Design and Control of the Brushless Doubly Fed Twin
Induction Generator (BDFTIG) using dSPACE

Thesis submitted for the degree of
Doctor of Philosophy
at the University of Leicester

by
Asim Bensadeq
Department of Engineering, University of Leicester
January 2012
Asim Bensadeq

Design and Control of the Brushless Doubly Fed Twin Induction Generator (BDFTIG) using dSPACE

Abstract

The aim of this research is to present indirect vector control (IVC) for a Brushless Doubly Fed Twin Induction Generator (BDFTIG) for wind energy conversion. The system is anticipated as an advanced solution to the conventional doubly fed induction generator (DFIG) to decrease the maintenance cost and increase the system reliability of the wind turbine system.

The proposed BDFTIG employs two cascaded induction machine sets, which consists of two wound rotor induction machines with their rotors connected in cascade to eliminate the brushes and copper rings in the DFIG. This new machine would ideally have one common rotor, and the two stators to be integrated within one housing. For the practical purpose of this research two separate DFIG’s were coupled together to a single prime mover. The dynamic model of the BDFTIG with the two machines' rotors electromechanically coupled in a back-to-back configuration is developed and implemented using Matlab/Simulink. Based on the model, the control scheme for flexible power flow control in the BDFTIG with a bidirectional converter is developed. Independent control of the active and reactive power flow is achieved by a four-quadrant power converter under the closed-loop stator flux oriented control scheme. In the proposed control strategy, the generator speed tracks the reference speed very well, and thus the maximum power extract. Which is the optimum speed derived from the maximum power point tracking of the wind turbine.
Acknowledgements

I would like to express my appreciation to Dr. P. Lefley his inspirational guidance, constant encouragement, advice throughout my research work and for their guidance and helping me with all kinds of practical problems, and for guiding me through the rocky roads of my research.

In addition I would like to thank Professor J. Fothergill for seeing the small positive in my work and giving me inspiration to prove myself through the research and his support during all that time. I would like to give special thanks also to my Mother, my Wife Manal and my Children Didi, Nano and Nuji for their unconditional support and motivation during my studies.
CHAPTER ONE: INTRODUCTION .........................................................1
1.1 Background of Wind Energy Applications .................................1
1.2 Classification of Wind Turbines and Generators ....................2
1.3 Most Popular Generator Topologies for Wind Applications .........9
1.3.1 Squirrel Cage Induction Generators ...........................................9
1.3.2 Doubly-Fed Induction Generators ...........................................12
1.3.3 Synchronous Generators .......................................................15
1.4 Motivation and Objective ..........................................................17
1.5 Thesis Outline ...........................................................................19

CHAPTER TWO: MACHINE CONTROL PRINCIPLE ............................21
2.1 Introduction ................................................................................21
2.2 Control Principle .........................................................................21
2.3 The Principle of FOC ...............................................................22
2.4 Conclusion ..................................................................................36

CHAPTER THREE: BDFTIG MODEL DEVELOPMENT ....................37
3.1 Introduction ................................................................................37
3.2 Principle Structure of BDFTIG ....................................................37
3.3 Equivalent Circuit Analysis of the BDFTIG ...............................39
6.4 Testing Results and Analysis ...........................................124
6.5 No Load Tests ..............................................................125
6.6 Low Power Tests ..........................................................127
6.7 Medium Power Tests .......................................................127
6.8 Conclusion ...................................................................128

CHAPTER SEVEN: CONCLUSIONS ...........................................138
7.1 Conclusions ................................................................138
7.2 Major Contributions ......................................................139
7.3 Further Research ........................................................140

APPENDICES

Appendix A- The M-file S-functions for The BDFTIG Modelling.
Appendix B- The Specification of both Induction Machines for the Simulink propose.
Appendix C- The BDFTIG Simulink Modelling Scheme.
Appendix D- Designing the Power Electronic Drive.
Appendix E- The Control Design for VSI Scheme.
Appendix F- The Control Design for VSR Scheme.
Appendix G- The Specification of both Induction Machines for the Practical propose.
Appendix H- The Control Design for the Practical Machine.
Appendix I- The Voltage and Current Transducer Circuit.
Appendix J- The Data for the Electrical Voltage Transfer Characteristic Figure 6-5.
Appendix K- The Electrical Frequency Relation for the BDFTIG.
List of Figures

Figure 1-1 Total Global Wind Energy Capacity (Courtesy of the GWEC)........................1
Figure 1-2 Installed Global Capacity Breakdown (Courtesy of the GWEC)..................2
Figure 1-3 Typical Turbine C_p Curve for different Blade Pitch Angles..........................4
Figure 1-4 Power Produced by The Variable and Constant Speed Wind Turbine...........7
Figure 1-5 Geared-drive Turbine Configurations.......................................................8
Figure 1-6 Squirrel cage Generator with an Indirect Grid Connection.........................12
Figure 1-7 DFIG Wind Turbine...................................................................................14
Figure 1-8 Typical BDFTIG Configuration Based on Cascaded Rotor.........................18

Figure 2-1 General Classification of Induction Machine Control Methods.....................22
Figure 2-2 Torque Control for Brushed DC motor......................................................23
Figure 2-3 Torque Control for an Induction Motor......................................................23
Figure 2-4 Transforms 3-phase to α-β reference.........................................................25
Figure 2-5 Transformation α-β to d-q reference frame...............................................25
Figure 2-6 Transformation d-q to α-β reference frame................................................26
Figure 2-7 Transformation α-β to 3-phase reference frame.........................................27
Figure 2-8 DVC Flux Phase Vector.............................................................................27
Figure 2-9 Flux Phase Vector Position.........................................................................28
Figure 2-10 Calculate the Rotor Flux Angle (θ)..............................................................29
Figure 2-11 Torque and Field Current Calculate...........................................................29
Figure 2-12 Programming Selected Switching..............................................................29
Figure 2-13 DVC with Torque, Field Current Control and Field Weakening...................29
Figure 2-14 DVC with Speed, Field Current Control and Field Weakening...................30
Figure 2-15 IVC Flux Phase Vector.............................................................................32
Figure 2-16 The Dynamic d-q axis Equivalent Circuits...............................................33
Figure 2-17 Indirect Vector Control.............................................................................35
Figure 2-18 Block Diagram for Voltage Compensation...............................................36

Figure 3-1 The BDFTIG Connection..........................................................................38
Figure 3-2 BDFTIG D-Q Transformation....................................................................41
Figure 3-3 The Rotations for the BDFTIG.................................41
Figure 3-4 Equivalent Circuits of $d$-$q$ Power Machine.........................43
Figure 3-5 Equivalent Circuits of $d$-$q$ Control Machine..........................45
Figure 3-6 Equivalent Circuit of the BDFTIG..................................49
Figure 3-7 Equivalent $d$-$q$ Circuits of BDFTIG................................49
Figure 3-8 BDFTIG Model in Simulink.........................................53
Figure 3-9 Three phase Converted to $d$-$q$....................................54
Figure 3-10 Angle's Velocity for both Machines..............................54
Figure 3-11 The Speed of BDFTIG at no-load..............................56
Figure 3-12 No-load Control Machine Current..............................57
Figure 3-13 The BDFTIG Torques at no load..............................57
Figure 3-14 Control Machine Excitation Voltage.............................58
Figure 3-15 Control Machine Excitation Current..............................58
Figure 3-16 The BDFTIG Torques..............................................58

Figure 4-1 Voltage Vector Position...........................................61
Figure 4-2 Voltage and Flux Vectors...........................................62
Figure 4-3 BDFTIG Systems with a back-to-back Converter..................63
Figure 4-4 VSR Circuit Model...................................................64
Figure 4-5 The Current Control Loops........................................68
Figure 4-6 The Zero-Pole Map of the DC Link Current Control Loop.........68
Figure 4-7 The Bode Diagram of the DC Link Current Control Loop...........69
Figure 4-8 DC Link Voltage Control Loop....................................70
Figure 4-9 The Zero-Pole Map of the DC Link Voltage Control Loop...........70
Figure 4-10 The Bode Diagram of the DC Link Voltage Control Loop..........71
Figure 4-11 Grid side Controller Scheme....................................71
Figure 4-12 The Block Diagram for the Speed Control.......................79
Figure 4-13 The Block Diagram for the Speed Control........................80
Figure 4-14 The Zero-Pole Map of the Speed Control Loop....................80
Figure 4-15 The Bode Plot of the Speed Control Loop........................81
Figure 4-16 The Block Diagram for PI Current Control........................81
Figure 4-17 The Block diagram for PI Current Control.................................................................83
Figure 4-18 The Zero-Pole Map of the Speed Control Loop.................................................................83
Figure 4-19 The Bode Plot of the Current Control Loop........................................................................84
Figure 4-20 The Generator Side Power Converter Control Block Diagram........................................84
Figure 4-21 Generator Side Power Converter Control Scheme..............................................................85
Figure 4-22 The BDFTIG Control Block Diagram..............................................................................86
Figure 4-23 Vector Control Implementation Principle..............................................................................87

Figure 5-1 Typical Turbine Characteristic Curves......................................................................................90
Figure 5-2 Turbine Power Curves...........................................................................................................92
Figure 5-3 Wind Turbine Block Diagram..................................................................................................93
Figure 5-4 Wind Turbine Model.............................................................................................................93
Figure 5-5 Optimal Power Speed Curve..................................................................................................94
Figure 5-6 Control Block Diagram.........................................................................................................95
Figure 5-7 VSR Controller Block..........................................................................................................95
Figure 5-8 V_s,ABC-DQ Block..................................................................................................................96
Figure 5-9 VSI Controller Block............................................................................................................96
Figure 5-10 ABC->DQ Block..................................................................................................................97
Figure 5-11 The Speed Angles Calculation.............................................................................................98
Figure 5-12 VSI Flux Estimation Block....................................................................................................98
Figure 5-13 VSI Decoupling Block..........................................................................................................99
Figure 5-14 VSI_PI Controllers..............................................................................................................99
Figure 5-15 Transfer Power Machine Current to Control Machine Current..............................................100
Figure 5.16- Generate the Control Machine Reference Current.................................................................101
Figure 5-17 BDFTIG System Model.......................................................................................................102
Figure 5-18 The Wind Speed Demand....................................................................................................103
Figure 5-19 The BDFTIG Shaft Speed....................................................................................................104
Figure 5-20 Speed Tracking....................................................................................................................105
Figure 5-21 The BDFTIG Mechanical Torque..........................................................................................105
Figure 5-22 The BDFTIG Mechanical Power..........................................................................................106
Figure 5-23 The Power Machine Stator Voltage....................................................................................106
Figure 6-14 The Power Machine Waveforms at Shaft Speed 700rpm..........................133
Figure 6-15 The Control Machine Waveforms at Shaft Speed 700rpm.........................134
Figure 6-16 The Power Machine Waveforms at Shaft Speed 700rpm.........................139
Figure 6-17 The Control Machine Waveforms at Shaft Speed 700rpm.........................137
Figure 6-18 The Power Machine Waveforms at Shaft Speed 700rpm.........................138
Figure 6-19 The Control Machine Waveforms at Shaft Speed 1000rpm......................139
List of Principal Symbols

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Real</th>
</tr>
</thead>
<tbody>
<tr>
<td>$R_r$</td>
<td>Rotor referred winding resistance, (Ω)</td>
</tr>
<tr>
<td>$R_s$</td>
<td>Stator winding resistance, (Ω)</td>
</tr>
<tr>
<td>$L_m$</td>
<td>Magnetising inductance, (H)</td>
</tr>
<tr>
<td>$L_o$</td>
<td>Air-gap inductance, (H)</td>
</tr>
<tr>
<td>$L_r$</td>
<td>Rotor inductance, (H)</td>
</tr>
<tr>
<td>$L_s$</td>
<td>Stator inductance, (H)</td>
</tr>
<tr>
<td>$f$</td>
<td>Frequency, (Hz)</td>
</tr>
<tr>
<td>$f_p$</td>
<td>Power Machine Frequency, (Hz)</td>
</tr>
<tr>
<td>$f_m$</td>
<td>Equivalent to Mechanical Shaft Frequency, (Hz)</td>
</tr>
<tr>
<td>$f_c$</td>
<td>Control Machine Frequency, (Hz)</td>
</tr>
<tr>
<td>$f_r$</td>
<td>Rotor Frequency, (Hz)</td>
</tr>
<tr>
<td>$B_p$</td>
<td>Power Machine Friction, (Kgm$^{-2}$)</td>
</tr>
<tr>
<td>$B_c$</td>
<td>Control Machine Friction, (Kgm$^{-2}$)</td>
</tr>
<tr>
<td>$J_p$</td>
<td>Power Machine Moment of inertia, (Kgm$^2$)</td>
</tr>
<tr>
<td>$J_c$</td>
<td>Control Machine Moment of inertia, (Kgm$^2$)</td>
</tr>
<tr>
<td>$T_e$</td>
<td>Electromagnetic Torque, (N.m)</td>
</tr>
<tr>
<td>$T_L$</td>
<td>Load Torque, (N.m)</td>
</tr>
<tr>
<td>$P_m$</td>
<td>Mechanical Power, (W)</td>
</tr>
<tr>
<td>$P$</td>
<td>Active Power, (W)</td>
</tr>
<tr>
<td>$Q$</td>
<td>Reactive Power, (VAR)</td>
</tr>
<tr>
<td>$p$</td>
<td>Pole Pairs</td>
</tr>
<tr>
<td>Symbol</td>
<td>Description</td>
</tr>
<tr>
<td>-----------------</td>
<td>--------------------------------------------------</td>
</tr>
<tr>
<td>( p_p, p_c )</td>
<td>Pole Pairs for Power and Control machines</td>
</tr>
<tr>
<td>( \tau_r )</td>
<td>Rotor time constant</td>
</tr>
<tr>
<td>( m_a )</td>
<td>modulation index</td>
</tr>
<tr>
<td>( \text{TSR}_{\text{opt}} )</td>
<td>Optimum Tip Speed Ratio</td>
</tr>
<tr>
<td>( v_r )</td>
<td>Rotor Voltage, (V)</td>
</tr>
<tr>
<td>( v_s )</td>
<td>Stator Voltage, (V)</td>
</tr>
<tr>
<td>( V_{dc} )</td>
<td>Supply Line Voltage, (V)</td>
</tr>
<tr>
<td>( \Psi_o )</td>
<td>Air-gap flux, (Wb)</td>
</tr>
<tr>
<td>( \Psi_{r\beta}, \Psi_{r\alpha} )</td>
<td>Rotor flux in the ( \alpha-\beta ) axis, (Wb)</td>
</tr>
<tr>
<td>( \Psi_s )</td>
<td>Stator flux, (Wb)</td>
</tr>
<tr>
<td>( \Psi_r )</td>
<td>Rotor flux, (Wb)</td>
</tr>
<tr>
<td>( i_s )</td>
<td>Stator currents, (A)</td>
</tr>
<tr>
<td>( i_r )</td>
<td>Rotor currents, (A)</td>
</tr>
<tr>
<td>( i_m )</td>
<td>Equivalent magnetising current, (A)</td>
</tr>
<tr>
<td>( I_{\text{DC}}^s )</td>
<td>stator converter DC link current, (A)</td>
</tr>
<tr>
<td>( I_{\text{DC}}^r )</td>
<td>rotor converter DC link current, (A)</td>
</tr>
<tr>
<td>( \omega_{\text{sync}} )</td>
<td>Synchronous speed, (r/s)</td>
</tr>
<tr>
<td>( \omega_p )</td>
<td>Power machine electrical frequencies, (r/s)</td>
</tr>
<tr>
<td>( \omega_r )</td>
<td>Rotor Frequency, (r/s)</td>
</tr>
<tr>
<td>( \omega_m )</td>
<td>Shaft mechanical speed, (r/s)</td>
</tr>
<tr>
<td>( \omega_c )</td>
<td>Angular speed for control machine, (r/s)</td>
</tr>
<tr>
<td>( \omega_{\text{slip}} )</td>
<td>Slip frequency, (r/s)</td>
</tr>
<tr>
<td>( \theta_r )</td>
<td>Rotor angle, (rad)</td>
</tr>
<tr>
<td>( \theta_p )</td>
<td>Power machine angle, (rad)</td>
</tr>
<tr>
<td>Symbol</td>
<td>Description</td>
</tr>
<tr>
<td>--------</td>
<td>-------------</td>
</tr>
<tr>
<td>$\theta_m$</td>
<td>Shaft mechanical angle, (rad)</td>
</tr>
<tr>
<td>A</td>
<td>Turbine swept area, (m)</td>
</tr>
<tr>
<td>P</td>
<td>Air density, (kg.m$^{-3}$)</td>
</tr>
</tbody>
</table>

**Superscripts**

<table>
<thead>
<tr>
<th>Superscript</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>d,q</td>
<td>The D–Q reference frame</td>
</tr>
<tr>
<td>α,β</td>
<td>The α,β reference frame</td>
</tr>
<tr>
<td>*</td>
<td>Demanded (reference value)</td>
</tr>
<tr>
<td>s</td>
<td>Derivative operator</td>
</tr>
</tbody>
</table>
INTRODUCTION

1.1 Background of Wind Energy Technologies

Over the last twenty years, the wind-energy generation industry has experienced quick and successful development. It has received much attention that brought it to the front position as the leading form of renewable-energy production. According to the Global Wind Energy Council (GWEC) [1], the total wind power generation capacity of the world has been growing by more than 30 percent annually since 1996 as shown Figure 1-1 [1].

![Figure 1-1 Total Global Wind Energy Capacity (Courtesy of the GWEC)](image)

In the 1980’s, the biggest wind energy marketplace became visible in California, and its appearance was caused by the oil and energy crisis at the time. Then, most of the turbines installed 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, the Californian market began to collapse, which forced upstart manufacturers out of the business. Wind energy not only has an economic impact on our society, but it has a big environmentally conscious European society as well.
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 third 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 (Courtesy of the GWEC)](Image)

The next section presents a brief introduction to the various types of wind turbines, and a power generator is very important in order to facilitate the main concepts discussed in this research.

1.2 Classification of Wind Turbines and Generators

The first windmills on record were built by the Persians in approximately 900 AD. These windmills were used for almost any mechanical task such as water pumping, grinding grain, sawing wood, and powering tools. These early windmills had four blades and were built on posts so that the windmill could be turned to
face the wind. The operation of a wind turbine is based on the behaviour of a simple windmill. Like the windmill, the blades of the turbine capture the energy available in the wind and convert it into rotational energy of the shaft. However, unlike the windmill, this energy is converted into electricity by 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 system 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 and grid connection.

The aerodynamic configuration divides the wind turbines to 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 the one major disadvantage that the main components of the energy conversion system such as the 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 reference 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 blades is actually only 30.1 percent. However, no turbine can ever operate at its greatest efficiency all the time. Instead, its operation is built around
the performance coefficient \( (C_p) \) of its blades. This is an aerodynamic characteristic of the blades, which determines the amount of energy extracted from the airflow at a given speed [5]. The performance coefficient, which is determined by the turbine blade design, can be considered as a function of the tip speed ratio (TSR) and the blade pitch. The TSR is in turn a function of the wind speed, \( \nu \), rotor speed, \( \omega_r \) and blade radius, \( R_r \) as follows:

\[
TSR = \frac{\omega_r R_r}{\nu}
\]  
(1.1)

A typical performance coefficient of the wind turbine at a given pitch angle at different degree is shown in Figure 1-3 (Courtesy of the http://www.mathworks.co.uk/help). The optimal \( C_p \) is only possible at the certain tip speed ratio [9].

![Figure 1-3 Typical Turbine C_p Curve for different Blade Pitch Angles](image-url)
For the curve given in Figure 1-3, the optimal $C_p$ occurs at the tip speed ratio of around 7 at $0^\circ$ Blade Pitch angles\(^1\).

Therefore, the absolute maximum power will only be delivered to the grid under these conditions. However, 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 to the system when the wind is too strong. To partly treat this problem, a pitch control mechanism or stall control is installed to regulate the position of the blades and maintain the highest possible power transfer to the system. Nevertheless, not all 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 wind turbine generator is based on the configuration of the coupling between the blade's shaft and the generator rotor. Thus, the geared-drive concept refers to the arrangement under which the blade's shaft, and the rotor are coupled through a step-up gearbox; the direct-drive concept refers to the wind turbine in which the blades are 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 blades of the turbine will not rotate faster than several dozen revolutions per minute. The generator, however, needs to rotate at several hundreds or thousands of revolutions per minute to produce current at the standard frequency 50 or 60 hertz. Therefore, the easiest way to increase the speed of the generator is to include a step-up gearbox. The main

---

\(^1\)Note the turbine has a tapered blade pitch angle. So at $0^\circ$ the adjustment angle the blade pitch will not be $0^\circ$.  

5
advantage of the geared-drive technology is the relative simplicity of the generator
design. It allows the use of 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 significant drawbacks
of the geared-drive are the necessity of regular maintenance and gearbox losses.
The direct-drive concept appears to eliminate the shortcomings of the geared-
drive turbines. One way to eliminate the gearbox is to design a generator with a
very low synchronous rotational speed. Since the synchronous speed is inversely
proportional to the number of its poles, as shown in equation 1.2, there exists a
way of increasing the number of poles to bring the synchronous speed down to
several dozen revolutions per minute. The absence of the high-maintenance
gearbox makes the direct-drive turbines well suited for the operation.

\[ \omega_{sync} = \frac{120 \, f}{p} \]  

(1.2)

However, this technology has a couple of very serious drawbacks that cannot be
ignored. The main disadvantage from that technology is that direct-drive turbines
require a power converter and a large-diameter heavy generator. Unfortunately,
current technologies do not provide economical solutions to these challenges, and
it remains to be seen if direct-drive units can be economic alternatives to the
geared drive turbines. Moreover, the generators are distinguished by their
operational modes, fixed speed or variable-speed operation. As the name implies,
fixed-speed wind electric conversion systems usually use squirrel cage induction
generators connected directly to the grid. In this configuration, it is not possible to
extract the optimum power from the wind due to constant-speed operation
regardless of the wind conditions. Also the reactive power control is not accessible
in this system. Instead capacitor banks are used to compensate for the lagging reactive power the induction generator presents to the grid. 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 system. Since the generator is used to run at a fixed-speed in spite of fluctuations in wind speed, it will result in instability of generated output voltage and power. Using shaft speed control, higher energy will be obtained. Zinger and Muljadi [22], compare the power extracted for a really variable-speed wind turbine system, with a 34m diameter rotor, against a constant speed wind turbine at different wind speeds. The results are illustrated in Figure 1-4 (courtesy of Zinger and Muljadi [22]). The Figure shows that the variable-speed system outputs more energy than the constant speed system. For example, with a fixed-speed system, for an average annual wind speed of 7m/s, the energy produced is 55kWat, while the variable-speed system can produce up to 75kWat, under the same conditions [22].

![Image of Figure 1-4](image)

**Figure 1-4 Power Produced by a Variable and Constant Speed Wind Turbine**
Under variable-speed operation, the rotational speed of the rotor is changed to extract more power at low or medium wind speeds, i.e. operation at maximum $C_p$. 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 to reduce mechanical power fluctuations by allowing the speed to change. The following diagram shows the various configurations of the geared drive in wind turbines [6].

![Geared Drive Turbine Configurations](image)

However, since variable-speed operation produces a variable frequency and voltage, the slip rings of the wound-field induction motor allow easy recovery of the slip power, which can be electronically controlled to control the speed of the
generator. The oldest technique to control this slip-power recovery is to mechanically vary the rotor resistance. Instead of wasting the slip power in the rotor circuit resistance, a better approach is to convert it to AC line power and return it back to the line as a demonstrated in the next section.

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 geared-drive generators. The field of wind production is still dominated by this concept, and a considerable number of various topologies have been developed for this purpose. Induction generators are the most popular generator in wind energy applications. The choice of this type of generator is dictated by the fact that the rotational speed of the 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.

1.3.1 Squirrel Cage Induction Generators

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

Most of the currently operational fixed speed induction generator wind turbines have the blade pitch control to adjust the blades in such a way as to limit the maximum speed and power. However, the response times of the mechanical components often prevent the system from a timely response to gusts of wind. This characteristic of the fixed speed induction generator wind turbine is the major cause of the output power instability and requires a very strong grid to allow for uninterrupted operation [8].

Fixed speed induction generator wind turbines have another weakness that becomes increasingly detrimental as more and more of these wind-power generators are called upon to play a larger role power generation. 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 cannot an induction generator produce any (leading) reactive power, but it actually produces more lagging reactive power during normal operation. Currently, reactive power generation and power factor correction is achieved on a small scale by the addition a bank of static capacitors of various sizes, ratings and switching them on and off to satisfy the grid demand. However, if induction generator wind turbines were to completely replace conventional power 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 enough reactive power generation capacity for induction generator-based wind turbines.

As maintained in the previous section, fixed speed induction generator wind turbines produce relatively high level of noise of their operation. The problem lies in the fact that there is a direct relation between the rotational speed of the blades, 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 quiet day, the turbine would be as noisy as during periods of high-wind.

To eliminate some of the shortcomings of the fixed speed induction generator wind turbine, the most obvious solution is to allow the turbine to operate at variable speed. The easiest way to allow variable-speed operation with the squirrel-cage rotor generator is to add a power converter between the turbine and the grid. Such a converter includes the AC/DC and the DC/AC sub converters, with the latter being connected to the grid, the arrangement, shown in Figure 1-6, is called squirrel cage generator with an indirect grid connection. This configuration allows the generator to run at a 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, whilst utilising MPPT.
The advantages of this system are its facility to make the best use of available wind power and that there is no need for a capacitor bank since the generator can draw its required reactive power from the dc link capacitor. However, the cost of the power converter can be high due to its large size.

The power converter size can be reduced by using it on the rotor side of a wound rotor induction generator. Thus variable-speed operation can be best accomplished with a wound type rotor. This type of machine is called a doubly fed induction machine (DFIM).

1.3.2 Doubly-Fed Induction Generators

An 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 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 the 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 the stator and rotor. Thus, the rotor emf can be expressed as:
Where $E_{\text{rotor}}$ is rotor emf, $E_{\text{stator}}$ is stator emf, $N_{\text{rotor}}$ is the number of windings in the rotor, $N_{\text{stator}}$ is the number of windings in the stator and $s$ is the slip.

The rotational speed of the motor is given as:

$$\omega_r = \omega_{\text{sync}} (1 - s)$$

(1.4)

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

$$S = \frac{P_{\text{rotor circuit}}}{P_{\text{air gap}}}$$

(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 extracted from the rotor. This is achieved by connecting an external circuit 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.

The DFIM has several advantages over a conventional induction machine in wind power applications. Firstly, as the rotor circuit is controlled by a power electronics converter, the induction generator can both import and export active power. This has important consequences for power system stability and allows the machine to support the grid during severe voltage disturbances; also, it has possibilities to
reduce stresses of the mechanic configuration, noise reduction and control active and reactive power. Secondly, the control of the rotor voltages and currents enables the induction machine to remain synchronized with the grid while the speed varies and with a high level of efficiency. Thirdly, the major advantage of the DFIM is that the power electronic converter only has to handle a fraction, typically 25-30 %, of the total machine power. The remaining power is fed to the grid directly from the stator. Therefore, the cost of the converter is low when compared with other variable-speed drives [2]. 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 1-7. To allow variable-speed operation, current is extracted from the rotor windings through the slip rings. The power to the rotor windings is generated by the turbine itself and then this power is fed back through a bi-directional converter. Since it is the converter that controls the amount of power extracted from the rotor, its rating determines the speed range of the wind turbine.

![Figure 1-7 DFIG Wind Turbines](image)

The doubly-fed configuration allows very flexible control of the generator [7, 10, 11, 12].
Since their emergence, DFIG wind turbines proved to be a very popular alternative to the fixed speed induction generator 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 is only at a certain value of TSR. For any other wind speed 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 TSR\textsubscript{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:

\[ \omega_s = \omega_m \pm \omega_r \] (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 TSR\textsubscript{opt}. Under this condition, the stator frequency is fixed to the grid frequency and rotor frequency is adjusted to increasing 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 limiting the maximum power, and the rotor frequency is adjusted accordingly to the maximum power limit [13].

1.3.3 Synchronous Generators

Another alternative to the induction generator wind turbines is presented by the use of the synchronous generator wind turbine for power conversion. In their operation, synchronous machines rely on the rotating magnetic field created by
the direct-current in the rotor windings, or by rotor mounted permanent magnets. Due to the flux generation, the frequency of the induced voltage in the stator winding always matches the synchronous speed defined in equation 1.2, hence the name – synchronous machine. Synchronous generators are much better suited for direct drive operation than induction generators, due to their construction and synchronous operation. For years the rotors of these machines were mainly based on electromagnetic poles because these are relatively cheap and are not subject to demagnetization. However, new technologies help to stretch the operational life of permanent magnets, making the rotors more compact and removing the reliance on DC power sources for rotor magnetization. All this helps to increase the number of poles, making for a more robust direct drive wind turbine based on permanent magnet synchronous generators (PMSG). Currently, there are several PMSG topologies being used in the industry or under investigation by researchers. 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 with the inclusion of the power converter. The reason for this requirement is the simple fact that the AC voltage and
frequency of these generators is merely a function of the wind speed and the blade pitch of the turbine. Therefore, to achieve appropriate output frequency regulation, it is essential to introduce a power converter unit between the generator and the grid. Hence, a typical configuration of a synchronous generator for wind turbine 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 of This Research

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 disadvantages that cannot be overlooked. In order to recover, the slip energy from the rotor to the grid, it is necessary to use a wound type rotor with slip rings and 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 months, which necessitates regular maintenance. Under the current conditions, when most of the turbines are organized into the wind farms 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 farms comprising dozens of turbines will be created. Depending on the wind climate of the given area, these farms may be built as far as 30 kilometres away from the coast line. Clearly, such an arrangement will favour the turbine design that requires the least frequent
inspection and maintenance. Under the new condition's 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 on offshore location [3]. The possible solution for these shortcomings is the Brushless Doubly Fed Twin Induction Generator (BDFTIG), which can be seen as an advanced version of the DFIG, because it is based on the same principle of 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 1-8. The main advantage is the absence of the brushes since the slip energy is exchanged through the second stator winding similar to the function performed by the rotor in the DFIG.

![Figure 1-8 Typical BDFTIG Configuration Based on a Cascaded Rotor](image)

Therefore, the main objectives of this thesis were to: 1) develop a mathematical dynamic model for the BDFTIG with a cascaded rotor. The model would be used in the simulation design; 2) design a suitable controller for the BDFTIG that would ensure stability and an optimal speed tracking loop in an independent and robust control with the operation of a variable-speed wind turbine for any operating condition. To simplify the design for the laboratory, reasons concerning development time and cost, the research was carried out using two cascaded
wound-rotor induction machines, with their rotors connected together externally, to simulate a brushless double fed twin induction generator.

1.5 Thesis Outline

The reminder of this thesis is organized in the following way to provide detailed information about the research work on the BDFTIG in next seven chapters.

Chapter Two: In this chapter, a review of the most significant induction machine control method is presented, including the principles field oriented control.

Chapter Three: The main points in this chapter are to present the principal and structure for the BDFTIG Model, and the work involved in creating the appropriate mathematical model of the BDFTIG. The chapter also gives a step by step development of the dynamic model in the $d_q$ reference frame and its implementation using a Matlab Simulink package. The simulation results of the proposed model are also presented in this chapter.

Chapter Four: Presents the controller design for the BDFTIG model. There are two types of control for this model. Presented in this chapter are control systems to control not only the active and reactive powers but also to control the DC link voltage and the shaft speed.

Chapter Five: Describes the implementation of the BDFTIG model with the control design using a Matlab Simulink package. Furthermore, in this chapter the simulation results are presented to ensure that the projected model and control designs are complete to be used in experiment.
In Chapter Six: The experimental platform is introduced, including the wind-turbine emulator and the dSPACE system. The experimental results for testing the system are provided and compared to the simulation data and analyzed.

Finally, Chapter Seven: Concludes the research in this thesis and lists the major contributions and other issues that require further research.
Chapter 2 Machine Control Principles

2.1 Introduction

This chapter serves as a tutorial, describing the principles of the modelling design and more details of the type of the control strategy, e.g. traditional control or vector control. The main objective in this chapter is to select the control method for the BDF-TIG. The controller should have high performance, simple algorithm design, simple tuning and operation.

2.2 Control Principle

In traditional control strategies, induction machines have been controlled by using a scalar control, also called "volts per hertz" (v/f control) where the supply frequency to the machine is modified to achieve changes in speed while the voltage magnitude is controlled in direct proportion to the applied frequency to ensure the machine operates at rated flux. This method is based on steady-state analysis of the induction machine, but for high-performance AC drives Vector Control techniques are used. M. Kazmierkowski [24], as shown in Figure 2-1 there are four variations of vector control and one of them is Field Oriented Control (FOC). It has good control dynamics compared to v/f control, and during the steady state the v/f control is smoother in operation. FOC is used widely at present with a higher performance by parameter identification in sensorless drives.

In scalar control, there is an inherent coupling effect between torque and flux, because both torque and flux are functions of voltage or current and frequency.
The scheme of FOC is to decouple the control of the induction motor's flux and torque via coordinate transformations during the transient condition, and to control not only the amplitudes of current and flux but also their phase angle. In this kind of method, by orienting the $d$-axis of the reference frame in the direction of the rotor or stator flux, independent control of the flux and torque is made possible.

**Figure 2-1 General Classification of Induction Machine Control Methods**

### 2.3 The Principle of FOC

There is a close similarity between torque control of a DC motor and FOC of an AC motor. The major difference is that synchronous motors develop a sinusoidal back EMF, as compared to a rectangular, back EMF for brushed DC motors. Both have stator created rotating magnetic fields producing torque in a magnetic rotor. The DC motor has a stationary field structure and a rotating armature winding supplied by a commutator and brushes. The field flux $\psi_f$ produced by field current.
If is orthogonal to the armature flux \( \psi_a \) produced by the armature current \( I_a \), as shown in Figure 2-2.

![Figure 2-2 Torque Control for Brushed DC Motor](image)

\[ T_e = K_t \psi_f \psi_a = K_t I_a I_f \]

Where \( I_a \) is the torque component and \( I_f \) represents the field component.

DC motor-like performance can be achieved with an induction motor if the motor control is considered in the synchronously rotating reference frame \((d-q)\) where the sinusoidal variables appear as DC quantities in the steady state.

Two control inputs \( i_{ds} \) and \( i_{qs} \) can be used for a vector controlled inverter as shown in Figure 2-3.

![Figure 2-3 Torque Control for an Induction Motor](image)

\[ T_e = K_t \psi_f i_s^q = K_t i_s^q i_s^d \]  \hspace{1cm} (2.1)

where \( i_s^q \) is the torque component and \( i_s^d \) represents the field component. The induction motor stator current \( d \)-component \( i_s^d \) is equivalent to the DC motor field.
component $I_f$, also the induction motor stator current $q$-component $I_s^q$ is equivalent of the DC motor torque component $I_f$.

The FOC approach is based around a dynamic analysis of the induction machine, by reducing the three-phase machine to a rotating two-phase winding machine equivalent. The idea behind vector control is that one winding is aligned to the machine flux, while the other is for the developed torque. Under FOC, the magnitude and position of the flux linkage are controlled in transient operation by adjusting the instantaneous amplitude, frequency and phase of the stator current.

The main objective of FOC is to independently control the torque and flux like a brushed DC motor with separate field excitation.

The initial starting point to develop the control scheme is by reducing the three-phase machine to a rotating two-phase winding machine equivalent for the BDFTIG. This transformation is made in two steps:

A- The Clarke transformation; this is a transfer from the three-phase stationary system to the two-phase, so-called $\alpha$- $\beta$, stationary co-ordinate system as follows:

\[
\begin{bmatrix}
X_\alpha \\
X_\beta
\end{bmatrix} = \begin{bmatrix}
\frac{2}{3} & -\frac{1}{3} & -\frac{1}{3} \\
0 & -\frac{1}{\sqrt{3}} & \frac{1}{\sqrt{3}}
\end{bmatrix} \begin{bmatrix}
X_a \\
X_b \\
X_c
\end{bmatrix}
\]

\[
X_\alpha = \frac{2}{3} X_a - \frac{1}{3} X_b - \frac{1}{3} X_c
\]

\[
X_\beta = -\frac{1}{\sqrt{3}} X_b + \frac{1}{\sqrt{3}} X_c
\] (2.2)
B- The Park transformation; this is a transfer from the \( \alpha-\beta \) stationary coordinate system to the \( d-q \) rotating coordinate system. In vector control, it is important to know the synchronously rotating rotor flux angle (\( \Theta \)) because it is used to transform the \( \alpha-\beta \) system into a synchronously rotating \( d-q \) system and vice versa.

\[
\begin{bmatrix}
X_d \\
X_q \\
X_0
\end{bmatrix} =
\begin{bmatrix}
\cos \Theta & \sin \Theta & 0 \\
-\sin \Theta & \cos \Theta & 0 \\
0 & 0 & 1
\end{bmatrix}
\begin{bmatrix}
X_\alpha \\
X_\beta \\
X_0
\end{bmatrix}
\]

\( X_d = X_\alpha \cos \Theta + X_\beta \sin \Theta \)

\( X_q = -X_\alpha \sin \Theta + X_\beta \cos \Theta \)  \hspace{1cm} (2.3)

The inverse transformation is the transformation of coordinates from the \( d-q \) rotating coordinate system to get back to the three-phase stationary coordinate system. This transformation is made in two steps:
A- The inverse Park transformation; to transfer from $d$-$q$ to $\alpha$-$\beta$, stationary frame.

\[
\begin{bmatrix}
X\alpha \\
X\beta \\
X0
\end{bmatrix} = \begin{bmatrix}
\cos \Theta & -\sin \Theta & 0 \\
\sin \Theta & \cos \Theta & 0 \\
0 & 0 & 1
\end{bmatrix}
\begin{bmatrix}
Xd \\
Xq \\
X0
\end{bmatrix}
\]

\[X_\alpha = X_d \cos \Theta - X_q \sin \Theta\]

\[X_\beta = X_d \sin \Theta + X_q \cos \Theta\]

![Diagram showing transformation from $d$-$q$ to $\alpha$-$\beta$ reference frame]

**Figure 2-6 Transformation $d$-$q$ to $\alpha$-$\beta$ reference frame**

B- The inverse Clarke transformation; to transfer from $\alpha$-$\beta$ stationary coordinate system to the three-phase.

\[
\begin{bmatrix}
Xa \\
Xb \\
Xc
\end{bmatrix} = \begin{bmatrix}
1 & 0 & 0 \\
-\frac{1}{2} & \frac{\sqrt{3}}{2} & 0 \\
-\frac{1}{2} & -\frac{\sqrt{3}}{2} & 0
\end{bmatrix}
\begin{bmatrix}
X\alpha \\
X\beta \\
X0
\end{bmatrix}
\]

\[X_a = X_a\]

\[X_b = \frac{-1}{2} X_a + \frac{\sqrt{3}}{2} X_\beta\]

\[X_c = \frac{-1}{2} X_a - \frac{\sqrt{3}}{2} X_\beta\]

(2.4)
As mentioned before, it is necessary to have knowledge of the rotor flux angle position (θ) in space in order to implement vector control. The way in which this position is obtained leads to the two types of vector control in use today; Direct Vector Control (DVC) and Indirect Vector Control (IVC).

**I-Direct Vector Control:**

In DVC the field angle is calculated by using the terminal voltages and currents. The d-q frame is rotating at synchronous speed ωe with respect to the stationary reference frame α-β, and at any point in time, the angular position of the d axis with respect to the α axis is θ as show in Figure 2-8.

From this phase diagram it can be written:

\[
\psi_{r\alpha} = \psi_r \cos \theta \quad \therefore \cos \theta = \frac{\psi_{r\alpha}}{\psi_r}
\]

\[
\psi_{r\beta} = \psi_r \sin \theta \quad \therefore \sin \theta = \frac{\psi_{r\beta}}{\psi_r}
\]
And $\Psi_r = \sqrt{\psi_{r\alpha}^2 + \psi_{r\beta}^2}$

Also $\Psi_r = \tan \frac{\psi_{r\beta}}{\psi_{r\alpha}}$ \hspace{1cm} (2.6)

Figure 2-9 Flux Phase Vector Position

To calculate the rotor flux angle position ($\theta$) in space used in direct field oriented control, it is necessary to measure the air-gap flux ($\psi_o$) directly by using hall probes or search coils mounted in the air-gap. The equations governing the fluxes are given by:

$$\Psi_r = L_o i_s + L_r i_r$$
$$\Psi_o = L_o i_s + L_o i_r$$
$$\Psi_s = L_s i_s + L_o i_r$$

Eliminating $i_r$ from first and second equations yields

$$\Psi_r = (1 + \sigma) \psi_o - L_o i_s \quad \text{where} \quad \sigma = (L_r - L_o)/L_o$$

$\therefore \quad \Psi_{r\alpha} = (1 + \sigma) \psi_{o\alpha} - L_o i_{s\alpha}$

And $\Psi_{r\beta} = (1 + \sigma) \psi_{o\beta} - L_o i_{s\beta}$

The angle ($\theta$) is calculated by using the terminal voltage and current or flux sensor.

$$\theta = \tan^{-1} \frac{\psi_{r\beta}}{\psi_{r\alpha}}$$ \hspace{1cm} (2.7)
Calculate the Rotor Flux Angle (θ)

From $i_{sd}$ and $i_{sq}$, the torque and field current are thus derived from the following equation:

$$T = K_t i_{sq} i_m \quad \text{and} \quad i_m = \frac{i_{sd}}{s \tau_r + 1} \quad (2.8)$$

Thus $i_m$ is $i_{sd}$ but filtered by a 1st order filter, time constant $\tau_r$.

Figure 2-11 Torque and Field Current Calculate

Figure 2-12 shows the design of the direct vector control with torque control, field current control and field weakening.

Referring to Equation 2.8, should $i_{sd}$ equals zero, then the minimum value of $i_{sd}$ is applied according to the block shown below:
The programming selected switch block is a function in Matlab/Simulink tool box used to avoid zero cross coupling in the output at any operating conditions by adding an initial value when $I_{sd}$ equal to zero (i.e. a minimum value).

The next figure shows another design for direct vector control with speed control, field current control and field weakening. It is this method that was used as a basis for the control system for the BDFTIG, will be explained in chapter three.
In the control scheme in Figure 2-14, the output of the speed PI controller is $i_{s_q}^*$, and the outputs from current loop controller are $v_{s_q}$ and $v_{s_d}$. These can then be transformed from a two phase rotating frame into a three phase stationary frame. The problem with direct vector control is the frequency $\omega_e$ of the drive is not controlled but derived from the Hall effect sensor and it may not be practical to implement it. Also the air gap flux can be directly measured in a machine using specially fitted search coils or Hall effect sensors. However, the drift in the integrator with a search coil is problematic at very low frequencies. Hall effect sensors tend to be temperature-sensitive and easily broken. Therefore, it will be necessary to use indirect vector control.

**II- Indirect Vector Control:**

Indirect field oriented control is a popular vector control approach and has become the usual method in commercial applications using field oriented control. It is similar to direct vector control except the unit vector signals $\cos \Theta_e$ and $\sin \Theta_e$ are generated in a feed forward manner. The $a-\beta$ axes are fixed and the $d-q$ axes are
rotating at synchronous speed and so there is a slip difference between the rotor speed and the synchronous speed. The supply frequency, $\omega_e$, is equal to the sum of the rotor angular velocity and the machine slip value given by:

$$\omega_e = \omega_r + \omega_{sl}$$

Since, $\Theta_e = \int \omega_e \, dt$

$$\Theta_e = \int (\omega_r + \omega_{sl}) \, dt$$

$$\therefore \Theta_e = \Theta_r + \Theta_{sl} \quad (2.9)$$

In order to guarantee decoupling between the stator flux and the torque, the torque component of the current, $i_{qs}$, should be aligned with the $q$ axis and the stator flux component of current, $i_{ds}$, should be aligned with the $d$ axis.

The $d$-$q$ axis equivalent circuits of the Induction machine to derive control terms are shown on the Figure 2-16.
From the equivalent circuits the following are derived:

- The rotor flux linkage equations:

\[
\begin{align*}
\psi_r^d &= L_r i_r^d + L_m i_s^d \\
\psi_r^q &= L_r i_r^q + L_m i_s^q
\end{align*}
\]  

From equation 2.10 obtains the \(d-q\) rotor current equation as show below:

\[
\begin{align*}
i_r^q &= \frac{\psi_r^q}{L_r} - \frac{L_m i_s^q}{L_r} \\
i_r^d &= \frac{\psi_r^d}{L_r} - \frac{L_m i_s^d}{L_r}
\end{align*}
\]  

- The rotor circuit equations:

\[
\frac{d\psi_r^d}{dt} + R_r i_r^d - (\omega_e - \omega_i) \psi_r^q = 0
\]

And \[
\frac{d\psi_r^q}{dt} + R_r i_r^q + (\omega_e - \omega_i) \psi_r^d = 0
\]

From the rotor circuit equations it is possible eliminate the rotor currents, which cannot be directly obtained.
\[
\frac{d\psi_r^d}{dt} + \frac{R_r\psi_r^d}{L_r} - \frac{R_rL_m i_s^d}{L_r} - (\omega_e - \omega_r) \psi_r^q = 0
\]

\[
\frac{d\psi_r^q}{dt} + \frac{R_r\psi_r^q}{L_r} - \frac{R_rL_m i_s^q}{L_r} + (\omega_e - \omega_r) \psi_r^d = 0
\] (2.12)

For decoupling control the total rotor flux needs to be aligned with the \(d\)-axis in this case the \(q\)-component rotor flux \(\psi_r^q\) will be zero.

Substituting into the equation 2.12, and letting \(\psi_r^d = L_m i_m\) to obtain the \(\omega_{slip}\):

\[
\omega_{slip} = \frac{i_{sq}}{\tau_r i_m}
\] (2.13)

Where \(\tau_r = \frac{L_r}{R_r}\) is rotor time constant and \(\omega_{slip} = \omega_e - \omega_r\)

From equation 2.13, it should be noted that \(i_{sd}\) is used in slip gain block instead \(i_m\) if the operating under constant flux not have a field weakening feature, hence the \(\frac{di_m}{dt}\) = zero and \(i_m = i_{sd}\)

Therefore the flux vector angle will be:

\[
\Theta_r = \int (\omega_r + \frac{i_{sq}}{\tau_r i_{sd}}) dt
\]

The full block diagram for IVC is illustrated in the next figure.
To improve the performance of the \( d-q \) control loop voltage compensation is added to the control system [5], assuming the stator equations for the induction machine are:

\[
\begin{align*}
\nu_{sd} &= R_s i_{sd} + \sigma L_s \frac{d i_{sd}}{dt} - \omega_e \sigma L_s i_{sq} + \omega_e \frac{L_o}{L_r} \psi_{rq} \\
\nu_{sq} &= R_s i_{sq} + \sigma L_s \frac{d i_{sq}}{dt} + \omega_e \sigma L_s i_{sd} + \omega_e \frac{L_o}{L_r} \psi_{rd}
\end{align*}
\]

(2.14)

As shown in the control design Figure 2-17, the \( i_{sq} \) and \( i_{sd} \) errors are processed by the PI controllers to give \( \nu_{sq}^* \) and \( \nu_{sd}^* \) respectively.

Where \( \nu_{sq} = R_s i_{sq} + \sigma L_s \frac{d i_{sq}}{dt} \) and \( \nu_{sd} = R_s i_{sd} + \sigma L_s \frac{d i_{sd}}{dt} \)

But \( \nu_{sd}^* = \nu_{sd} + \dot{\nu}_{sd} \) and \( \nu_{sq}^* = \nu_{sq} + \dot{\nu}_{sq} \)

Therefore the voltage compensation:

\[
\dot{\nu}_{sq} = \omega_e \sigma L_s i_{sq} + \omega_e \frac{L_o}{L_r} \psi_{rd}
\]
\[ \dot{v}_{sd} = -\omega_e \sigma L_s i_{sd} + \omega_e \frac{L_o}{L_r} \psi_{rq} \] (2.15)

Figure 2-18 Block diagram for Voltage Compensation

2.4 Conclusion

In this chapter a review of the principal FOC methods for induction machines has been presented. It is clear that the advantages of FOC are not only to decouple the control of the induction motor’s flux and torque via coordinate transformations, but also to control the phase angle and to control the amplitudes of the current and flux. A FOC scheme similar to that shown in Figure 2-16 was implemented on the BDFTIG test rig with the speed control. Further detail will be presented in chapter four after the BDFTIG model has been described in the next chapter.
Chapter 3 BDFTIG Model Development

3.1 Introduction

In the following chapter, the complete system model design for the BDFTIG will be presented. The model is initially derived for the machine equivalent circuits, followed by the system equations. The equations provide the basis for developing the machine model and the FOC system within MATLAB/SIMULINK® software.

3.2 Principle Structure of BDFTIG

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. 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 BDFTIG modelling. To allow variable speed operation, however, these torques need to be variable quantities. This is achieved by inserting an AC-DC-AC power converter between one of the machines forming the BDFTIG and connecting the other machine 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.
For the experimental rig, the BDFTIG consists of two separate wound rotor induction machines, the main induction machine of the desired power rating is referred to as the power machine and other machine is referred to as the control machine. The reduced ratings of the control machine are justified by the fact that this part of the BDFTIG performs only regulatory functions and handles a fraction of the power that flows through the power machine. The power and the control machines are connected mechanically and electrically. The first requirement is to make clear the electromechanical interconnection that exists between the power and the control machines. The straightforward ways to connect these two machines is in the back-to-back method with no phase inversion on the rotor side, as shown Figure 3-1.

![Diagram of BDFTIG Connection](image)

**Figure 3-1 The BDFTIG Connection**

From the above discussion, an important conclusion regarding the operational speed of the BDFTIG can be drawn. Clearly under normal operating conditions there exists two excitation voltages applied to the stator windings of the BDFTIG. Furthermore, these voltages generally have different frequencies. Therefore, the mechanical speed of the BDFTIG is both the function of a power machine and the control machine excitation frequency. The general expression for the mechanical speed of the BDFTIG is given in the next equation. Whether the two frequencies combine in an additive or a subtractive manner is determined by the rotor
interconnection in the BDFTIG, however, in the generation mode it is preferable that the control machine frequency carries a positive sign. (i.e. the rotational sequence of the stator magnetic field of the control machine is in opposition to the direction of rotation of the shaft. Hence $\omega_r = \omega_c + \omega_m$).

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

The power machine winding is fed from the grid and the control machine winding is fed from an adjustable voltage and frequency source. The BDFTIG is suitable for high power applications since the power machine stator can be at a high power and the brushless slip energy recovery/injection in the control machine stator can be at a lower power.

In this type of connection, the rotor currents produced by the two machines join in the subtractive technique, and the rotor voltages have the same signs,

i.e. $i_r = i_{r_p} = -i_{r_c}$ and $v_r = v_{r_p} = v_{r_c}$

These connections actually have an effect on the distribution of the magnetic fields and flux inside the BDFTIG, producing the two counter-rotating torques as will be discussed in the following sections.

**3.3 Equivalent Circuit Analysis of the BDFTIG**

The purpose in this section is to create the mathematical equations of the dynamic performance of the BDFTIG. As long as the equations are known, any control algorithm can be implemented on a PC and modelled in Simulink.
By simplifying the controller algorithm, the machine quantities should be expressed in the \( d-q \) frame by employing Park’s and Clark’s transformation. The reason for this 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. More detail how to choose the suitable reference frame is explaining in the next section.

Following the construction of the BDFTIG model, there is a choice for choice one of three reference frames to be used:

Firstly, the reference frame attached to the power machine stator. Secondly, the reference frame attached to the control machine stator. Thirdly, the reference frames attached to the rotor. The obvious choice would be to use the reference frame on the rotor, as its rotational speed is the same for both the power and the control machines forming the BDFTIG. However, this is not a useful selection, because that frame does not rotate at a constant speed, additionally; the currents and voltages would retain their sinusoidal nature, presenting a considerable challenge for controller design [19]. The best selection that allows transformation of all the voltages and currents into equivalent DC values under steady state operation lies in selecting the synchronously rotating reference frame attached to the power machine stator.
In Figure 3-2, \( D_{sp}/Q_{sp} \) stand for the stationary reference frame attached to the power machine stator while \( D_e/Q_e \) is the synchronous reference frame rotation at \( \omega_e \). The transformation angle for the stator quantities is the synchronous angle, which for a ‘stiff’ grid always rotates at a constant speed. \( D_r/Q_r \) is the \( d\)-\( q \) reference frame attached to the rotor. This stationary frame, however, is rotating with respect to the stator stationary reference frame at an angular speed of \( \omega_r \). This speed can be easily obtained as a difference between the synchronous speed and the shaft electrical frequency as shown in the equation below.

\[
\omega_r = \omega_p - P_p \omega_m
\]

For the control machine, the rotor frame would be the same as the power machine due to the back-to-back connection. But its stator frame rotates at the speed \( \omega_c \), which is shown in Figure 3-2. Moreover, it also shows the angular relationship between the power machine stator, the power and the control machine rotors and control machine stator with the selected synchronous reference frame. Furthermore, the control machine is rotating with respect to the power machine. Therefore, to plot 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 the next equation.
\[ \theta_c = \theta_P - P_p \theta_m - P_c \theta_m \quad \text{or} \quad \omega_c = \omega_P - \omega_m (P_p + P_c) \]

The complete rotation for the BDFTIG scheme is shown in next figure:

![Diagram showing the complete rotation for the BDFTIG scheme](image)

**Figure 3-3 The Rotations for the BDFTIG**

### 3.4 Electrical System Equations for BDFTIG

The BDFTIG consists of two separate wound rotor induction machines, a power machine and a control machine. The next two sections present the derivation of the electrical for both halves of the BDFTIG.

**3.4.1- Power Machine Modelling**

The equivalent circuit of the power machine part of the BDFTIG is shown in Figure 3-4 [24].
The general form of the vector equations of the BDFTIG are presented below:

\[ v_s^q = R_s i_s^q + L_s \frac{di_s^q}{dt} + \omega_p L_s i_s^d + L_m \frac{di_p^q}{dt} + \omega_p L_m i_p^d \]

\[ v_s^d = R_s i_s^d + (L_s i_s^q + L_m i_p^q) s + (L_s i_s^d + L_m i_p^d) \omega_p \]

The power machine stator flux linkage current relations are:

\[ \psi_s^q = L_s i_s^q + L_m i_p^q \]

\[ \psi_s^d = L_s i_s^d + L_m i_p^d \]  \hspace{1cm} (3.1)

\[ \therefore v_s^q = R_s i_s^q + \frac{d\psi_s^q}{dt} + \omega_p \psi_s^d \]

\[ v_r^q = R_r i_r^q + L_r \frac{di_r^q}{dt} + \omega_r L_r i_r^d + L_m \frac{di_s^q}{dt} + \omega_r L_m i_s^d \]

\[ v_r^d = R_r i_r^d + (L_r i_r^q + L_m i_s^q) s + (L_r i_r^d + L_m i_s^d) \omega_r \]

The power machine rotor flux linkage current relations are:
\[ \psi_{r_p} q = L_{r_p} i_{r_p} q + L_{mp} i_{sp} q \]

\[ \psi_{r_p} d = L_{r_p} i_{r_p} d + L_{mp} i_{sp} d \]  

(3.2)

\[ \therefore v_{r_p} q = R_{r_p} i_{sp} q + \frac{d\psi_{r_p} q}{dt} + \omega_p \psi_{r_p} d \]

\[ v_{sp} d = R_{sp} i_{sp} d + L_{sp} \frac{di_{sp} d}{dt} - \omega_p L_{sp} i_{sp} q + L_{mp} \frac{di_{sp} d}{dt} - \omega_p L_{mp} i_{r_p} q \]

\[ v_{sp} d = R_{sp} i_{sp} d + (L_{sp} i_{sp} q + L_{mp} i_{r_p} q) \psi_{sp} \]

\[ \therefore v_{sp} d = R_{sp} i_{sp} d + \frac{d\psi_{sp} d}{dt} \]

\[ v_{r_p} d = R_{r_p} \frac{di_{r_p} d}{dt} + L_{r_p} \frac{dr_{r_p} d}{dt} + \omega_r L_{r_p} i_{sp} q + L_{mp} \frac{dr_{r_p} d}{dt} + \omega_r L_{mp} i_{sp} q \]

\[ v_{r_p} d = R_{r_p} i_{sp} d + (L_{r_p} i_{sp} q + L_{mp} i_{r_p} q) \psi_{r_p} \]

\[ \therefore v_{r_p} d = R_{r_p} i_{sp} d + \frac{d\psi_{r_p} d}{dt} \]

\[ \begin{bmatrix} v_{sp} q \\ v_{sp} d \\ v_{r_p} q \\ v_{r_p} d \end{bmatrix} = \begin{bmatrix} R_{sp} + SL_{sp} & \omega_p L_{sp} & SL_{mp} & \omega_p L_{mp} \\ -\omega_p L_{sp} & R_{sp} + SL_{sp} & -\omega_p L_{mp} & SL_{mp} \\ SL_{mp} & \omega_r L_{mp} & R_{rp} + SL_{rp} & \omega_r L_{rp} \\ -\omega_r L_{mp} & SL_{mp} & -\omega_p L_{rp} & R_{rp} + SL_{rp} \end{bmatrix} \begin{bmatrix} i_{sp} q \\ i_{sp} d \\ i_{r_p} q \\ i_{r_p} d \end{bmatrix} \]  

(3.3)

The electrical torque creation in the power machine is governed by the same principles that apply for any induction machine. The general equation of the electrical torque in this case is simply:

\[ T_e = \frac{3}{2} \left( \frac{p}{2} \right) \psi_m l_r \]
In the \(d-q\) reference frame, however, the last equation may be rearranged to show the torque as a function control, for grid connection the power machine has a constant rms voltage because that the power machine is connected to a ‘stiff’ grid with constant rms voltage. The torque could be;

\[ T_p = -\frac{3}{2} \left( \frac{P}{2} \right) (\psi_{sp}^q I_{sp}^d - \psi_{sp}^d I_{sp}^q) \]  

(3.4)

It is clearly shown from the above equation that the only control variables 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.

3.4.2- Control Machine Modelling

Figure 3-5 shows the equivalent circuit for the control machine from which electrical system equations can be derived.

\[
\begin{align*}
\psi_{sc}^q &= R_{sc} I_{sc}^q + L_{sc} \frac{dI_{sc}^q}{dt} + \omega_c L_{sc} I_{sc}^d + L_{sc} \frac{dI_{sc}^d}{dt} + \omega_c L_{mc} I_{rc}^d
\end{align*}
\]
The control machine stator flux linkage current relations are:

\[ \psi_{sc}^q = L_{sc} \dot{i}_{sc}^q + L_{mc} \dot{i}_{rc}^q \]

\[ \psi_{sc}^d = L_{sc} \dot{i}_{sc}^d + L_{mc} \dot{i}_{rc}^d \]  

\[ \therefore v_{sc}^q = R_{sc} \dot{i}_{sc}^q + \frac{d\psi_{sc}^q}{dt} + \omega_c \psi_{sc}^d \]

\[ v_{rc}^q = R_{rc} \dot{i}_{rc}^q + L_{rc} \frac{d\dot{i}_{rc}^q}{dt} + \omega_r L_{rc} \dot{i}_{rc}^d + L_{mc} \frac{d\dot{i}_{sc}^q}{dt} + \omega_r L_{mc} \dot{i}_{sc}^d \]

\[ v_{rc}^q = R_{rc} \dot{i}_{rc}^q + (L_{rc} \dot{i}_{rc}^q + L_{mc} \dot{i}_{sc}^q) \mathbf{s} + (L_{rp} \dot{i}_{rp}^d + L_{mc} \dot{i}_{sc}^d) \omega_r \]

The control machine rotor flux linkage current relations are:

\[ \psi_{rc}^q = L_{rc} \dot{i}_{rc}^q + L_{mc} \dot{i}_{sc}^q \]  

\[ \therefore v_{rc}^q = R_{rc} \dot{i}_{rc}^q + \frac{d\psi_{rc}^q}{dt} + \omega_r \psi_{sc}^d \]

\[ v_{sc}^d = R_{sc} \dot{i}_{sc}^d + L_{sc} \frac{d\dot{i}_{sc}^q}{dt} - \omega_c L_{sc} \dot{i}_{sc}^q + L_{mc} \frac{d\dot{i}_{rc}^d}{dt} - \omega_c L_{mc} \dot{i}_{rc}^q \]

\[ v_{sc}^d = R_{sc} \dot{i}_{sc}^d + \mathbf{s} (L_{sc} \dot{i}_{sc}^d + L_{mc} \dot{i}_{rc}^d) - \omega_c (L_{sc} \dot{i}_{sc}^q + L_{mc} \dot{i}_{rc}^q) \]

\[ \therefore v_{sc}^d = R_{sc} \dot{i}_{sc}^d + \frac{d\psi_{sc}^d}{dt} - \omega_c \psi_{sc}^q \]

\[ v_{rc}^d = R_{rc} \dot{i}_{rc}^d + L_{rc} \frac{d\dot{i}_{rc}^q}{dt} + \omega_r L_{rc} \dot{i}_{rc}^q + L_{mc} \frac{d\dot{i}_{sc}^d}{dt} + \omega_r L_{mc} \dot{i}_{sc}^d \]
\begin{align*}
\nu_{rc} &= R_{rc} i_{rc} + (L_{rc} i_{rc} + L_{mc} i_{sc}) s + (L_{rp} i_{rp} q + L_{mc} i_{sc}) \omega_r \\
\therefore \nu_{rc} &= R_{rc} i_{rc} + \frac{d\psi_{rc}}{dt} + \omega_r \psi_{rc} \\
\begin{bmatrix}
\nu_{sc} \\ \nu_{rd} \\ \nu_{rq} \\ \nu_{rd}
\end{bmatrix} &=
\begin{bmatrix}
R_{sc} + S L_{sc} & \omega_{cp} L_{sc} & S L_{mc} & \omega_{cL_{mc}} \\
-\omega_c L_{sc} & R_{sc} + S L_{sc} & -\omega_c L_{mc} & S L_{mc} \\
S L_{mc} & \omega_r L_{mc} & R_{rc} + S L_{rc} & \omega_r L_{rc} \\
-\omega_r L_{mc} & S L_{mc} & -\omega_r L_{rc} & R_{rc} + S L_{rc}
\end{bmatrix}
\begin{bmatrix}
I_{sc} q \\ I_{rd} \\ I_{rq} \\ I_{rd}
\end{bmatrix} \\
(3.7)
\end{align*}

As stated before, 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 essential rotor flux, as shown below;

\begin{align*}
\dot{i}_{rp} &= -i_{rc} = i_r \\
\psi_r &= \psi_{rp} - \psi_{rc} \\
\nu_r &= \nu_{rc} \quad \therefore 0 = \nu_{rp} - \nu_{rc} \\
0_r q &= R_{rp} i_{rp} q + L_{rp} \frac{d i_{rp} q}{dt} + \omega_r L_{rp} i_{rd} + L_{mp} \frac{d i_{sp} q}{dt} + \omega_r L_{mp} i_{sp} + R_{rc} i_{rp} q + R_{rc} \frac{d i_{rc} q}{dt} \\
&+ \omega_r L_{rc} i_{rd} - L_{mc} \frac{d i_{sc} q}{dt} - \omega_r L_{mc} i_{sc} q
\end{align*}

But \( L_r = L_{rp} + L_{rc} \) and \( R_r = R_{rp} + R_{rc} \)

\begin{align*}
0_r q &= R_r i_{rp} q + L_r \frac{d i_{rp} q}{dt} + \omega_r L_r i_{rd} + L_{mp} \frac{d i_{sp} q}{dt} + \omega_r L_{mp} i_{sp} - L_{mc} \frac{d i_{sc} q}{dt} - \omega_r L_{mc} i_{sc} q \\
0_r q &= R_r i_{rp} q + (L_r i_{rp} q + L_{mp} i_{sp} q - L_{mc} i_{sc} q) s + (L_r i_{rd} + L_{mp} i_{sp} - L_{mc} i_{sc}) \omega_r \\
0_r q &= R_r i_{rp} q + L_{mp} i_{sp} q - L_{mc} i_{sc} q
\end{align*}

The combined rotor flux linkage current relations are:

\begin{align*}
\psi_r q &= L_r i_{rp} q + L_{mp} i_{sp} q - L_{mc} i_{sc} q
\end{align*}
\[
\psi_r^d = L_r i_r^d + L_{m_p} i_{s_p}^d - L_{m_c} i_{s_c}^d
\]  
\hfill (3.8)

\[
\therefore 0_r^q = R_r i_r^q + \frac{d\psi_r^q}{dt} + \omega_r \psi_r^d
\]

\[
0_r^d = R_r i_r^d + L_r \frac{di_r^d}{dt} + \omega_r L_r i_r^q + L_{m_p} \frac{d i_{s_p}^d}{dt} + \omega_r L_{m_p} i_{s_p}^q - L_{m_c} \frac{d i_{s_c}^d}{dt} - \omega_r L_{m_c} i_{s_c}^q
\]

\[
0_r^d = R_r i_r^d + (L_r i_r^d + L_{m_p} i_{s_p}^d - L_{m_c} i_{s_c}^d) s + (L_r i_r^q + L_{m_p} i_{s_p}^q - L_{m_c} i_{s_c}^q) \omega_r
\]

\[
\therefore 0_r^d = R_r i_r^d + \frac{d\psi_r^d}{dt} + \omega_r \psi_r^q
\]

To state that electrical torque for the control machine is the same as the general equation for the electrical torque is not acceptable because the stator fluxes of the control machine are variable. The control machine torque must be expressed as a function of the excitation current. The purpose of this research is to provide a flexible power control of the BDFTIG. The next equation is the control machine torque, and it is given in terms of the control variables.

\[
T_c = -\frac{3}{2} \left( \frac{P_c}{2} \right) L_{m_c} (i_{s_c}^d i_r^q - i_{s_c}^q i_r^d)
\]  
\hfill (3.9)

The option of the rotor current as the second variable is clearly shown. It also demonstrates that there exists an electric coupling between the two stators of the BDFTIG, which is achieved through the common rotor current.
3.4.3- Complete BDFIG Model

To complete the full model of the BDFTIG, the sub-models of the power and the control machines need to be joined together. This is done by combining equation 3.3 with equation 3.7 and noting that all the rotor quantities can be added together to represent the common rotor.

\[
\begin{align*}
\psi_c &= L_{sc}\omega_\psi \psi_c - L_{mc}i_r \\
\psi_r &= L_{mp}\omega_\psi \psi_r - L_{mr}i_r \\
\psi_p &= L_{sp}\omega_\psi \psi_p + L_{mp}i_r
\end{align*}
\]

Figure 3-6 Equivalent Circuit of the BDFTIG

Converting the three-phase machine to the two-phase equivalent circuit by applying the standard Park’s and Clark’s transformation, the resulting model becomes as shown below;

\[
\begin{align*}
\psi_c &= L_{sc}\omega_\psi \psi_c - L_{mc}i_r \\
\psi_r &= L_{mp}\omega_\psi \psi_r - L_{mr}i_r \\
\psi_p &= L_{sp}\omega_\psi \psi_p + L_{mp}i_r
\end{align*}
\]

Figure 3-7 Equivalent d-q Circuits of the BDFTIG

The resulting BDFTIG dynamic electric model is given in next equation;
The dynamic equations together with the equivalent circuits of $d$-$q$ BDFTIG in Figure 3-7 demonstrate that there exists a certain amount of cross coupling in the rotor $d$-$q$ flux components as shown in next equations:

$$\psi_r^q = -\frac{R_r I_r^q + \frac{d\psi_r^d}{dt}}{\omega_r}$$

$$\psi_r^d = -\frac{R_r I_r^d + \frac{d\psi_r^q}{dt}}{\omega_r}$$

The conclusion from these equations is at steady state the active and reactive power flowing through the power machine may not be controlled in a completely decoupled method as in the DFIG. However, the effects of the rotor flux cross coupling can be reduced. This consideration will be taken into account for the design of the controller for BDFTIG.

The total electric torque ($T_e$) for BDFTIG is the sum of the individual torques from both machines:

$$T_e = -\frac{3}{4} \left[ P_p (\psi_s^q I_s^d - \psi_s^d I_s^q) + P_c L_{m_c} (I_s^d I_r^q - I_s^q I_r^d) \right]$$

(3.11)
The total electric torque equation can be expressed as a function of two currents; the power stator machine current and control machine stator current, as shown in Equation 3.11.

The electric torque equation is also equivalent to the load, the friction and total inertia of the power and control machines:

\[
T_e = T_L + (B_P^P + B_F^C) \omega_m + (j_s^P + j_s^C) \frac{d\omega_m}{dt}
\]  

(3.12)

Rearranging the previous equation to be deriving the shaft speed as shown below;

\[
\frac{d\omega_m}{dt} = \frac{1}{j_s^P + j_s^C} [T_e - T_L - (B_P^P + B_F^C) \omega_m]
\]

Hence, the shaft speed \( \omega_m = \int \frac{T_e - T_L - \omega_m (B_P^P + B_F^C)}{(j_s^P + j_s^C)} \) dt  

(3.13)

3.5 Simulink Implementation of the BDFTIG Model

Simulink is an environment for simulation and design for dynamic modelling. It presents an interactive graphical interface to simulate, implement and test a variety of time-varying systems [9]. For the correct simulation of the new controller, it was required to make sure that the BDFTIG model developed in the previous section was providing a suitable representation of the real generator. In this case, the power machine has a fixed stator voltage of 415V/50Hz and is fed from the grid, and the load torque applied from the wind turbine. This Simulink model was carried out using two 4kW machines each with four poles. The complete power
and control machine parameters with wind turbine input functions are presented in the Appendix ‘B’.

Last equations are used to build the Simulink model as shown in Figure 3-8, which were implemented in the BDFTIG system using various blocks from the Simulink libraries. The whole system is modelled in the continuous time domain with the variable-step (stiff/TR-BDF2) solver.
The three-phase voltages for the power and control machines are converted to the $d$-$q$ reference frame by the ABC<<DQ0 block as shown below;
Furthermore, this block produced the instantaneous angle’s velocity for the power machine, control machine and the rotor as clear from Subsystem block in Figure 3-9. The detail within the angle’s velocity is shown in Figure 3-10. Furthermore, the three phase voltage for the power and the control machines are transfer to $d$-$q$ reference frame.

As shown from the Simulink Model, Figure 3-8 the $d$-$q$ output voltage for the power and the control machine used with the velocity angles, (theta), are used to
build the model by the S-Function’s technique. The S-Function is a computer language description of Simulink blocks. The advantages of using S-functions are speed of development, generating special code for Simulink S-function to run in real time is faster and avoiding the time-consuming compile-link-execute cycle required by development in a compiled language, and also to have easier access to the MATLAB toolbox functions. There are six inputs to the S-functions, the \(d_q\) voltage and current for the power and the control machines, the mechanical torque produced from the wind turbine and last input the synchronous speed. As shown in Appendix ‘A’ and Figure 3-8, the outputs from the modelling are the currents, the torques, the fluxes and the shaft speed. The equation implementation in the S-functions is produced from the dynamic equations 3.10, as show below:

\[
[A] =
\begin{bmatrix}
L_{sp} & 0 & L_{mp} & 0 & 0 & 0 \\
0 & L_{sp} & 0 & L_{mp} & 0 & 0 \\
L_{mp} & 0 & L_r & 0 & L_{mc} & 0 \\
0 & L_{mp} & 0 & L_r & 0 & L_{mc} \\
0 & 0 & L_{mc} & 0 & L_{sc} & 0 \\
0 & 0 & L_{mc} & 0 & L_{sc} & 0
\end{bmatrix}
\]

\[
[B] =
\begin{bmatrix}
R_{sp} & \omega_p L_{sp} & 0 & \omega_p L_{mp} & 0 & 0 \\
-\omega_p L_{sp} & R_{sp} & -\omega_p L_{mp} & 0 & 0 & 0 \\
0 & \omega_r L_{mp} & R_r & \omega_r L_r & 0 & \omega_r L_{mc} \\
-\omega_r L_{mp} & 0 & -\omega_r L_r & R_r & -\omega_r L_{mc} & 0 \\
0 & 0 & 0 & \omega_r L_{mc} & R_{sc} & \omega_r L_{sc} \\
0 & 0 & -\omega_r L_{mc} & 0 & -\omega_r L_{sc} & R_{sc}
\end{bmatrix}
\]

\[
[V] =
\begin{bmatrix}
v_{sp}q \\
v_{sp}d \\
v_{r}q \\
v_{r}d \\
v_{sc}q \\
v_{sc}d
\end{bmatrix}
\]

\[
[i] =
\begin{bmatrix}
i_{sp}q \\
i_{sp}d \\
i_{r}q \\
i_{r}d \\
i_{sc}q \\
i_{sc}d
\end{bmatrix}
\]
\[ V = [B][I] + s[A][I] \quad \text{so} \quad V = BI + A \hat{I} \quad \text{and} \quad \hat{I} = A^{-1} V - B A^{-1} I \]

The next section is to test the modelling without any control and to present the Simulink results.

### 3.6 BDFTIG Model Simulation Results

To test the BDFTIG the model was implemented using Matlab/Simulink package as shown Figure 3-8. Once it was successfully tested, this model was used in all the simulations presented in these theses. The main tests consisted of disabling one side of the BDFTIG like a power machine. This test can be done by creating a short circuit on control machine stator side and applying a constant AC voltage on the power machine, thus making the natural speed of the system to be 78.53 r/s or 750 rpm, as shown in Figure 3-11, because both machines have four poles each. In this type of test the load torque was varied to allow both motoring and generation modes of operation.

![Figure 3-11 The Speed of BDFTIG at no-load](image)

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 close to zero at steady state Figure 3-12.

![Figure 3-12 No-load Control Machine Current](image)

The next figure describes the electrical torque for the power machine, control machine and the modelling total torque at no load.

![Figure 3-13 The BDFTIG Torques at no load](image)

The simulation was carried into the next stage; the system is tested when an external voltage applied to the control machine side. The voltage was applied while the load torque was kept constant to maintain the generation mode of operation.
As Figure 3-15 shows, when the control machine excitation was applied, there generate the control machine current.

Finally, Figure 3-16 shows the electrical torques create by the BDFTIG. As expected, under short circuit and no load conditions the total electrical torque of the BDFTIG is generated by the power machine alone.
Once the BDFTIG becomes loaded or an excitation voltage is applied on the control side, the individual torques of the two machines in the BDFTIG combine in an additive manner. Similar results were obtained for the BDFTIG formed by the two machines with different power ratings and unequal number of poles.

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

3.7 Conclusion

This chapter has provided the detailed analysis of operational principles of the BDFTIG. 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 behaviour of the BDFTIG. As expected, the speed and power of BDFTIG 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 BDFTIG controller design that will be discussed in the following chapter.
Chapter 4- BDFITG Controller Design

4.1 Introduction

There are several ways to control the power output of wind turbines. These techniques depend on the design of the control system in the model. In order to maintain the wind turbine efficiency, it must be able to meet the power demand by providing a maximum output at the required power factor. Therefore, it is necessary that the controller allows independent control of these two parameters of the BDFITG in the wind turbine. The primary function of such a controller would be to allow an optimum speed tracking to 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 the 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.

4.2 Stator Flux Field Oriented Control

The control design for the BDFITG was developed on the stator flux field oriented control (FOC). This means that the selected reference frame is aligned and rotating with the stator flux vector of the power machine, because its stator flux vector has two unique properties: Under normal operational conditions and connected to a 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.

The next step was to investigate the behaviour of the voltage vector. When using an induction machine with two poles, it can be shown that there exists a single voltage vector that rotates at a synchronous speed with the supply frequency, as shown in the Figure 4-1. This vector is an algebraic sum of the individual phase voltage vectors and for a balanced three-phase system; it is 3/2 of the phase voltage magnitude. The importance of the voltage vector is that it always has a constant rms amplitude and speed which can be easily measured if the machine is connected to the grid.

![Figure 4-1 Voltage Vector Position](image)

A different technique was used to derive the stator flux vector. This 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 in the stationary frame:

\[
V_{sp} = R_{sp} I_{sp} + \frac{d}{dt} \psi_{sp}
\]  

(4.1)

Therefore, 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 favour 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 next section.

![Figure 4-2 Voltage and Flux Vectors](image)

Figure 4-2 Voltage and Flux Vectors

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 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.

### 4.3 Controller Design Principles for the BDFTIG

As discussed in the earlier sections, the main reason of the controller design was to apply the optimal speed tracking loop and control the reactive power in an independent and robust manner. The approach taken in the control of BDFTIG is to insert a quantity of additional rotor current into the control machine stator to control the amount of the electrical torque created by the machine. This task necessitated the generation of the currents of a variety of frequencies and amplitudes, which can be reached with an AC to the AC power converter. The
back to back Power Width Modulation (PWM), power converter was selected in this experiment due to its flexibility and high performs of controllability. The BDFTIG system with a back to back converter is shown in next figure.

![BDFTIG System Diagram](image)

**Figure 4-3 The BDFTIG Systems with a back-to-back Converter**

The back to back AC to AC Power converter consists of two converters, machine side and grid side converters that are connected back to back. The first converter is the Voltage Source Rectifier (VSR) and second one is the Voltage Source Inverter (VSI) connected via a common DC link. The DC link capacitor is positioned between both converters, as energy storage, in order to keep the voltage ripple in the dc-link voltage small. Both VSR and VSI are vector controlled, giving the required degree of freedom in choosing the operational strategy as well as independent running of the parameters such as power factor and current magnitude. The next sections explain and present the detailed information for the controller design in the Grid side power converter and machine side power converter.

**4.3.1 The Control for the Grid-Side Power Converter**

The main objective of the grid-side power converter is to maintain a fixed DC link voltage constant in any case of the operational circumstances of the modelling...
and regardless of the magnitude and direction of slip power flow. The rectifier presents the dual function of a bidirectional converter as well as rectifier. The $d_q$ axes currents at the input of the rectifier are used to regulate DC link voltage and supply reactive power respectively. Vector control can be applied to the VSR to enable independent control of the active and reactive power. A power circuit of a PWM voltage source converter is shown in Figure 4-4. Where, $(R, L)$ is the line inductor between generator and the converter terminal, $(V_a)$ is the generator phase voltage, $(V_{a}^*)$ is the bridge converter voltage controllable according to the demanded DC voltage level, $(i_a)$ is the line current, $(I_{dc}^*)$ is the converter DC output current, $(v_{dc})$ is the converter DC output controlled voltage and $(I_a)$ is the load current [5].

![VSR Circuit Model](image)

**Figure 4-4 VSR Circuit Model**

The three phase voltages across the voltage source rectifier circuit are:

$$\begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} = R \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + L \frac{d}{dt} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \begin{bmatrix} v_a^* \\ v_b^* \\ v_c^* \end{bmatrix}$$

Transfer the equations in a synchronous $d-q$ reference frame as shown below:
\[
\begin{bmatrix}
  v_q \\
  v_d
\end{bmatrix} = R \begin{bmatrix}
  i_q \\
  i_d
\end{bmatrix} + sL \begin{bmatrix}
  i_q \\
  i_d
\end{bmatrix} + \omega_e L \begin{bmatrix}
  -i_q \\
  i_q
\end{bmatrix} + \begin{bmatrix}
  v_q^* \\
  v_d^*
\end{bmatrix}
\] (4.2)

\[v^d = R_i i_d + L \frac{d i_d}{dt} - \omega_e L i_q + v^d^*\]

\[v^q = R_i i_q + L \frac{d i_q}{dt} + \omega_e L i_d + v^q^*\]

The total active and reactive power flows in the voltage source rectifier circuit in Figure 4-4 can also be defined. The general expressions for the active and reactive power flow, assuming the power machine winding resistance and harmonics are neglected, are shown in equation 4.3.

\[P_s = \frac{3}{2} \left( v_s^q i_s^q + v_s^d i_s^d \right)\]

\[Q_s = \frac{3}{2} \left( v_s^q i_s^d - v_s^d i_s^q \right)\] (4.3)

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 \(d\)-axes align to the synchronous reference frame rotating with the voltage vector \(v_s^d\), the power machine flux vector will be perpendicular to the power machine voltage vector. Therefore, the \(q\)-component of the voltage \(v_s^q\) always remains at zero. However, the above equations can be simplified by an appropriate selection of the reference frame. The power flow expressions are;

\[P_s = \frac{3}{2} \left( v_s^d i_s^d \right)\]
The magnitude of the DC link voltage is obviously a function of the active power flow in the voltage source rectifier. Assuming the resistive losses and the magnetizing losses due to the switching have been neglected, the active power applied to the converter is:

\[ V_{dc} I_{dc}^s = \frac{3}{2} v_s^d I_s^d \]  \hspace{1cm} (4.5)

The DC-link voltage produced by the VSR is a function of the modulation index \( m_a \) and the supply line voltage \( V_{dc} \) as shown in next equation [5].

\[ v_s^d = \frac{m_a}{2\sqrt{2}} V_{dc} \]

\[ V_{dc} = \frac{2\sqrt{2}}{m_a} v_s^d \]  \hspace{1cm} (4.6)

Re-arranging the equations 4.5 and 4.6 to derive the converter DC link current as shown below;

\[ I_{dc}^s = \frac{3m_a}{4\sqrt{2}} I_s^d \]  \hspace{1cm} (4.7)

However, the general expression for the DC link capacitance is;

\[ C \frac{dV_{dc}}{dt} = I_{dc}^s - I_{dc}^r \]
Rearranging and expanding to demonstrate the DC-link voltage is a function of the 
$d$-component of the supply current as shown in next equations:

\[ C \frac{dV_{dc}}{dt} = \frac{3m_a}{4\sqrt{2}} I_s^d - I_{dc}^r \]

\[ \frac{d}{dt} V_{dc} = \frac{1}{C} \left( \frac{3}{\sqrt{2}} m_a I_s^d - I_{dc}^r \right) \quad (4.8) \]

Equation 4.8 can be represented using a first order linear system. This equation is 
the basis for developing a standard PI controller. It confirms this equation; the DC link voltage can be controlled using the $d$- 
component of the supply current $I_s^d$. The DC-link control loop has to be expanded 
to include the inner current control loop for a suitable running operating value of 
the $I_s^d$ reference signal. The control law for the current loop is relatively 
straightforward, since the mathematical representation of the plant can be derived 
directly from equation 4.2 as:

\[ H_i(s) = \frac{I(s)}{V(s)} = \frac{1}{L_s + R} \]

\[ \frac{1}{H_i(s)} = L_s + R \quad (4.9) \]

For the inner loop the converter is modelled as a linear amplifier in equation 4.10. This expression is based on the VSR operation as a controllable converter whose 
DC-link voltage is a function of the fundamental component of the phase voltage.

\[ G_i(s) = 0.5m_a V_{dc} \quad (4.10) \]
The PI controller is \[ \frac{1.657(s + 889.38)}{s} \]

The complete mathematical equation for the VSR current control loop as shown in Appendix ‘F’.

\[ I_s^- \xrightarrow{K(s + a)} \frac{V_s^-}{s} \xrightarrow{\frac{m_g V_{dc}}{2}} V_s \xrightarrow{\frac{1}{L_s + R}} I_s \]
From figures 4-6 and 4-7 shown the control loop is stable.

The next step is to rearrange the equation 4.2 to create the reference value for the supply side converter and the command signals for the VSR controller.

\[
V_d^* = \frac{I_s d}{H_i(s)} + (\omega_e L I_q + V_d)
\]

\[
V_q^* = \frac{I_s q}{H_i(s)} - (\omega_e L I_d) \tag{4.11}
\]

The standard PI controller with the transfer function for the voltage source rectifier controller is shown in equation 4.12:

\[
G(s) = \frac{K(s+a)}{s} \tag{4.12}
\]

The design of the DC link voltage controller as for the outer voltage loop is easily derived, and assumed that the inner \(I_d\) is ideal from equation 4.7, the effective transfer function of the plant is;
\[
H_v(s) = \frac{V(s)}{I(s)} = \frac{1}{C_s} \tag{4.13}
\]

The close-loop block diagram is shown in Figure 4-8, which the converter itself is modelled differently for both the inner and outer loops. In the case of the outer loop it comes from equation 4.7:

\[
G_v(s) = \frac{I_{\text{in}}}{I_d} = \frac{3m_a}{4\sqrt{2}} \tag{4.14}
\]

The PI controller is

\[
\frac{1.8614(s + 888.7)}{S}
\]

The complete mathematical equation for the VSR voltage control loop is shown in Appendix ‘F’.
From Figures 4-9 and 4-10, it is seen that the control loop is stable.

Therefore the control schematic of the grid-side is shown in Figure 4-11.

There results and the implementation of the grid-side controller will be discussed in the following chapters.
4.3.2 The control for the Generator side Power Converter

The control machine of the BDFTIG 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 BDFTIG [2]. The active and reactive power flow equations for the power machine are:

$$P_p = \frac{3}{2} (v_{sp}^q i_{sp}^q + v_{sp}^d i_{sp}^d)$$

$$Q_p = \frac{3}{2} (v_{sp}^q i_{sp}^d - v_{sp}^d i_{sp}^q)$$  \hspace{1cm} (4.15)

The power machine’s winding resistance is neglected. The following reference frame alignment is made; to align the $d$-axes of the reference frame with the stator flux vector and power machine flux vector is perpendicular to the power machine voltage vector. Therefore, the $d$-component of the stator voltage of the power machine ($v_{sp}^d$) and the $q$-component of the flux vector of power machine ($\psi_{sp}^q$) always remains at zero. In this case the following constraints are applied to the system:

$$v_{sp}^d = \psi_{sp}^q = 0 \quad \text{and} \quad v_{sp}^q \neq \psi_{sp}^d \neq 0$$

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 equation 4.15, the final controller power equations take the following form:
The reactive power \( Q_p \), is controlled by the \( d \)-axis current of the power machine \( (i_{sp}^d) \), where the active power \( P_p \), is dominated by the \( q \)-axis current of the power machine \( (i_{sp}^q) \). It can be clearly seen from equation 4.16, that the inner loop control parameters are the \( d-q \) components of the power machines stator current. Since the only variable quantity that can be controlled directly in the whole BDFTIG system is the control machine current, this needs to be expressed in terms of these variables. This cannot be done directly and requires some manipulation of the stator fluxes of the BDFTIG.

Rearranging the power machine stator flux \( \psi_{sp} \) in equation 3.1 obtains the power machine stator current, \( i_{sp} \) is shown below:

\[
\dot{i}_{sp}^d = \frac{\psi_{sp} d - L_{mp} \dot{i}_r^d}{L_{sp}} \quad (4.17)
\]

Because the reference frame is aligned with the \( d \)-component of the \( \psi_{sp} \), the \( q \)-component in this reference frame aligned remains at zero.

\[
L_{sp} \dot{i}_{sp}^q + L_{mp} \dot{i}_r^q = 0
\]

Therefore, the \( q \)-component of the power machine stator current is:
\[ i_{sp}^q = \frac{-L_{mp} \hat{i}_r^q}{L_{sp}} \]  

(4.18)

Rearranging the rotor flux \( \psi_r \) equation 3.8 to get rotor current, \( \hat{i}_r \) as shown below:

\[ \hat{i}_r^d = \frac{\psi_r^d - L_{mp} i_{sp}^d + L_{mc} \hat{i}_{sc}^d}{L_r} \]  

(4.19)

\[ \hat{i}_r^q = \frac{\psi_r^q - L_{mp} i_{sp}^q + L_{mc} \hat{i}_{sc}^q}{L_r} \]  

(4.20)

To separate the power machine stator current \( \hat{i}_{sp} \), eliminating the rotor current \( i_r \) from the power machine stator current equations 4.17 and 4.18, by substituting for the rotor current \( \hat{i}_r^d \) and \( \hat{i}_r^q \) in equation 4.19 and 4.20 then rearranging to produce the following:

\[ i_{sp}^d = \frac{L_r \psi_{sp}^d}{L_{sp} L_r - L^2_{mp}} - \frac{L_{mp} \psi_r^d}{L_{sp} L_r - L^2_{mp}} - \frac{L_{mp} L_{mc} \hat{i}_{sc}^d}{L_{sp} L_r - L^2_{mp}} \]  

(4.21)

\[ i_{sp}^q = -\frac{L_{mp} \psi_r^q}{L_{sp} L_r - L^2_{mp}} - \frac{L_{mp} L_{mc} \hat{i}_{sc}^q}{L_{sp} L_r - L^2_{mp}} \]  

(4.22)

These equations confirm that there exists an electrical coupling between the control machine stator through the rotor to the power machine stator. The power machine stator current is determined by the power machine stator flux \( \psi_{sp} \), rotor flux \( \psi_r \) and control machine stator current \( \hat{i}_{sc} \).

Another aspect of the control is the presence of the power machine stator flux and rotor flux in the control equations. 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 4.2. 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 $\psi_s$, the $q$-component always remains equal to zero. Taking all of this into consideration, the power machine stator flux is then calculated as shown in Equation 4.23:

$$\psi_s^d = \int (v_s^q \, dt) / \omega_p$$

(4.23)

However, for a ‘stiff’ 50Hz grid the expression in Equation 4.23 can be approximated as in equation 4.24, because both the amplitude and the frequency of the supply voltage are considered to be constant:

$$\psi_s^d \approx \frac{v_s^q}{2\pi 50}$$

(4.24)

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 the control machine stator current. It is based on rearranging the Equation 4.21 to get the value of the rotor flux $\psi_r^d$:

$$L_{sp} L_r i_s^d - \frac{L_{sp}^2}{L_{mp}} i_s^d = L_r \psi_s^d - L_{mp} L_{mc} i_{sc}^d$$

$$\psi_r^d = L_{mp} i_s^d - \frac{L_{sp} L_r i_s^d}{L_{mp}} + \frac{L_r \psi_s^d}{L_{mp}} - L_{mc} i_{sc}^d$$

(4.25)
Rearranging Equation 4.22 to get the value of the rotor flux $\psi_r^q$:

\[
L_s p L_r \ \hat{i}_s^q - L_m p ^2 \hat{i}_s^q = - L_m p \ \psi_r^q - L_m \ i^q
\]

\[
\psi_r^q = L_m p \ i^q - \frac{L_s p L_r \ i^q}{L_m} - L_m \ i^q
\] (4.26)

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 this is by reverting to the machine stator flux $\psi_{sc}$ in Equation 3.5 for the control machine stator expression and substituting for the rotor current, $i_r$, in Equations 4.19 and 4.20.

\[
\psi_{sc}^d = L_{sc} \ i_{sc}^d - \frac{L_m c \ \psi_{sc}^d}{L_r} + \frac{L_m c \ L_m p \ i_{sp}^d}{L_r} - \frac{L_m c ^2 \ i_{sc}^d}{L_r}
\] (4.27)

\[
\psi_{sc}^q = L_{sc} \ i_{sc}^q - \frac{L_m c \ \psi_{sc}^q}{L_r} + \frac{L_m c \ L_m p \ i_{sp}^q}{L_r} - \frac{L_m c ^2 \ i_{sc}^q}{L_r}
\] (4.28)

Substituting the current of the power machine in Equations 4.21 and 4.22 into the $d$-$q$ flux equations of the control machine in Equations 4.27 and 4.28 respectively:

\[
\psi_{sc}^d = L_{sc} \ i_{sc}^d - \frac{L_m c \ \psi_r^d - L_m c ^2 \ i_{sc}^d}{L_r}
\]

\[
\frac{L_m c \ L_m p \ i_{sp}^d}{L_s p L_r - L_m p ^2} \ L_m c \ L_m c L_r \ \psi_r^d + L_r \ L_m p ^2 \ L_m c ^2 \ i_{sc}^d
\] (4.29)

\[
\psi_{sc}^q = L_{sc} \ i_{sc}^q - \frac{L_m c \ \psi_r^q - L_m c ^2 \ i_{sc}^q}{L_r} - \frac{L_m p \ L_m c \ L_r \ \psi_r^q + L_r \ L_m p ^2 \ L_m c ^2 \ i_{sc}^q}{L_s p L_r - L_m p ^2}
\] (4.30)
Rearranging the control machine stator flux $\psi_{sc}^d$ and $\psi_{sc}^q$ Equations 4.29 and 4.30; to obtain the control machine stator currents:

$$i_{sc}^d = \frac{\psi_{sc}^d \ L_r + L_{mc} \ \psi_{r}^d - L_{mc} \ L_{mp} \ i_{sp}^d}{L_r \ L_{sc} - L_{mc}^2} \tag{4.31}$$

$$i_{sc}^q = \frac{\psi_{sc}^q \ L_r + L_{mc} \ \psi_{r}^q - L_{mc} \ L_{mp} \ i_{sp}^q}{L_r \ L_{sc} - L_{mc}^2} \tag{4.32}$$

To derive the final control voltage command signals that can be used as reference inputs for the VSI PWM drive, $v_{sc}^d*$ and $v_{sc}^q*$, substitute into the voltage equation of the control machine equations the flux of the control machine, Equations 4.29 and 4.30, as shown below:

$$v_{sc}^d* = R_{sc} \ i_{sc}^d + L_{sc} \ \frac{d}{dt} \ [L_{mc} \ \psi_{r}^d - L_{mc}^2 \ i_{sc}^d] - \frac{L_{mc} L_{mp} \ L_{sc} L_{mp} \ i_{sp}^d}{L_{sp} \ L_r - L_{mp}^2} + \omega_c \ [L_{mc} L_{sp} \ \psi_{r}^d + L_{mc}^2 \ L_{sp} \ i_{sp}^d + L_{mc} L_{sp} L_{sc} L_{mp} \ i_{sc}^d - L_r L_{sp} L_{sc} L_{ms}^2 \ i_{sp}^d] + \omega_c \ [L_{mc} L_{sp} L_{mp} \ \psi_{r}^d + L_{mc} L_{sp} L_{mp} \ i_{sp}^d - L_r L_{sp} L_{sc} L_{mp} L_{ms} L_{sp} \ i_{sc}^d] + \omega_c \ [L_{mc} L_{sp} L_{mp} \ \psi_{r}^d - L_{mc} L_{sp} L_{mp} L_{ms} L_{sp} L_{sc} L_{mp} \ i_{sc}^d] + \omega_c \ [L_{mc} L_{sp} L_{mp} \ \psi_{r}^d - L_{mc} L_{sp} L_{mp} L_{ms} L_{sp} L_{sc} L_{mp} \ i_{sc}^d] + \omega_c \ [L_{mc} L_{sp} L_{mp} \ \psi_{r}^d - L_{mc} L_{sp} L_{mp} \ i_{sp}^d - L_r L_{sp} L_{sc} L_{mp} L_{ms} L_{sp} L_{sc} L_{mp} \ i_{sc}^d] + \omega_c \ [L_{mc} L_{sp} L_{mp} \ \psi_{r}^d - L_{mc} L_{sp} L_{mp} L_{ms} L_{sp} L_{sc} L_{mp} \ i_{sc}^d]$$

As shown in the control design, there are three control loops with PI controllers; the speed control loop and two currents loops. The current errors are processed to give the voltage of the control machine $v_{sc}^q$ and $v_{sc}^d$ respectively. Then these
voltages are compared with the compensation voltages $v_{sc}^d$ and $v_{sc}^q$ to obtain the reference voltages $v_{sc}^d*$ and $v_{sc}^q*$.

But $v_{sc}^d = v_{sc}^d* - v_{sc}^d$ and $v_{sc}^q = v_{sc}^q* - v_{sc}^q$

Therefore the compensation voltages $v_{sc}^d$ and $v_{sc}^q$ are used to ensure good tracking of the control machine stator current components and to improve the performance of the $d$-$q$ control loop [3]. Substituting the current of the power machine $i_{sp}^d$, Equation 4.21 into the machine reactive power $Q_p$ Equation 4.16;

$$Q_p = \frac{3}{2} v_{sp}^q \left[ \frac{L_r \psi_{sp}^d}{L_{sp} L_r - L_{mp}^2} - \frac{L_{mp} \psi_r^d}{L_{sp} L_r - L_{mp}^2} - \frac{L_{mp} L_m \psi_{sc}^d}{L_{sp} L_r - L_{mp}^2} \right]$$

A close look at that equation shows that the reactive power is a function of the four variables, two of them are constants ($v_{sp}^q$ and $\psi_{sp}^q$) 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 below:

$$i_{sc}^d* = \left[ \frac{2Q_p L_{mp}^2}{3 v_{sp}^q L_{mp} L_m} - \frac{2Q_p L_{sp} L_r}{L_{mp} L_m} \right] + \left[ \frac{L_r \psi_{sp}^d}{L_{mp} L_m} - \frac{\psi_r^d}{L_m} \right]$$

(4.35)
The tuning of the PI controller is difficult because the derivation of the plant transfer function for the BDFTIG is very complicated. Therefore, it is not possible to employ the traditional method for the PI control design without adjustment by tuning the PI control gain at different wind speed until the stable point for the system has been found. The principle for the selection of the PI gains is based on the evaluation of the performance of the whole system on the limit of its stability. Figure 4-12 shows the layout speed control loop.

When considering the design of the speed control loop, it is necessary to identify all the dynamics or delays between the controller output ($i_{sp}^{q}$) and the speed feedback signal, $\omega_m$.

The current loop dynamics and filter dynamics are very fast compared to $\tau_m$. Therefore, they can be ignored. Where $\tau_m$ is the time constant equal to the moment of inertia divided by the approximate friction, see Figure 4-12, mechanics block.

Referring to Equation 3.12 and put them into Laplace transformation as shown in next equation:
\[ T_e(s) - T_L(s) = [(B_F^p + B_F^c) + s(j_s^p + j_s^c)] \omega_m(s) \]

\[ \frac{T_e(s) - T_L(s)}{\omega_m(s)} = (B_F^p + B_F^c) + s(j_s^p + j_s^c) \]

The speed PI is shown in Figure 4-13.

![Figure 4-13 The Block Diagram for the Speed Control Loop](image)

The complete mathematical equation for the VSI speed PI controller is shown in Appendix ‘E’.

The PI speed controller is \( \frac{13.59(s + 8.9376)}{S} \)

To determine maximum magnitude of a proportional gain of the PI controller zero-pole map and bode based technique was used. The pole, zero and bode diagram of the open loop transfer function of the speed control is shown in next figures.

![Figure 4-14 The Zero-Pole Map of the Speed Control Loop](image)
Figure 4-15 The Bode Plot of the Speed Control Loop

From the figures shown above, it is seen that designed loop is stable because the phase margin, PM, is $0 < \text{PM} < 180^\circ$, and the gain margin, GM, is positive value.

Next step, design of the PI current controller as shows the current control loop in Figure 4-16. The PI controller is tuned for a second order system using recognised tuning rules. These tuning rules are derived by optimizing the integrated absolute errors of a set point and load disturbance responses under robustness and bandwidth constraints.

Figure 4-16 The Block Diagram for the PI Current Control
To design the current control system it is necessary to identify all these dynamics or delays between the controller output \( (v_{sc}^{d,q}) \) and the feedback signal \( (i_{sc}^{d,q}) \). These dynamic or delays are:

First, the inverter delay is the delay before the demand voltage actually appears on the motor lines. Assuming a fast microprocessor, the current loop sampling frequency is (at least) twice the switching frequency, \( f_s \), the sampling frequency is 10 kHz, therefore the sample time,

\[
T_{\text{sample}} = \frac{1}{f_s} = 100\mu s
\]

Second, the delay between the motor voltage and current expressed as a Laplace Transformation:

\[
v_{sc}(s) = R_{sc}i_{sc}(s) + sL_s i_{sc}
\]

\[
\frac{i_{sc}}{v_{sc}} = \frac{1}{R_{sc}(s\tau_s+1)}
\]

Where \( \tau_s \) is called the effective stator time constant is equal to \( \frac{L_s}{R_s} = \frac{0.041}{5.25} = 7.8\text{ms} \).

Third, noises filter on the current measurement. This will be an anti-aliasing filter for the A/D converter. If the current is corrupted with noise \( \geq f_s \text{ Hz} \), the filter must have of cut-off frequency \( < \frac{f_s}{2} \). Therefore to design \( \tau_f = 200\mu s \) (5kHz).

For the purpose of the control design, the machine stator time constant, \( \tau_s \) is dominant and the others can be ignored. Therefore, the block diagram is;
The PI controller is \[ \frac{67.57(s + 957.8)}{s} \]

The complete mathematical equation for the VSI current PI control is shown in the Appendix ‘E’.
From Figures 4-18 and 4-19, it can be seen that the designed control loop is a stable.

Figure 4-20 shows the block diagram for the control system of the BDFTIG on the Generator side. Also, Figure 4-21 shows the complete block diagram for the BDFTIG modelling on the generator side.
The operational sequence of the controller was implemented as follows: first the grid side of the converter (VSR) was energized and operated in the uncontrolled rectifier mode under no-load conditions. Once activated after 0.2 second, the VSR controls the DC link voltage to the required level, maintaining unity power factor on the grid side. After a further 1.3 seconds the VSI was turned on and drives the
BDFTIG to whatever the reference speed was set to (initially zero). Once the VSI controller is operational, the first wind speed step change takes place at 2.0 seconds. The simulation then proceeds with remaining step changes in the wind speed input.

Due to the possible harmonic noise in the line voltage produced by the VSR the low pass filter was used to smooth the signal. The complete control block diagram is shown in Figure 4-22.

![Figure 4-22 The BDFTIG Control Block Diagram](image)

The Vector control standard used in the BDFTIG scheme is shown below:
From Figure 4-23, the three phase input voltage fed to the power machine stator, then implement the Park/Clarke transformation to feed back the three phase control machine voltage and current to the control design for BDFTIG.

4.4 Conclusion

In this chapter, the indirect vector control scheme was describe, to control the power flow through the power machine, including the reactive power, \( Q_p \) and the active power \( P_p \) at any given operating conditions of the wind turbine. The \( P_p \) and \( Q_p \) of the power machine stator can be dynamically controlled via the rotor circuit from the control machine stator, by adjusting the phase and magnitude of the stator current (excitation current). 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. 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 regulated through active power control.

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 5.
Chapter 5 BDF{TIG Simulation and Results

5.1 Introduction

In order to simulate the performance of the controller for the BDF{TIG-based wind turbine system it was necessary to develop a comprehensive model of the whole system that would be flexible enough to repeat the performance characteristics under different operational conditions. It was created using Simulink including elements from the Matlab software package. The system consisted of the three major components: the complete modelling of the BDF{TIG with bi-directional converter, the controllers for the BDF{TIG modelling and the aerodynamic model of the wind turbine. The bi-directional converter exchanges the slip power between the control machine and the grid, which is quite similar to the traditional DFIG system. The controller and the turbine model, however, are more complicated and require special discussion, which is presented in the following sections of this chapter.

5.2 Turbine Aeromechanical Model

The main purpose for the variable-speed wind turbine is to optimize the power extraction with high efficiency and stability. As explained before the design of the generator is concentrated around the power coefficient of the turbine. This coefficient is a function of different factors such as blade pitch angle or nacelle
height above the ground. For a typical horizontal axis turbine, this coefficient is described by Equation 5.1.

\[ C_p = C_1 \left( \frac{C_2}{\lambda} + C_3 \beta + C_5 \right) e^{C_6 \lambda} \]  

Where \( C_{1-6} \) are various performance coefficients, (these coefficients driven from wind turbine block in Matlab/Simulink \( C_1 = 0.5176, C_2 = 116, C_3 = 0.5, C_4 = 5, C_5 = 21 \) and \( C_6 = 0.0068 \)), and \( \lambda \) is the tip speed ratio of the rotor blade tip speed to wind speed, the instantaneous \( \lambda \) is defined by Equation 5.2 [9].

\[ \frac{1}{\lambda} = \frac{1}{\lambda - 0.08 \beta - 0.035 \beta^3 + 1} \]  

The combination of Equations 5.1 and 5.2 produces the standard power coefficient curves for various TSRs and blade pitch angles as shown in Figure 5-1. From these curves, it is evident, that the wind turbine is at its most efficient when the TSR is at the optimal value for the given turbine design.
The amount of power extracted by the turbine is then directly proportional to the power coefficient and is described by the mathematical formula in Equation 5.3:

$$P_m = C_p \frac{\rho A}{\nu \omega}$$

(5.3)

This expression demonstrates the third-order relationship between the wind speed, and the amount of the power extracted by the turbine. Such behaviour clearly limits the operational range of the wind turbine to a narrow region of 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 5-2, 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 5-2 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 shown in Figure 5-2.
This maximum power tracking is achieved through the manipulation of the turbine electrical torque by controlling the excitation of the control machine in order to control the loading of the power machine on the grid [23, 24]. As discussed previously the aerodynamic behaviour of the turbine can be described by its performance coefficient given in Equation 5.1. For a given blade design, the Equation in 5.1 simply becomes a function of the speed of wind, the pitch angle of the blades and the rotational speed of the turbine. 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 Sim Power Systems 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 as shown in Figure 5-3.
In this research, the wind-turbine block was modified as shown in Figure 5-4 to include the optimal speed estimation which is required for the BDFTIG control scheme proposed in this thesis. In a 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 from a look-up table. A similar method was used for the modelling 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.

The wind-turbine block in Figure 5-4 became an important part of the system model and was used as an input source for the controllers described in the
following section. Figure 5-5 shows the mechanical power versus the generator rotor speed for the wind turbine design in order to plot the optimal power speed curve (shown dotted in red). It is important to say that each wind turbine design will have a different power versus rotor speed graph. In addition, the power coefficient of each turbine will be determined by their blade design and pitch angle parameters inputted to the wind-turbine block.

![Figure 5-5 Optimal Power Speed Curve](image)

**Figure 5-5 Optimal Power Speed Curve**

### 5.3 Controller Models

The two converters models described in Sections 4.3.1 and 4.3.2 (VSR and VSI), were implemented in the BDFTIG control scheme as shown in Figure 5-6.
Starting with the VSR controller, which controls the ‘front end’ the power electronic converter model, its purpose is to control the level of the DC link voltage, regardless of the load (control machine) on the output of the VSI. A detailed explanation of the VSR block is given below and shown in Figure 5-7.

The ‘ABC->DQ’ block in Figure 5-7 is to transform the three phase rectifier voltages to the $d\_q$ axis reference frame. The $d\_axes$ aligning to synchronous reference frame rotation with voltage vector as previously described in Section 4.2. Furthermore, generates the rotational angle by using the angles calc. block as shown in Figure 5-8.
Referring to Figure 5-7, the VSR block contains three PI controllers to control the DC link voltage. Two to derive the \( d_q \) components of the input voltage to the reversible rectifier, and a third PI controller is used to produce the \( d \)-component of the reference supply current, \( I_d^* \). Together with Equation 4.11, the final output of the VSR controller block is a three phase voltage of magnitude \( V_{s_c} \), which is then processed by the PWM block in Figure 5-17.

Figure 5-9 shows the composition of the VSI controller block, which were implemented in the BDFTIG system.

The “ABC->DQ0” block in Figure 5-10 is not only transferred three phase vectors to the \( d_q \) reference frame, but it also generates the speed angle for both
machines by using the angles calc. Block. More detail for this block is shown in Figure 5-11.

![Figure 5-10 Vp- ABC->DQ Block](image)

The speed angle block describes the relationship between the shaft speed \( (\omega_m) \), the electrical excitation frequencies of the machine stators \( (\omega_c) \), and electrical frequencies of the power machine stators \( (\omega_p) \). The ‘abc_to_alpha_beta Transformation’ block transforms the three phase voltage for the power machine to the alpha_beta reference frame, in order to calculate the power machine angle given by Equation 5.4.

\[
\theta_p = \tan^{-1} \frac{V_{sb}}{V_{sa}}
\]  

(5.4)
The second part in the VSI control block shown in Figure 5-9 is the flux estimator, which represents Equations 4.21 and 4.22 as shown in Figure 5-12.

Furthermore, the VSI block contains the decoupling block, shown in Figure 5-13. As described in Section 3.3.3, there exists partial cross coupling between the torque and control machine flux, which requires compensation. The cross coupling equation is discussed and described by Equations 4.33 and 4.34 in Chapter 4.
The final block used in the VSI block Figure 5-9 is the control block as shown in Figure 5-14.

The control block controls the voltage applied to the control machine together with the excitation frequency, $\omega_c$. As mentioned before, the active reactive power of the machine stator, $P_p$ and $Q_p$, can be controlled from the control machine stator via
the rotor circuit, by adjusting the phase and magnitude of the stator current of the control machine. $P_p$ and $Q_p$ are proportional to the $i_{sc}^q$ and $i_{sc}^d$, respectively.

The controller block also contains a closed loop PI speed control, where the speed reference is the optimal shaft speed derived from the wind-turbine block as shown in Figure 5-4. The speed control is required for the turbine maximum power point tracking at optimum shaft speed for a given wind speed. Furthermore, the speed control is required for machine synchronisation to the grid upon start up [3].

However, the output from the speed controller is (related to) to power machine q_component of current, $i_{sp}^q$. This must be converted to the control machine current, $i_{sc}^q$. The next block in sequence in Figure 5-14, implements Equation 4.32 to convert $i_{sp}^q$ to $i_{sc}^q$ in conjunction with the rotor flux $\psi'$. This conversion block is shown in Figure 5-15.

![Figure 5-15 Transfer Power Machine Current to Control Machine Current](image)

The $d$_component reference of the control machine current is derived from Equation 4.35, using the rotor flux $\psi'$, the $d$_component of the power machine flux $\psi_p^d$, and the reactive power $Q_p$ and $v_{sp}^q$. This block is shown in Figure 5-16.
Finally the $d_q$ components of the control machine voltage $v_{sc}^q$ and $v_{sc}^d$, are derived from the respective PI controller using $i_{sc}^*$ and $i_{sc}$ feedback for the respectively $d_q$ components of the control machine current.

Going back to Figure 5-9 the outputs from the decoupling block and VSI_PI controllers block are combined to generate the (PWM) voltage applied to the control machine stator.

To improve the action of the PI regulators it is feasible to include the low-pass filters in the current feedback loop.

Figure 5-17 is a present a BDFTIG Simulink modelling.
5.4 BDFTIG System Simulation Results

The modelling and control system for the BDFTIG was tested in Simulink. With a number of step changes in the simulated wind speed to test modally fully, a specific set of the wind speed data was applied to evaluate high speed, low speed and transient performance of the BDFTIG turbine. The wind input consisted of a speed ramp from 7m/s to 17m/s in step increment of 1m/s shown in Figure 5-18. Although under real experiment conditions such step change are not realistic, the ramped step change to the input provide a suitable means of analysing the
behaviour of the system over a range of shaft speed and including a transient response.

The Mechanical power signal was generated from the wind-turbine block. Furthermore, the optimal shaft speed estimation is created from the wind-turbine block as well as being dependent on the wind speed input. In a real system, the optimal shaft speed estimation could be done from the reading from an anemometer situated on the turbine nacelle and fed to the computer to generate the optimal shaft speed estimation. The modelling generates the shaft speed as shown in Figure 5-19.
The speed tracking output from the BDFTIG modelling is shown in Figure 5-20. The shaft speed demand is shown by the green graph and the simulated shaft speed from the model is shown by the blue graph. A port from the initial turn-on transient, the shaft speed tracks the demand very well. It can be see that small overshoots occur at each step change of no more than 0.02%. The overshoots are critically damped. i.e. no oscillation or undamped instability can be seen.
Figure 5-20 Speed Tracking

Figure 5-21 shows the mechanical shaft torque. The mechanical torque is negative because the machine is in generator mode, and when there is a step change in the wind speed, there is a corresponding step increase (negatively) in the shaft torque.

Figure 5-21 The BDFTIG Mechanical Torque
Figure 5-22 shows the mechanical power from the wind turbine, it can be seen that for a linear increase in the wind speed, there is an exponential (cubic) relationship in the corresponding increase in the mechanical power.

![Figure 5-22 The BDFTIG Mechanical Power](image1)

As shown in the BDFTIG System Model in Figure 5-17, the input to the BDFTIG modelling is the power machine voltage and current, which are supplied from the grid as shown in Figures 5-23 and 5-24 below.

![Figure 5-23 The Power Machine Stator Voltage](image2)
Figure 5-24 shows the three phase stator currents in the power machine. It can be seen that the magnitude increases with the increase in wind speed.

![Figure 5-24 The Power Machine Stator Current](image)

Looking at the \( d-q \) components of the power machine current, Figure 5-25, it can be clearly seen that the magnitude of the \( q \) component (green graph) increases (negatively) with the wind speed, ranging from just under -1 Amp to -6 Amps. It is interesting to see that when the wind speed suddenly increase, than is a momentary change in the current, before settling back to a new value.

![Figure 5-25 The Power Machine d-q Current](image)
Figure 5-26 showing the active power in the power machine also shows that at these wind speed transitions, there is a reversal of the power flow. This indicates that the speed is being actively driven i.e. forcing the machine to motor to the new optimum shaft speed for the new wind speed. Further analysis of the power machine $d$-component of current shows gradual increases from 3.02 Amps to 3.3 Amps, despite the power machine reactive power, $Q_p$, being fixed in the model.

Figure 5-26 The Power Machine Active Power

Figure 5-27 and 5-28 shows the current in the rotor circuit, both in the time domain and the $d_q$ reference frame.
Figures 5-29 and 5-30 shows the current in the stator of the control machine, both in the time domain and the \( d-q \) reference frame. Also shown in Figure 5-31 the control machine stator voltage (in the time domain).
It is interesting to note that when the shaft speed is at 78.54 rad/s (750rpm), see Figure 5-19, the excitation frequency of the control machine is 0Hz, see Figures 5-29 and 5-31. The injection of dc current (and voltage) corresponds to a rotor electrical frequency of 25Hz, (at 750 rpm), the rotor of which is in the same direction as the shaft rotation. Hence from \( f_p = f_m + f_r \), \( f_p = 25 \text{Hz} + 25 \text{Hz}, \) \( f_p = 50 \text{Hz}, \) i.e. the excitations frequency of the power machine from the grid. The machine is said to be operating of synchronism. Looking at Figure 5-32, which
shows the control machine angle, the sine and cosine terms are seen to reverse their order, see expanded in the control machine is reversed above synchronism.

Figure 5-31 The Control Machine Stator Voltage
Table 5.1 shows for each value of wind speed, the optimum shaft speed, the frequency of the currents in the rotor circuit and the required excitation frequency of the stator of the control machine. It can be seen that the sum of the shaft rotation in revs per second plus the rotor electrical frequency should always add up to 50 cycles per sec, which is the electrical excitation frequency for the grid. Proving the frequency relationships shown in Figure 3-3 and also in Appendix K.
The next step is to analyse the power flow in the BDFTIG system. The mechanical power into the system is shown in Figure 5-22 and the actually power flow out of the power machine is shown in Figure 5-26. However, it can be seen by inspection that trend or shape of these two graphs is not entirely the same. Also it can be seen that at maximum wind speed (17m/s) the mechanical input power is 5248 watts, but the electrical output power from the power machine is only 3566 watts, giving on apparent efficiency of only 67.9%. However, the power flow in the stator of the control machine must also be taken into account.

<table>
<thead>
<tr>
<th>Wind Speed(m/s)</th>
<th>Equivalent to Shaft speed (after tacho) (Hz), From Figure 5-14</th>
<th>Rotor Electrical Frequency (Hz), From Figure 5-19</th>
<th>Control Mach Electrical Frequency (Hz), From Figure 5-23</th>
</tr>
</thead>
<tbody>
<tr>
<td>7</td>
<td>12.362</td>
<td>37.627</td>
<td>25.25</td>
</tr>
<tr>
<td>8</td>
<td>13.999</td>
<td>35.985</td>
<td>22</td>
</tr>
<tr>
<td>9</td>
<td>15.749</td>
<td>34.237</td>
<td>18.499</td>
</tr>
<tr>
<td>10</td>
<td>17.499</td>
<td>32.499</td>
<td>15</td>
</tr>
<tr>
<td>11</td>
<td>19.249</td>
<td>30.749</td>
<td>11.5</td>
</tr>
<tr>
<td>12</td>
<td>20.999</td>
<td>29.001</td>
<td>8</td>
</tr>
<tr>
<td>13</td>
<td>22.749</td>
<td>27.251</td>
<td>4.5</td>
</tr>
<tr>
<td>14.3</td>
<td>24.999</td>
<td>25</td>
<td>0</td>
</tr>
<tr>
<td>15</td>
<td>26.25</td>
<td>23.75</td>
<td>-2.5</td>
</tr>
<tr>
<td>17</td>
<td>29.7492</td>
<td>20.249</td>
<td>-9.5</td>
</tr>
</tbody>
</table>

Table 5.1- The Electrical Frequency Relation for the BDFTIG
Figure 5-33 shows the active power flow in the control machine stator. The trend is interesting to see for an increase in wind speed. It can be seen that initially the power absorbed increase, reached a maximum, and then reduce, and finally goes negative at maximum wind speed. At this point the control machine is generating (not absorbing) real power. Hence the net power flow from the BDFTIG should include the power flow in each half of the machine. Table 5.2 summarises the power flow in the system. For the example quoted total output power from the system in 3565 watts plus 354 watts from the control machine, the total will be 3919 watts, which an efficiency of 74.6%.
<table>
<thead>
<tr>
<th>Wind Speed (m/s)</th>
<th>Mechanical Power (w)</th>
<th>Control Machine Active Power (w)</th>
<th>Power Machine Active Power (w)</th>
<th>Net Power to the Grid (w)</th>
<th>Efficiency %</th>
</tr>
</thead>
<tbody>
<tr>
<td>7</td>
<td>366.38</td>
<td>383.43</td>
<td>-551.25</td>
<td>-167.82</td>
<td>45.806</td>
</tr>
<tr>
<td>8</td>
<td>546.89</td>
<td>441.98</td>
<td>-752.34</td>
<td>-310.35</td>
<td>56.7476</td>
</tr>
<tr>
<td>9</td>
<td>778.69</td>
<td>498.31</td>
<td>-990.82</td>
<td>-492.5</td>
<td>63.2486</td>
</tr>
<tr>
<td>10</td>
<td>1068.2</td>
<td>535.88</td>
<td>-1251.5</td>
<td>-715.6</td>
<td>66.996</td>
</tr>
<tr>
<td>11</td>
<td>1421.7</td>
<td>550.11</td>
<td>-1534.5</td>
<td>-984.41</td>
<td>69.2411</td>
</tr>
<tr>
<td>12</td>
<td>1845.8</td>
<td>532.24</td>
<td>-1836</td>
<td>-1303.8</td>
<td>70.6365</td>
</tr>
<tr>
<td>13</td>
<td>2346.7</td>
<td>477.98</td>
<td>-2159</td>
<td>-1681</td>
<td>71.6309</td>
</tr>
<tr>
<td>14.286</td>
<td>3114</td>
<td>328.37</td>
<td>-2587.1</td>
<td>-2258.7</td>
<td>72.5343</td>
</tr>
<tr>
<td>15</td>
<td>3605</td>
<td>203.72</td>
<td>-2837.2</td>
<td>-2633.5</td>
<td>73.0505</td>
</tr>
<tr>
<td>17</td>
<td>5247.9</td>
<td>-353.76</td>
<td>-3565.9</td>
<td>-3919.6</td>
<td>74.6902</td>
</tr>
</tbody>
</table>

Table 5.2- The Electrical Power Characteristic for the BDFTIG

The remaining results from the simulation are:

Figure 5-34 the control machine reactive power. Here the reactive power for the control machine changes because it is controlled to maintain constant reactive power at the output of the power machine.

![Figure 5-34 The Control Machine Reactive Power](image-url)
Figure 5-35 to 5-37 which show the $d_q$ flux components of the power machine, control machine and the rotor. The $d$ component of the power machine flux is Cleary held constant, and the $q$ component increase with load.

\begin{figure}
\centering
\includegraphics[width=\textwidth]{power_machine_d_q_flux.png}
\caption{Figure 5.35- The Power Machine $d$-$q$ Flux}
\end{figure}

\begin{figure}
\centering
\includegraphics[width=\textwidth]{control_machine_d_q_flux.png}
\caption{Figure 5-36 The Control Machine $d$-$q$ Flux}
\end{figure}
Figure 5-37 The Rotor $d$-$q$ Flux

Figure 5-38 shows the power factor for the power machine. It is change with the power flow change.
Figure 5-39 show the electromagnetic total torque for the BDFTIG model.

![Figure 5-39 The Total Torque](image)

The active power flow in both parts of the BDFTIG 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 BDFTIG. The distribution of the torques generated with this topology is also leaning towards the power machine as shown in Figure 5-37. Such a total torque is quite logical, considering the relative size and impedances of the power and control machines.

Figure 5-40 shows graphically the cross coupling between $d-q$ components of the control machine voltage. As mentioned in Section 3.3.3, there exists a certain amount of cross coupling in the rotor $d-q$ fluxes which must be compensated for.
5.5 Conclusion

The simulation results for the BDFTIG wind turbine system confirmed correct operation of the controller, presented in Chapter four. This is confirmed by analysing the voltages, currents, flux components, torque and power flows in both of the BDFTIG system. Also, as predicted by Equations 3.10 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 and power flow direction as can be clearly seen from the Figures 5-29, 5-31 and 5-32.
Chapter 6 Experimental Testing and Results

6.1 Construction of the BDFTIG

To verify the results obtained with the BDFTIG 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 6-1. The prototype of the wind turbine consisted of the prime-mover in the form of the DC machine, two induction machines forming the BDFTIG as well as the bidirectional power converter with the controller connected to a PC.

Figure 6-1 Turbine Generator Setup

In the experimental setup, the BDFTIG was formed using two identical 1.5 hp 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 impossible to avoid the use of commutation brushes, these, however, did have no noticeable impact on the system performance. The electromechanical parameters of the two induction machines used in the experiment are provided in Appendix ‘H’.
The power machine of the BDFTIG was directly connected to the 240V/50Hz power grid, while the control machine was connected to the grid through the bidirectional converter and an isolation transformer as shown in Figure 6-2. The connection for the power converter was as following: an isolation transformer was connected to the EMC low-pass filter as described in Section 3.3.1. This was interfaced with the power converter which was attached to the stator connection box of the control machine. Overall, the whole setup was very compact with few open electrical connections.

![Figure 6-2 BDFTIG Electrical Connection](image)

The back-to-back power converter itself was purposely designed and built as shown in Appendix ‘D’ for the multipurpose drive system utilising separate voltage and frequency variables. Later found a company which was able to modify a standard drive to achieve the same functionality. This company is called Control Techniques Limited.
6.2 Controller Implementation

The control was implemented using the dSPACE platform. The dSPACE repository software serves a specific need as a digital archives system access and preservation of digital content. The dSPACE manages and distributes digital items, made up of digital files. Also, it can customize the system to meet their individual needs and manage the submission process themselves [25]. The controller design modelling developed in Chapter 4 was an implementation in the hardware via the dSPACE package, and synchronising the control modelling with grid connection. For implementing the control models on dSPACE, many parts will be considered. Firstly, adding RTI block to the Simulink model which connects it to the I/O interface of the real-time hardware. Secondly, the Math works Real time Workshop (RTW) is used to generate C-code out of the Simulink model. Finally, the dSPACE Control-Desk is used to download the model into the dSPACE hardware. The controller system used in this experiment consisted of the Voltage and Current Transducer circuit as shown in Figure 6-3 and the circuit diagram shown in Appendix ‘G’. The system voltages and currents were sensed and inputted to the Voltage and Current Transducer circuit to be converted into the appropriate voltage signals for the dSPACE input which is ±10V. These signals were received by the RTI and used for the control algorithm implementation.
The raw data for the angle speed calculations for VSI was obtained using incremental encoder attached to the shaft of the BDFTIG. The sensor had the resolution of 500 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.

6.3 Wind Drive Implementation

To drive the BDFTIG in the generation mode a DC machine was used as a prime mover. This machine was rated at 1400 rpm. However, to fully implement a wind drive system a DC drive would have been required to drive the prime mover of the test rig. The DC drive would either than be programmed with real wind data, or preferably, to be connected to the dSPAE system, to close the loop and to receive
wind speed demand signals. Due to time constraints the wind drive emulator was not built, and the DC machine speed was controlled open loop.

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 behaviour of the turbine. However, at this stage its operation was limited to providing the desirable torque for the evaluation of the BDFTIG. The overall structure of the test setup is shown in Figure 6-4.

![Figure 6-4 BDFIG Wind Turbine System Diagram](image)

### 6.4 Testing Results and Analysis

The testing of the BDFTIG was carried out using the setup described in Section 6.1. The performance of the BDFTIG 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 as an open loop with fixed input voltage fed from power converter to the control machine stator. The input's voltages set to 71v and fixed the shaft speed to 750rpm then measure the input frequency fed from drive to the control machine stator also
measure the output voltage and frequency at the power machine stator. Repeat the experiment again with different shaft speed to 1000rpm than to 1250rpm. The results show in the excel plot. The date for next plots is in Appendix ‘J’.

![Figure 6-5 Electrical Voltage Transfer Characteristic](image)

From last figure, it shows the relation between the input frequency to the control machine and the output voltage from the power machine. The relation is not constant due to the control machine magnetising current change. The magnetising current equation is;

\[ i_m = \frac{V_{in}}{2\pi f_{in} L_m} \]

As see from last equation the indirect proportional between input frequency and magnetising current when input voltage is constant. In that situation at fixed input
voltage and increased the frequency in the control machine, the rotor voltage equation will be:

\[ E_{\text{rotor}} = \frac{d\psi_c}{dt} \]

The conclusion from that, when increased the frequency the output voltage in power machine will be a decrease until the steady-state asymptote.

![Figure 6-6 Electrical Frequency Transfer Characteristic](image)

From the electrical frequency transfer characteristic plot, show the constant relation between input control machine frequency and the output power machine frequency in many different speeds.
6.5 No Load Tests

The testing of the BDFIG was carried out with no load test. The initial experiment involved a no-load operation to check the validity of the BDFIG model described in Chapter 3. For this phase, as in every other experiment, the DC link voltage of the power converter was kept at 240 volts, with the grid-side voltage stepped down by an isolation transformer to a value from 60 volts and further increased to 240 volts by a variac. 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 bellow, with experimental plots in Figure 6-7.

![Figure 6-7 Control Machine Waveforms](image)

From the above figures it is evident that the theoretical results were confirmed and that the current required sustaining a constant DC link is minimal – around 90 mA. In this an all other experiments the power factor of the VSR was kept at unity to reduce the reactive power consumption.
In the next step, the operational speed of the BDFTIG almost to 700 rpm by applying the necessary voltage to the control machine stator under the no-load conditions; the power machine stator current increased. The power machine waveforms for these conditions were recorded as shown in Figure 6-8. Since the setup was functioning under no load, it is evident that all 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.

![Power Machine Stator Waveforms at Shaft Speed 700rpm](image)

**Figure 6-8 Power Machine Stator Waveforms at Shaft Speed 700rpm**

The VSI controller was set to reduce the power machine reactive power to 33 percent of the nominal. The power machine results of this test are shown in Figure 6-9.
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 6-10.

**Figure 6-9 Power Machine Stator Waveforms at Shaft Speed 700rpm**

**Figure 6-10 System Waveforms at Shaft Speed 700rpm**
From the Figure 6-8 and Figure 6-9 one immediate characteristic of the prototype, BDFTIG can be observed. It is immediately obvious that the current system consumes the very large amount of the reactive power which, in fact, is twice as much as the consumption of the individual machines forming the BDFTIG. Thus, at no load, the power machine of the BDFTIG is already operating at the rated current of around 4 Amperes. Such behaviour would clearly disadvantage the BDFTIG reducing its efficiency and limiting its range, as will be shown in the following sections.

6.6 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 bellow. 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 BDFTIG was acting as a simple induction generator providing the base values for the power flows as shown in Figure 6-11.
As expected, under the given torque the output of the power machine was recorder 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.

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 700 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 shown to happen in Figure 6-12.
The effect on the power machine stator waveforms was minimal Figure 6-13 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. 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 700 rpm. The corresponding power machines stator waveforms are given in Figure 6-14 and demonstrate that the power quality on this side has improved in accordance with the control machine behaviour.

Figure 6-14 The Power Machine Waveforms at Shaft Speed 700rpm
The control machine stator waveforms are shown in Figure 6-15, indicating that the system operates at lagging power factor, injecting the reactive power into the system.

![Figure 6-15 The Control Machine Waveforms at Shaft Speed 700rpm](image)

Several observations regarding the low-power tests can be made. As it already has been noted, the efficiency of the BDFTIG is relatively poor, allowing for only 72 percent of the input mechanical power to be transformed to the output electrical power. Such behaviour is attributed to the construction of the BDFTIG 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 BDFTIG have high impedance values 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 4 Amperes Figure 6-13. While it was possible to safely operate the system under these conditions for a short period of time, clearly the system would achieve dangerously high operating currents under higher input torques. Although in the Matlab/Simulink model a torque limiting block could be implemented, (limiting torque and hence current). Speed control of the wind turbine would still be feasible as the speed demand can be derived from $C_p$ characteristic of the turbine, and hence rotor speed demand as a function of wind speed for maximum $C_p$ (i.e. MPPT). Another solution is 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 6-14 show that the reduction in the power machine reactive power is achieved through the proportional increase in reactive power though 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 BDFTIG and the reactive power consumption of its power machine Figure 6-15. Therefore, the dynamic range of the BDFTIG would be reduced – subject to the current rating of the control machine.

To explain such behaviour it is necessary to look at the mutual inductance parameters for both machines provided in Appendix ‘G’. From there clearly both machines have relatively low mutual inductance. Although it is not within the scope of this work to analyze the details of the BDFTIG construction, nevertheless, from the Induction machine theory, it is evident that 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 BDF TIG. This will also impact the efficiency of the system, because cut down, reducing the active power spending of the whole system.

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

6.7 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 6-16.

![Figure 6-16 The Power Machine Waveforms at Shaft Speed 700rpm](image)
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.

To confirm that the VSR was also operating properly, the corresponding waveforms are given in Figure 6-18. 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 6-10.

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 6-17 The Control Machine Waveforms at Shaft Speed 700rpm
Finally, to see how the system would behave in the super-synchronous region, the speed reference was set to 1000 rpm with the reactive power level at 3800 VAR. To reduce the load on the VSI, the speed increase was carried out in steps, going from 700 rpm to around 800 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 6-19.
6.8 Conclusion

The experiments with the prototype BDFTIG system supported 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 BDFTIG. 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. 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.
Chapter 7 Conclusions

7.1 Conclusions

From the experimental results obtained in this project several conclusions can be drawn regarding the design of the flexible power controller for the BDFTIG. The work carried out in this project resulted in the development of the dynamic mathematical model for the BDFTIG, 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 behaviour of the generator under various conditions, establishing the basis for the controller design.

The control scheme developed for the independent control of the active and reactive power flows in the BDFTIG has been tested using the mathematical model and experimental setup. The aim was to allow the generator to maximize the power extraction using the MPPT algorithm and to have an independent power quality adjustment for the system. From the results obtained, it was determined that the controller does provide the required independence between the active power and reactive power regulation despite the cross-coupling effects that are inherent with the BDFTIG. 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 twin generator can be effectively used in wind power applications, replacing the current DFIG configuration. It does not solve all the problems associated with the DFIG; however, it allows the simplification of the generator design and the reduction in the maintenance cost. This would be especially beneficial in off-shore applications
where maintenance cost associated with the inspection of the slip ring brushes is especially large. The data has confirmed the effectiveness of the flexible power flow control, which can be achieved with a power converter with a rating much less than the total rating of the machine.

7.2 Major Contributions

One of the main contributions of this work achieved a new model for the BDFTIG. The model shown in Figure 3-6 allows the accurate illustration of the characteristics of the generator; it was designed primarily for wind energy applications and can be used in conjunction with Sim Power Systems toolbox in Simulink. The model provides an indispensable tool for any future research into the behaviour of the BDFTIG.

Based on that model the second major contribution that was identified were new modes of operation of the BDFTIG. Furthermore, the control system for the grid connected wind-power application was made with the analysis of the simulation. 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 BDFTIG. As part of the control scheme, an effective decoupling procedure between the flux and torque the cross coupling issue being unique to the BDFTIG was introduced. This procedure enhanced the robustness of the controller providing independent control of the active and reactive power flow in the machine.

As a result of this research, the advantages of combining two AC machines (mechanically, electrically and magnetically) to derive the BDFTIG are as follows:
1- The machine is able to have independent close loop output voltage and frequency control and with a variable shaft speed; which is ideal for standalone generation systems.

2- The machine can demonstrate variable shaft speed/variable power generated into a fixed voltage and fixed frequency grid connection; which is ideal for grid connected wind turbine applications.

3- In a variable speed grid connected application, the system can independently control the reactive power into the grid as well as control the shaft speed as part of an MPPT system for operating the wind turbine at maximum power extraction for a given wind speed.

7.3 Further Research

As the results of this work have shown the performance and efficiency of the BDFTIG system very much depend on the generator design and its characteristics. This is especially important with regards to the reactive power consumption by the BDFTIG and power quality correction. Therefore, some further research is required into the optimization of the generator design for wind-power applications. Suggested research topics should include the study of the influence of the generator mutual inductances on the behaviour of the system and their optimization. It would also be useful to look into improving the design of the control machine, reducing its volume for the same rating and to provide enhanced power factor correction performance for the system.

Future research could examine the behaviour of the BDFTIG with squirrel-cage rotor designs.
Furthermore, future work to be considered should include a new model for a stand-alone generator instead of grid connected. In the stand-alone generator mode, the prime mover may be a diesel generator set or a gas turbine. The output voltage and frequency can be controlled separately to allow the output frequency to be independently set to either 50 or 60 Hz, and the voltage set accordingly.
Appendix

Appendix (A)- The M-file S-functions For The BDFTIG Modelling

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

% (t=current time), (x=state vector), (u=input), (flag=task to be performed)

Rsp=Pparam1(1);
L1sp=Pparam1(2);
Lmp=Pparam1(3);
Rrp=Pparam2(1);
L1rp=Pparam2(2);
Pp=Pparam2(3);
Lsp=Pparam1(2)+Pparam1(3);
Lrp=Pparam2(2)+Pparam1(3);

Rsc=Cparam1(1);
L1sc=Cparam1(2);
Lmc=Cparam1(3);
Rrc=Cparam2(1);
L1rc=Cparam2(2);
Pc=Cparam2(3);
Lsc=Cparam1(2)+Cparam1(3);
Lrc=Cparam2(2)+Cparam1(3);
Lr=Lrc+Lrp;
Rr=Pparam2(1)+Cparam2(1);
Jp=Pmech(1);
Jc=Cmech(1);
Fp=Pmech(1);
Fc=Cmech(1);
J=Pmech(1)+Cmech(1);
\[ F = P_{\text{mech}}(2) + C_{\text{mech}}(2); \]

\[ B = \begin{bmatrix} R_{\text{sp}} & L_{\text{sp}} & 0 & L_{\text{mp}} & 0 & 0 \\ -L_{\text{sp}} & R_{\text{sp}} & -L_{\text{mp}} & 0 & 0 & 0 \\ 0 & L_{\text{mp}} & R_{\text{r}} & L_{\text{r}} & 0 & L_{\text{mc}} \\ -L_{\text{mp}} & 0 & -L_{\text{r}} & R_{\text{r}} & L_{\text{mc}} & 0 \\ 0 & 0 & L_{\text{mc}} & R_{\text{sc}} & L_{\text{sc}} \\ 0 & 0 & -L_{\text{mc}} & 0 & -L_{\text{sc}} & R_{\text{sc}} \end{bmatrix}; \]

\[ A = \begin{bmatrix} L_{\text{sp}} & 0 & L_{\text{mp}} & 0 & 0 & 0 \\ 0 & L_{\text{sp}} & 0 & L_{\text{mp}} & 0 & 0 \\ L_{\text{mp}} & 0 & L_{\text{r}} & 0 & L_{\text{mc}} & 0 \\ 0 & L_{\text{mp}} & 0 & L_{\text{r}} & 0 & L_{\text{mc}} \\ 0 & 0 & L_{\text{mc}} & 0 & L_{\text{sc}} & 0 \\ 0 & 0 & 0 & L_{\text{mc}} & 0 & L_{\text{sc}} \end{bmatrix}; \]

\[ C = \text{eye}(7,7); \]

\textbf{switch} flag,\%
\textbf{Initialization}\%
\textbf{case} 0,\%
\ \ \ \ \ \ \ \ \ \ \ \ \ \ \ \ \ \ \ \ \ \ \ \ \ \ \ \ \ \ \ \ \ \ \ \ \ \ \ \ \ \ \ \ \ \ \ \ \ \ \ \ \ \ \ \ \ \ \ \ \ \ \ \ \ \ \ %to \begin{bmatrix} x_0 & = & \text{zeros}(7,1); \\ \text{str} & = & []; \\ \text{ts} & = & [0 \ 0]; \end{bmatrix}
% Derivatives

\[ u(1) = W_p; \quad u(2) = V_{spq}; \quad u(3) = V_{spd}; \quad u(4) = V_{scq}; \quad u(5) = V_{scd}; \quad u(6) = TL \]
\[ x(1) = ispq; \quad x(2) = ispd; \quad x(3) = irpq; \quad x(4) = irpd; \quad x(5) = iscq; \quad x(6) = iscd \]
\[ x(7) = W_m; \quad x(8) = T_e; \quad x(9) = T_e_p; \quad x(10) = T_e_c; \]

**case 1**, %flag_1(calculation of derivative)

\[ \text{ang}_{\text{speed}} = [1 \ u(1) \ 1 \ u(1) \ 1 \ 1 \ u(1) \ 1 \ u(1) \ 1 \ 1 \ 1 \ u(1) \ 1 \ u(1) \ 1 \ 1 \ 1 \ u(1) \ 1 \ u(1) \ 1 \ 1 \ 1 \ u(1) \ 1 \ u(1) \ 1 \ 1 \ 1 \ u(1) \ 1 \ u(1) \ 1 \ 1 \ 1 \ u(1) \ 1 \ u(1) \ 1 \ 1 \ 1 \ u(1) \ 1 \ u(1) \ 1 \ 1 \ 1] \]

\[ B_w = B.*\text{ang}_{\text{speed}}; \]
\[ U_v=\text{transp}([u(2) \ u(3) \ 0 \ 0 \ u(4) \ u(5)]); \]
\[ \text{sys}(1:6) = A*(B_w*x(1:6) + U_v); \]

% Fluxes power machine
\[ \phi_d = L_{sp}*x(2) + L_{mp}*x(4); \]
\[ \phi_q = L_{sp}*x(1) + L_{mp}*x(3); \]
\[ T_e_p = -1.5*P_p*(\phi_q*x(2) - \phi_d*x(1)); \]

% Fluxes control machine
\[ T_e_c = 1.5*P_c*L_{mc}*(x(6)*x(3) - x(5)*x(4)); \]

% Torque
\[ T_e = T_e_p + T_e_c; \]
\[ \text{sys}(7) = (T_e - F*x(7) - u(6))/J; \]

% 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*(phi_q*x(2)-phi_d*x(1));

%Control machine
Te_c=1.5*Pc*Lmc*(x(6)*x(3)-x(5)*x(4));
%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 (B)- The Specification of both Induction Machines for the Simulink propose

%clc
f=50;
we=2*pi*f;            %314.159 r/s = 3000 rpm
Pb_p=4000;
Vab_p=415;           %3_phase Vrms
Vb_p=Vab_p/sqrt(3);    %240 Vrms/ph
lb_p=Pb_p/(3*Vb_p);    %5.56 A
Zb_p=Vb_p/lb_p;       %43.2 ohm
Lb_p=Zb_p/we;          %137.5 mH

%Power machine parameters
Rsp=5.25;
Llsp=.04;
Lmp=0.5344;
Rrp=3.75;
Llrp=0.033;
Pp=2;
Jp=0.152;
Fp=0.0147;
Lsp=Llsp+Lmp;
Lrp=Llrp+Lmp;
Pb_c=4000;
Vab_c=415;           %3_phase Vrms
\[ V_{b_c} = \frac{V_{ab_c}}{\sqrt{3}}; \quad \%240 \text{ Vrms/ph} \]
\[ I_{b_c} = \frac{P_{b_c}}{3 \cdot V_{b_c}}; \quad \%5.56 \text{ A} \]
\[ Z_{b_c} = \frac{V_{b_c}}{I_{b_c}}; \quad \%43.2 \text{ ohm} \]
\[ L_{b_c} = \frac{Z_{b_c}}{\omega}; \quad \%137.5 \text{ mH} \]

%Control machine parameters
\[ R_{sc} = 5.25; \]
\[ L_{isc} = 0.04; \]
\[ L_{mc} = 0.5344; \]
\[ R_{rc} = 3.75; \]
\[ L_{lr} = 0.033; \]
\[ P_{c} = 2; \]
\[ J_{c} = 0.152; \]
\[ F_{c} = 0.0147; \]
\[ L_{sc} = L_{isc} + L_{mc}; \]
\[ L_{rc} = L_{lr} + L_{mc}; \]

%Total rotor parameters
\[ R_{r} = R_{r_p} + R_{rc}; \]
\[ L_{r} = L_{r_p} + L_{rc}; \]

%Linkage constants
\[ K_{1} = L_{r} - \left( L_{mp}^2 \right) / L_{sp}; \]
\[ K_{2} = L_{mp} - L_{r} \cdot L_{sp} / L_{mp}; \]
\[ K_{3} = L_{sc} - \left( L_{mc}^2 \right) / K_{1}; \]
%Natural speed

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

%Turbine Settings:
Vbase=15;
Pmax=0.95;
Wbase=1.05;

%Filter Settings
Lf=0.08*Lb_p;
Rf=0.04*Zb_p;
Appendix (C)- The BDFTIG Simulink Modelling Scheme

The Complete Simulink Scheme for the Modelling
\[
\theta_p = \text{Inv}_\tan(V_p\_alpha/V_p\_beta)
\]

\[
\text{abc} \rightarrow \text{Vp\_alpha\_beta}
\]

\[
\text{abc to alpha beta Transformation}
\]

\[
\text{Mechanical shaft speed} \rightarrow \text{shaft speed angle}
\]

\[
\frac{1}{s} \rightarrow \text{Elec shaft speed}
\]

\[
\pm \theta_r \rightarrow \text{angles calc.}
\]
abc_to_alpha_beta
Transformation

Turbine
Wind Turbine
\[ cp(\lambda, \beta) \]

DC control

\[ \text{abc to \alpha\beta transformation} \]

ABC->DQ

\[ \text{Vs abc to \alpha\beta transformation} \]
\[ \theta_p = (\frac{1}{\tan}) \times (\text{Vsp}_\alpha / \text{Vsp}_\beta) \]

**Generate Theta**

\[ \text{abc} \rightarrow \text{Vp}_\alpha / \text{Vp}_\beta \]

**Abc to Alpha Beta Transformation**

\[ V_d = \frac{2}{3} (V_a \sin \omega t + V_b \sin (\omega t + 2\pi / 3) + V_c \sin (\omega t + 4\pi / 3)) \]
\[ V_q = \frac{2}{3} (V_a \cos \omega t + V_b \cos (\omega t + 2\pi / 3) + V_c \cos (\omega t + 4\pi / 3)) \]
\[ V_0 = \frac{1}{3} (V_a + V_b + V_c) \]
\[
\text{Eq 4.32}
\]
\[
\text{Eq 4.35}
\]

**Modulation Calc.**
3-phase instantaneous active and reactive power
Gilbert Sylvestre, Pierre-Octoux
Power System Simulation Laboratory
IREQ, Hydro-Quebec

This block computes the 3-phase instantaneous real power and reactive power using the following equations:

1) \( P = V_a I_a + V_b I_b + V_c I_c \)
2) \( Q = -\sqrt{3} (V_b c^* I_a + V_c a^* I_b + V_a b^* I_c) \)

Note: Equation 2 is valid only for a balanced and harmonic-free system.
Appendix (D)- Designing the Power Electronic Drive

For this project there is a cascaded induction machine with its rotors connected in series. The stator winding in control machine number B is connected to a balanced 3-phase sinusoidal source of 120° phase difference each. The source is the power electronic circuit which consists of:

- A 3-phase signal generator with variable frequency input control.
- A variable command gain amplifier circuit to vary the amplitude of the 3-3phase signal and power protection circuit to protect the amplifier.
- Three 1kW Power Amplifier.

A 3-phase signal is generated from signal generator with 120° phase change balanced and the frequency is commonly adjusted for all three signals. The variable command gain amplifier circuit has a common gain adjustment for all three signals. The oscillators and variable gain amplifiers provide the minimum frequency and voltage for the induction machine to run above zero speed. The circuit of the complete experimental design is shown in next diagram.
Circuit diagram for the Power Electronic Drive
Experimental results from Power Electronic Drive

Before any serious experiment could begin it was necessary to ensure that it was a 3 phase output balanced from signal generator as shown in next figure.

These three signals are connected to the three Linear Variable Gain Amplifier pin number 3 in order to variable command gain adjustment for all three signals through voltage gain which is fed from variable voltage (-1V to +1V). As shown in next figure, the output from Linear Variable Gain Amplifier pin number 10.
These signals from three variable gain amplifiers are connected to 1 kW power through the protection circuit to protect the power amplifiers as shown before.
Appendix (E)- The Control Design for VSI Scheme

1- The Speed Control for VSI Control Scheme.

The Complete Block Diagram for Speed Control

\[ T_e - T_L = B \omega_m + j \frac{d\omega_m}{dt} \]

\[ \frac{d\omega_m}{dt} = \frac{T_e - T_L - B\omega_m}{j} \]

\( T_e(s) - T_L(s) = B \omega_m(s) + sj \omega_m(s) \)

\[ \frac{T_e(s) - T_L(s)}{\omega_m(s)} = B + sj \]

Power rated 4 kW  Rated speed \((\omega_m) = 1400 \text{ rpm}\)

Rated speed in mechanical = \( \frac{1400 \times 2\pi}{60} = 146.6 \text{ rad/s} \)

Rated speed in electrical = \( \frac{146.6 \times 4}{2} = 293.2 \text{ rad/s} \)

Synchronous speed \((\omega_s) = \frac{120f}{p} = 1500 \text{ rpm} \)

Synchronous speed electrical = 314.1 rad/s

\[ T_e - T_L = \frac{power}{rated \text{ speed}} = \frac{4000}{146.6} = 27.29 \text{N.m} \]

\( \omega_c = \text{Synchronous speed electrical} - \text{Rated speed in electrical} \)
\[ \omega_c = 314.16 - 293.2 = 20.95 \text{rad/s} \]

\[ K_c = \frac{T_c - T_L}{\omega_c} = \frac{27.29}{20.959} = 1.3 \]

Closed loop transfer function:

\[ \frac{\omega_m^*}{\omega_m} = \frac{G(s)}{1 + G(s)} \]

\[ G(s) = [1.3K \left( \frac{s+a}{s}\right)] \left[ \frac{1}{sj+B} \right] \]

\[ G(s) = [1.3K \left( \frac{s+a}{s}\right)] \left[ \frac{1/j}{s+(B/j)} \right] \]

\[ G(s) = [1.3K \left( \frac{s+a}{s}\right)] \left[ \frac{6.5789}{s+0.0967} \right] \]

Ch.eq 1 + G(s) H(s) = 0

\[ S^{1→} = S \left( S + 0.0967\right)+ 1.3K \left( S+a\right) \]

\[ = S^2 +0.0967 S + 1.3 K S + 1.3 K a \]

\[ = S^2 + [0.0967+ (1.3 K)] S + 1.3 K a \]

Standard forma = \( S^2 + 2 \zeta \omega_n S + \omega_n^2 \)

Assume \( \zeta = 0.707 \) and \( B/W = 2 \text{ Hz} \)

So  
\[ [(0.0967+ (1.3 k)] = 2 \times 0.707 \times 2\pi \times 2 = 17.7688 \]

Therefore  \( 1.3 K = 17.672 \)

\[ K = \frac{17.67}{1.3} = 13.59 \]

\[ S^{0→} = 1.3 \times 13.59 a = \omega_n^2 \]
\[ W_n^2 = 157.9 \]

Therefore \( a = \frac{157.9}{17.67} = 8.9376 \)

The PI controller is \( \frac{13.59(s+8.9376)}{s} \)

2- The current control for VSI control scheme.

Assume the \( \omega_{bm} = 200\text{Hz} \), PWM and \( \zeta =0.70 \). For this system these switching frequencies were selected to be 5 kHz. The choice was based on the need to minimize the switching noises, as well as the limitations of the dSPAC.

\[
\begin{align*}
\frac{G(s)}{1+G(s)} &= \frac{k(s+a)}{s} \\
G(s) &= \frac{1}{s(\tau_s+1)} \\
G(s) &= \frac{1}{s(s+128.2)} \\
\text{Ch.eq 1 + G(s) H(s) = 0} \\
S^{1-} &= S(s + 128.2) + 24.4k(s+a) \\
&= S^2 + 128.2S + 24.4KS + 24.4Ka \\
&= S^2 + (128.2 + 24.4K)S + 24.4Ka
\end{align*}
\]
Standard form: \( S^2 + 2\zeta W_n S + W_n^2 \)

So \((128.2 + 24.4\ K) = 2 \times 0.707 \times 2\pi \times 200 \)

\[ 24.4\ K = 1648.68 \]

Therefore \( K = \frac{1648.68}{24.4} = 67.57 \)

\( S^0 - S = 24.4\ K a = W_n^2 \)

= 24.4\ Ka = (2\pi \times 10)^2 = 1579136.7

Therefore \( a = \frac{15791367}{24.4 \times 67.57} = 957.8 \)

The PI controller is \( \frac{67.57(s + 957.8)}{S} \)
Appendix (F)- The Control Design for VSR Scheme

1- Current Control

![Block diagram for PI Current Control](image)

Closed loop transfer function:
\[
\frac{I_s}{I_s^*} = \frac{G(s)}{1 + G(s)}
\]

\[
G(s) = \frac{1071.45K(s+a)}{s(s+1)}
\]

Ch.eq 1 + G(s) H(s) = 0

\[
S^{1\rightarrow} = S(S+1) + 1071.45K(S+a)
\]

\[
= S^2 + S + 1071.45KS + 1071.45Ka
\]

\[
= S^2 + (25 + 1071.45K)S + 1071.45Ka
\]

Standard form = \(S^2 + 2 \zeta W_n S + W_n^2\)

So \((25 + 1071.45K) = 2 \times 0.707 \times 2\pi \times 200\)

\[
1071K = 1751.8848
\]

Therefore \(K = \frac{1751.8848}{1071.45} = 1.635\)

\[
S^{0\rightarrow} = 1071.54Ka = W_n^2
\]

\[
= 1071.54Ka = (2\pi \times 10)^2 = 1579136.7
\]

Therefore \(a = \frac{1579136.7}{1071.54 \times 1.635} = 889.38\)

The PI controller is \(\frac{1.657(s + 889.38)}{s}\)
2- DC Link Control

![Figure 4.8- DC link voltage control loop](image)

Closed loop transfer function:

\[
\frac{I_s}{I_s^*} = \frac{G(s)}{1 + G(s)}
\]

\[
G(s) = \frac{954.59K(s+a)}{s(s)}
\]

Ch.eq 1 + G(s) H(s) = 0

\[
S^{1→} = S \cdot (S + 954.59k \cdot (S+a))
\]

\[
= S^2 + 954.59KS + 954.59Ka
\]

\[
= S^2 + (954.59K) S + 954.59Ka
\]

Standard forma = \(S^2 + 2\zeta W_n S + W_n^2\)

So \((054.59K) = 2 \times 0.707 \times 2\pi \times 200\)

\[
954.59K = 1776.8848
\]

Therefore \(K = \frac{1776.8848}{954.59} = 1.8614\)

\[
S^{0→} = 954.59Ka = W_n^2
\]

\[
= 954.59Ka = (2\pi \cdot 200)^2 = 1579136.7
\]

Therefore \(a = \frac{15791367}{954.59 \times 1.8614} = 888.7\)

The PI controller is \(\frac{1.8614(s + 888.7)}{s}\)
Appendix (G)- The Specification of both Induction Machines for the Practical purpose

Power rated 1.5 hp = (1.5 * 745.6 = 1.11kW)

Rated speed (\(\omega_r\)) = 1400 rpm

Rated Voltage = 240 V

Rated Current = 4.2 A

Base Frequency = 50 Hz

Number of poles = 4

Moment of inertia = 0.0226 kg.m\(^2\)

Friction = 0.00114 kg m\(^2\)/s

Rotor resistance = 0.39 Ω

Stator resistance = 0.19 Ω

Stator inductance = 0.21mH

Rotor inductance = 0.6mH

Magnetizing inductance = 4mH
Appendix (H)- The Control Design for the practical Machine

1- PI Speed Control for the Practical propose

Rated speed in mechanical = \( \frac{1400 \times 2\pi}{60} = 146.6 r/s \)

Rated speed in electrical = \( \frac{146.6 \times 4}{2} = 293.2 r/s \)

Synchronous speed \((W_e) = \frac{120f}{p} = \frac{120 \times 50}{4} = 1500 rpm\)

Synchronous speed in mechanical = \( \frac{1500 \times 2\pi}{60} = 157.07 r/s \)

Synchronous speed in electrical = \( \frac{157.07 \times 4}{2} = 314.16 r/s \)

The Block diagram for Speed Control

\[
T_e = T_L + B_r \omega_r + J \frac{d\omega_r}{dt}
\]

\(T_e(s) = T_L(s) + B_r \omega_r(s) + Js W_r(s)\)

\[
T_e = T_L + B W_{r(s)} + J_s W_{r(s)} T
\]

\[
T_e - T_L(s) = \frac{JS + B}{W_r}
\]

\[
\frac{W_r}{Te - T_L} = \frac{1}{JS + B}
\]
\[ k_{\text{slip}} = \frac{T_e - T_L}{W_{\text{slip}}} \]

\[ T_e - T_L = \frac{\text{power}}{\text{rated speed}} = \frac{1118.6}{146.6} = 7.629 \text{Nm} \]

\[ W_{\text{slip}} = \text{synchronous speed (} W_e \text{) - rated speed (} W_r \text{)} \quad \text{(both in electrical)} \]

\[ W_{\text{slip}} = 314.16 - 293.2 = 20.959 \text{r/s} \]

\[ K_{\text{slip}} = \frac{T_e - T_L}{W_{\text{slip}}} = \frac{7.629}{20.959} = 0.364 \]

**PI Control:**

\[ G(s) = K \frac{s + a}{s} \cdot \frac{1}{j \cdot K_{\text{slip}} + B} \]

\[ G(s) = K \cdot K_{\text{slip}} \frac{s + a}{s} \cdot \frac{1/j}{s + B/j} \]

\[ G(s) = k \frac{s + a}{s} \cdot \frac{16.1}{s + 0.05} \]

\[ 1 + G(s) H(s) = 0 \]

\[ S^1_{\rightarrow} = S (S + 0.05) + k (S + a) \quad (16.1) \]

\[ = S^2 + 0.05 S + 16.1 KS + 16.1 Ka \]

\[ = S^2 + (0.05 + 16.1 K) S + 16.1 Ka \]

Standard form \[ = S^2 + 2 \zeta W_n S + W_n^2 \]

Assume \[ \zeta = 0.707 \] and \[ B/W = 10 \text{ Hz} \]

\[ \text{So} \quad (0.05 + 16.1 K) = 2 \times 0.707 \times 2\pi \times 10 \]

\[ 16.1 K = 44.372 \]

Therefore \[ K = \frac{44.372}{16.1} = 2.756 \]

\[ S^0_{\rightarrow} = 16.1 Ka = W_n^2 \]

\[ = 16.1 Ka = 2\pi \times 10 = 3947.8 \]
Therefore \[ Ka = \frac{3947.84}{16.1} = 245.2 \]

The PI control is \[ \frac{2.756(S + 245.2)}{S} \]

2- PI Current Control for the Practical purpose

Design the current loops

\[ \omega_{bw} = 200 \text{Hz}, \text{PWM switching frequency} = 10 \text{kHz}, \text{& } \zeta = 0.707 \]

The stator time constant \[ \frac{L_s}{R_s} = \frac{0.25e^{-3}}{0.19} = 1.32 \text{ms} \]

The current control;

![Block Diagram for PI Control]

Closed loop transfer function:

\[ \frac{i_{sc}^q}{i_{sc}^d} = \frac{G(s)}{1+G(s)} \]

\[ G(s) = \frac{K(s+a)}{S(S+600)+4000K} = \frac{K(s+a)}{S(S+600)+4000K} = \frac{K(s+a)}{S(S+760)} \]

Ch.eq 1 + G(s) H(s) = 0

\[ S^{1} = S(S + 760) + 4000K(S+a) \]
\[ = S^2 + 760S + 4000K + 4000K \]
\[ = S^2 + 760S + 4000K + 4000K \]

Standard form \[ = S^2 + 2\zeta\omega_nS + \omega_n^2 \]

Assume \( \zeta = 0.707 \) and B/W = 200 Hz
So \((760 + 4000 \text{ K}) = 2 \times 0.707 \times 2\pi \times 200 = 1776.88\)

\[4000 \text{ K} = 1016.88\]

Therefore \(K = \frac{1648.68}{24.4} = 3.93\)

\(S^{0 \rightarrow} = 4000 Ka = W_n^2\)

\(= 4000 Ka = (2\pi \times 10)^2 = 1579136.7\)

Therefore \(a = \frac{15791367}{4000 \times 3.39} = 100.36\)

The PI controller is \(\frac{3.93(s + 100.36)}{S}\)
Appendix (I) The Voltage and Current Transducer Circuit
**Appendix (J) The Data for the Electrical Voltage Transfer Characteristic**

**Figure 6-5**

<table>
<thead>
<tr>
<th>At Shaft Speed 1250rpm</th>
<th>At Shaft Speed 1000rpm</th>
<th>At Shaft Speed 750rpm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Input Frequency</td>
<td>Output Voltage</td>
<td>Output Frequency</td>
</tr>
<tr>
<td>18</td>
<td>290</td>
<td>99.1</td>
</tr>
<tr>
<td>23.4</td>
<td>260</td>
<td>104.2</td>
</tr>
<tr>
<td>27.8</td>
<td>231</td>
<td>106.4</td>
</tr>
<tr>
<td>30.9</td>
<td>212</td>
<td>109.9</td>
</tr>
<tr>
<td>36.8</td>
<td>198</td>
<td>112.4</td>
</tr>
<tr>
<td>40.7</td>
<td>188</td>
<td>120.5</td>
</tr>
<tr>
<td>45.1</td>
<td>177</td>
<td>125</td>
</tr>
<tr>
<td>49.5</td>
<td>170</td>
<td>130</td>
</tr>
<tr>
<td>53.7</td>
<td>164</td>
<td>133.3</td>
</tr>
<tr>
<td>60.2</td>
<td>159</td>
<td>135</td>
</tr>
<tr>
<td>64.5</td>
<td>156</td>
<td>142.9</td>
</tr>
<tr>
<td>68.4</td>
<td>151</td>
<td>147</td>
</tr>
<tr>
<td>74</td>
<td>150</td>
<td>151.5</td>
</tr>
<tr>
<td>76.3</td>
<td>147</td>
<td>153</td>
</tr>
<tr>
<td>82.6</td>
<td>144</td>
<td>158</td>
</tr>
<tr>
<td>87.7</td>
<td>142</td>
<td>161</td>
</tr>
<tr>
<td>90</td>
<td>138</td>
<td>166</td>
</tr>
<tr>
<td>99.01</td>
<td>137</td>
<td>172</td>
</tr>
<tr>
<td>101</td>
<td>136</td>
<td>179</td>
</tr>
<tr>
<td>104</td>
<td>134</td>
<td>181</td>
</tr>
<tr>
<td>108</td>
<td>134</td>
<td>182</td>
</tr>
</tbody>
</table>
## Appendix K - The Electrical Frequency Relation for the BDFTG.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>7</td>
<td>38.48rs⁻¹</td>
<td>12.25Hz 367.51rpm</td>
<td>78.53rs⁻¹ 25 Hz 750rpm</td>
<td>114.65rs⁻¹ 37.5Hz 1094.8rpm</td>
<td>193V</td>
<td>432.3W</td>
<td>-569.6w</td>
<td>366.38w</td>
<td>-9.52N.m</td>
</tr>
<tr>
<td>8</td>
<td>43.98rs⁻¹</td>
<td>14Hz 420rpm</td>
<td>69.11rs⁻¹ 22Hz 660rpm</td>
<td>508.3W</td>
<td>113.1rs⁻¹ 36Hz 1080rpm</td>
<td>-766.8w</td>
<td>546.89w</td>
<td>-12.4N.m</td>
<td>-258.5w</td>
</tr>
<tr>
<td>9</td>
<td>49.48rs⁻¹</td>
<td>15.75Hz 472.5rpm</td>
<td>55.2x⁻¹ 17.57Hz 527.1rpm</td>
<td>575W</td>
<td>107.82rs⁻¹ 34.16Hz 1029.6rpm</td>
<td>-984.5w</td>
<td>778.69w</td>
<td>-15.7N.m</td>
<td>-409.5w</td>
</tr>
<tr>
<td>10</td>
<td>54.98rs⁻¹</td>
<td>17.5Hz 525rpm</td>
<td>47.12s⁻¹ 1.5Hz 450rpm</td>
<td>624.4W</td>
<td>1021rs⁻¹ 32.5Hz 975rpm</td>
<td>-1220.8w</td>
<td>1068.2w</td>
<td>-19.4N.m</td>
<td>-596.4w</td>
</tr>
<tr>
<td>11</td>
<td>60.47rs⁻¹</td>
<td>19.25Hz 577.3rpm</td>
<td>36.12rs⁻¹ 11.5Hz 345rpm</td>
<td>652.5W</td>
<td>96.59rs⁻¹ 30.75Hz 922.5rpm</td>
<td>-1472.8w</td>
<td>1421.7w</td>
<td>-23.5N.m</td>
<td>-820.3w</td>
</tr>
<tr>
<td>12</td>
<td>65.97rs⁻¹</td>
<td>21Hz 630rpm</td>
<td>25.13rs⁻¹ 8Hz 240rpm</td>
<td>651.4W</td>
<td>91.1rs⁻¹ 29Hz 870rpm</td>
<td>-1737.9w</td>
<td>1845.8w</td>
<td>-27.9N.m</td>
<td>-1086.5w</td>
</tr>
<tr>
<td>13</td>
<td>71.47rs⁻¹</td>
<td>22.74Hz 682.46rpm</td>
<td>14.13rs⁻¹ 4.5Hz 135rpm</td>
<td>612.9W</td>
<td>85.6rs⁻¹ 27.25Hz 997.46rpm</td>
<td>-2013w</td>
<td>2346.7w</td>
<td>-32.8N.m</td>
<td>-1400.1w</td>
</tr>
<tr>
<td>14</td>
<td>76.97rs⁻¹</td>
<td>24.5Hz 735rpm</td>
<td>5.6rs⁻¹ 1.8Hz 54rpm</td>
<td>527.2W</td>
<td>81.68rs⁻¹ 26Hz 780rpm</td>
<td>-2293.4w</td>
<td>2931w</td>
<td>-38N.m</td>
<td>-1765.8w</td>
</tr>
<tr>
<td>14.28</td>
<td>78.54rs⁻¹</td>
<td>25Hz 750rpm</td>
<td>0 0</td>
<td>DC 493.2W</td>
<td>78.54rs⁻¹ 25Hz 750rpm</td>
<td>-2375w</td>
<td>3114w</td>
<td>-39.6N.m</td>
<td>-1881.8w</td>
</tr>
<tr>
<td>14.5</td>
<td>79.7rs⁻¹</td>
<td>25.36Hz 760.8rpm</td>
<td>2.38rs⁻¹ -0.76Hz 22.8rpm</td>
<td>464.26w</td>
<td>76.65rs⁻¹ 24.4Hz 732rpm</td>
<td>-2437w</td>
<td>3256w</td>
<td>42.4N.m</td>
<td>-1972.7w</td>
</tr>
<tr>
<td>15</td>
<td>82.467rs⁻¹</td>
<td>26.249Hz 787.49rpm</td>
<td>-7.85rs⁻¹ -2.5Hz 75rpm</td>
<td>385W</td>
<td>74.61rs⁻¹ 23.75Hz 712.45rpm</td>
<td>-2579.7w</td>
<td>3605w</td>
<td>-43.8N.m</td>
<td>-2194.7w</td>
</tr>
<tr>
<td>15.25</td>
<td>85.215rs⁻¹</td>
<td>26.25Hz 787.5rpm</td>
<td>-10.36rs⁻¹ -3.3Hz 99rpm</td>
<td>527.2W</td>
<td>73.29rs⁻¹ 23.33Hz 699.9rpm</td>
<td>-2605.9w</td>
<td>3788.2w</td>
<td>-44.4N.m</td>
<td>-2311.6w</td>
</tr>
<tr>
<td>15.5</td>
<td>86.59rs⁻¹</td>
<td>27.56Hz 826.8rpm</td>
<td>-13.44rs⁻¹ -4.28Hz 128.4rpm</td>
<td>468.5w</td>
<td>71.8rs⁻¹ 22.85Hz 685.71rpm</td>
<td>-2722.4w</td>
<td>3977.6w</td>
<td>-45.9N.m</td>
<td>-2433.7w</td>
</tr>
<tr>
<td>15.75</td>
<td>87.864rs⁻¹</td>
<td>28Hz 840rpm</td>
<td>-15.71rs⁻¹ -5Hz 150rpm</td>
<td>523.4W</td>
<td>70.68rs⁻¹ 22.5Hz 675rpm</td>
<td>-2793.5w</td>
<td>4173.3w</td>
<td>-47.4N.m</td>
<td>-2559.6w</td>
</tr>
<tr>
<td>16</td>
<td>89.339rs⁻¹</td>
<td>28.44Hz 853.2rpm</td>
<td>-18.85rs⁻¹ -6Hz 180rpm</td>
<td>61.8W</td>
<td>69.11rs⁻¹ 22Hz 660rpm</td>
<td>-2864.3w</td>
<td>4375.1w</td>
<td>-48.9N.m</td>
<td>-2690.9w</td>
</tr>
<tr>
<td>16.25</td>
<td>90.713rs⁻¹</td>
<td>28.88Hz 866.4rpm</td>
<td>-21.58rs⁻¹ -6.87Hz 204rpm</td>
<td>71W</td>
<td>67.54rs⁻¹ 21.5Hz 645rpm</td>
<td>-2934.9w</td>
<td>4583.4w</td>
<td>-50.5N.m</td>
<td>-2826w</td>
</tr>
<tr>
<td>16.5</td>
<td>90.988rs⁻¹</td>
<td>28.03Hz 840.9rpm</td>
<td>-23.56rs⁻¹ -7.5Hz 225rpm</td>
<td>80.8W</td>
<td>66.75rs⁻¹ 21.25Hz 637.5rpm</td>
<td>-3005.1w</td>
<td>4798.2w</td>
<td>-52.7N.m</td>
<td>-2969w</td>
</tr>
<tr>
<td>16.55</td>
<td>91.263rs⁻¹</td>
<td>29.05Hz 871.5rpm</td>
<td>-24.5rs⁻¹ -7.8Hz 234rpm</td>
<td>82.9W</td>
<td>66.28rs⁻¹ 21.1Hz 633rpm</td>
<td>-3019.1w</td>
<td>4842w</td>
<td>-53N.m</td>
<td>-2969w</td>
</tr>
<tr>
<td>16.6</td>
<td>92.088rs⁻¹</td>
<td>29.31Hz 879.3rpm</td>
<td>-24.82rs⁻¹ -7.9Hz 237rpm</td>
<td>85W</td>
<td>65.97rs⁻¹ 21Hz 630rpm</td>
<td>-3033.1w</td>
<td>4886w</td>
<td>-53.1N.m</td>
<td>-3207w</td>
</tr>
<tr>
<td>16.7</td>
<td>92.18rs⁻¹</td>
<td>29.36Hz 880.8rpm</td>
<td>-8.45Hz 253.5rpm</td>
<td>89.2W</td>
<td>65.43rs⁻¹ 20.83Hz 624.9rpm</td>
<td>-3061.1w</td>
<td>4974.8w</td>
<td>-53.9N.m</td>
<td>-3084w</td>
</tr>
<tr>
<td>16.75</td>
<td>92.262rs⁻¹</td>
<td>29.36Hz 881.04rpm</td>
<td>-26.92rs⁻¹ -8.57Hz 257.1rpm</td>
<td>91.45V</td>
<td>64.79rs⁻¹ 20.625Hz 618.75rpm</td>
<td>-3074</td>
<td>5019.7w</td>
<td>-54.4N.m</td>
<td>-3114w</td>
</tr>
<tr>
<td>17</td>
<td>93.462rs⁻¹</td>
<td>29.749Hz 829.49rpm</td>
<td>-29.84rs⁻¹ -9.5Hz 285rpm</td>
<td>102.5W</td>
<td>63.62rs⁻¹ 20.249Hz 607.49rpm</td>
<td>-3144w</td>
<td>5247.9w</td>
<td>-56.1N.m</td>
<td>-3267w</td>
</tr>
</tbody>
</table>
REFERENCES


**PUBLICATIONS**

