angle, which for the stiff grid always rotates at constant speed (Figure 2-3a).

Figure 2-3b depicts the reference transformations of the rotor quantities with D_s^r/Q_s^r denoting the d-q reference frame attached to the shaft of the rotor. This stationary frame, however, is rotating with respect to the stator stationary reference frame at an angular speed of ω_r . This speed can be easily obtained as a difference between the synchronous speed and the shaft electrical frequency as shown in (2.11).

Figure 2-3: Power Machine D-Q Transformation

$$\omega_r = \omega_p - P_r \omega_m \quad (2.11)$$

To perform the d-q transformation on the power machine variables the appropriate equations from (2.6) are used and combined with the flux equations. The standard Clarke/Park transforms (given in Appendix A) are applied to produce (2.12):

$$\begin{bmatrix} V_{sp}^q \\ V_{sp}^d \\ V_{rp}^q \\ V_{rp}^d \end{bmatrix} = \begin{bmatrix} R_{sp} + sL_{sp} & \omega_p L_{sp} & sL_{mp} & \omega_p L_{mp} \\ -\omega_p L_{sp} & R_{sp} + sL_{sp} & -\omega_p L_{mp} & sL_{mp} \\ sL_{mp} & \omega_r L_{mp} & R_{rp} + sL_{rp} & \omega_r L_{rp} \\ -\omega_r L_{mp} & sL_{mp} & -\omega_r L_{rp} & R_{rp} + sL_{rp} \end{bmatrix} \begin{bmatrix} I_{sp}^q \\ I_{sp}^d \\ I_{rp}^q \\ I_{rp}^d \end{bmatrix} \quad (2.12)$$

The equivalent d-q circuit that represents the dynamic system (2.12) is given Figure 2-4.

Figure 2-4: Power Machine D-Q Equivalent Circuits

The electrical torque production in the power machine is governed by the same principles as would apply for any induction machine. The general expression of the electrical torque in this case is simply:

$$T_e = \frac{3}{2} \left(\frac{P}{2} \right) \Phi_m \times I_r \quad (2.13)$$

In the d-q reference frame, however, the expression in (2.13) can be expanded and rearranged as to show the torque as a function of certain control variables. Keeping in mind that the power machine is connected to a stiff grid with constant voltage, the best expression for the power machine torque would be the one given in (2.14):

$$T_e^p = - \left(\frac{3}{2} \right) \left(\frac{P_p}{2} \right) \left(\Phi_{sp}^q I_{sp}^d - \Phi_{sp}^d I_{sp}^q \right) \quad (2.14)$$

The above expression clearly shows that the only control variables in this case are the d-q components of the stator current, because the power machine stator fluxes are almost constant. Furthermore, when the controller reference frame is aligned with one of the flux components, the number of the control variables is reduced, as will be discussed in Chapter 3.

2.2.2 Control Machine Modeling

For the control machine, the rotor frame would be same as power machine due to the back-to-back connection. But its stator frame rotates at the speed ω_c , which is shown in Figure 2-5. Moreover, it also shows the angle relationship of power machine stator, power and control machine rotors and control machine stator with the selected synchronous reference frame.

Figure 2-5: Control Machine D-Q Transformation

What the above figure reveals is the fact that the control machine is actually rotating with respect to the power machine. This perceived rotation is not physical of course, but the stator of the power machine “sees” the stator of the control machine rotating due to the difference in the number of poles and the slip present in the system. Therefore, to map the control machine stator onto the common reference frame the following sequence of rotations is required: power machine stator to common rotor, followed by common rotor to control machine stator. Mathematically these rotations are described in (2.15).

$$\begin{aligned}\theta_c &= \theta_p - P_p \theta_m - P_c \theta_m \\ \text{or} \\ \omega_c &= \omega_p - P_p \omega_m - P_c \omega_m\end{aligned}\tag{2.15}$$

The transformation of the rotor quantities is the same as in Section 2.2.1, because both machines have a common rotor, whose quantities are rotating at the electrical speed ω_r . When the d-

q transformation for the control machine is performed on the relevant equations in (2.6) combined with the fluxes in (2.10). Applying Clarke/Park transforms, the resulting model becomes as shown in (2.16):

$$\begin{bmatrix} V_{sc}^q \\ V_{sc}^d \\ V_{rc}^q \\ V_{rc}^d \end{bmatrix} = \begin{bmatrix} R_{sc} + sL_{sc} & \omega_c L_{sc} & sL_{mc} & \omega_c L_{mc} \\ -\omega_c L_{sc} & R_{sc} + sL_{sc} & -\omega_c L_{mc} & sL_{mc} \\ sL_{mc} & \omega_r L_{mc} & R_{rc} + sL_{rc} & \omega_r L_{rc} \\ -\omega_r L_{mc} & sL_{mc} & -\omega_r L_{rc} & R_{rc} + sL_{rc} \end{bmatrix} \begin{bmatrix} I_{sc}^q \\ I_{sc}^d \\ I_{rc}^q \\ I_{rc}^d \end{bmatrix} \quad (2.16)$$

For the system in (2.16) the d-q equivalent circuit is shown in Figure 2-16. It is very similar to the circuits in Figure 2-4 with the difference in the stator excitation frequencies.

Figure 2-6: Control Machine D-Q Equivalent Circuits

To express the electrical torque of the control machine the same standard expression in (2.13) is used. This time, however, there can be no simplification because the stator fluxes of the control machine will never be constant. Yet, it is clear that the torque must be expressed as function of the excitation current. Several standard equations can be used, but keeping in mind that the purpose of this research is to provide a flexible power control of the BDFIG, the control machine torques expression in (2.17) is given in terms of the future control quantities.

$$T_e^c = -\frac{3}{2} \left(\frac{P_c}{2} \right) L_{mc} \left(I_{sc}^d I_r^q - I_{sc}^q I_r^d \right) \quad (2.17)$$

The choice of the rotor current as the second variable is based on the fact that there exists an electric coupling between the two stators of the BFIG, which is achieved through the common rotor current. With the hindsight knowledge of the controller design, the torque expression in (2.17) offers the best picture of the inner workings of the BDFIG.

2.2.3 Complete BDFIG Model

To complete the formation of the BDFIG, the models of power and control machines need to be brought together. This is done by combining (2.12) with (2.16) and noting that all the rotor quantities can be added together to represent the common rotor. The resulting BDFIG dynamic electric model is given in (2.18).

$$\begin{bmatrix} V_{sp}^q \\ V_{sp}^d \\ V_r^q \\ V_r^d \\ V_{sc}^q \\ V_{sc}^d \end{bmatrix} = \begin{bmatrix} R_{sp} + sL_{sp} & \omega_p L_{sp} & sL_{mp} & \omega_p L_{mp} & 0 & 0 \\ -\omega_p L_{sp} & R_{sp} + sL_{sp} & -\omega_p L_{mp} & sL_{mp} & 0 & 0 \\ sL_{mp} & \omega_r L_{mp} & R_r + sL_r & \omega_r L_r & sL_{mc} & \omega_r L_{mc} \\ -\omega_r L_{mp} & sL_{mp} & -\omega_r L_r & R_r + sL_r & -\omega_r L_{mc} & sL_{mc} \\ 0 & 0 & sL_{mc} & \omega_c L_{mc} & R_{sc} + sL_{sc} & \omega_c L_{sc} \\ 0 & 0 & -\omega_c L_{mc} & sL_{mc} & -\omega_c L_{sc} & R_{sc} + sL_{sc} \end{bmatrix} \begin{bmatrix} I_{sp}^q \\ I_{sp}^d \\ I_r^q \\ I_r^d \\ I_{sc}^q \\ I_{sc}^d \end{bmatrix} \quad (2.18)$$

The equivalent d-q circuit for the BDFIG is somewhat complicated, because it is the combination of the equivalent circuits for both the power and control machines (Figure 2-7).

Figure 2-7: BDFIG D-Q Equivalent Circuits

The circuits together with the dynamic equations in (2.18) demonstrate that there exists a certain amount of cross coupling in the rotor d-q flux components as shown in (2.19):

$$\begin{aligned}\Phi_r^q &= \frac{R_r I_r^d + \frac{d}{dt} \Phi_r^d}{\omega_r} \\ \Phi_r^d &= -\frac{R_r I_r^q + \frac{d}{dt} \Phi_r^q}{\omega_r}\end{aligned}\tag{2.19}$$

This leads to the conclusion that at steady state the active and reactive power flowing through the power machine may not be controlled in a completely decoupled manner as in DFIG. However, the effects of the rotor flux cross coupling can be reduced, by noting that it is a function of rotor resistance, which can be minimized with certain rotor designs. Also the cross coupling is affected by the rotor angular speed with the grates effect around the synchronous speed. These two considerations will be taken into account for the design of the controller for BDFIG.

Regardless of the cross coupling, the full electrical torque of the BDFIG system is defined by the combination of (2.14) and (2.17):

$$T_e = -\frac{3}{4} \left(P_p \left(\Phi_{sp}^q I_{sp}^d - \Phi_{sp}^d I_{sp}^q \right) + P_c L_{mc} \left(I_{sc}^d I_r^q - I_{sc}^q I_r^d \right) \right) \quad (2.20)$$

Finally, the mechanical model of the BDFIG is defined by the frictions and inertias of the power and control machines:

$$(J_p + J_c) \frac{d\omega_m}{dt} = T_e - (F_F^p + F_F^c) \omega_m - T_L \quad (2.21)$$

2.3 Model Simulation Results

For an accurate simulation of the wind turbine system and the proposed controller it was essential to ensure that the BDFIG model developed in the previous section was providing a proper representation of the actual generator. To test the BDFIG the model was implemented using Matlab/Simulink package as shown Figure 2-8. The bulk of the model is contained within the S-Function (given in Appendix B), which allows to solve the state-space differential equations in (2.18). Once it was successfully tested, this model was used in all the simulations presented in this paper.

The main tests consisted of disabling one side of the BDFIG (by creating a short circuit on either power or control machine stator side) and applying a constant AC voltage on the opposite side, while varying the load torque. These simulation tests were carried out using two 2kW machines with 4 poles in the power and control machine stators. In every case a fixed stator voltage of 208V/60Hz was applied and the load torque was varied so as to allow both motoring and generation modes of operation.

Figure 2-8: BDFIG Model in Simulink

The simulation tests performed on the system can be broken into two categories: short circuit tests and controllability tests. The first set was carried out using the shorted control machine stator side thus making the natural speed of the system to be 900 rpm, because both machines have four poles each. Figure 2-9 demonstrates the speed-torque curve of the model under the pseudo steady state conditions; the torque-speed curve is very similar to the regular induction machine as expected. The simulation was carried into three different stages from zero to 6s in 2 second per stage. From time zero to 2s the system operates in the no-load condition, therefore, the system starts and runs nearly at its natural speed with very small electrical torque at the end of this stage. Because the slip of the system at no-load is negligible the frequency and the amplitude of the induced control machine current are virtually zero at steady state (Figure 2-10). In the second stage from 2s to 4s, the load torque is decreased at 2.25s to put the BDFIG into the generation mode and left there till 4s (Figure 2-11). The system responds as expected by increasing its speed and moving into super-synchronous mode of operation, while the electrical torque changes to match the load demand. At the same time the current induced in the control machine increases, its frequency changing to match the slip of the system as shown in Figure 2-12. In the third stage, the controllability of the system is tested when an external voltage is applied on the control machine side at 4.25s (Figure 2-13). The voltage was applied while the load torque was kept constant to

maintain the generation mode of operation. Due to the random nature of the external voltage (no phase or frequency synchronization with the power machine), the resulting speed of the BDFIG was decreased from super-synchronous to sub-synchronous. As Figure 2-14 shows, when the control machine excitation was applied, there was a change in the control machine current frequency, amplitude and phase. The resulting rotor speed decrease is as shown in Figure 2-15 and the total electrical torque remained unchanged. Finally, Figure 2-16 shows the electrical torques generated by the BDFIG over the test range. As expected, under the short circuit and no load conditions the total electrical torque of the BDFIG is generated by the power machine alone. Once the BDFIG becomes loaded or an excitation voltage is applied on the control side, the individual torques of the two machines in the BDFIG combine in the additive manner. Similar results were obtained for the BDFIG formed by the two machines with different power ratings and unequal number of poles.

The results obtained after the extensive simulations of the proposed BDFIG model provided sufficient evidence to conclude that the model developed describe the dynamic performance of BDFIG precisely. The simulation plots described above also present the clear picture of the operational characteristics of the BDFIG such as torque generation and the effects of the control side excitation. Through control machine side voltage/current control, the BDFIG speed can be adjusted.

Figure 2-9: Speed-Torque Curve of BDFIG

Figure 2-10: No-load Control Machine Current

Figure 2-11: Generation Mode of BDFIG

Figure 2-12: Generation Mode Control Current

Figure 2-13: Control Machine Excitation Voltage

Figure 2-14: Control Machine Excitation Current

Figure 2-15: BDFIG Response to Control Excitation

Figure 2-16: BDFIG Torques Over the Tested Range

2.3 Conclusion

This chapter has provided the detailed analysis of operational principles of the BDFIG. In this chapter, the dynamic model of the generator was developed based on the selected d-q reference frame. The model was implemented in MATLAB/Simulink. The simulation results verified that the model can precisely describe the dynamic behavior of BDFIG. As expected, the speed and power of BDFIG can be controlled through adjusting the voltage/current applied to the control machine stator. The model discussed above is an important part of this thesis work, which offers the basis for the BDFIG controller design that will be discussed in the following chapter.

Chapter 3 Controller Design

3.1 Wind Turbine Operation

3.1.1 Variable Speed Operation

The main objective for the variable speed wind turbine operation is to optimize the power extraction and to increase efficiency and stability/reliability of the system. As discussed in Section 1.2 the design of the generator is concentrated around the power coefficient of the turbine. This coefficient is a function of various factors such blade pitch angle or nacelle height above the ground as well as propeller design. For a typical horizontal axis turbine this coefficient is described by (3.1)

$$C_p = c_1 \left(\frac{c_2}{\hat{\lambda}} + c_3 \beta + c_4 \right) e^{\frac{c_5}{\hat{\lambda}}} + c_6 \lambda, \quad (3.1)$$

where c_{1-6} are various performance coefficients and λ is defined in (1.1). The instantaneous $\hat{\lambda}$ in (3.1) is defined by (3.2) as:

$$\frac{1}{\hat{\lambda}} = \frac{1}{\lambda - 0.08\beta} - \frac{0.035}{\beta^3 + 1} \quad (3.2)$$

The combination of (3.1) and (3.2) produces the standard power coefficient curves for various TSR and blade pitch angles as shown in Figure 3-1. From these curves it is evident, that the wind turbine is at its most efficient when TSR is at the optimal value for the given propeller design.

Figure 3-1: Typical Turbine Characteristic Curves

The amount of power extracted by the turbine is then directly proportional to the power coefficient and is described by the mathematical formula in (3.3):

$$P_m = C_p \frac{\rho A}{2} v^3 \quad (3.3)$$

This expression demonstrates the third order relationship between the wind speed and the amount of the power extracted by the propeller. Such a behavior clearly limits the operational range of the wind turbine to a narrow region of the wind speeds. For an increase of the wind speed by 1m/s from 10m/s to 11m/s, for instance, the captured wind power goes up by about 33 percent.

This limitation is well demonstrated in Figure 3-2, where it is evident that the operational scope of the wind speeds for the particular turbine is limited to the range of around 8m/s to 22m/s. The upper limit is determined by the strength of the structure, while the lower limit is usually dictated by the minimal output efficiency, which in case of Figure 3-2 is around 25 percent.

Under such limitations the purpose of the controller is to maintain the maximum possible power coefficient for any wind conditions within the operational range. In practice this translates

into designing the controller that would follow the optimal power curve in Figure 3-2. This maximum power tracking is achieved through the manipulation of the turbine electrical torque by means of injection of the excitation current through the slip recovery loop of DFIG or BDFIG [23, 24].

Figure 3-2: Turbine Power Curves

3.1.2 Reactive Power Regulation

For a regular generator, however, it is not enough to simply maintain a desirable operational speed – it is also necessary to provide an adequate power factor as required by the customer. Since the induction machines have a lagging power factor, the controller is required to at least be able to provide a unity factor operation.

3.1.3 Requirements for Controller Design of BDFIG

The main requirements on the controller design inherit directly from all the information outlined in the previous section. For a wind turbine to be an efficient addition to the common

electrical grid, it must be able to meet the energy demand by providing a maximum output at the desired power factor. Therefore, it is imperative that the controller allows independent control of these two parameters of the BDFIG in the wind turbine. The primary function of such a controller would be to allow an optimum speed tracking or provide the maximum available power output for the given wind conditions. If the range of the operational speeds for the turbine is chosen to be between 6m/s and 14m/s, the controller needs to provide fast tracking response throughout this operational window. The secondary requirement for the design is to provide an effective power factor control regardless of the turbine speed and power output.

The desired performance characteristic of the BDFIG controller, therefore, would be the ability of the regulator to maintain the unity power factor throughout the operational range of the BDFIG, while providing the optimal active power output for the given wind conditions.

3.2 Stator Flux Based FOC

The regulator design for the BDFIG is developed on stator flux field oriented control (FOC). This implies that the selected reference frame is aligned to and rotating with the stator flux vector of the machine. For a BDFIG the above statement carries some ambiguity, because there are two stators in this generator. However, common sense dictates the choice of the power machine stator, because its stator flux vector has two unique properties. Under normal operational conditions and stiff grid the power machine stator flux vector has constant electrical frequency and constant amplitude. Therefore it is a natural choice for a reference frame in the controller design.

First, it is necessary to examine the behavior of the voltage vector and its components. Using the example of a 2-pole induction machine, it can be shown that there exists a single voltage vector that rotates at a synchronous speed with the supply frequency, as in Figure 3-3. This vector is a geometric sum of the individual phase voltage vectors and for a balanced 3-phase system it is always $\frac{3}{2}$ of the phase voltage magnitude. The significance of that vector is that it always has a

constant amplitude and speed (which can be easily measured) if the machine is connected to a stiff electrical grid.

Figure 3-3: Voltage Vector Position

Another quantity that has the similar characteristics to the voltage vector is the stator flux vector. Unlike the voltage vector, however, flux vector cannot be measured directly but needs to be estimated instead. This is done through the use of the dynamic equation for the power machine at stationary frame:

$$\mathbf{V}_{sp} = R_{sp} \mathbf{I}_{sp} + \frac{d}{dt} \Phi_{sp} \quad (3.4)$$

The amplitude and electrical speed of the flux vector for a stiff grid connection are then the function of the stator resistance and its inductance. The relative positions of the voltage and flux distributions can be depicted as in Figure 3-4. It is clear that the flux vector always lags the voltage vector by 90° (due to the stator inductance regardless of the current) plus by a small angle ϵ associated with the stator resistance, which increases as more current flows through the windings. Therefore, to estimate the flux vector position those two parameters need to be taken into account.

Yet, it is possible to simplify the situation by examining the contribution made by the stator resistance to the flux angular position. As many research works have previously stated, the following mathematical relationship holds for any induction machine:

$$\lim_{R_s \rightarrow 0} \varepsilon = 0 \quad (3.5)$$

In most cases the stator resistance of the induction machines can be considered negligible and the flux angle is assigned to be 90° behind the voltage vector.

Figure 3-4: Flux Vector Position

If the above assumptions hold true, the FOC angle is then determined by measuring the stator voltage and converting it to the stationary α - β frame, then the flux angle is calculated as:

$$\theta_\phi = \tan^{-1} \left(\frac{V_{sp}^\beta}{V_{sp}^\alpha} \right) - \frac{\pi}{2} \quad (3.6)$$

The relationship between the voltage and flux vector in the induction machine can be graphically illustrated in Figure 3-5.

Thus, there actually exist two options for the reference frame selection – it can be attached either to the stator voltage vector or the flux vector. The choice is usually made in favor of the flux vector because it provides a more stable and predictable reference frame. However, voltage oriented control can still be used for the control of the power converters that are not directly connected to the induction machine as will be shown in Section 3.3.1.

Figure 3-5: Voltage and Flux Vectors

3.3 BDFIG Controller Design

As mentioned in the previous sections the main purposes of the controller design was to implement the optimal speed tracking loop and to allow reactive power control in an independent and robust manner. The approach taken in the control of BDFIG is to inject some extra rotor current into the system control machine stator to manipulate the amount of the electrical torque produced by the machine. This task requires the generation of the currents of various amplitudes and frequencies which can be achieved with an AC/AC power converter. For this particular research a back-to-back PWM power converter was chosen for its flexibility and high degree of controllability. Such a converter is based on the voltage source rectifier (VSR) and a voltage source inverter (VSI) connected through a common DC-link. Both VSR and VSI are vector controlled, giving the required degree of freedom in choosing the operational strategy as well as independent management of the key parameters such as current magnitude and power factor. The following sections present the controller design for the both sides of the power converter and provide the detailed information on their operation.

3.3.1 Grid-Side Power Converter Control

The purpose of the grid-side power converter is to establish a fixed DC-link voltage regardless of the operational conditions of the BDFIG. The rectifier performs the dual function of the boost-converter as well as regulation of the power flow quality in the slip recovery loop. A vector control can be applied to the VSR to enable independent control of the active and reactive power. For this portion of the converter the control strategy is relatively straightforward and remains unchanged from the scheme proposed for the operation of the DFIG in [25].

In this case the whole converter circuit can be modeled as shown in Figure 3-6. Such a circuit is defined by the following set of equations in a synchronous d - q reference frame:

$$\begin{bmatrix} V_q \\ V_d \end{bmatrix} = R \begin{bmatrix} I_q \\ I_d \end{bmatrix} + sL \begin{bmatrix} I_q \\ I_d \end{bmatrix} + \omega_e L \begin{bmatrix} I_d \\ -I_q \end{bmatrix} + \begin{bmatrix} V_q^* \\ V_d^* \end{bmatrix}, \quad (3.7)$$

where ω_e is the electrical frequency of the grid in radians per second.

Figure 3-6: VSR Circuit Model

The total active and reactive power flows in the circuit in Figure 3-6 can also be defined. The general expressions for the power flow, assuming balanced and harmonic-free system, are shown in (3.8).

$$\begin{aligned}
P &= \frac{3}{2}(V_d I_d + V_q I_q) \\
Q &= \frac{3}{2}(V_q I_d - V_d I_q)
\end{aligned} \tag{3.8}$$

However, the above equations can be simplified by a proper selection of the reference frame. For the grid-side converter, the choice of that reference frame is limited to the one that aligns to the grid voltage vector. Then, if the d -axis is aligned to the synchronous reference frame rotating with the voltage vector, the power flow expressions would take on the form shown in are (3.9):

$$\begin{aligned}
P &= \frac{3}{2}(V_d I_d) \\
Q &= -\frac{3}{2}(V_d I_q)
\end{aligned} \tag{3.9}$$

The magnitude of the DC-link voltage is clearly a function of the active power flow in the VSR. Assuming negligible switching losses, the power conservation law applied to the converter produces:

$$V_{dc} I_{in} = \frac{3}{2} V_d I_d \tag{3.10}$$

The DC-link voltage produced by the VSR is the function of the modulation index m_a and the supply line voltage as in (3.11), the expression in (3.10) can be re-arranged and expended to demonstrate that the DC-link voltage is the function of d -component of the supply current (3.12).

$$V_{dc} = \frac{2\sqrt{2}V_d}{m_a} \tag{3.11}$$

$$\frac{d}{dt} V_{dc} = \frac{1}{C} \left(\frac{3}{4\sqrt{2}} m_a I_d - I_o \right) \tag{3.12}$$

The equation in (3.12) can be easily represented using the first order linear system, while treating I_o as a disturbance which will be compensated for using a standard PI regulator. The expression in (3.12) confirms that the DC-link voltage can be manipulated using the d -component of the supply current, forming the outer voltage control loop.

The DC-link control loop needs to be expanded further to include the inner current control loop for a proper management of the I_d reference signal. The control law for the current loop is relatively straightforward, since the mathematical representation of the plant can be derived directly from (3.7) as:

$$H_i(s) = \frac{I(s)}{V(s)} = \frac{1}{Ls + R} \quad (3.13)$$

The command signals for the VSR controller then also come from (3.7):

$$\begin{aligned} V_d^* &= -\frac{I_d}{H_i(s)} + (\omega_e L I_q + V_d) \\ V_q^* &= -\frac{I_q}{H_i(s)} - (\omega_e L I_d) \end{aligned} \quad (3.14)$$

Therefore the final form of the grid-side controller is shown in Figure 3-7. The compensation block in that figure contains the bracketed expression from (3.14).

Figure 3-7: Grid-side Controller Structure

The VSR controller is regulated using the standard PI controllers with the transfer function shown in (3.15):

$$G(s) = \frac{K_p s + K_i}{s} \quad (3.15)$$

The tuning of the regulators in the case of the grid-side converter is helped by the fact that it is relatively easy to obtain the plan transfer function for the whole system. The plant model for the inner current loop has already been shown in (3.13). As for the outer voltage loop it is easily derived from (3.12) as:

$$H_v(s) = \frac{V(s)}{I(s)} = \frac{1}{Cs} \quad (3.16)$$

The converter itself is modeled differently for both the inner and outer loops. In the case of the outer loop it is comes from the combination of (3.9) and (3.11):

$$G_v(s) = \frac{3m_a}{4\sqrt{2}} \quad (3.17)$$

For the inner loop the converter is modeled as a linear amplifier in (3.18). This expression is based on the VSR operation as a boost converter whose DC-link voltage is a function of the fundamental component of the phase voltage.

$$G_i(s) = 0.5m_a V_{dc} \quad (3.18)$$

When the plant, converter and PI regulator models are combined into the appropriate control loops, the base parameters for the PI gains then can be calculated. These are shown in Table 3-1 and were used tune the controller both during the simulation stage as well as during the experiments. There results and the implementation of the grid-side controller will be discussed in the following chapters.

Current Loop		Voltage Loop	
K_p	K_i	K_p	K_i
$\frac{2L}{m_a V_{dc}}$	At least 5 times smaller than K_p	$\frac{4\sqrt{2}C}{3m_a}$	$\frac{2R}{m_a V_{dc}}$

Table 3-1: Grid-side Controller Gains

3.3.2 Generator-Side Power Converter Control

The control machine of the BDFIG is managed in the synchronous d-q frame aligned to the stator flux vector of the power machine. This arrangement is similar to the one used in the DFIG control and was selected with the assumption that it would allow decoupled control of the torque and the active power in the BDFIG.

To identify and isolate the control variables it is necessary to examine the equations governing the two quantities that need to be controlled. As described in (1.12) the total electrical torque can be expressed as a function of the two currents: the power stator machine current and the control machine stator current, as shown in (3.19):

$$T_e = -\frac{3}{4} \left(P_p \left(\Phi_{sp}^q I_{sp}^d - \Phi_{sp}^d I_{sp}^q \right) + P_c L_{mc} \left(I_{sc}^d I_r^q - I_{sc}^q I_r^d \right) \right) \quad (3.19)$$

The reactive power flow on the power machine side, however, initially is only a function of the power machine stator current:

$$Q_p = \frac{3}{2} \left(V_{sp}^q I_{sp}^d - V_{sp}^d I_{sp}^q \right) \quad (3.20)$$

The torque equation in (3.19) contains too many variables to present a clear basis for the controller design; however, it can be replaced by (3.21), because the mechanical speed of the BDFIG is related to the active power flow in the power machine.

$$P_p = \frac{3}{2} \left(V_{sp}^q I_{sp}^q + V_{sp}^d I_{sp}^d \right) \quad (3.21)$$

Further simplifications are possible because of the use of the stator flux FOC as described in Section 3.2. It was thought best to align the d-axis of the reference frame with the stator flux vector Φ_{sp} . Then the stator flux and voltage vectors of the power machine were aligned in the manner depicted in Figure 3-8.

Figure 3-8: *D-Q* Frame Alignment

In this case the following constraints would be applied to the system:

$$\begin{aligned} V_{sp}^d &= 0; V_{sp}^q \neq 0 \\ \Phi_{sp}^d &\neq 0; \Phi_{sp}^q = 0 \end{aligned} \quad (3.22)$$

The choice of this particular alignment was made, in hindsight, with the purpose of simplifying the active power control loop by removing the necessity of dealing with the power machine stator flux *q*-component in the controller design. When all the above assumptions are applied to (3.21) and (3.20), the final controller power equations take the following form:

$$\begin{aligned} P_p &= \frac{3}{2} V_{sp}^q I_{sp}^q \\ Q_p &= \frac{3}{2} V_{sp}^q I_{sp}^d \end{aligned} \quad (3.23)$$

From (3.23) it is evident that the inner loop control parameters are the *d-q* components of the power machine stator current. Since the only variable quantity that can be controlled directly in the whole BDFIG system is the control machine current, (3.23) needs to be expressed in terms of these variables. This can not be done directly and requires some manipulations of the stator fluxes of the BDFIG. The most efficient approach is to bring all the control equations into the desired form before converting them into *d-q* reference frame. Rearranging the power machine stator flux and the rotor flux equations from (2.10) produces:

$$\mathbf{I}_{sp} = \frac{\Phi_{sp} - L_{mp}\mathbf{I}_r}{L_{sp}} \quad (3.24)$$

$$\mathbf{I}_r = \frac{\Phi_r - L_{mp}\mathbf{I}_{sp} + L_{mc}\mathbf{I}_{sc}}{L_r} \quad (3.25)$$

To separate the power machine stator current $\mathbf{I}_{sp}$, the rotor current in (3.25) is substituted into (3.24) and re-arranged to produce the following:

$$\mathbf{I}_{sp} = \frac{L_r}{L_{sp}L_r - L_{mp}^2} \Phi_{sp} - \frac{L_{mp}}{L_{sp}L_r - L_{mp}^2} \Phi_r - \frac{L_{mp}L_{mc}}{L_{sp}L_r - L_{mp}^2} \mathbf{I}_{sc} \quad (3.26)$$

The expression in (3.26) demonstrates the complexity of the BDFIG system. It confirms that there exists an electrical coupling between the control machine stator through the rotor to the power machine stator and shows that the power machine stator current is actually a function of three variables. This, however, does not present much of a problem, because one of the variables – the power machines stator flux Φ_{sp} has a constant value due to the stiff grid connection.

Before substituting (3.26) back into (3.23), it needs to be transformed into the d - q reference frame. Now that the reference frame is oriented along the d -component of the power machine stator flux, the equations in (3.26) take on the form of:

$$\begin{aligned} I_{sp}^q &= -\frac{L_{mp}}{L_{sp}L_r - L_{mp}^2} \Phi_r^q - \frac{L_{mp}L_{mc}}{L_{sp}L_r - L_{mp}^2} I_{sc}^q \\ I_{sp}^d &= \frac{L_r}{L_{sp}L_r - L_{mp}^2} \Phi_{sp}^d - \frac{L_{mp}}{L_{sp}L_r - L_{mp}^2} \Phi_r^d - \frac{L_{mp}L_{mc}}{L_{sp}L_r - L_{mp}^2} I_{sc}^d \end{aligned} \quad (3.27)$$

Then (3.27) is combined with (3.23), it produces the expanded power flow expression for the BDFIG.

$$\begin{aligned} P_p &= -\frac{3}{2} V_{sp}^q \left(\frac{L_{mp}}{L_{sp}L_r - L_{mp}^2} \Phi_r^q + \frac{L_{mp}L_{mc}}{L_{sp}L_r - L_{mp}^2} I_{sc}^q \right) \\ Q_p &= \frac{3}{2} V_{sp}^q \left(\frac{L_r}{L_{sp}L_r - L_{mp}^2} \Phi_{sp}^d - \frac{L_{mp}}{L_{sp}L_r - L_{mp}^2} \Phi_r^d - \frac{L_{mp}L_{mc}}{L_{sp}L_r - L_{mp}^2} I_{sc}^d \right) \end{aligned} \quad (3.28)$$

The power terms in (3.28) are both expressed as functions of the control machine stator current that can be directly controlled. However, the rotor flux also prominently figures in those expressions. From the flux matrix in (2.10) it is clear that the rotor flux is the function of both the control and power machine stator currents. That is, one of the control variables is itself a function of the controllable quantity. Further more, it has already been shown in (2.19) that there exists a certain amount of cross-coupling between the d - q components of the rotor flux, therefore the overall controller would have to be designed to accommodate these two issues of the BDFIG.

To begin the implementation of the power flow equations (3.28) inside the controller it is first necessary to develop the relationship between the control current signals and their equivalent voltage commands that can be utilized with the voltage source inverter. Looking back at the simplified dynamic equations of the control machine it can be seen that the voltage command signals can be expressed in terms of the stator flux and current:

$$\mathbf{V}_{sc} = R_{sc} \mathbf{I}_{sc} + \frac{d}{dt} \Phi_{sc} + j\omega_c \Phi_{sc} \quad (3.29)$$

Because the control machine stator flux is not a constant quantity or cannot be measured directly it needs to be expressed in terms of the other parameters that are known precisely or can be estimated. One of the ways to do it is by reverting to the flux matrix (2.10) for the control machine stator expression and substituting (3.25) into it:

$$\Phi_{sc} = \frac{L_{mc} L_{mp}}{L_r} \mathbf{I}_{sp} - \frac{L_{mc}}{L_r} \Phi_r + \frac{L_{sc} L_r - L_{mc}^2}{L_r} \mathbf{I}_{sc} \quad (3.30)$$

The power machine stator current then can be replaced by the formula derived in (3.26) to produce (3.31) after some re-arrangement and simplification:

$$\Phi_{sc} = \frac{L_{mc} L_{mp}}{L_r L_{sp} - L_{mp}^2} \Phi_{sp} - \frac{L_{mc} L_{sp}}{L_r L_{sp} - L_{mp}^2} \Phi_r + \left(L_{sc} - \frac{L_{mc}^2 L_{sp}}{L_r L_{sp} - L_{mp}^2} \right) \mathbf{I}_{sc} \quad (3.31)$$

Before combining equations (3.28) and (3.31), they can be transformed into the d - q reference frame. When completed, they respectively become:

$$V_{sc}^q = R_{sc} I_{sc}^q + \frac{d}{dt} \Phi_{sc}^q + j\omega_c \Phi_{sc}^d \quad (3.32)$$

$$V_{sc}^d = R_{sc} I_{sc}^d + \frac{d}{dt} \Phi_{sc}^d - j\omega_c \Phi_{sc}^q$$

$$\begin{aligned} \Phi_{sc}^q &= -\frac{L_{mc} L_{sp}}{L_r L_{sp} - L_{mp}^2} \Phi_r^q + \left(L_{sc} - \frac{L_{mc}^2 L_{sp}}{L_r L_{sp} - L_{mp}^2} \right) I_{sc}^q \\ \Phi_{sc}^d &= \frac{L_{mc} L_{mp}}{L_r L_{sp} - L_{mp}^2} \Phi_{sp}^d - \frac{L_{mc} L_{sp}}{L_r L_{sp} - L_{mp}^2} \Phi_r^d + \left(L_{sc} - \frac{L_{mc}^2 L_{sp}}{L_r L_{sp} - L_{mp}^2} \right) I_{sc}^d \end{aligned} \quad (3.33)$$

Combining (3.32) and (3.33) together, produces the final control voltage command signals that can be used as a reference inputs for the VSI PWM drive:

$$\begin{aligned} V_{sc}^d &= R_{sc} I_{sc}^d + \frac{d}{dt} (\delta_2 \Phi_r^d + \delta_3 I_{sc}^d) - \omega_c (\delta_2 \Phi_r^q + \delta_3 I_{sc}^q) \\ V_{sc}^q &= R_{sc} I_{sc}^q + \frac{d}{dt} (\delta_2 \Phi_r^q + \delta_3 I_{sc}^q) + \omega_c (\delta_1 \Phi_{sp}^d + \delta_2 \Phi_r^d + \delta_3 I_{sc}^d) \end{aligned} \quad (3.34)$$

The inductance terms in front of the fluxes and currents can be considered as leakage constants; therefore, in the future they will be referred to as δ_1 , δ_2 and δ_3 , which are defined in (3.35):

$$\begin{aligned} \delta_1 &= \frac{L_{mc} L_{mp}}{L_r L_{sp} - L_{mp}^2} \\ \delta_2 &= \frac{L_{mc} L_{sp}}{L_r L_{sp} - L_{mp}^2} \\ \delta_3 &= \left(L_{sc} - \frac{L_{mc}^2 L_{sp}}{L_r L_{sp} - L_{mp}^2} \right) \end{aligned} \quad (3.35)$$

The PI controller design is based on the suppression of the derivative terms in (3.34) and the reduction of the effect of the terms associated with the stator resistances; the rest of the terms act as a disturbance.

As (3.34) show, there are several cross coupling terms acting as the disturbance to the final control signals outputs. The cross coupling components produced by the stator flux Φ_{sp} and Φ_r are similar to the traditional DFIG, however, there is a unique disturbance created by the cross

coupling of the control machine stator current which is only present in the BDFIGs. Simulation show that the disturbances associated with the leakage constants δ_1 and δ_2 may be considered insignificant for the generators with the larger ratings, and under certain conditions be suppressed by a well-tuned PI regulator. The disturbance associated with the leakage constant δ_3 , however, is always considerable and needs to be included into the design as a decoupling term. Nevertheless, in this thesis all the disturbance terms have been included into the controller so it can be universally used for the BDFIGs of different ratings.

Another aspect of the control equations in (3.34) is the presence of the power machine stator flux and the rotor flux in as the control variables. Neither of these quantities can be measured directly and would have to be estimated from the available voltage and current signals. The estimation of the power machine stator flux follows from the theory presented in Section 3.2. As with the stator flux angle estimation, it is assumed that the stator resistance is negligible and therefore the magnitude of the flux remains constant. Furthermore, because the reference frame is aligned with the d-component of the Φ_{sp} , the q-component always remains at zero. Taking all of this into consideration, the power machine stator flux is then calculated as presented (3.36):

$$\Phi_{sp}^d = \int V_{sp}^q dt \quad (3.36)$$

However, for a stiff 60Hz grid the expression in (3.36) can be approximated as (3.37), because both the amplitude and the frequency of the supply voltage are considered to be constant:

$$\Phi_{sp}^d \approx \frac{V_{sp}^q}{2\pi 60} \quad (3.37)$$

The estimation of the rotor flux, on the other hand, is more complicated and requires the knowledge of the power machine stator flux and current, as well as control machine stator current. It is based on the rearranged rotor flux equation from (2.10) with the substitution of the (3.25) for the power machine stator current. The final form of the rotor flux estimation expressions is given in (3.38):

$$\Phi_r^q = \frac{L_{mp}^2 - L_r L_{sp}}{L_{mp}} I_{sp}^q - L_{mc} I_c^q$$

$$\Phi_r^d = \frac{L_r}{L_{mp}} \Phi_{sp}^d + \frac{L_{mp}^2 - L_r L_{sp}}{L_{mp}} I_{sp}^d - L_{mc} I_c^d$$
(3.38)

The flux estimations in (3.37) and (3.38) together with the control machine stator currents are then used to reconstruct the voltage command signals in (3.34).

With the flux estimation in place it is now possible to present the complete structure of the generator side VSI controller, its block diagram given in Figure 3-9. As can be seen the controller relies only on the voltage and current measurements on the stator sides of both machines forming the BDFIG.

Figure 3-9: Generator-side VSI FOC

The FOC angle calculation block in Figure 3-9 performs the functions outlined in Section 3.2, while the decoupling block performs the calculations of the disturbance terms associated with δ_1 , δ_2 and δ_3 . More specifically, the d - q components of the disturbance are:

$$V_{comp}^d = \omega_c \left(\frac{L_{mc} L_p}{L_r L_{sp} - L_{mp}^2} \Phi_q^r - \left(L_{sc} - \frac{L_{mc}^2 L_{sp}}{L_r L_{sp} - L_{mp}^2} \right) I_q^c \right)$$

$$V_{comp}^q = -\omega_c \left(-\frac{L_{mc} L_{mp}}{L_r L_{sp} - L_{mp}^2} \Phi_d^p + \frac{L_{mc} L_p}{L_r L_{sp} - L_{mp}^2} \Phi_d^r - \left(L_{sc} - \frac{L_{mc}^2 L_{sp}}{L_r L_{sp} - L_{mp}^2} \right) I_d^c \right)$$
(3.39)

Figure 3-9 also reflects the simplifications that can be carried on the reactive power control equation in (3.28). Closer look at that expression reveals that the reactive power is a function of the four variables two of which are constants (V_{sp}^q and Φ_{sp}^d), in addition, the rotor flux is available from the estimation block. Therefore, it is possible to simplify the current control loop for the reactive power by separating the control variable I_{sc}^d as shown bellow:

$$I_{sc}^d(ref) = \left(-\frac{2}{3} \frac{Q_p^{ref}}{V_{sp}^q} + \frac{L_r}{L_{sp}L_r - L_{mp}^2} \Phi_{sp}^d - \frac{L_{mp}}{L_{sp}L_r - L_{mp}^2} \Phi_r^d \right) \frac{L_{sp}L_r - L_{mp}^2}{L_{mp}L_{mc}} \quad (3.40)$$

The same, however, can not be done with the active power current control loop because it uses the outer speed control loop to generate the reference signal I_{sc}^q .

The tuning of the PI regulators in the case of the generator-side VSI is not as simple as for the VSR discussed previously. The problem lies in the fact that the derivation of the plant transfer function for the BDFIG is a very complicated procedure. Therefore it is impossible to employ the classical method of the PI regulator design; instead, Ziegler-Nichols tuning method was used for this task [26]. Here the criterion for the selection of the PI gains was base on the evaluation of the performance of the whole system on the limit of its stability. Using this method, the ultimate gain and period (K_u and P_u) can be determined for any unknown system, which occur when it becomes marginally stable. Once these parameters are obtained the PI gains are rolled back in accordance with the Ziegler-Nichols optimal gain calculation given in Table 3-2.

K_p	K_i
$0.45K_u$	$0.54 \frac{K_u}{P_u}$

Table 3-2: Ziegler-Nichols PI Gains for Generator-side Converter

3.4 Conclusion

In this chapter, the control scheme for active and reactive power control of BDFIG was developed. The wind turbine operation requires the speed control and reactive power control for maximum power extraction and reactive power support for the grid. These two requirements are

independent, similar to the regular generator. The theoretical analysis carried out on the design of the controller for the bidirectional power converter shows that the active power and reactive power are independently related to the control machine stator current if the cross-coupling terms are fully compensated. Thus, the generator speed can be well regulated through active power control. The block diagrams for the VSR and VSI controllers are developed in this chapter and implemented in a DSP based platform as shown in Figure 3-10. The implementation of the controller design presented in this chapter was first done in Matlab/Simulink for simulation purposes. The results of this work are thoroughly explained in Chapter 4.

Figure 3-10: Full BDFIG Controller

Chapter 4 BDFIG Controller Modeling and Simulation

4.1 Wind Turbine System in Simulink

To simulate the performance of the controller for the BDFIG-based wind turbine it was necessary to develop a comprehensive model of the whole system that would be flexible enough to replicate the performance characteristics under various operational conditions. It was created using Simulink and some elements of the Matlab software package. Incorporated into it was the BDFIG model presented previously in the Section 2.3. The full model of the wind turbine system is shown in Figure 4-1.

The system consists of the three major components: the main power circuit (BDFIG with fractional back-to-back converter), the controller for the main power circuit, and the aerodynamic model of the wind turbine. The back-to-back converter exchanges the slip power between control machine and grid, which is quite similar to traditional DFIG. The controller and the turbine model, however, are more complicated and require special discussion, which is presented in the following sections of this chapter.

Figure 4-1: Wind Turbine System Model

4.1.1 Turbine Aeromechanical Model

As discussed previously in Section 3.1.1 the aerodynamic behavior of the turbine can be described by its performance coefficient given in (3.31). For a given blade design, the equation in (3.1) simply becomes a function of the speed of wind, the pitch angle of the blades and the rotational speed of the propeller. With only these three parameters to consider, it is possible to model the aeromechanical performance of the wind turbine using the standard block provided with the Simulink's SimPowerSystems block set. This block uses the preset parameters of the wind turbine to calculate the generated mechanical torque based on the generator speed, pitch angle and the wind speed.

In this research, the wind turbine block was modified as shown in Figure 4-1 to include the optimal speed estimation which is required for the BDFIG control scheme proposed in this thesis. In real system such estimation could be done based on the reading from the anemometer

situated on the turbine's nacelle and fed to the computer for the optimal speed look-up table. Similar method was used for the modeling purposes in this research. Another addition to the wind turbine model was the inclusion of the saturation block for the wind speed input signal to emulate the appropriate power control through either pitch angle or active stalling.

Figure 4-2: Wind Turbine Model

The wind turbine block in Figure 4-2 became an important part of the system model and was used as an input source for the controllers described in the following section.

4.1.2 Controller Models

The two converter models described in Sections 3.3.1 and 3.3.2 were implemented in the wind turbine system using various blocks from the Simulink libraries. The whole system is modeled in continuous time domain with the variable-step (stiff/TR-BDF2) solver. For PWM generation the simple SPWM scheme was selected to simplify the model, however, for the further study of the BDFIG systems it would be beneficial to experiment with various PWM schemes, such as SVPWM.

Figure 4-3 shows the composition of the VSR controller block, which implements equations from (3.14) and given previously in Figure 3-7. The block “ABC->DQ0” was implemented to

transfer the measured grid voltage and current into the synchronous reference frame. In the simulation the grid is ideal system with zero impedance and no harmonics. Thus the synchronous angle for the transformation can be extracted through the voltage vector obtained by the Clarke transform. However, this method has lots of problems in the real system with noise, harmonics and line impedance, which is discussed in Chapter 5. The PI regulator blocks model the saturated PI controller with an On/Off switch to emulate their implementation in the DSP.

Figure 4-3: VSR Controller Block

Figure 4-4 shows the Simulink implementation of the controller design outlined in Section 3.3.2. – it is a mathematical representation of the block diagram in Figure 3-9. This controller is more complicated and distributed between the four main subsystems. The “ABC->DQ0” block is similar to the VSR side, except that all the variables are transformed into stator flux oriented frame as previously described in Section 3.2. The contents of the flux estimation block are shown in Figure 4-5 which represents equations (3.37) and (3.38). Some of the leakage constants used in those equations were represented as a single variable and pre-loaded before the execution of the script. The scripts for the calculations of the various parameters are given in Appendix C.

In the heart of the FOC for the VSI lies the Control subsystem containing all the PI regulators and shown in Figure 4-6. The subsystem uses the equations in (3.28) to calculate some of the reference signals from the active and reactive power demand imposed upon the BDFIG system. To enhance the action of the PI regulators it is feasible to include the low-pass filters in the cur-

rent feedback loop. Since the feedback signals are all DC values, the cut off frequencies for the filters can be selected quite low, only to allow a reasonable oscillation during the transient response to the reference command. The low-pass filters in the speed loop, however, are not required because the high frequency fluctuations of the torque will be smoothed out by the mechanical inertia of the turbine/generator system.

Finally, the contents of the decoupling block are shown in Figure 4-7, which compensates the cross coupling discussed in Chapter 3. This together with the controller block is used to generate the voltage command signals for the PWM as described by (3.34).

Figure 4-4: VSI Controller Block

Figure 4-5: VSI Flux Estimation Block

Figure 4-6: VSI PI Controllers

Figure 4-7: VSI Decoupling Block

The wind turbine system shown in Figure 4-1 and described above represents the working model of the research presented in Chapters 2 and 3. This model was designed in SI units to represent the actual prototype system used in the experimental stage; however, it can be easily converted to the per-unit form without any loss of accuracy. The system was rigorously tested to determine its behavior under different operational conditions and the results of these tests are presented in the following sections.

4.2 BDFIG System Simulation Results

It is necessary to describe the simulation conditions imposed on the system. To test the model fully a specific set of wind speed data was applied to evaluate both high-speed and low-speed performance of the BDFIG turbine. The corresponding speed demand on the generator is shown in Figure 4-8. The system starts at around 380 rpm and continues to operate as the speed picks up to the maximum in a 3-second intervals and then drops down to 370 rpm. For the speed demand signal, the step input was chosen because it represents such operational conditions of the system that could provide an adequate measure of its performance. From the figure it also can be seen that for most of the time the system operates in the sub-synchronous mode and only briefly operates in the super-synchronous region when the speed demand approaches the rated speed of the turbine.

Figure 4-8: Speed Demand Profile

The system under the consideration for this simulation was a 10kW BDFIG, consisting of an 8-pole power machine and a 6-pole 2kW control machine. The complete electromechanical parameters of the system are given in Appendix D.

To decrease simulation times and to simplify the test the system can be actually split into two parts: one costing of the grid side VSR power converter driving a variable load and a BDFIG

with the control winding connected to the VSI fed from the constant DC voltage source. This an arrangement is perfectly valid because it allows to concentrate more on the VSI converter controlling the system, rather than on the VSR side which was proven to work in many previous experiments. Therefore, the following pages will briefly show the simulation results for the power converter connected to the BDFIG system and then concentrate on the BDFIG control using the idealized VSI converter.

The purpose of the grid side VSR converter is to perform the function of the boost-rectifier, maintain constant DC link voltage and exchanges the energy between grid and DC link, regardless of the load connected to the VSI side. Secondary function of the VSR is to allow flexible control of the reactive power flow to the grid, however, most of the time it is preferable to maintain the unity power factor. Several papers have presented the models for such a rectifier and one of them was used in this research [25].

Figure 4-9: DC Link Voltage of the VSR

Figure 4-9 shows the DC link voltage for the system operating under the conditions described by Figure 4-8. In this case the reference voltage signal was set at 300 volts, while the rectifier was forced to operate at a unity power factor. As expected the controller was able to maintain a constant DC link voltage, while the notches seen in Figure 4-9 correspond to the instances when the

BDFIG was changing its operational speed. A stable DC link voltage was the first stage in achieving proper operation of the BDFIG system.

The other benchmark of the performance of the BDFIG turbine is its optimal speed tracking ability at unity power factor. Figure 4-10 demonstrates this characteristic of the proposed controller design. Here, in Figure 4-10a, the turbine starts in the motoring mode and when the controller is activated it quickly reaches the desired operational speed. Figure 4-10b demonstrates the corresponding active power output of the generator. It can be seen that when the speed rapidly decreases the controller forces the system in the regions outside its rated power. Such a behavior should not be a concern in real system because there is a number of ways to limit the peak power output during the slow-down of the turbine. One of the ways is to provide a ramped speed signal to the controller to smoothen the operation.

Figure 4-10 a, b: BDFIG Speed Tracking Performance

However, the active power flow through the power machine of the BDFIG does not present the complete picture of the system performance. As stated in Chapter 3, the amount of power generated or consumed by the power machine of the BDFIG is actually a function of the control machine power flow. The idealized active/reactive power flows in the control machine is shown in Figure 4-11. As expected the both active and reactive power are flowing into the control machine side while the BDFIG is operating in the sub-synchronous mode and change their direction when operation becomes super-synchronous. It can also be seen from Figure 4-11a, that the ac-

tive power flow is only a fraction of the power machine rating and is related to the required operational range of the turbine.

Figure 4-11 a, b: Active/Reactive Power Flow in Control Machine

The second important benchmark for the performance of the proposed converter scheme is the degree of the independence between the active and reactive power flows in the BDFIG. This can be determined by looking at the impact that the change in generator speed has on the reactive power in the power machine. Figure 4-12a,b shows that as the reactive power consumption increases at time 5s, there is a slight change in the active power output, but now change to the mechanical speed of the system. This is due to the fact that the controller implements the optimal speed and not the optimal power tracking algorithm. The same kind of performance is achieved when the speed demand is changed while the reactive power demand remains constant as in Figure 4-13. Here the speed is changed at time 3s which affects only the active power output of the power machine, while the steady state reactive power consumption remains unaffected.

Figure 4-12 a, b: Active Power Decoupling

Figure 4-13 a, b: Reactive Power Decoupling

As discussed in Section 3.3.2 the power flows of the control machines in the above figure are directly proportional to the amplitude and the frequency of the external voltage applied to the terminals of this part of the BDFIG. The theory predicted that the frequency of the excitation voltage would increase with the increasing slip of the system, while its amplitude would be proportional to the overall power factor. This is confirmed by the plot of the fundamental components of the control machine stator current in Figure 4-14a: the lowest frequency and amplitude correspond to the nearly synchronous operation. Also, as predicted by equations (2.18) to accomplish the transition between the sub-synchronous and super-synchronous regions of operation, the control machine stator current would have to change its phase sequence as can be clearly seen from the Figure 4-14b. On of the important observations that can be made from the

control machine stator voltage is the amount of the variation in its amplitude throughout the operation region. In this case the maximum peak voltage was around 100V. This in relationship to the DC link voltage indicates that the VSI is operating at a relatively low modulation index. However, depending on the pulse width modulation scheme the preferable modulation index m_a would be around 0.75. The conclusion that can be made thus far is that it may be preferable to design the control machine side with more optimized design, including the consideration for both BDFIG and power converters.

Figure 4-14 a, b: Control Machine Current

The active power flow in both parts of the BDFIG is the function of the electrical torque generated by the machines. For this reason it is beneficial to exam the total electrical torque as well as its components from the power and control sides of the BDFIG. The distribution of the torques generated with this topology is also leaning towards the power machine as shown in Figure 4-15. Such a distribution is quite logical, considering the relative size and impedances of the power and control machines. Both Figure 4-15 and Figure 4-14 confirm the notion of the control machine acting as an auxiliary device and providing a fractional power to or from the system

Figure 4-15: Torque Distribution in BDFIG

Finally, Figure 5-16 shows the efficiency of the given BDFIG system. Here the total input power is the product of the mechanical torque and the mechanical speed, while the total output power is the sum of the power generated in the main winding and the control winding. As can be seen in Figure 4-11, for most of the time the control machine consumes the power, reducing the total power output of the system at low operational speeds. However, the efficiency of the system remains fairly good over its operational range.

Overall, the collected data from the simulations of the 10kW system confirms that when the BDFIG design is in compliance with the constraints laid out in Chapter 2, the rating and efficiency of the system can be optimized as to produce an economically viable system.

4.4 Conclusion

The simulation results for the BDFIG wind turbine system confirmed the correctness of the controller design presented in Chapter 3. It was clearly shown that it is possible to control the speed and the amount of the generated power through the injection of the current into the stator of the control machine of the BDFIG. The tests of the 10kW system also confirmed the theory

that BDFIG requires special considerations during the construction such as presented in Chapter 2. The modeling revealed that a great emphasis should be put on minimizing excitation current requirements for the BDFIG as well as on proper relationship between the pole pair numbers in both the power and control machines of the system. However, the definitive conclusions can only be drawn after the prototype system was fully tested and some verification data was provided for the comparison. Chapter 5 deals with this matter, describing the test setup, the process as well as the comparative analysis of the data from the simulations and experiment.

Chapter 5 Experimental Testing and Results

5.1 Experimental Setup

5.1.1 Formation of the BDFIG

To verify the results obtained with the BDFIG wind turbine system model presented in the previous chapters, an experimental setup has been constructed to act as a test bench for the proposed controller. The whole prototype system used in this experiment is shown in Figure 5-1. The prototype of the wind turbine consisted of the prime-mover in the form of the DC machine (A), two induction machines (B, C) forming the BDFIG as well as the bidirectional power converter with the controller connected to a PC.

Figure 5-1: Turbine Generator Setup

In the experimental setup the BDFIG was formed using two identical 2kW LabVolt wound-rotor induction machines. These were mechanically coupled in the back to back fashion, while their rotors were interconnected without any phase inversion between them. Clearly, in such a system it was not possible to avoid the use of commutation brushes, these, however, did had no

noticeable impact on the system performance. The electromechanical parameters of the two induction machines used in the experiment are provided in Table 5-1.

Power	2 kW	Stator Resistance	0.46 Ohm/0.021 p.u.
Stator Voltage	208 V	Rotor Resistance	0.70 Ohm/0.032 p.u.
Rotor Voltage	208 V	Stator Leakage Inductance	3.5 mH/0.061 p.u.
Current	10 A	Rotor Leakage Inductance	3.5 mH/0.061 p.u.
Rated Speed	1760 rpm	Mutual Inductance	50 mH/0.871 p.u.
Poles	4	Rated Torque	11 N.m

Table 5-1: Power and Control Machine Parameters

The power machine of the BDFIG (Figure 5-1,A) was directly connected to the 208V/60Hz power outlet, while the control machine (Figure 5-1,C) was connected to the grid through the bidirectional converter and an isolation transformer as shown in Figure 5-2. The connection for the power converter was as following: isolation transformer (D) was connected to the low pass filter (E) as described in Section 3.3.1. This was interfaced with the power converter (F), which was attached to the stator connection box of the control machine (G). Overall, the whole setup was very compact with few open electrical connections.

Figure 5-2: Bidirectional Converter

The back-to-back power converter itself was purposely designed and built for the multipurpose system. The processing power of the converter came from the Texas Instruments' F2812 DSP board with 150MHz clock. The DC link voltage was rated at 900V, with the AC side volt-

age rated up to 300 volts and current of 30 amperes. The elaborate protection circuitry was built-in using the FPGA and allowing over-current, over-voltage and over-temperature detection. The converter also had an array of sensors allowing detection and measurement of the various quantities required in this project.

5.1.2 Controller Implementation

The controller design developed in Chapter 3 was implemented using the DSP-FPGA platform incorporated into the bidirectional power converter design. The controller system used in this experiment consisted of the analogue signal conditioning board, DSP, FPGA, an interface circuit and a LED display as shown in Figure 5-3.

The system voltages and currents were sensed and inputted to the conditioning circuit to be converted into the appropriate voltage signals for the analogue-to-digital converter. These were received by the DSP and used for the control algorithm implementation. The final output signal of the DSP board consisted of the PWM commands for the appropriate VSR and VSI switches. The role of the FPGA in this experiment was to provide the phase information for the grid-side VSR and to provide protection for the power converter in case of abnormal operational conditions. For this purpose the over-voltage, over-current and over-temperature circuits were interfaced with the FPGA to provide instantaneous protection of the switches by disabling the PWM signals generated by the DSP. Therefore, under this arrangement all of the computing functions are implemented in the DSP, while the FPGA fulfills purely protective and synchronization functions.

The controller algorithms from Chapter 3 were transferred onto the DSP using the C programming language. All the computations in the program were carried out using IQ math format, which allows high precision manipulations with the floating type variables. The complete code for the controller is given in Appendix E and contains all the comments necessary for its under-

standing. However, it is necessary to discuss some fundamental concepts of the controller implementation using DSP platform.

Figure 5-3: Controller Structure

The controller algorithm used with this system contains two independent but essential parts regulating the behavior of the rectifier and the inverter side of the converter. Both processes are discretized with the switching frequencies serving as a time base. For this system these switching frequencies were selected to be 4.5 kHz and 3.8 kHz for VSR and VSI respectively. The choice was based on the need to minimize the switching noises, as well as the limitations of the DSP.

The operational sequence of the controller was developed to be as following: first the grid-side of the converter was energized and operating the uncontrolled rectifier mode under no-load conditions. Once activated, the VSR boosted the DC voltage to the required level, maintaining unity power factor on the grid side. At this time the VSI was turned on and left in the idle mode, effectively producing a short circuit as seen by the control machine stator windings. After a short

period of time necessary for the DC voltage stabilization the power machine stator windings were energized, bringing the BDFIG to slightly below its synchronous speed. When the generator reached a steady state operation the VSI controller became fully engaged driving the BDFIG to whatever the reference speed was set to be. Naturally, the allowed reference speed range was limited to roughly ± 25 percent of the synchronous speed to allow for a safe operation of the BDFIG. Once fully operational the controller accepted manual inputs to regulate the DC link voltage, speed and power factor of the system. The turn-off sequence for the converter was the opposite of the star-up procedure, allowing for gradual disconnection of the machine and the converter.

It is necessary to mention separately the angle and speed computations in the controller implementation. Due to the possible harmonic noise in the line voltage produced by the VSR, an all digital PLL was used to synchronize the PWM with the grid voltage. The ADPLL designed for the purpose by the Ryerson team [27] was implemented in the FPGA and provided precise phase information for the grid side voltages. The raw data for the angle speed calculations for VSI was obtained using incremental encoder attached to the shaft of the BDFIG. The sensor had the resolution of 3600 pulses per revolution, allowing for the final accuracy of 0.025 degrees. Such a performance allowed the system to match closely with model used in the simulation.

5.1.3 Wind Drive Implementation

To drive the BDFIG in the generation mode a DC motor was used as a prime mover. The motor used in the experiment was rated at 1760 rpm, however, it was not perfectly suitable for the application.

The prime mover in the experiment was itself a part of the new design for the wind turbine emulator which in the future should be able to imitate the behavior of the turbine. However, at this stage its operation was limited to providing the desirable torque for the evaluation of the BDFIG. The overall structure of the test setup is shown in Figure 5-4.

Figure 5-4: BDFIG Wind Turbine System Diagram

5.2 Testing Results and Analysis

The testing of the BDFIG was carried out using the setup described in Section 5.1. The performance of the BDFIG and the bidirectional power converter was evaluated at several load conditions, as well as in both the sub-synchronous and super-synchronous regions of operation.

The initial experiment involved a no-load operation to check the validity of the BDFIG model described in Chapter 2. For this phase, as in every other experiment, the DC link voltage of the power converter was kept at 110 volts, with the grid-side voltage stepped down by an isolation transformer to a value of 105 volts and further reduced to 65 volts by a variac. The lowering of the DC link voltage was done to keep the average modulation index for the VSI side PWM at reasonable levels, as indicated by the simulation results.

5.2.1 No Load Tests

At first, a no load test was carried out by connecting the power machine to the grid and shortening the stator windings of the control machine, without any input torque to the BDFIG. Under the no-load voltage and current of the converter on the grid side are shown below, with experimental plots in Figure 5-5a and theoretical in Figure 5-5b.

Figure 5-5: VSR Waveforms at $\omega_m=900$ rpm, $Q_p=3800$ VA, $P_p=0$ W

From the above figures it is evident that the theoretical results were confirmed and that the current required to sustain a constant DC link is minimal – around 200 mA. In this and all other experiments the power factor of the VSR was kept at unity to reduce the reactive power consumption of the system.

In the next step the operational speed of the BDFIG was reduced from almost synchronous (900 rpm) to 710 rpm by applying the necessary voltage to the control machine stator under the no load conditions; the grid side current to the converter increased to maintain the constant DC link voltage. The power machine waveforms for these conditions were recorded as shown in Figure 5-6a-b. Since the setup was functioning under no load, it is evident that all of the current flowing through the stator windings of the power machine represents the reactive power needs of the system. Therefore, as both the simulation and experiment results show, the power quality of the system in these conditions is very poor. It also can be observed that the amplitude of that current is very large, close to rated value.

The power factor on the VSR side was kept at unity as shown in Figure 5-6c-d which depict the grid side current with respect to the grid side line-to-line voltage. As expected there is phase shift of 30 degrees between the two, in both theoretical (Figure 5-6d) and experimental (Figure 5-6c) results.

Another test was performed to evaluate the response of the system to the change in the reactive power flow by channeling the portion of the reactive power through the control machine, while the generator speed remained constant at 710rpm with no load. The VSI controller was set to reduce the power machine reactive power to 33 percent of the nominal. The results of this test are shown in Figure 5-7a-b for the power machine and Figure 5-7c-d for the VSR. Firstly, the change in reactive power flow through the control machine caused an increased power flow into the grid side of the inverter as in Figure 5-7c-d. However, it had no effect on the power quality, because the VSR regulator was set to the unity power factor, maintaining 30 degrees shift between the line current and the line-to-line voltage.

Figure 5-6: System Waveforms at $\omega_m=710$ rpm, $Q_p=3800$ VA, $P_p=0$ W

The power machine waveforms in Figure 5-7a-b demonstrate the reduction in the amplitude of the stator current as compared to Figure 5-6a-b and a slight improvement in the power factor. The difference between the theoretical and experimental current is explained in terms of the harmonics from the control machine being transferred to the power machine side, causing slight unwanted oscillations.

Figure 5-7: System Waveforms at $\omega_m=710$ rpm, $Q_p=1260$ VA, $P_p=0$ W

From Figure 5-6 and Figure 5-7 one immediate characteristic of the prototype BDFIG can be observed. It is immediately obvious that the current system consumes very large amount of the reactive power which, in fact, is twice as much as the consumption of the individual machines forming the BDFIG. Thus, at no load the power machine of the BDFIG is already operating at the rated current of around 10 Amperes. Such a behavior would clearly disadvantage the BDFIG reducing its efficiency and limiting its range, as will be shown in the following sections.

As to the operation of the VSR in the system, it has been shown that the converter is acting as prescribed by the theoretical calculations. The above results have shown that the VSR regulator

is capable of independent control of the DC link voltage while maintaining the required unity power factor. The only deviation from the theoretical results lays in the harmonic content of the VSR current waveforms (Figure 5-7), however, this discrepancy was caused by the large simulation step chosen to speed up the computational time.

5.2.2 Low Power Tests

Once the proper operation of the converter has been established, the system was loaded by driving the prime mover to produce the required amount of torque. This was changed to evaluate the system and some of the results are presented below.

Initially the input torque was set to 5.5 N.m and the controller was disabled (shorted control machine stator windings), allowing the system to achieve the super-synchronous operation at 930 rpm. In this configuration the BDFIG was acting as a simple induction generator providing the base values for the power flows as shown in Figure 5-8. As expected, under these conditions all of the reactive power (around 3850 VA) is consumed by the power machine, however, it can also be observed, that the active power is now also flowing out of the power machine, with the angle between the current and voltage calculated to be roughly 105 degrees. Under the given torque the output of the power machine was recorded at around 390 watts, at the same time the input mechanical power could be estimated at around 535 watts. When these two are compared the resulting efficiency of the system is roughly 73 percent, confirming the experimental predictions of the low efficiency close to the bottom of the allowed operational range.

Figure 5-8: Power Machine Waveforms at $\omega_m=930$ rpm, $Q_p=3850$ VA, $P_p=-390$ W

With the base values established and the torque kept constant, several evaluation runs were performed to see the effectiveness of the controller. The speed reference of the BDFIG was set to 810 rpm – well below the natural speed, while maintaining steady reactive power flow to the power machine stator. To accomplish the speed change, as the theory prescribes, the induced current in the control windings would have to be of the required slip frequency and almost in phase with the line voltage. This is exactly what the experimental results show to happen in Figure 5-9a-d. The effect on the power machine stator waveforms was minimal (Figure 5-9a-b) with only a tiny fraction of the active power being transferred from the control machine stator to the power machine stator. This is the expected outcome, since there was no input torque change during this phase of experiment, therefore the active power output remained fairly constant. At the same time the reactive power consumption remained constant as well, indicating the decoupled nature of the control algorithm. For this phase again the experimental and simulation waveforms match quite well, demonstrating the accuracy of the mathematical model. The slight difference in the amplitude of the power machine voltage is attributed to the simplifications of the mathematical model, and can be eliminated by further tune-up.

Figure 5-9: BDFIG Waveforms at $\omega_m=810$ rpm, $Q_p=3850$ VA, $P_p=-397$ W

The next phase involved changing the reactive power distribution between the power and control machines, at constant input torque and system speed. For evaluation purposes it was again thought to reduce the reactive power flow through the power machine to 33 percent of the original value, while maintaining the constant mechanical speed of 810 rpm. The corresponding power machines stator waveforms are given in Figure 5-10a-b and demonstrate that the power quality on this side has improved in accordance with the control machine behavior. The control machine stator waveforms are shown in Figure 5-10c-d, indicating that the system operates at lagging power factor, injecting the reactive power into the system.

Figure 5-10: BDFIG Waveforms at $\omega_m=810$ rpm, $Q_p=1280$ VA, $P_p=-401$

Several observations regarding the low power tests can be made. As already has been noted, the efficiency of the BDFIG is relatively poor, allowing for only 72 percent of the input mechanical power to be transformed to the output electrical power. Such a behavior is attributed to the construction of the BDFIG where all the stator and rotor parameters appear in series when viewed from the power machine stator side. This is further aggravated by the fact that the particular machines forming the BDFIG have high impedance values (Table 5-1) increasing the electrical losses of the system.

The test has also confirmed the deficiency of this particular prototype system with respect to the reactive power consumption. The operation under the low load has already caused the power machine to operate at the currents exceeding its ratings of 10 Amperes (Figure 5-9a-b). While it was possible to safely operate the system under these conditions for a short period of time, it is clear that the system would achieve dangerously high operating currents under higher input torques. The obvious solution would be to channel a portion of the reactive power through the control machine stator windings; however, for this particular system it is only a temporary fix. When examined closely, the control machine stator waveforms in Figure 5-10c-d show that the reduction in the power machine reactive power is achieved through the proportional increase in reactive power through the control machine. Because the two machines are identical, the stator current on the control machine side would approach its rated value while reducing both the speed of the BDFIG and the reactive power consumption of its power machine (Figure 5-10c). Therefore, the dynamic range of the BDFIG would be reduced – subject to the current rating of the control machine.

To explain such a behavior it is necessary to look at the mutual inductance parameters for both machines provided in Table 5-1. From there it is clear that both machines have relatively low mutual inductance – less than 1 p.u. Although it is not within the scope of this work to analyze the details of the BDFIG construction, nevertheless, from the IM theory it is evident that a higher mutual inductance values would be beneficial for the efficiency of the whole system. In particular, the improved mutual inductance of the control machine would reduce the strain on the converter to provide the sufficient current for power quality correction, increasing the operational range and flexibility of the BDFIG. This will also impact the efficiency of the system, because the input current required to maintain the DC link voltage would also be cut down, reducing the active power consumption of the whole system.

Yet, regardless of these drawbacks, the test system performed as expected demonstrating independent control of both the reactive power flow and speed.

5.2.3 Medium Power Tests

To verify the decoupled performance characteristics of the system a further, test was carried out by increasing the driving torque to 8.9 N.m, while maintaining the same reference levels for the generator speed and reactive power flow. The resulting waveforms are given in Figure 5-11a-d. Once the input torque was increased the recorded power output of the power machine increased to 592 watts, while the reactive power consumption remained virtually unchanged. With the increased torque input the power factor, as expected, has improved even further, however, it remained very low.

Figure 5-11: BDFIG Waveforms at $\omega_m = 810$ rpm, $Q_p = 1285$ VA, $P_p = 592$ W

To confirm that the VSR was also operating properly, the corresponding waveforms are given in Figure 5-12. These waveforms show that regardless of the BDFIG operational conditions, the VSR still maintains the unity power factor; the current consumption further increased, if compared to the levels in Figure 5-7. From these figures it is evident, that the increase in reactive power consumption on the control machine stator side is accompanied by the increase in the active power consumption on the VSR side. Therefore, it is preferable to keep the reactive power on the control machine side as low as possible, to minimize the power needs of the VSR. This requirement ties up with the conclusions drawn in the previous sections, further emphasizing the need for the good control machine design.

Figure 5-12: VSR Waveforms at $\omega_m=810$ rpm, $Q_p=1285$ VA, $P_p=-592$ W

Finally, to see how the system would behave in super-synchronous region, the speed reference was set to 1000 rpm with the reactive power level at 3800 VA. To reduce the load on the VSI, the speed increase was carried out in steps, going from 810 rpm to around 900 rpm and then to 1000 rpm. The resulting power machine output decreased to roughly 585 watts. The most dramatic change was recorded, however, in the control machine stator and VSR waveforms. Under the super-synchronous speed conditions the power began to flow out of the control machine through the power converter to the grid, as shown in Figure 5-13a-b. Here it can be seen that the

control machine power factor is not unity, due to the fact that the controller is trying to maintain a constant reactive power on the power machine side by injecting some of it on the control machine side. The harmonics of the control machine current have increased in both the experimental and theoretical results due to the very low VSI modulation index required to achieve this speed.

Figure 5-13: System Waveforms at $\omega_m=1000$ rpm, $Q_p=3800$ VA, $P_p=-585$ W

Similarly to the VSI side, the VSR current has also been reversed, indicating that power is flowing from the converter to the grid. Figure 5-13c-d demonstrates that kind of behavior: the

amount of active power (the power factor is kept at unity) is very small, with the current being slightly more than 710 mA.

5.2.4 Speed Tracking

Finally, to evaluate the dynamic properties of the setup, several tests were carried out, where the input torque, speed and reactive power were in turn changed to obtain a speed profile for the BDFIG. The speed data logged during the experiment was combined to provide a glimpse at the speed tracking performance of the experimental setup. In theory the operational range of the generator was limited by the power rating of the converter. Yet the data obtained in this project showed that the actual limitation is imposed by the current rating of the converter or the control machine – whichever is less. This is altogether not unexpected, because the bidirectional power converter serves the dual function of speed and power quality adjustments. At low input torques the system was successfully tested and operated at the speed ranges of 22 percent of the natural speed.

Figure 5-14: BDFIG Speed Tracking Experimental Result

As can be seen from Figure 5-14, the system exhibits satisfactory speed tracking performance, maintaining the desired steady state value regardless of the conditions. The plot demonstrates the response of the system to the input torque increase (marker A) and to the step change in speed demand (marker B) from sub-synchronous to super-synchronous. The corresponding theoretical results, simulating the behavior from Figure 5-14, are given in Figure 5-15. For these conditions, the power flows were measured and averaged for each sector, providing the valuable data for comparison in Table 5-2.

Figure 5-15: BDFIG Speed Tracking Simulation Result

Region	Input Torque (N.m)	Power Machine Active Power Output (W)	Power Machine Reactive Power Consumption (VA)	Mechanical Speed (rpm)
I	5.5	397	1285	810
II	8.8	607	1280	810
III	8.8	598	1277	890
IV	11.5	814	1398	890
V	8.8	587	1390	940
VI	8.8	593	3800	1000

Table 5-2: BDFIG Power Flow

The reason for the reactive power change in regions IV-VI is related to the limitations imposed by the control machine current ratings: at higher input torque it was impossible to maintain the required power quality without considerably exceeding the rated current of the machine. When plotted, the active power output comparison chart is given in Figure 5-16 and shows that the experimental system has consistently lower output than the model by around 14 percent. The source of this deviation is clearly related to the simplification and the assumptions of the made during the design stage. As such the model does not take into the account the losses associated the harmonics present in the system or the switching loses of the converter.

Figure 5-16: BDFIG Power Flow Comparison Chart

5.3 Conclusion

The experiments with the prototype BDFIG system support the theoretical results obtained using the models developed in Chapters 3 and 4. The data confirms the practicality of the controller design that allows the independent control of active and reactive power flows in the BDFIG. It was shown that the controller allows a wide operational range for the system and the flexibility of the reactive power regulation. More detailed conclusions are provided in the next chapter.

Chapter 6 Conclusions

6.1 Conclusions

From the experimental results obtained in this project several conclusions can be drawn regarding the design of the flexible power controller for the BDFIG. The work carried out in this project resulted in the development of the dynamic mathematical model for the BDFIG, the accuracy of which was verified by both the simulation and experimental results. The D-Q dynamic model provided an accurate representation of the dynamic behavior of the generator under various conditions, establishing the basis for the controller design. It can also be used in the future research to examine the behavior of the BDFIG generators with squirrel-cage rotor designs.

The control scheme developed for the independent control of the active and reactive power flows in the BDFIG has been tested using the mathematical model and experimental setup. The aim was to allow the generator to maximize the power extraction using MPPT algorithm and to have an independent power quality adjustment for the system. From the obtained results it was determined that the controller does provide the required independence between active power and reactive power regulation despite the cross-coupling effects that are inherent to the BDFIG. Therefore, the decoupling mechanism designed to suppress the cross-coupling was shown to be very effective.

Overall, this work has shown that the brushless doubly fed induction generator can be effectively used in the wind power applications, replacing the current DFIG configuration. It does not solve all the problems associated with DFIG, however, it allows the simplification of the generator design and the reduction in the maintenance cost. This would be especially beneficial in the off-shore applications where maintenance cost associated with the inspection of the commutation

brushes is especially large. The other advantages of the BDFIG were also shown. The data has confirmed the effectiveness of the flexible power flow control, which can be achieved by means of a small fraction-power converter.

6.2 Major Contributions

One of the main contributions of this work was the development of the dynamic simulation model of the BDFIG in Matlab/Simulink environment. The model shown in Figure 2-8 allows the accurate representation of the characteristics of the generator; it can be used for the wind both as a generator and as a motor and can be used in conjunction with SimPowerSystems toolbox in the Simulink. The developed model provides an indispensable tool for any future research into the behavior of the BDFIG.

Based on that model the second major contribution was made in the form of the development of the BDFIG control system for the wind power applications. The research has provided the relationship between the control machine stator voltages and the active and reactive power flows in the power machine of the BDFIG. As part of the control scheme an effective decoupling procedure that dealt with the cross coupling issues unique to the BDFIG was introduced. It enhanced the robustness of the controller, providing for an independent control of the two power flows in the BDFIG.

6.3 Further Research

As the results of this work have shown the performance and efficiency of the BDFIG system very much depend on the generator design and its characteristics. This is especially important with regards to the reactive power consumption by the BDFIG and power quality correction.

Therefore, some further research is required into the optimization of the generator design for the wind power applications. Suggested research topics should include the study of the influence of the generator mutual inductances on the behavior of the system and their optimization. It would also be useful to look into the improving the design of the control machine, reduce its volume while keeping its ratings as to provide enhanced power factor correction performance for the system. Finally, the controller design can be carried even further by tying together the VSI and VSR regulation of the power converter to enhance the overall (combination of the power machine side and VSR grid side) optimal power tracking and power factor correction.

Appendices

Appendix A

Clarke Transform:

$$\begin{bmatrix} V_\alpha \\ V_\beta \end{bmatrix} = \begin{bmatrix} \frac{2}{3}V_a & -\frac{1}{3}V_b & -\frac{1}{3}V_c \\ 0 & -\frac{1}{\sqrt{3}}V_b & \frac{1}{\sqrt{3}}V_c \end{bmatrix}$$

Park Transform:

$$\begin{bmatrix} V_d \\ V_q \end{bmatrix} = \begin{bmatrix} V_\alpha \cos(\theta) & V_\beta \sin(\theta) \\ -V_\alpha \sin(\theta) & V_\beta \cos(\theta) \end{bmatrix}$$

Appendix B

BDFIG Model S-Function (BDFIG3_b.m)

```
function [sys,x0,str,ts] =
BDFIG3_b(t,x,u,flag,Pparam1,Pparam2,Cparam1,Cparam2,
Pmech,Cmech)

Rsp=Pparam1(1);
Lmp=Pparam1(3);
Rsc=Cparam1(1);
Lmc=Cparam1(3);
Pp=Pparam2(3);
Pc=Cparam2(3);
Lsp=Pparam1(2)+Pparam1(3);
Lrp=Pparam2(2)+Pparam1(3);
Lsc=Cparam1(2)+Cparam1(3);

Lrc=Cparam2(2)+Cparam1(3);
Lr=Lrc+Lrp;
Rr=Pparam2(1)+Cparam2(1);
J=Pmech(1)+Cmech(1);
F=Pmech(2)+Cmech(2);

B = [Rsp Lsp 0 Lmp 0 0
      -Lsp Rsp -Lmp 0 0 0
      0 Lmp Rr Lr 0 -Lmc
      -Lmp 0 -Lr Rr Lmc 0
      0 0 0 -Lmc Rsc Lsc
      0 0 Lmc 0 -Lsc Rsc];
```

```

A=[Lsp 0 Lmp 0 0 0
  0 Lsp 0 Lmp 0 0
  Lmp 0 Lr 0 -Lmc 0
  0 Lmp 0 Lr 0 -Lmc
  0 0 -Lmc 0 Lsc 0
  0 0 0 -Lmc 0 Lsc];
C = eye(7,7);

switch flag,

%%%%%%%%%%%%%%
% Initialization %
%%%%%%%%%%%%%%
case 0,
    sizes = simsizes;
    sizes.NumContStates = 7;
    sizes.NumDiscStates = 0;
    sizes.NumOutputs = 10;
    sizes.NumInputs = 6;
    sizes.DirFeedthrough = 0;
    sizes.NumSampleTimes = 1;

    sys = simsizes(sizes);
    x0 = zeros(7,1);
    str = [];
    ts = [0 0];

%%%%%%%%%%%%%%
% Derivatives %
%%%%%%%%%%%%%%
case 1,
    ang_speed = [1 u(1) 1 u(1) 1 1
                  u(1) 1 u(1) 1 1 1
                  1 u(1)-Pp*x(7) 1 u(1)-Pp*x(7) 1 u(1)-Pp*x(7)
                  u(1)-Pp*x(7) 1 u(1)-Pp*x(7) 1 u(1)-Pp*x(7) 1
                  1 1 1 u(1)-x(7)*(Pp+Pc) 1 u(1)-x(7)*(Pp+Pc)
                  1 1 u(1)-x(7)*(Pp+Pc) 1 u(1)-x(7)*(Pp+Pc) 1];

    B_w = B.*ang_speed;

    U_v=transp([u(2) u(3) 0 0 u(4) u(5)]);

    sys(1:6) = A\(-B_w*x(1:6) +U_v);

```

```

%Fluxes
%power machine
phi_d=Lsp*x(2)+Lmp*x(4);
phi_q=Lsp*x(1)+Lmp*x(3);
Te_p=-1.5*Pp*Lmp*(phi_d*x(3)-phi_q*x(4))/Lsp;
%control machine
Te_c=1.5*Pc*Lmc*(x(5)*x(4)-x(6)*x(3));
%Torque
Te=Te_p+Te_c;
sys(7)=(Te-F*x(7)-u(6))/J;

%%%%%%%%%%%%%%
% Outputs %
%%%%%%%%%%%%%%
case 3,
    %Currents and speed
    sys(1:7) = C*x;
    %Fluxes
    %power machine
    phi_d=Lsp*x(2)+Lmp*x(4);
    phi_q=Lsp*x(1)+Lmp*x(3);
    Te_p=-1.5*Pp*Lmp*(phi_d*x(3)-phi_q*x(4))/Lsp;
    %control machine
    Te_c=1.5*Pc*Lmc*(x(5)*x(4)-x(6)*x(3));
    %Torque
    Te=Te_p+Te_c;
    sys(8)=Te;
    sys(9)=Te_p;
    sys(10)=Te_c;

%%%%%%%%%%%%%%
% Unhandled flags %
%%%%%%%%%%%%%%
case { 2, 4, 9 },
    sys = [];

%%%%%%%%%%%%%%
% Unexpected flags %
%%%%%%%%%%%%%%
otherwise
    error(['Unhandled flag = ',num2str(flag)]);

end

```

Appendix C

BDFIG Parameter Calculations for 2kW system (params_2kw_v3.m)

```
%clc
we=2*pi*60;
Pb_p=2000;
Vab_p=208;
Vb_p=Vab_p/sqrt(3);
Ib_p=Pb_p/(3*Vb_p);
Zb_p=Vb_p/Ib_p;
Lb_p=Zb_p/we;
Cb_p=1/(we*Zb_p);

%Power machine parameters = Contro machine parameters
Rsp=0.9; Llsp=0.0035; Lmp=0.0503;
Rrp=0.7; Llrp=0.0035; Pp=2;
Jp=0.1; Fp=0.00078;
%-----
Lsp=Llsp+Lmp;
Lrp=Llrp+Lmp;

Pb_c=2000;
Vab_c=208;
Vb_c=Vab_c/sqrt(3);
Ib_c=Pb_c/(3*Vb_c);
Zb_c=Vb_c/Ib_c;
Lb_c=Zb_c/we;
Cb_c=1/(we*Zb_c);

%Control machine paramerers
Rsc=0.9; Llsc=0.0035; Lmc=0.0503;
Rrc=0.7; Llrc=0.0035; Pc=2;
Jc=0.1; Fc=0.00078;
%-----
Lsc=Llsc+Lmc;
Lrc=Llrc+Lmc;

%Total rotor parameters
Rr=Rrp+Rrc;
Lr=Lrp+Lrc;
```

```
%Leakage constants
sigma_1=Lmp/(-Lr*Lsp+Lmp^2);
sigma_2=Lmp*Lmc/(-Lsp*Lr+Lmp^2);
sigma_3=Lr/(-Lr*Lsp+Lmp^2);
Lr_r=(Lsp-Lmp^2)/Lsp;

%Natural speed
wn=2*pi*60/(Pp+Pc);
Tb=Pb_p/(wn);
J=Jp+Jc+Jp;
F=Fp+Fc;

%Turbine Settings:
Vbase=13.5;
Pmax=0.95;
Wbase=1.05;

%Filter Settings
Lf=0.08*Lb_p;
Rf=0.04*Zb_p;
disp('POWER MACHINE PARAMETERS')
disp('Electrical:')
disp(' Rs   Ls   Lm   Rr   Lr   Poles')
disp(sprintf('%1.3f %1.3f %1.3f %1.3f %1.3f %1.3f\n',Rsp,Lsp,Lmp,Rrp,Lrp,Pp*2))
disp('Mechanical:')
disp(' J   F')
disp(sprintf('%1.3f %1.3f\n',Jp,Fp))
disp('CONTROL MACHINE PARAMETERS')
disp('Electrical:')
disp(' Rs   Ls   Lm   Rr   Lr   Poles')
disp(sprintf('%1.3f %1.3f %1.3f %1.3f %1.3f %1.3f\n',Rsc,Lsc,Lmc,Rrc,Lrc,Pc*2))
disp('Mechanical:')
disp(' J   F')
disp(sprintf('%1.3f %1.3f\n',Jc,Fc))
disp(sprintf('Natural speed: %1.2f rad/s',wn))
disp(sprintf('Rated Torque: %3.1f N.m',Tb))
```

Appendix D

BDFIG Parameters for 10kW system

Power Machine:

Power	10 kW	Stator Resistance	0.019 p.u.
Stator Voltage	208 V	Rotor Resistance	0.011 p.u.
Rotor Voltage	208 V	Stator Leakage Inductance	0.05 p.u.
Current	20.8 A	Rotor Leakage Inductance	0.05 p.u.
Speed	900 rpm	Mutual Inductance	2.03 p.u.
Poles	8	Rated Torque	138.5 N.m

Control Machine:

Power	2 kW	Stator Resistance	0.019 p.u.
Stator Voltage	208 V	Rotor Resistance	0.018 p.u.
Rotor Voltage	208 V	Stator Leakage Inductance	0.04 p.u.
Current	5.5 A	Rotor Leakage Inductance	0.04 p.u.
Speed	1200 rpm	Mutual Inductance	1.4 p.u.
Poles	6	Rated Torque	15.9 N.m

Appendix E

DSP Program Code

```
#include "DSP281x_Device.h"
#include "DSP281x_Examples.h"
#include "DSP281x_FPGA.h"
#include <stdio.h>
#include "IQmathLib.h"
#include "parameter.h"
#include "adc_casc16.h"
#include "dlog4ch.h"
```

```
// Useful definitions
#define ENCODER_RES 3600
#define VSR_period 17123 // for Fsw = 4380 Hz
#define VSI_period 20492 // for Fsw = 3660 Hz
#define Lf 0.005
```

```
#define sqrt3 1.73205 // sqrt(3)
#define PI 3.14159265358979
```

```
// External function declarations
ADC16_MEASURE adc16 = ADC16_DEFS;
DLOG_4CH dlog = DLOG_4CH_DEFAULTS;
```

```
extern void DSP28x_usDelay(Uint32 Count);
```

```
// Function declarations
interrupt void RECT_ISR (void);
interrupt void INV_ISR (void);
interrupt void PDPINT_ISR (void);
```

```

void InitADC (void);
void CalADC (void);
void InitGPIO (void);
void InitTimers (void);
void InitQEP (void);
void InitPLL (void);
void InitLPF (void);
void InitPI (void);
void InitPROTECT (void);
void InitDlog (void);
void DC_Relay_Open (void);
void DC_Relay_Close (void);
void RECT_Start (void);
void INV_Start (void);
void VSI_Off (void);
void VSR_Off (void);
void THETA_READ (void);
void ADC_VSR_READ (void);
void VSR_REGULATE (void);
void SVPWM_VSR (void);
void ADC_VSI_READ (void);
void SPEED_READ (void);
void VSI_REGULATE (void);
void SVPWM_VSI (void);

void Clarke (float A, float B, float C, _iq *Valpha, _iq
*Vbeta);
void Park (_iq Va, _iq Vb, _iq Angle, _iq *Vd, _iq *Vq);

// Flags
int16 MODE = 3; // default stste - VSI_Only
volatile Uint16 System_Go = FALSE;
volatile Uint16 FULL_MODE = FALSE;
volatile Uint16 DSP_Off = FALSE;
volatile Uint16 VSR_Relay = FALSE;
volatile Uint16 VSI_Relay = FALSE;
volatile Uint16 CONV_VSR = FALSE;
volatile Uint16 CONV_VSI = FALSE;
Uint16 VsrTicker = 0, VsiTicker = 0;

// Datalog Channels
int16 DlogCh1 = 0;
int16 DlogCh2 = 0;
int16 DlogCh3 = 0;
int16 DlogCh4 = 0;

// ADC variables
// zeroing for the A channels of ADC
int32 ChA_zeros[8] = {0,0,0,0,0,0,0,0};
// zeroing for the B channels of ADC
int32 ChB_zeros[8] = {0,0,0,0,0,0,0,0};

// QEP-related variables
float QepMaxCount;

//===== VSR variables =====//
float Vdc_ref=180, Ilq_ref=0, \
Vl_ab, Vl_bc, Vl_ca, Il_a, Il_b, Il_c, \

```

```

VdcN, VdcP, Theta_cnt;

_iq Vl_alpha, Vl_beta, Vl_d, Vl_q, Il_alpha, \
Il_beta, Il_d, Il_q, Theta_vg, VDC, DC_base, \
Vdc_DR;

// Controller parameters
_iq DC_err, DC_integral, Ild_err, Ild_integral, \
Ilq_err, Ilq_integral, Ild_ref, Vld_cnt, \
Vlq_cnt, Vld_comp, Vlq_comp;

float Ki_dc, Kp_dc, Ki_ild, Kp_ild, Ki_ilq, Kp_ilq;

Uint16 T1c,T2c,T0c;

//===== VSI variables =====//
int16 Poles;

float Speed_ref, lcq_ref, lcd_ref, \
Vp_ab, Vp_bc, Vp_ca, lp_a, lp_b, lp_c, \
lc_a, lc_b, lc_c;

_iq Vp_alpha, Vp_beta, Vp_d, Vp_q, lp_alpha, \
lp_beta, lp_d, lp_q, lc_alpha, lc_beta, \
lc_d, lc_q, Theta_v, Theta_phi, Theta_c, \
Theta_m, Phi_pd, Phi_rd, Phi_rq;

// QEP variables
_iq Speed_mech = 0;
int16 QEP_step = 0, Count, OldCount=0;

// Controller parameters
_iq W_err, W_integral, lcd_err, lcd_integral, \
lcq_err, lcq_integral, lcd_8y6ref, Vcd_cnt, \
Vcq_cnt, Vcd_comp, Vcq_comp;

float Ki_w, Kp_w, Ki_icd, Kp_icd, Ki_icq, Kp_icq;

// Clarke-Park variables
float Va, Vb, Vc;
_iq sinA, cosA;

// Useful pointers
int16 *PA1;

// Temporary variables
_iq Temp = 0;
float debug_var[10];

//SVPWM variables
_iq18 Vref;
Uint16 T1,T2,T0;

// Filter variables
_iq a_lc, b_lc, lcd_old = 0, lcq_old = 0;

void main()
{

```

```

    InitSysCtrl();
    XintfRegs.XINTCNF2.all = 0x07;
EALLOW;
    SysCtrlRegs.HISPCP.all = 0x0000;
    // SYSCLKOUT/1
EDIS;

    // Disable and clear all CPU interrupts:
    DINT;
    IER = 0x0000;
    IFR = 0x0000;

    InitPieCtrl();
    InitPieVectTable();
    InitADC ();
    DELAY_US(80000);
    CalADC ();
    InitGPIO ();
    InitTimers();
    InitQEP();
    InitPLL();
    InitPI();
    InitPROTECT();
    InitDlog();

    // Initialize Interrupts
EALLOW;
    PieVectTable.T3CINT = &RECT_ISR;
    PieVectTable.T1CINT = &INV_ISR;
EDIS;

    PieCtrlRegs.PIEIER2.bit.INTx5 = 1;
    PieCtrlRegs.PIEIER4.bit.INTx5 = 1;

    IER |= M_INT4;
    IER |= M_INT2;

    EINT;
    ERTM;

//=====
//          EXECUTION SEQUENCE
//=====

// Step 1: Start System
    while (System_Go == FALSE)
    {
        ADC_VSR_READ();
    }

// Step 2: Chose operational mode: VSR, VSI or Full
//((VSR+VSI)

    switch (MODE)
    {
        case 1:
            goto FULL;
            break;

```

```

        case 2:
            goto VSR_Only;
            break;
        case 3:
            goto VSI_Only;
            break;
        default:
            goto VSR_Only;
            break;
    }

FULL:
    FULL_MODE = TRUE;

VSR_Only:
// Step 3: Start VSR in "diode rectifier" mode
    DC_Relay_Open();
    DELAY_US(6000);
    GpioDataRegs.GPBDAT.bit.GPIOB7 = 1;
    VSR_Relay = TRUE;

// Step 4: Start VSR in "boost rectifier" mode
    while (CONV_VSR == FALSE)
    {
        ADC_VSR_READ();
        if (DSP_Off == TRUE)
        {
            DC_Relay_Close();
            goto THE_END;
        }
    }
    // setting Vdc reference @ +10V
    Vdc_ref = _IQtoF(VDC) + 10.0;
    DC_Relay_Close();
    DELAY_US(60000);
    RECT_Start();

    if (FULL_MODE == FALSE)
        goto MAIN_LOOP;

VSI_Only:
    if (FULL_MODE == FALSE)
        DC_Relay_Open();

    GpioDataRegs.GPBDAT.bit.GPIOB11 = 1;
    VSI_Relay = TRUE;

// Step 5: Start inverter operation
    while (CONV_VSI == FALSE)
    {
        if (DSP_Off == TRUE)
            goto THE_END;
    }

    DC_Relay_Close();
    DELAY_US(6000);
    INV_Start();

```



```

MAIN_LOOP:
// Step 6: Loop till turned off
while (DSP_Off == FALSE)
{
    if (lp_c > 13)
        break;
    if (VDC > _IQ(200))
        break;
}

THE_END:
// Step 7: Turn off VSI and BDFIG
VSI_Off();
GpioDataRegs.GPBDAT.bit.GPIOB11 = 0;

// Step 8: Turn off VSR
VSR_Off();
GpioDataRegs.GPBDAT.bit.GPIOB7 = 0;

IER = 0x0000;
IFR = 0x0000;
DINT;

FansReg.FAN_CONFIG.all = 0x000F;
// EvaRegs.T1CON.bit.TENABLE = 0;
EvaRegs.T2CON.bit.TENABLE = 0;
// EvbRegs.T3CON.bit.TENABLE = 0;
}

/*****
    INTERRUPT SERVICE ROUTINES
*****/

void RECT_ISR (void)
{
    // EINT;
    if (CONV_VSR == TRUE)
    {
        ADC_VSR_READ();
        THETA_READ();
        VSR_REGULATE();
        SVPWM_VSR();
        VsrTicker++;

        DlogCh1 =
(int16)_IQtoIQ15(_IQ(Va/300.0));
        DlogCh2 = (int16)_IQtoIQ15(Theta_vg);
        DlogCh3 =
(int16)_IQtoIQ15(_IQdiv(VI_d, _IQ(100)));
        DlogCh4 =
(int16)_IQtoIQ15(_IQdiv(VI_q, _IQ(100)));
    }

    // dlog.update(&dlog);
    EvbRegs.EVBIFRA.bit.T3CINT = 1;
    EvbRegs.EVBIMRA.bit.T3CINT = 1;
}

// Acknowledge interrupt to receive more inter-
// rupts from PIE group 4
PieCtrlRegs.PIEACK.all = PIEACK_GROUP4;
}

void INV_ISR (void)
{
    OldCount = Count;
    Count = (int16)EvaRegs.T2CNT;
    // EINT;
    if (CONV_VSI == TRUE)
    {
        Icd_ref = _IQ(debug_var[3]);
        SPEED_READ();
        ADC_VSI_READ();
        // VSI_REGULATE();
        // SVPWM_VSI();
        VsiTicker++;

        DlogCh1 =
(int16)_IQtoIQ15(_IQ(Vp_ab/300.0));
        DlogCh2 =
(int16)_IQtoIQ15(_IQ(Vp_bc/300.0));
        DlogCh3 =
(int16)_IQtoIQ15(Theta_phi);
        DlogCh4 = (int16)_IQtoIQ15(Theta_c);

        // DlogCh4 = (int16)_IQtoIQ15(Phi_rq);
        // DlogCh4 = (int16)_IQtoIQ15(Theta_c);
    }

    // OldCount = Count;

    dlog.update(&dlog);
    EvaRegs.EVAIMRA.bit.T1CINT = 1;
    EvaRegs.EVAIFRA.bit.T1CINT = 1;
    // Acknowledge interrupt to receive more inter-
    // rupts from PIE group 2
    PieCtrlRegs.PIEACK.all = PIEACK_GROUP2;
}

void PDPINT_ISR (void)
{
}

/*****
    INITIALIZATION ROUTINES
*****/

void InitADC (void)
{
    adc16.init(&adc16);
    DELAY_US(800000);
}

```

```

}

void CalADC (void)
{
    int16 i=0;

    while (i<201)
    {
        AdcRegs.ADCTRL2.bit.SOC_SEQ1 = 1;
        adc16.read(&adc16);

        ChA_zeros[0] = ChA_zeros[0] +
        (Uint16)adc16.ADCINA0;
        ChA_zeros[1] = ChA_zeros[1] +
        (Uint16)adc16.ADCINA1;
        ChA_zeros[2] = ChA_zeros[2] +
        (Uint16)adc16.ADCINA2;
        ChA_zeros[3] = ChA_zeros[3] +
        (Uint16)adc16.ADCINA3;
        ChA_zeros[4] = ChA_zeros[4] +
        (Uint16)adc16.ADCINA4;
        ChA_zeros[5] = ChA_zeros[5] +
        (Uint16)adc16.ADCINA5;
        ChA_zeros[6] = ChA_zeros[6] +
        (Uint16)adc16.ADCINA6;
        ChA_zeros[7] = ChA_zeros[7] +
        (Uint16)adc16.ADCINA7;

        ChB_zeros[0] = ChB_zeros[0] +
        (Uint16)adc16.ADCINB0;
        ChB_zeros[1] = ChB_zeros[1] +
        (Uint16)adc16.ADCINB1;
        ChB_zeros[2] = ChB_zeros[2] +
        (Uint16)adc16.ADCINB2;
        ChB_zeros[3] = ChB_zeros[3] +
        (Uint16)adc16.ADCINB3;
        ChB_zeros[4] = ChB_zeros[4] +
        (Uint16)adc16.ADCINB4;
        ChB_zeros[5] = ChB_zeros[5] +
        (Uint16)adc16.ADCINB5;
        ChB_zeros[6] = ChB_zeros[6] +
        (Uint16)adc16.ADCINB6;
        ChB_zeros[7] = ChB_zeros[7] +
        (Uint16)adc16.ADCINB7;

        DELAY_US(8000);
        i++;
    }

    ChA_zeros[0] = ChA_zeros[0]/200;
    ChA_zeros[1] = ChA_zeros[1]/200;
    ChA_zeros[2] = ChA_zeros[2]/200;
    ChA_zeros[3] = ChA_zeros[3]/200;
    ChA_zeros[4] = ChA_zeros[4]/200;
    ChA_zeros[5] = ChA_zeros[5]/200;
    ChA_zeros[6] = ChA_zeros[6]/200;
    ChA_zeros[7] = ChA_zeros[7]/200;
    ChB_zeros[0] = ChB_zeros[0]/200;
    ChB_zeros[1] = ChB_zeros[1]/200;

```

```

        ChB_zeros[2] = ChB_zeros[2]/200;
        ChB_zeros[3] = ChB_zeros[3]/200;
        ChB_zeros[4] = ChB_zeros[4]/200;
        ChB_zeros[5] = ChB_zeros[5]/200;
        ChB_zeros[6] = ChB_zeros[6]/200;
        ChB_zeros[7] = ChB_zeros[7]/200;
    }

void InitGPIO (void)
{
    EALLOW;

    // Set up LED Drivers
    GpioMuxRegs.GPFDIR.all |= 0x3FCF;
    GpioMuxRegs.GPADIR.all |= 0xE000;
    GpioMuxRegs.GPBDIR.all |= 0xE000;

    // Set up PWMs
    GpioMuxRegs.GPBMUX.all |= 0x003F;
    GpioMuxRegs.GPAMUX.all |= 0x003F;

    // Set up QEP
    GpioMuxRegs.GPAMUX.all |= 0x0700;

    // Set up Converter Relay Drivers
    GpioMuxRegs.GPAMUX.bit.T2PWM_GPIOA7 = 0;
    GpioMuxRegs.GPADIR.bit.GPIOA7 = 1;

    GpioMuxRegs.GPBMUX.bit.TCLKINB_GPIOB12 = 0;
    GpioMuxRegs.GPBDIR.bit.GPIOB12 = 1;

    // Set up External Relay Drivers
    GpioMuxRegs.GPBMUX.bit.T4PWM_GPIOB7 = 0;
    GpioMuxRegs.GPBDIR.bit.GPIOB7 = 1;
    GpioMuxRegs.GPBMUX.bit.TDIRB_GPIOB11 = 0;
    GpioMuxRegs.GPBDIR.bit.GPIOB11 = 1;
    GpioMuxRegs.GPAMUX.bit.TDIRA_GPIOA11 = 0;
    GpioMuxRegs.GPADIR.bit.GPIOA11 = 1;
    GpioMuxRegs.GPAMUX.bit.TCLKINA_GPIOA12 = 0;
    GpioMuxRegs.GPADIR.bit.GPIOA12 = 1;

    EDIS;
}

void InitTimers (void)
{
    EvaRegs.GPTCONA.all = 0;
    EvbRegs.GPTCONB.all = 0;

    // Initialize Timer1 for VSI interrupts
    EvaRegs.EVAIMRA.bit.PDPINTA = 1;
    EvaRegs.ACTRA.all = 0x0999; //PWM1 active high
    EvaRegs.DBTCONA.all = 0x0FF4; //dead band
    EvaRegs.T1CON.all = 0x0802; // not started
    EvaRegs.COMCONA.all = 0xA000; // update twice
    EvaRegs.T1PR = (int16)VSI_period; // PWM half period
    EvaRegs.T1CMPR = (int16)(VSI_period>>1);

```

```

        // interrupt on PWM quarter period
        EvaRegs.EVAIMRA.bit.T1CINT = 1;
        //enable compare interrupt
        EvaRegs.T1CNT = 0;
        EvaRegs.CMPR1 = 0x0000;
        EvaRegs.CMPR2 = 0x0000;
        EvaRegs.CMPR3 = 0x0000;
        EvaRegs.COMCONA.all |= 0x0200;

        // Initialize Timer3 for VSR interrupts
        EvbRegs.ACTRB.all = 0x0666; //PWM1 active high
        EvbRegs.DBTCNB.all = 0x0FF4; //dead band
        EvbRegs.T3CON.all = 0x0802; // not started
        EvbRegs.COMCONB.all = 0xA000; // update twice
        EvbRegs.T3PR = VSR_period; // PWM half period
        EvbRegs.T3CMPR = VSR_period>>1;
        // interrupt on PWM quarter period
        EvbRegs.EVBIMRA.bit.T3CINT = 1;
        //enable compare interrupt
        EvbRegs.T3CNT = 0;
        EvbRegs.CMPR4 = 0x0000;
        EvbRegs.CMPR5 = 0x0000;
        EvbRegs.CMPR6 = 0x0000;

        EvaRegs.T1CON.bit.TENABLE = 1;
        EvaRegs.T2CON.bit.TENABLE = 1;
        EvbRegs.T3CON.bit.TENABLE = 1;
    }

void InitQEP (void)
{
    // CAP3 enabled, rising edge
    EvaRegs.CAPCONA.all = 0x9004;
    EvaRegs.T2CON.all = 0x1870; //counter is NOT started
    QepMaxCount = 4.0*ENCODER_RES;
    EvaRegs.T2PR = (Uint16)(4*ENCODER_RES-1);
}

void InitPLL (void)
{
    ZeroCrossA.PHASE_SHIFT = 0x4620; //angle offset
    ZeroCrossA.PHASE_SHIFT_CH = 1; //on Vbc
    ZeroCrossB.PHASE_SHIFT = 0x4620;
    ZeroCrossB.PHASE_SHIFT_CH = 1;
    PA1 = (int16 *)0x2016;
    *PA1 = 0x0118;
}

void InitLPF (void)
{
    float denum = 0;

    denum = 1 + 6.283185*30/7320.0;
    a_lc = _IQ((denum-1)/(denum));
    b_lc = _IQ(1/(denum));
}

void InitPI (void)
{
    Ki_dc = 0.0005;
    Kp_dc = 0.45;
    DC_err = 0;
    DC_integral = 0;

    Ki_ilq = 0.001;
    Kp_ilq = 0.6;
    llq_err = 0;
    llq_integral = 0;

    Ki_ild = 0.001;
    Kp_ild = 0.6;
    lld_err = 0;
    lld_integral = 0;

    Poles = Pp+Pc;

    Ki_w = 0.001;
    Kp_w = 0.5;
    W_err = 0;
    W_integral = 0;

    Ki_icq = 0.003;
    Kp_icq = 0.3;
    lcq_err = 0;
    lcq_integral = 0;

    Ki_icd = 0.001;
    Kp_icd = 0.2;
    lcd_err = 0;
    lcd_integral = 0;
}

void InitPROTECT (void)
{
}

void InitDlog (void)
{
    dlog.iptr1 = &DlogCh1;
    dlog.iptr2 = &DlogCh2;
    dlog.iptr3 = &DlogCh3;
    dlog.iptr4 = &DlogCh4;
    dlog.trig_value = 0x0;
    dlog.size = 0x400;
    dlog.prescalar = 1;
    dlog.init(&dlog);

    DlogCh1 = 0;
    DlogCh2 = 0;
    DlogCh3 = 0;
    DlogCh4 = 0;
    dlog.update(&dlog);
}

```

```

/*****
//      SUBPROGRAM ROUTINES
*****/
void DC_Relay_Open (void)
{
    GpioDataRegs.GPACLEAR.bit.GPIOA7 = 1;
    DELAY_US(10000);
    GpioDataRegs.GPBCLEAR.bit.GPIOB12 = 1;
    DELAY_US(80000);
}

void DC_Relay_Close (void)
{
    GpioDataRegs.GPASET.bit.GPIOA7 = 1;
    DELAY_US(10000);
    GpioDataRegs.GPBCSET.bit.GPIOB12 = 1;
    DELAY_US(80000);
}

void RECT_Start (void)
{
    EvbRegs.T3CNT = 0;
    // enable full compare: FCOMPOE=1
    EvbRegs.COMCONB.all |= 0x0200;
}

void INV_Start (void)
{
    EvaRegs.T1CNT = 0;
    // enable full compare: FCOMPOE=1
    EvaRegs.COMCONA.all |= 0x0200;
}

void VSI_Off (void)
{
    EvaRegs.EVAIMRA.bit.T1CINT = 1;
    EvaRegs.CMPR1 = 0x0000;
    EvaRegs.CMPR2 = 0x0000;
    EvaRegs.CMPR3 = 0x0000;
    // disable enable full compare: FCOMPOE=1
    //EvaRegs.COMCONA.all &= 0xFDF;
    //EvaRegs.T1CON.bit.TENABLE = 0;
}

void VSR_Off (void)
{
    EvbRegs.CMPR4 = 0x0000;
    EvbRegs.CMPR5 = 0x0000;
    EvbRegs.CMPR6 = 0x0000;
    // disable enable full compare: FCOMPOE=1
    EvbRegs.COMCONB.all &= 0xFDF;
    EvbRegs.T3CON.bit.TENABLE = 0;
}

void THETA_READ (void)
{
    // voltage angle in p.u.
    float Theta_cnt = 0;

    Theta_cnt = (3999.0-ZeroCrossA.PHASE_OUT)/4000.0;

    if (Theta_cnt < 0.25)
        Theta_vg = _IQ(Theta_cnt) + _IQ(0.75);
    else
        Theta_vg = _IQ(Theta_cnt) - _IQ(0.25);
}

void SPEED_READ (void)
{
    float Angle = 0, Temp_speed = 0;

    // mech. angle in degrees: A = counter*360/14400 =
    //counter/40;
    Angle = Count*0.02500; Theta_m = _IQ(Angle/360.0);

    // Theta_m in p.u. : Angle/360
    if (Count < OldCount)
        QEP_step = QepMaxCount - OldCount + Count;
    else
        QEP_step = Count - OldCount;

    // Calculating speed using proportionality constant
    // @ 900 rpm Qep_step = 59.1
    if (QEP_step > 10)
    {
        Temp_speed = QEP_step*15.23;
    }
    else
        Temp_speed = 0.0;

    Speed_mech = _IQ(Temp_speed);
}

void ADC_VSR_READ (void)
{
    AdcRegs.ADCTRL2.bit.SOC_SEQ1 = 1;
    adc16.read(&adc16);

    V1_ab = 0.925*(-(int16)ChA_zeros[3] +
(int16)adc16.ADCINA3)/V1_res;
    V1_bc = 0.962*(-(int16)ChA_zeros[4] +
(int16)adc16.ADCINA4)/V1_res;
    V1_ca = 0.925*(-(int16)ChA_zeros[5] +
(int16)adc16.ADCINA5)/V1_res;

    I1_a = 0.893*((int16)ChA_zeros[1] -
(int16)adc16.ADCINA1)/I1_res;
    I1_c = 1.174*((int16)ChA_zeros[2] -
(int16)adc16.ADCINA2)/I1_res;
    I1_b = -(I1_a + I1_c);

    VdcP = ((int16)ChA_zeros[6] -
(int16)adc16.ADCINA6)/DC_res;
    VdcN = ((int16)ChA_zeros[7] -
(int16)adc16.ADCINA7)/DC_res;
}

```

```

VDC = _IQ((VdcN + VdcP)*0.948);
DC_base = _IQdiv(VDC, _IQ(sqrt3));
}

void ADC_VSI_READ (void)
{
    AdcRegs.ADCCTRL2.bit.SOC_SEQ1 = 1;
    adc16.read(&adc16);

    Vp_ab = 1.1497*(-(int16)ChB_zeros[6] +
(int16)adc16.ADCINB6)/Vp_res;
    Vp_bc = 1.1551*(-(int16)ChB_zeros[7] +
(int16)adc16.ADCINB7)/Vp_res;
    Vp_ca = 1.1633*(-(int16)ChB_zeros[1] +
(int16)adc16.ADCINB1)/Vp_res;

    lp_a = ((int16)ChA_zeros[0] -
(int16)adc16.ADCINA0)/lp_res;
    lp_c = ((int16)ChB_zeros[0] -
(int16)adc16.ADCINB0)/lp_res;
    lp_b = -(lp_a + lp_c);

    lc_a = ((int16)ChB_zeros[4] -
(int16)adc16.ADCINB4)/lp_res;
    lc_c = ((int16)ChB_zeros[5] -
(int16)adc16.ADCINB5)/lp_res;
    lc_b = -(lc_a + lc_c);

    VdcP = ((int16)ChA_zeros[6] -
(int16)adc16.ADCINA6)/DC_res;
    VdcN = ((int16)ChA_zeros[7] -
(int16)adc16.ADCINA7)/DC_res;
    VDC = _IQ((VdcN + VdcP)*0.948);
    DC_base = _IQdiv(VDC, _IQ(sqrt3));
}

void VSR_REGULATE (void)
{
    Va = (Vl_ab - Vl_ca)/3.0;
    Vb = (Vl_bc - Vl_ab)/3.0;
    Vc = (Vl_ca - Vl_bc)/3.0;

    // Clarke (Va, Vb, Vc, &Vl_alpha, &Vl_beta);
    Theta_vg = _IQatan2PU(Vl_beta, Vl_alpha);
    Park (Vl_alpha, Vl_beta, Theta_vg, &Vl_d,
    &Vl_q);

    Clarke (Il_a, Il_b, Il_c, &Il_alpha, &Il_beta);
    Park (Il_alpha, Il_beta, Theta_vg, &Il_d, &Il_q);

    Temp = _IQ(376.99111*Lf);
    Vld_comp = Vl_d + _IQmpy(Il_q, Temp);
    Vlq_comp = _IQmpy(Il_d, Temp);

    // Vdc regulator
    DC_err = _IQ(Vdc_ref) - VDC;

```

```

    DC_integral += _IQmpy(DC_err, _IQ(Ki_dc));
    // Integral saturation
    if(DC_integral > _IQ(8.0))
        DC_integral = _IQ(8.0);
    if(DC_integral < _IQ(-8.0))
        DC_integral = _IQ(-8.0);

    lld_ref = DC_integral + _IQmpy(DC_err,
_IQ(Kp_dc));

    // ll_d regulator
    lld_err = lld_ref - ll_d;
    lld_integral += _IQmpy(lld_err, _IQ(Ki_ild));
    // Integral saturation
    if(lld_integral > _IQ(3.5))
        lld_integral = _IQ(3.5);
    if(lld_integral < _IQ(-3.5))
        lld_integral = _IQ(-3.5);

    Vld_cnt = -(lld_integral + _IQmpy(lld_err,
_IQ(Kp_ild))) + Vld_comp;
    debug_var[3] = _IQtoF(Vld_cnt);
    Vld_cnt = _IQdiv(Vld_cnt, DC_base);

    // ll_q regulator
    llq_err = _IQ(llq_ref) - ll_q;
    llq_integral += _IQmpy(llq_err, _IQ(Ki_ilq));
    // Integral saturation
    if(llq_integral > _IQ(3.5))
        llq_integral = _IQ(3.5);
    if(llq_integral < _IQ(-3.5))
        llq_integral = _IQ(-3.5);

    Vllq_cnt = -(llq_integral + _IQmpy(llq_err,
_IQ(Kp_ilq))) - Vllq_comp;
    debug_var[4] = _IQtoF(Vllq_cnt);
    Vllq_cnt = _IQdiv(Vllq_cnt, DC_base);
}

void VSI_REGULATE (void)
{
    iq Temp_ang;

    Va = (Vp_ab - Vp_ca)/3.0;
    Vb = (Vp_bc - Vp_ab)/3.0;
    Vc = (Vp_ca - Vp_bc)/3.0;

    Clarke(Va, Vb, Vc, &Vp_alpha, &Vp_beta);

    Theta_v = _IQatan2PU(Vp_beta, Vp_alpha);
    if(Theta_v < _IQ(0.25))
        Theta_phi = Theta_v + _IQ(0.75);
    else
        Theta_phi = Theta_v - _IQ(0.25); // flux
    angle lags voltage angle by pi/2 (0.25 p.u.)

```

```

Park (Vp_alpha, Vp_beta, Theta_phi, &Vp_d,
&Vp_q);

Clarke(lp_a, lp_b, lp_c, &lp_alpha, &lp_beta);
Park (lp_alpha, lp_beta, Theta_phi, &lp_d,
&lp_q);

Temp_ang = _IQmpy(_IQ(Poles), Theta_m);
Theta_c = Theta_phi + _IQfrac(Temp_ang);

if(Theta_c < 0)
    Theta_c = Theta_c + _IQ(1);
/* if(Theta_c > _IQ(1))
    Theta_c = _IQ(1);
if(Theta_c < 0)
    Theta_c = 0;
*/

Clarke(lc_a, lc_b, lc_c, &lc_alpha, &lc_beta);
Park (lc_alpha, lc_beta, Theta_c, &lc_d, &lc_q);

debug_var[6] = _IQtoF(lc_d);
/* lc_d = _IQmpy(lc_d, a_lc) + _IQmpy(lcd_old,
b_lc);
lc_d_old = lc_d;
lc_q = _IQmpy(lc_q, a_lc) + _IQmpy(lcq_old,
b_lc);
lcq_old = lc_q;

*/

// Calculating rotor fluxes
Phi_pd = _IQdiv(Vp_q, _IQ(376.9111));
Phi_rd = _IQmpy(_IQ(2.139199), Phi_pd);
Phi_rd += _IQmpy(_IQ(-0.0647993), lp_d);
Phi_rd -= _IQmpy(_IQ(0.0502996), lc_d);
Phi_rq = _IQmpy(_IQ(-0.0647993), lp_q);
Phi_rq -= _IQmpy(_IQ(0.0502996), lc_q);

//Calculating decoupling terms
Vq_d = _IQmpy(lc_d, _IQ(0.01203));
Vq_d += _IQmpy(Phi_pd, _IQ(0.77639));
Vq_d -= _IQmpy(Phi_rd, _IQ(0.83041));

Vd_d = _IQmpy(Phi_rd, _IQ(0.83041));
Vd_d -= _IQmpy(lc_q, _IQ(0.01203));

delta_w = _IQ(376.99) -
_IQmpy(_IQ(Poles*PI/30), Speed_mech);

Vd_d = _IQmpy(Vd_d, delta_w);
Vq_d = _IQmpy(Vq_d, delta_w);

//Speed Regulation
W_err = _IQ(Speed_ref) - Speed_mech; // both in
rpm
W_integral += _IQmpy(W_err, _IQ(Ki_w));
if(W_integral > _IQ(50))

```

```

W_integral = _IQ(50);
if(W_integral < _IQ(-10))
    W_integral = _IQ(-10);

lcq_ref = -(W_integral + _IQmpy(W_err,
_IQ(Kp_w)));

//lc_q Regulation
lcq_err = lcq_ref - lc_q;
lcq_integral += _IQmpy(lcq_err, _IQ(Ki_icq));
// Integral saturation
if(lcq_integral > _IQ(15))
    lcq_integral = _IQ(15);
if(lcq_integral < _IQ(-15))
    lcq_integral = _IQ(-15);

Vcq_cnt = lcq_integral + _IQmpy(lcq_err,
_IQ(Kp_icq));

//lc_d Regulation
lcd_err = lcd_ref - lc_d;
lcd_integral += _IQmpy(lcd_err, _IQ(Ki_licd));
// Integral saturation
if(lcd_integral > _IQ(15))
    lcd_integral = _IQ(15);
if(lcd_integral < _IQ(-15))
    lcd_integral = _IQ(-15);

Vcd_cnt = lcd_integral + _IQmpy(lcd_err,
_IQ(Kp_licd));

Vcq_cnt = _IQdiv(Vcq_cnt, DC_base);
Vcd_cnt = _IQdiv(Vcd_cnt, DC_base);
}

void SVPWM_VSR (void)
{
    int16 sector;
    Uint16 comp1, comp2, comp3, comp4;
    _iq28 T1_sin, T2_sin, Theta, Theta_sec;

    Vref = _IQ18mag(_IQtoIQ18(Vld_cnt),
_IQtoIQ18(Vlq_cnt));
    if(Vref > _IQ18(0.98))
        Vref = _IQ18(0.98);

    debug_var[5] = _IQ18toF(Vref);
    Vref = Vref*((int16)VSR_period>>2);
    //count value of every half PWM period

    Theta = _IQtoIQ28(_IQatan2(Vlq_cnt, Vld_cnt));
    Theta +=
_IQ28mpy(_IQtoIQ28(Theta_vg), _IQ28(6.28331));
    //Phase for SVPWM

```

```

if(Theta > _IQ28(6.28331))
    Theta = Theta - _IQ28(6.28331);
if( Theta < 0 )
    Theta = Theta + _IQ28(6.28331);

sector = Theta/_IQ28(1.0471973);
Theta_sec = Theta -
_IQ28mpyl32(_IQ28(1.0471973),(long)(sector));

T1_sin = _IQ28sin(_IQ28(1.0471973) -
Theta_sec);
T2_sin = _IQ28sin(Theta_sec);
T1 = _IQ18mpylQX(T1_sin, 28, Vref, 18)>>16; //
T1/2
T2 = _IQ18mpylQX(T2_sin, 28, Vref, 18)>>16; //
T2/2
T0 = (int16)VSR_period - T1 - T2; // T0/2

comp1 = T0>>1;
comp2 = comp1 + T1;
comp3 = comp2 + T2;
comp4 = comp1 + T2;

switch (sector)
{
case 0:
    EvbRegs.CMPR4 = comp1;
    EvbRegs.CMPR5 = comp2;
    EvbRegs.CMPR6 = comp3;
break;
case 1:
    EvbRegs.CMPR4 = comp4;
    EvbRegs.CMPR5 = comp1;
    EvbRegs.CMPR6 = comp3;
break;
case 2:
    EvbRegs.CMPR4 = comp3;
    EvbRegs.CMPR5 = comp1;
    EvbRegs.CMPR6 = comp2;
break;
case 3:
    EvbRegs.CMPR4 = comp3;
    EvbRegs.CMPR5 = comp4;
    EvbRegs.CMPR6 = comp1;
break;
case 4:
    EvbRegs.CMPR4 = comp2;
    EvbRegs.CMPR5 = comp3;
    EvbRegs.CMPR6 = comp1;
break;
case 5:
    EvbRegs.CMPR4 = comp1;
    EvbRegs.CMPR5 = comp3;
    EvbRegs.CMPR6 = comp4;
break;
}
}

```

```

void SVPWM_VSI (void)
{
    int16 sector_c;
    Uint16 comp1c,comp2c,comp3c,comp4c;
    _iq28 T1_sin_c,T2_sin_c, Theta_sec_c, Vref_c;
    _iq Angle_c;

    Vcd_cnt = _IQ(debug_var[1])/_IQtoF(DC_base);
    // + Vp_d;
    Vcq_cnt = _IQ(debug_var[2])/_IQtoF(DC_base);
    // + Vp_q;

    Vref_c = _IQ18mag(_IQtoIQ18(Vcd_cnt),
_IQtoIQ18(Vcq_cnt));
    if(Vref_c > _IQ18(0.98))
        Vref_c = _IQ18(0.98);

    Vref_c = Vref_c*((int16)VSI_period>>2);
    //count value of every half PWM period

    Angle_c = _IQatan2(Vcq_cnt, Vcd_cnt);
    Angle_c += _IQmpy(Theta_c,_IQ(6.28331)) -
_IQ(0.1399); //Phase for SVPWM

    if(Angle_c > _IQ(6.28331))
        Angle_c = Angle_c - _IQ(6.28331);
    if( Angle_c < 0 )
        Angle_c = Angle_c + _IQ(6.28331);

    sector_c =
_IQtoIQ28(Angle_c)/_IQ28(1.0471973);
    Theta_sec_c = _IQtoIQ28(Angle_c) -
_IQ28mpyl32(_IQ28(1.0471973),(long)(sector_c));

    T1_sin_c = _IQ28sin(_IQ28(1.0471973) -
Theta_sec_c);
    T2_sin_c = _IQ28sin(Theta_sec_c);
    T1c = _IQ18mpylQX(T1_sin_c, 28, Vref_c,
18)>>16; // T1/2
    T2c = _IQ18mpylQX(T2_sin_c, 28, Vref_c,
18)>>16; // T2/2
    T0c = (int16)VSI_period - T1c - T2c; // T0/2

    comp1c = T0c>>1;
    comp2c = comp1c + T1c;
    comp3c = comp2c + T2c;
    comp4c = comp1c + T2c;

    switch (sector_c)
    {
    case 0:
        EvaRegs.CMPR2 = comp1c;
        EvaRegs.CMPR1 = comp2c;
        EvaRegs.CMPR3 = comp3c;
    break;
    case 1:

```

```

        EvaRegs.CMPR2 = comp4c;
        EvaRegs.CMPR1 = comp1c;
        EvaRegs.CMPR3 = comp3c;
    break;
    case 2:
        EvaRegs.CMPR2 = comp3c;
        EvaRegs.CMPR1 = comp1c;
        EvaRegs.CMPR3 = comp2c;
    break;
    case 3:
        EvaRegs.CMPR2 = comp3c;
        EvaRegs.CMPR1 = comp4c;
        EvaRegs.CMPR3 = comp1c;
    break;
    case 4:
        EvaRegs.CMPR2 = comp2c;
        EvaRegs.CMPR1 = comp3c;
        EvaRegs.CMPR3 = comp1c;
    break;
    case 5:
        EvaRegs.CMPR2 = comp1c;
        EvaRegs.CMPR1 = comp3c;
        EvaRegs.CMPR3 = comp4c;
    break;
}
}

```

```

/*****
//      AUXILIARY FUNCTIONS
*****/

void Clarke (float A, float B, float C, _iq *Valpha, _iq
*Vbeta)
{
    *Valpha = _IQ(A);
    *Vbeta = _IQ(0.57735*(B - C));
}

void Park (_iq Va, _iq Vb, _iq Angle, _iq *Vd, _iq *Vq)
{
    sinA = _IQsinPU(Angle);
    cosA = _IQcosPU(Angle);

    *Vd = _IQmpy(Va,cosA) + _IQmpy(Vb,sinA);
    *Vq = _IQmpy(Vb,cosA) - _IQmpy(Va,sinA);
}

```


References

- [1] Global Wind Energy Council. (2007, February). "Global Wind Energy Markets Continue to Boom" [Online]. Available: <http://www.gwec.net/>
- [2] Dinic, N. Fox, B. Flynn, D. Xu, L. Kennedy, A., "Increasing wind farm capacity", in IEE Proceedings on Generation, Transmission and Distribution, v.153, July 2006, pp.493-498
- [3] Hamburg Messe, "Wind energy study 2004," Hamburg Messe, May, 2004.
- [4] Gorlov A., Gorban' A., Silantyev V., "Limits of the Turbine Efficiency for Free Fluid Flow", Journal of Energy Resources Technology, vol. 123, December 2001, pp. 311-317.
- [5] D. A. Spera, "Turbine technology: Fundamental concepts of wind turbine engineering," New York: ASME Press, 1994, pp. 638-639.
- [6] L. H. Hansen, P. H. Madsen, F. Blaabjerg, H. C. Christensen, U. Lindhard and K. Eskildsen, "Generators and power electronics technology for wind turbines," in Proceedings IECON, 2001, pp. 2000-2005.
- [7] S. Muller, M. Deicke and R. W. De Doncker, "Doubly fed induction generator systems for wind turbines", IEEE Industry Applications Magazine, vol. 8, May/June 2002, pp. 26-33.
- [8] P. Fairley, "Steady as she blows", IEEE Spectrum, vol. 40(8), pp. 35-39, August 2003.
- [9] N. Mohan, W. P. Robbins and T. M. Undeland, "Power electronics: Converters, applications and design", 3d ed., New York: John Wiley and Sons, 2003, pp. 80-113.
- [10] H. M. Kojabadi, C. Liuchen and T. Boutot, "Development of a novel wind turbine simulator for wind energy conversion systems using an inverter-controlled induction motor," IEEE Transactions on Energy Conversion, vol. 19(3), September 2004, pp. 547-552.

- [11] X. Zhang, D. Xu and Y. Liu, "Predictive functional control of a doubly fed induction generator for variable speed wind turbines," in Proceedings Fifth World Congress on Intelligent Control and Automation, June 2004, pp. 3315-3319.
- [12] Horiuchi, N., Kawahito, T., "Torque and power limitations of variable speed wind turbines using pitch control and generator power control", Power Engineering Society Summer Meeting, 2001. IEEE, vol.1, July 2001, pp. 638-643
- [13] J. B. Ekanayake, L. Holdsworth, X. G. Wu and N. Jenkins, "Dynamic modeling of doubly fed induction generator wind turbines", IEEE Transactions on Power Systems, vol. 18(1), February 2003, pp. 803-809.
- [14] K. S. Rongve, B. I. Naess, T. M. Undeland and T. Gjengedal, "Overview of torque control of a doubly fed induction generator," in Proceedings Power Tech Conference, June 2003.
- [15] B. J. Chalmers, W. Wu and E. Spooner, "An Axial-Flux Permanent-Magnet Generator for Gearless Wind Energy System", IEEE Transactions on Energy Conversion, vol. 14, pp. 251-257, June. 1999.
- [16] M. Dubois, H. Polinder and J. A. Ferreira, "Comparison of generator topologies for direct-drive wind turbines," in Proceedings NORPIE, 2000, pp. 22-26
- [17] Parviainen, M. Niemela and J. Pyrhonen, "Modeling of axial flux permanent-magnet machines," IEEE Transactions on Industry Applications, vol. 40, pp. 1333-1340, 2004.
- [18] L. W. M. M. Rademakers, H. Braam, M. B. Zaaier and G. J. W. v. Bussel. (2003, June). "Assessment and optimisation of operation and maintenance of offshore wind turbines", ECN Windenergie, [Online]. Available: <http://www.ecn.nl>
- [19] S. Williamson, A. C. Ferreira and A. K. Wallace., "Generalized theory of the brushless doubly-fed machine. 1. Analysis", IEEE Proceedings on Electric Power Applications vol. 144(2), 1997, pp. 111-122.
- [20] S. Williamson and A. C. Ferreira and A. K. Wallace., "Generalized theory of the brushless doubly-fed machine. 2. Model verification and performance," IEE Proceedings on Electric Power Applications, vol. 144(2), 1997, pp. 123-129.

- [21] G. Boardman, J. G. Zhu and Q. P. Ha. "General reference frame modeling of the doubly fed twin stator induction machine using space vector", 2002 Australasian Universities Power Engineering Conference. [Online]. Available: www.itee.uq.edu.au/~aupec/aupec02/
- [22] B. K. Bose, "Modern Power Electronics and AC Drives", Upper Saddle River: Prentice Hall PTR, 2002, pp. 56-70.
- [23] Jia Yaoqin, Yang Zhongqing, Cao Binggang, "A new maximum power point tracking control scheme for wind generation", in Proceedings PowerCon 2002, October 2002
- [24] Moor, G.D. Beukes, H.J., "Maximum power point trackers for wind turbines", in Proceeding PESC, June 2004
- [25] R. Pena, J. C. Clare and G. M. Asher, "Doubly fed induction generator using back-to-back PWM converters and its application to variable-speed wind-energy generation", in Proceedings Electric Power Applications, vol. 143, 1996, p. 231-241.
- [26] G. Franklin, J.D. Powel, A. Emmi-Naeini, "Feedback Control of Dynamic Systems", Don Mills: Addison-Wesley Publishing Co., pp. 103-106. 1986
- [27] D.Xu, Y.W. Li, B. Wu, "Direct PWM Synchronization Using an All Digital Phase-Locked Loop for High Power Grid-Interfacing Converters", in Proceedings Applied Power Electronics Conference, February 2007.