A Thesis
entitled

Analysis and Study of Floating Offshore Wind Turbines
by
Mehran Ahmadi

Submitted to the Graduate Faculty as partial fulfillment for the requirements of the
Master of Science Degree in Electrical Engineering

Dr. Abdollah Afjeh, Committee Chair
Dr. Vijay Devabhaktuni, Committee Member
Dr. Mohsin Jamali, Committee Member
Dr. Efstratios Nikolaidis, Committee Member
Dr. Patricia R. Komuniecki, Dean
College of Graduate Studies

The University of Toledo
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An Abstract of

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Floating wind turbines offer a means to vastly expand the number of possible sites for offshore wind energy plants. By using a floating support platform secured by mooring lines, a wind turbine can be installed in waters exceeding the 30m depth that limits installation of conventional bottom-fixed offshore wind turbines. However, to be economically viable advances in floating offshore wind turbine system design and deployment are necessary to significantly reduce the cost and improve the reliability of floating wind turbines.

This thesis develops a model-based simulation of floating offshore wind turbines in the MATLAB/Simulink environment. When necessary, the National Renewable Energy Laboratory’s FAST code is used to conduct wind turbine simulations. Methods to link FAST to Simulink are developed in this thesis to accomplish this task. Modeling the wind turbine in the Simulink environment enables an efficient system level view of the
entire wind turbine system. A number of design approaches to reduce the cost of offshore turbines are proposed in this thesis and studied in this modeling environment.

A doubly-fed induction generator (DFIG) is proposed for wind turbine application. The primary advantage of DFIGs for wind turbines is that they allow the amplitude and frequency of their output voltages to be maintained at a constant value, no matter the wind speed. Because of this feature, DFIGs can be directly connected to the AC power network and remain synchronized at all times with that power network. Another advantage is the ability to control the power factor while keeping the power electronic devices in the wind turbine at a moderate size. In order to link a Simulink DFIG model to FAST, the model must be expressed in time domain. This thesis develops the time-domain modeling and simulation of DFIGs.

Floating offshore wind turbines encounter greatly increased loading, which decreases fatigue life. One method to reduce the cost and mitigate offshore wind turbine structural loads is the application of structural control techniques commonly used in skyscrapers and bridges. Tuned mass dampers have been used to reduce loads in simulations of offshore wind turbines. This thesis discusses expanding the structural control methods by developing a set of optimum passive and active tuned mass dampers for offshore wind turbine platforms.

Additionally, a new, high-efficiency, DC/DC bidirectional converter for a power quality conditioner for floating offshore wind turbines is proposed and analyzed. The power quality conditioner is used to smooth the variable turbine power and the DC/DC bidirectional converter acts as an interface circuit between the DC bus and ultracapacitors to manage the power flow during charging and discharging modes. Simulation results and experimental results are presented to verify the operation of the converter.
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List of Symbols

$C_L$ .................. Lift coefficient
$C_D$ .................. Drag coefficient
$\rho$ .................. Density
$A$ .................... Area of rotor disk
$T_{em}$ ................. Electromagnetic torque
$T_m$ ................... Mechanical torque
$Q_s$ .................. Stator reactive power
$L_m$ .................. Generator magnetizing inductance
$L_s$ .................. Stator per phase winding inductance
$L_r$ .................. Rotor per phase winding inductance
$L_{ls}$ ................. Stator per phase leakage inductance
$L_{lr}$ ................. Rotor per phase leakage inductance
$R_s$ .................. Stator per phase winding resistance
$R_r$ .................. Rotor per phase winding resistance
$P$ ..................... Number of generator poles
$w$ ..................... Synchronous rotational speed
$w_r$ ................... Rotor mechanical speed
$\varphi_{ds}$ ............ Stator $d$ winding flux linkage
$\varphi_{qs}$ ............ Stator $q$ winding flux linkage
$\varphi_r$ ............... Rotor $d$ winding flux linkage
$\varphi_{qr}$ ............ Rotor $q$ winding flux linkage
$\theta_{dr}$ .............. Rotor $d$ winding voltage
$\theta_{qr}$ .............. Rotor $q$ winding voltage
$\theta_{ds}$ .............. Stator $d$ winding voltage
$\theta_{qs}$ .............. Stator $q$ winding voltage
$i_{dr}$ ................. Rotor $d$ winding current
$i_{qr}$ ................. Rotor $q$ winding current
$i_{ds}$ ................. Stator $d$ winding current
$i_{qs}$ ................. Stator $q$ winding current
$r$ ..................... Rotor radius
$S_1$ .................. Switch $S_1$
$S_2$ .................. Switch $S_2$
$C_r$ .................. Resonant capacitor
$L_r$ .................. Resonant inductor
List of Abbreviations

AC ....................... Alternating current
ADAMS ................... Automatic dynamic analysis of mechanical systems
AMD ..................... Active mass damper
BDC ...................... Bidirectional converter
DC ....................... Direct current
DFIG ..................... Doubly fed induction generator
DOF ...................... Degree of freedom
FOWT ..................... Floating offshore wind turbine
HEV ........................ Hybrid electric vehicles
HMD ........................ Hybrid mass damper
IBDC ..................... Isolated bidirectional converter
IGBT ........................ Insulated gate bipolar transistor
MOSFET .................. Metal oxide semiconductor field effect transistor
NIBDC ................... Non-isolated bidirectional converter
NREL ...................... National renewable energy laboratory
PWM ........................ Pulse width modulation
rms ........................ Root mean square
SAMD ..................... Semi-active mass damper
SC ........................ Structural control
TMD ........................ Tuned mass damper
TLCD ..................... Tuned liquid column damper
TLD ........................ Tuned liquid damper
TSD ........................ Tuned sloshing damper
UPS ........................ Uninterruptible power supplies
VSI ........................ Voltage source inverter
ZCT ........................ Zero current transition
ZVT ........................ Zero voltage transition
Chapter One

Introduction

1.1 Floating offshore wind turbines

In recent years, wind energy has become one of the most important and promising sources of renewable energy, which demands additional transmission capacity and better means of maintaining system reliability. As wind power continues its rapid growth worldwide, offshore wind farms are likely to comprise a significant portion of the total production of wind energy and may even become a sizable contributor to the total electricity production in some countries. The high quality offshore wind resource and the proximity to load centers make offshore wind energy a compelling proposition [2], [64]. Offshore wind turbines have the potential to be a significant contributor to global energy production because of the proximity of the high quality wind resource to coastal energy loads. However, due to the addition of wave and current loads, offshore structures must be made stronger, and thus more expensive than their land based counterparts. The reliability of offshore turbines suffers from the higher loading, and the inaccessibility of
the turbines for maintenance compounds this problem. The ability to reduce loads is therefore extremely important for offshore wind turbines, as it allows for increased reliability and possibly lighter and cheaper structures [2], [3].

In order to access offshore winds far offshore over deep water, floating platforms for wind turbines are being designed and studied. With few water depth and sea floor restrictions, these platforms could be placed anywhere in the oceans with suitable electricity transmission. Also, since the platforms can be towed by boats, the wind turbines could be moved or brought to shore for maintenance or decommissioning. Floating wind turbines, however, have been shown to experience much higher fatigue and ultimate loading than onshore or fixed bottom offshore turbines, and therefore could
benefit greatly from load reduction techniques. One method to reduce loading is to utilize structural control systems, which have been used successfully in civil structures to achieve improved structural response [1-3]. In wind turbine applications, fatigue is a design driver. While fixed bottom offshore platforms can benefit from structural control due to reduced fatigue damage, floating platforms experience increased motion due to relative platform flexibility and any reduction in these motions should result in a significant decrease in fatigue. The application of these systems to offshore wind turbines is the subject of this Master’s research. As shown in Figure 1.1, three common types of floating offshore wind turbines are spar buoys, tension leg platforms, and barges floating wind turbines.

1.2 Structural control of floating offshore wind turbines

The control of civil engineering structures has been an active research area for over two decades. The goal of this body of work has been to protect structures from dynamic loading due to earthquakes, wind, waves, and other sources. There are three major categories of control methods for structures: passive, semi-active, and active [3]. Passive structural control systems have constant parameters and no energy input to the system. A simple example of a passive system is a tuned mass–spring–damper (TMD) that is tuned to absorb energy at one of the natural frequencies of the entire structure. Semi-active control approaches may also be employed to mitigate structural response [2], [3]. In contrast to a passive system, the parameters of a semi-active system are tunable over time, providing more flexibility and better performance than the simpler passive TMD. In some cases, semi-active systems use feedback control to tune the device in
response to the motion of the structure. Such systems require the addition of sensors to measure structural response, and a control algorithm to command the variable parameters in the device. Finally, active control approaches are the most complex of the three control methods. The effectiveness of a passive TMD can be improved by adding a controlled force actuator. This combination is known as a hybrid mass damper (HMD) [3]. A system of only a mass and an actuator in which the actuator provides both the restoring and damping forces on the mass is known as an active mass damper (AMD). In these concepts, a mass is actively displaced with an actuator relative to the structure so as to exert an inertial force on the main structure. This force is commanded by a control algorithm using information available from sensors that measure structural response, excitation, and other key signals. A wide range of potential actuators exist for structural control, including tuned mass dampers (TMD), tuned sloshing dampers (TSD), tuned liquid dampers (TLD), tuned liquid column dampers (TLCD), controllable fluid dampers, pendulum dampers, hydraulic or servomotor active mass dampers, and more [2], [3]. The investigations carried out in this research utilize an ideal tuned mass damper system with ideal linear springs and dampers, and in the active control case, an ideal hybrid mass damper with an actuator that has no actuator dynamics or control–structure interaction. Future work is planned to consider realistic devices, actuators, and control–structure interaction. Structural control systems have been implemented successfully in a variety of configurations, often in large buildings in Asia where the earthquake risk is high. Two successful examples of HMDs implemented in practice can be found in Nagashima et al. [4] and in Yamanaka and Okuda [5]. In both cases, the addition of HMDs resulted in
significant reductions in the vibrations of large office buildings. More details can be found in the literature.

1.3 Existing wind turbines simulation tools

A number of design tools available to the offshore wind industry have the capability to model floating offshore wind turbines in a coupled time-domain dynamic analysis. This section presents the methods employed by those design tools and includes four categories: structural dynamics, aerodynamics, hydrodynamics and mooring lines [6].

1. **FAST with AeroDyn and HydroDyn by NREL** is a publicly available simulation tool for horizontal-axis wind turbines that was developed by the National Renewable Energy Laboratory (NREL), largely by Jonkman (Figure 1-2). The FAST code was developed for the dynamic analysis of conventional fixed-bottom wind turbines, but has been extended with additional modules to enable coupled dynamic analysis of floating wind turbines.

2. **ADAMS by MSC ADAMS (Automatic Dynamic Analysis of Mechanical Systems)** is a commercially available general-purpose MBS code developed by MSC Software Corporation (Figure 1-3). The code is not wind turbine-specific and also is used by the automotive, aerospace, and robotics industries. ADAMS models of wind turbines can be generated using the FAST tool’s FAST-to-ADAMS pre-processor functionality.
3. **Bladed by GL Garrad Hassan GH Bladed** is an integrated software tool for calculating wind turbine performance and dynamic response. It originally was developed by GL Garrad Hassan for modeling onshore fixed-bottom wind turbines. It has been extended, however, to include hydrodynamic loading for modeling offshore wind turbines. In the last year, the core structural dynamics of the code has been re-written to incorporate MBS.

4. **SIMPACK by SIMPACK AG SIMPACK** is a commercially available general-purpose MBS code developed by SIMPACK AG. The code is used by the automotive, railway, aerospace, and robotics industries. A version of SIMPACK—SIMPACK Wind—offers extensions to the original code that allow integrated wind turbine simulation. The SIM-PACK code has been used to model a floating wind turbine in Matha et al [6].
1.4 Doubly-fed induction generators for FOWTs

Doubly-fed electric machines are basically electric machines that are fed ac currents into both the stator and the rotor windings. Most doubly-fed electric machines in industry today are three-phase wound-rotor induction machines. Although their principles of operation have been known for decades, doubly-fed electric machines have only recently entered into common use. This is due almost exclusively to the advent of wind power technologies for electricity generation. Doubly-fed induction generators (DFIGs) are by far the most widely used type of doubly-fed electric machine, and are one of the most common types of generator used to produce electricity in wind turbines. Doubly-fed
induction generators have a number of advantages over other types of generators when used in wind turbines. The primary advantage of DFIGs when used in wind turbines is that they allow the amplitude and frequency of their output voltages to be maintained at a constant value, regardless of wind speed. Because of this, DFIGs can be directly connected to the ac power network and remain synchronized at all times with the ac power network. Other advantages include the ability to control the power factor (e.g., to maintain the power factor at unity), while keeping the power electronics devices in the wind turbine at a moderate size.

1.5 Thesis objectives

The main objective of this thesis is to develop the modeling and simulation of floating offshore wind turbines in SIMULINK/MATLAB environment and compare the results with the other simulation tools such as FAST, ADAMS, and so on.

The second objective is to compare the available generators in terms of efficiency, cost, load reduction and reliability, and choose the most appropriate generator for floating offshore wind turbines. In order to link the SIMULINK with FAST software, the generator must be modeled in time domain.

Various structural control techniques which can reduce the loads in floating offshore wind turbines need to be discussed and compared in terms of performance, cost, and complexity. The structural control methods can be modeled in SIMULINK environment.

The last objective is to introduce a new high efficient DC/DC bidirectional converter in a power quality conditioner for floating offshore wind turbines.
1.6 Thesis organization

This introduction is followed by Chapter 2 where the floating offshore wind turbine is modeled in MATLAB/ SIMULINK environment. Chapter 3 describes the advantages of DFIGs compared with the other generators for floating offshore wind turbines and develops the modeling and simulation of doubly-fed induction generators in time domain. In chapter 4, the previously proposed structural control techniques that can be applied in the floating offshore wind turbines to reduce loads are discussed and compared. In chapter 5, a new bidirectional DC/DC converter for a power quality conditioner for floating offshore wind turbines is proposed, and analyzed in detail. Simulation and experimental results are presented to verify the operation of the converter. Chapter 6 concludes this work by stating the summary of this thesis.
Chapter Two

Modeling of Floating Offshore Wind Turbines using MATLAB/SIMULINK

2.1 Overview of floating offshore wind turbine model

SIMULINK, developed by is a data flow graphical programming language tool for modeling, simulating and analyzing multi-domain dynamic systems. Its primary interface is a graphical block diagramming tool and a customizable set of block libraries. It offers tight integration with the rest of the MATLAB environment and can either drive MATLAB or be scripted from it. SIMULINK is widely used in control theory and digital signal processing for multi-domain simulation and Model-Based Design.

A wind turbine consists of a number of different subsystems that use different technologies. Different subsystems are built, and then integrated together. The model consists of the following blocks:

- Blades
- Nacelle
2.2 Determine ideal pitch actuator requirements

In a pitch actuation system, there is a mechanical linkage that can rotate the blade of the wind turbine to a certain angle. A control system in the wind turbine determines what that angle should be. The control system for the actuator will determine how much the mechanical linkage has extended or contracted in order to determine the force that actuator should apply. This includes the magnitude of that force, and the speed at which that force should be applied to achieve a desired performance. An ideal actuator is used in our system. Figure 2-1 shows the pitch actuation system which consists of an ideal actuator, blade actuation linkage, and actuation controller.

![Pitch actuation system](image)

Figure 2-1: Pitch actuation system
The blade and mechanical linkage is modeled in Figure 2-2, and the pitch actuator control is shown in Figure 2-3.

![Blade and mechanical linkage model](image)

Figure 2-2: Blade and mechanical linkage model
The performance of the system is shown in Figure 2-4 where the red line shows the command, and the yellow line is the actual pitch of the blade. Figure 2-5 shows the force required for the actuation system, magnitude and speed. This information is used to size the actuator.

Figure 2-4: Actual pitch angle (continuous yellow line) and command pitch angle (dashed red line)
2.3 Supervisory control system of wind turbines

The supervisory control of a wind turbine needs to analyze the operating conditions for the wind turbine, and determine which system should be turned on or turned off. A very simplified version of that specification shown in Figure 2-6 is illustrated as follows:

**Park state:** In the park state, the wind turbine should not be rotating. So the park brake will be turned on. The pitch brake will be turned off and the blades are locked, and pointed in the wind direction. The generator is not connected to the grid.

**Startup state:** If the wind gets above the certain speed (cut-in speed) then the wind turbine should be spinning and attempting to produce power. In this state, park...
brake would be turned off. The pitch brake is turned off, and generator is still not connected to the grid.

**Generating state:** When the turbine speed gets within a certain range (between cut-in and cut-out limits), the wind turbine could transition to generating state where the generator is connected to the grid.

**Brake mode:** Based on a number of conditions shown in Figure 2-6, the turbine may exit the generating state, and be slowed down. This could happened when the wind speed gets too low, or gets too fast in order to prevent the wind turbine failure due to excessive loads in which case it will be brought to a stop mode.

![Figure 2-6: Supervisory control of wind turbine](image-url)
2.4 Stateflow model

This supervisory control logic should be included in the model. To implement this event-based controller in SIMULNK, the stateflow model shown in Figure 2-6 is used. In the stateflow model, it is easy to determine which state the wind turbine is in, what the conditions are to transition to a different state, and based on the state, which subsystems are turned on or turned off.

To verify the operation of the stateflow model, the system shown in Figure 2-7 is used, which consists of a signal builder that specifies the wind and turbine speeds which are inputs for the turbine state machine. The simulation results shown in Figure 2-8 verify the operation of the system by showing the wind turbine transition from state to state. It is observed that in a short period of time, is managed to go through a normal cycle: park, start up, generating, brake, and then back to park again.

Figure 2-7: Stateflow testing model
Figure 2-8: Stateflow testing simulation results
2.5 **Determine yaw actuator requirements**

The yaw actuation system rotates the nacelle about its axes. The tower supports the nacelle, and the yaw ring is attached to the tower. The yaw ring is a very large gear affixed to the nacelle. On different sides of the yaw ring, there are the yaw gears, and yaw gears are driven by yaw motors. As the motor drives the yaw gears, they rotate around the yaw ring, and that is what rotates the nacelle. To accomplish yaw control, we need to determine the torque requirements for the yaw actuator. As shown in Figure 2-9, once there is a yaw command, which is the angle that nacelle should point, we need to figure out how much torque the motor should produce. The yaw control system takes the current nacelle yaw angle, compares it to the command yaw angle, and produces the yaw rate command. The yaw rate command will be kept within a specified limit. This rate will be compared to the nacelle yaw rate, and that gives rise to an appropriate torque command. As Figure 2-10 shows, with step input, the controller limits the rate that can turn the nacelle at a certain amount. Figure 2-11 shows the amount of torque that the actuator should provide.

![Figure 2-9: Yaw control system](image-url)
Figure 2-10: Nacelle yaw (deg) and nacelle yaw rate (deg/s)

Figure 2-11: Yaw actuator torque (Nm)
2.6 Modeling the wind forces on the blades

The wind passes over the blades, producing lift and a moment that rotates the rotor. The interaction of wind with the blades to produce the moment must be modeled. Two methods are used to accomplish this task: (1) using base Simulink, and (2) using Embedded MATLAB.

2.6.1 Single Element Model

The easiest way to estimate the turbine rotor moment is to assume that the blade is simply one element. Given the wind speed and direction, the airfoil profile, and rotor speed, a single value of lift and drag can be calculated. This single element model is useful for quick and simple approximations; however the interaction between the wind and the blades requires more complex models.

2.6.2 Multiple Element Model

Along the blade, the wind speed and direction will vary. For a more accurate model, the blade can be divided into elements, and the lift and drag on each element can be estimated using local values of wind speed and direction and the airfoil section characteristics. Figure 2.12 shows the single element and multiple element model of the blade.
2.6.3 Calculating Lift and Drag

The force on the blades depends on airfoil profile, wind speed and direction, and rotor speed. Figure 2-13 shows the cross section of a blade, and illustrates how the lift and drag can be calculated using airfoil characteristics, as follows [86]:

Figure 2-12: Blade single element model (left), and multiple element model (right)

Figure 2-13: Cross section of the blade
Lift = 0.5 V^2 A \rho C_L \hspace{1cm} (1)

Drag = 0.5 V^2 A \rho C_D \hspace{1cm} (2)

where \( C_L \) and \( C_D \) = \( f \) (Angle of attack, Airfoil section, ... ) \hspace{1cm} (3)

Angle of attack = Inflow Angle − Pitch Angle \hspace{1cm} (4)

Inflow Angle = Arctan \left( \frac{\text{Pure wind}}{\text{Rotation wind}} \right) \hspace{1cm} (5)

Rotation wind = Rotor speed \times \text{Radius} \hspace{1cm} (6)

These equations are simplified version, neglecting the induced flow, but are adequate for the purpose of this research. The lift and drag depend upon the lift and drag coefficients which, in turn, depend upon the angle of attack. The angle of attack is the angle between the inflow angle and the pitch angle. Neglecting the induced flow, if the blade rotation speed, and the wind speed and direction are known, the inflow angle can be calculated from the velocity diagram. Given a pitch angle, this allows us to calculate the angle of attack, and then lift and drag. The model of one blade is shown in Figure 2-14. The related equations are modeled in Simulink as shown in Figure 2-15. The lift and drag coefficients used in industry are often obtained from a lookup specified for the blade section airfoil and then used to compute blade forces in the simulation.
2.6.4 **Segmented blade approach**

Because the blade is spinning, the wind speed varies along the blade. In the blade tip region, the elements move faster than the elements close to the center of the blade. Therefore, this radial dependence should be taken into account to more accurately
calculate the lift and drag. To that end, the blade is divided into segments, calculating lift and drag for each segment, and summing them together to calculate the blade force and the moment. This procedure has been implemented using embedded MATLAB, as shown in Figure 2-16.

![Figure 2-16: Schematic of segmented blade modeling approach](image)

### 2.7 Tower subsystem

The tower subsystem is shown in Figure 2-17. Note that the platform and mooring lines effect are modeled using the output data generated by the FAST software. This is the only use of FAST software in the modeling approach. In the future, the platform and mooring lines will be modeled in SIMULINK environment, as well.
Figure 2-17: Tower subsystem including hydrodynamic forces (platform and mooring lines) obtained from FAST software

2.8 Simulation results

The modeling of the floating offshore wind turbine is shown in figure 2-18. Simulation results of this model are shown in Figures 2-19 through 2-21. At the beginning of the simulation, the wind speed is too low, so the system is in park and does not move. Once the wind speed is high enough, the system will begin to move. The blades will be pitched in order to efficiently capture the wind and generate lift, and turn the rotor. Once the wind turbine has reached its nominal speed, the controller will pitch the blades in order to maintain the turbine’s rated power. Looking at the pitch actuator force plot, it can be observed how much force the actuator should produce in order to turn the blades, and maintain a certain angle. The system is accelerating up to the generator
nominal speed. As the wind speed and direction change, the pitch of the blades is changed to capture the power efficiently and the yaw angle of the nacelle will change to direct the turbine in the wind. As the simulation continues, when the wind speed drops, the blades will be pitching to compensate for that. When at some point the wind speed is too low to produce power, the supervisory logic controller decides that it is time to turn the wind turbine off. Looking at the nacelle yaw block, the angle of the nacelle is set such that it is always pointed into the wind, and the yellow line shows how the yaw system is attempting to track that angle. The yaw actuator torque block shows how much torque the necessary yaw actuator in order to keep the nacelle pointed into the wind.

Figure 2-18: Floating offshore wind turbine main blocks in SIMULINK
Figure 2-19: Speed and direction of wind

Figure 2-20: Rotor Speed (rpm)
2.9 Conclusion

In this chapter, the floating offshore wind turbine including blades, tower, pitch and yaw actuation systems, blade aerodynamic loads, and main controller is modeled in MATLAB environment. The platform and mooring lines effect are modeled using the output data generated by the FAST software. To simplify the analysis, in the modeling of aerodynamics loads, the induced flow is neglected. In the pitch and yaw actuation system, the conventional PID controller is used. The mechanical systems are also assumed ideal.
Chapter Three

Modeling of Doubly-Fed Induction Generators for Floating Offshore Wind Turbines

3.1 Introduction

Figure 3-1 shows the application of Doubly-Fed Induction Generators (DFIGs) in floating offshore wind turbines where a DFIG consists of a wound rotor induction generator and an AC/DC/AC IGBT-based PWM converter. $V_r$ represents the rotor voltage and $V_{gc}$ is the grid side voltage. The AC/DC/AC converter is basically a PWM converter which uses sinusoidal PWM technique to reduce the harmonics present in the wind turbine driven DFIG system. $C_{\text{rotor}}$ is the rotor side converter and $C_{\text{grid}}$ is the grid side converter. To control the speed of wind turbine gear boxes, an electronic control can be used. The stator winding is connected directly to the 50 Hz grid while the rotor is fed at variable frequency through the AC/DC/AC converter. The DFIG technology allows extracting maximum energy from the wind for low wind speeds by optimizing the turbine
speed, while minimizing mechanical stresses on the turbine during gusts of wind. The optimum turbine speed producing maximum mechanical energy for a given wind speed is proportional to the wind speed during stand-up phase of the turbine operation. Another advantage of the DFIG technology is the ability for power electronic converters to generate or absorb reactive power, thus eliminating the need for installing capacitor banks as in the case of squirrel-cage induction generator.

![Figure 3-1: Basic diagram of doubly fed induction generator with converters](image)

As mentioned, the stator is directly connected to the AC mains, while the wound rotor is fed from the Power Electronics Converter via slip rings to allow the DIFG to operate at a variety of speeds in response to a changing wind. Indeed, the basic concept is to interpose a frequency converter between the variable frequency induction generator
and fixed frequency grid. The DC capacitor linking stator- and rotor-side converters allows the storage of power from the induction generator for further generation. To achieve full control of grid current, the DC-link voltage must be boosted to a level higher than the amplitude of grid line-to-line voltage. The slip power can flow in both directions, i.e. to the rotor from the supply and from supply to the rotor and hence the speed of the machine can be controlled from either rotor- or stator-side converter in both super and sub-synchronous speed ranges. As a result, the machine can be controlled as a generator or a motor in both super and sub-synchronous operating modes realizing four operating modes. Below the synchronous speed in the motoring mode and above the synchronous speed in the generating mode, the rotor-side converter operates as a rectifier and the stator-side converter as an inverter, where slip power is returned to the stator. Below the synchronous speed in the generating mode and above the synchronous speed in the motoring mode, the rotor-side converter operates as an inverter and stator side converter as a rectifier, where slip power is supplied to the rotor. At the synchronous speed, slip power is taken from supply to excite the rotor windings, and in this case the machine behaves as a synchronous machine [2].

The mechanical power and the stator electric power output are computed as follows:

\[ P_r = T_m \times W_r \] (7)

\[ P_s = T_{em} \times W_s \] (8)

For a lossless generator the mechanical equation is:

\[ J \frac{dW_r}{dt} = T_m - T_{em} \] (9)

In steady-state at fixed speed for a loss-less generator

\[ P_r = P_m - P_s = T_m W_r - T_{em} W_s = -SP_s \] (10)
where $S = (W_s - W_r) / W_s$ is defined as the slip of the generator. Generally the absolute value of slip is much lower than 1, and consequently, $P_r$ is only a fraction of $P_s$. Since $T_m$ is positive for power generation and since $\omega_s$ is positive and constant for a constant frequency grid voltage, the sign of $P_r$ is a function of the slip sign. $P_r$ is positive for negative slip (speed greater than synchronous speed) and it is negative for positive slip (speed lower than synchronous speed). For super-synchronous speed operation, $P_r$ is transmitted to DC bus capacitor and tends to raise the DC voltage. For sub-synchronous speed operation, $P_r$ is taken out of DC bus capacitor and tends to decrease the DC voltage. $C_{grid}$ is used to generate or absorb the power $P_{gc}$ in order to keep the DC voltage constant. In steady-state for a lossless AC/DC/AC converter, $P_{gc}$ is equal to $P_r$ and the speed of the wind turbine is determined by the power $P_r$ absorbed or generated by $C_{rotor}$. The phase-sequence of the AC voltage generated by $C_{rotor}$ is positive for sub-synchronous speed and negative for super-synchronous speed. The frequency of this voltage is equal to the product of the grid frequency and the absolute value of the slip. $C_{rotor}$ and $C_{grid}$ have the capability to generate or absorb reactive power and could be used to control the reactive power or the voltage at the grid terminals [8].
3.2 Advantages of doubly-fed induction generators

DFIGs offer the following advantages:

1- The system reliability will increase by elimination of the gear boxes and the power electronic converters.

2- The system efficiency will increase because the losses in the gear box and power electronic converters are eliminated.

3- They can operate in generator/motor mode for both sub/super-synchronies speed mode with four possible operation conditions.

4- A speed variation of ±30% around synchronous speed can be obtained by the use of power converter of 30% of nominal generated power.

5- They do not need necessarily to be magnetized from the power grid since it can be magnetized from the rotor circuit too.

6- The size of the converter is not related to the total generator power but to the selected speed range and hence to the slip power.

7- DFIGs allow the amplitude and frequency of their output voltages to be maintained at a constant value, no matter the speed of the wind blowing on the wind turbine rotor.

8- The ability to control the power factor (e.g., to maintain the power factor at unity), while keeping the power electronics devices in the wind turbine at a moderate size.

Permanent Magnet Synchronous Generator (PMSG), Field excited synchronous generator (FESG) and the Induction Generator (IG) are the other candidates for wind turbine application. As permanent magnet excitation eliminates the excitation losses of a FESG.
hence PMSG will be more favored option. The direct drive, grid connected IG and PMSG
generators are intended for fixed speed operations. When the PMSG generator is
connected to the grid, the speed is determined by the grid frequency and is constant. If the
torque to the generator is increased (sudden blow of wind), the generator will produce
electromagnetic force to resist an increase in speed. Therefore, a blow of wind leads to
large stresses on the wind turbine’s drive train. However IG allows a small change of
speed with the change of torque going to the generator and lower stresses/tear and wear
of the drive train. As the IG and the PMSG machine have similar Stator, the cost
difference is mainly due to the rotor. The PM’s cost is always going to be more than that
of aluminum and one can see that the cost of the induction generator is expected to be
much lower than the PMSG generators for the same power rating. But PMSG generators
have higher efficiency so the higher material cost may be somewhat compensated for the
extra electricity generated. Also, inductive power factor of the induction generators
require capacitors for power factor correction and may increases the overall cost of the
IG. So, a trade-off analysis is needed for case by case basis before declaring any one
machine best for an application or an Installation.

3.3 Time-domain simulation of the DFIG

The time-domain simulation of DFIG connected to a grid will be explained in this
section. The simulation consists of a bidirectional pulse-width-modulation (PWM)
converter, a power system, and an induction machine. In order to link an DFIG model to
FAST in a Simulink environment, the model must be expressed in time domain. There is
a model for wind turbines with the DFIG in Simulink, but it is not used in this paper because it is in phasor domain [2].

### 3.2.1 Power system connection

The power system connection is represented by three constant voltage sources connected in series with its Thevenin equivalent impedance. In other words, the grid connection model is based on short-circuit level (SCL) at the point of common coupling.

### 3.2.2 Bidirectional converter

Six controlled voltage and current sources with their limiters have been used to model the bidirectional PWM converter. The converter dynamics including switch dynamics have not been considered in this paper.

### 3.2.3 Induction machine

The induction machine is modeled by Simulink and FAST. Simulink is used to simulate the electrical dynamics of the machine, where FAST models the mechanical dynamics. The induction machine operates in either generator or motor mode. The mode of operation is dictated by the sign of the mechanical torque $T_m$. The electrical part of the machine is represented by a fourth-order, state-space model. All electrical variables and parameters are referred to the stator. All stator and rotor quantities are in the synchronously rotating reference frame ($d – q$ frame). The model of the induction machine in Simulink is based on $d – q$ equivalent model, shown in Figure 3-2. To solve
the related equations, they can be rearranged in state–space form. The induction machine modeling equations can be written as:

\[
\frac{d}{dt} \varphi_{qs} = \varphi_{qs} - \omega_e \varphi_{ds} + \frac{R_s}{\sigma L_s} \left( \frac{L_m}{L_r} \varphi_{qr} - \varphi_{qs} \right) \quad (11)
\]

\[
\frac{d}{dt} \varphi_{ds} = \varphi_{ds} + \omega_e \varphi_{qs} + \frac{R_s}{\sigma L_s} \left( \frac{L_m}{L_r} \varphi_{dr} - \varphi_{ds} \right) \quad (12)
\]

\[
\frac{d}{dt} \varphi_{qr} = \varphi_{qr} - (\omega_e - \omega_r) \varphi_{dr} + \frac{R_r}{\sigma L_r} \left( \frac{L_m}{L_s} \varphi_{qs} - \varphi_{qr} \right) \quad (13)
\]

\[
\frac{d}{dt} \varphi_{dr} = \varphi_{dr} - (\omega_e - \omega_r) \varphi_{qr} + \frac{R_r}{\sigma L_r} \left( \frac{L_m}{L_s} \varphi_{ds} - \varphi_{dr} \right) \quad (14)
\]

\[
i_{qs} = \frac{1}{\sigma L_s} \varphi_{qs} - \frac{L_m}{\sigma L_s L_r} \varphi_{qr} \quad (15)
\]
\[ i_{ds} = \frac{1}{\sigma L_s} \varphi_{ds} - \frac{L_m}{\sigma L_s L_r} \varphi_{dr} \]  

(16)

\[ i_{qr} = \frac{1}{\sigma L_s} \varphi_{qr} - \frac{L_m}{\sigma L_s L_r} \varphi_{qs} \]  

(17)

\[ i_{dr} = \frac{1}{\sigma L_s} \varphi_{dr} - \frac{L_m}{\sigma L_s L_r} \varphi_{ds} \]  

(18)

\[ T_e = \frac{1.5 p L_m}{\sigma L_s L_r} (\varphi_{qs} \varphi_{dr} - \varphi_{qr} \varphi_{ds}) \]  

(19)

\[ \frac{d}{dt} \omega_r = \frac{p}{J} (T_e - T_m) \]  

(20)

\[ \frac{d}{dt} \theta_r = \omega_r \]  

(21)

Assuming a large inertia for the mechanical shaft, \( \omega_r \) can be considered a constant in (7) and (8). With this assumption, the mechanical dynamics of the generator [(14) and (15)] and involved mechanical parts of the wind turbine (gear box, low-speed shaft, and high-speed shaft) have been modeled with more details by FAST in longer time step. The shaft torsional dynamics are considered in FAST, whereas they cannot be modeled by using (14) and (15). The \( d-q \) model requires that all the three-phase variables be transformed into the two-phase rotating frame. Consequently, the induction machine model will have the blocks transforming the three-phase voltages to \( d-q \) frame and \( d-q \) currents back to the three-phase system.
3.4 Design controllers for DFIG and wind turbine

When compared with fixed-speed wind turbines, variable-speed wind turbines can extract more power by operating with a controlled tip speed ratio, which will enable maximum power tracking. Wind turbines usually have at least three different possible control actuators: blade pitch, generator torque, and machine yaw. To control a variable-speed wind turbine, it is important to know the relationship between generated power, rotation speed, and wind speed.

The amount of power produced by a turbine can be expressed as

\[ P = \frac{1}{2} \rho A C_p V^3, \]

where \( P \) is the generated power, \( A \) is the area of the rotor disk, and \( C_p \) is the power coefficient. The power coefficient \( C_p \) is a function of the blade pitch angle \( \beta \) and the tip speed ratio \( \lambda = \frac{\Omega r}{V} \), where \( \Omega \) is the rotor speed and \( r \) is the rotor radius. For an optimum energy production strategy, \( \lambda \) and \( \beta \) should be chosen to give an optimum \( C_p \). The turbine should operate at this tip speed ratio, regardless of the wind speed. However, operating wind turbines at the optimum \( C_p \) over a large range of wind speeds is not practical. The aerodynamic forces in wind turbines are related to the square of the mean wind speed. At higher wind speeds, the turbine must, therefore, be designed to withstand higher forces, which increases the machines weight and cost. Rated wind speed is the velocity at which maximum output power (rated power) is achieved. For wind speeds above this rated wind speed, power must be held constant by the use of wind turbine controls, or else the power would increase in proportion to the cube of the wind speed and overheat the generator and power electronic system. Blade pitch, the most effective method of controlling aerodynamic loads, is used to limit the rotation speed above rated wind speed. Generator torque (power) is used not only to maximize the captured power from wind below rated
wind speed, but also to limit the captured power above rated wind speed. In addition, the output power of the turbine can be limited by yawing the machine out of the wind, thereby decreasing the projected rotor area $A$ and reducing power. Most often, yaw control is used only to respond to changes in wind direction in an attempt to reduce the yaw error (the angle between the mean wind direction and the direction of orientation of the turbine) and thereby maximize power. The controller consists of three main parts: the current controller, the rotor pitch controller, and the power controller. These parts will be explained in following sections.

3.3.1 Pitch controller

The pitch controller is used to regulate speed in region 3 of operation. Above the rated wind speed, the generated output power will change only in proportion to rotor speed since the torque remains constant; thus, power regulation is entirely dependent upon speed regulation. A PID controller has been implemented as the pitch controller. The pitch demand is limited to the range of $\beta_{\text{min}}$ to $\beta_{\text{max}}$, where $\beta_{\text{min}}$ is the pitch angle at which optimum rotor aerodynamic performance is achieved, when the rotor speed is below the desired set point $\omega_{\text{rated}}$ in region 2 of operation. An integrator antiwindup must be included in the controller to prevent the windup. The pitch actuator model is a simple second-order system:

$$H(s) = \frac{\beta_{1,2,3}(s)}{\beta^*(s)} = \frac{\omega_n^2}{S^2 + 2\zeta \omega_n S + \omega_n^2}$$

(22)
with $\zeta = 80\%$ of critical damping and a natural frequency that is multiple of the rotor speed. In this case, $\omega_n = 4\Omega$ has been used.

The pitch angle is kept constant at zero degrees until the speed reaches point D speed of the tracking characteristic. Beyond point D the pitch angle is proportional to the speed deviation from point D speed. For electromagnetic transients in power systems the pitch angle control is of less interest. The wind speed should be selected such that the rotational speed is less than the speed at point D.

### 3.3.2 DFIG current controller

The induction machine is controlled in a synchronously rotating $d - q$ axis frame with the $d$-axis aligned along the stator flux position. This permits decoupled control of electromagnetic torque and rotor excitation currents. The bidirectional PWM converter provides the actuation, and the control requires the measurement of the stator and rotor currents, stator voltages, and the rotor position. Aligning stator flux along $d$-axis, the induction machine equations may be rewritten as follows:

$$|\varphi_s| = \varphi_{ds} \rightarrow L_m |i_{ms}| = L_s i_{ds} + L_m i_{dr}$$  \hspace{1cm} (23)

$$\varphi_{dr} = L_r i_{dr} + L_m i_{ds} = \frac{L_m^2}{L_s} |i_{ms}| + \sigma L_r i_{dr}$$  \hspace{1cm} (24)

$$\varphi_{qr} = L_r i_{qr} + L_m i_{qs} = \sigma L_r i_{qr}$$  \hspace{1cm} (25)

where $|i_{ms}|$ is stator magnetizing current space phasor modulus and $\omega_{slip} = (\omega_e - \omega_r)$ is slip frequency (in radians per second). The following steps are used to implement the control algorithm.

1) Estimation of $\omega_e$ by a phase-lock loop (PLL) and calculation of $\omega_{slip} = (\omega_e - \omega_r)$. 

40
2) Three-to-two phase Clark’s transformation of measured rotor and stator currents.

3) Estimation of the stator flux linkage space phasor angular position $\rho_s$ with respect to stationary direct axis and stator magnetizing current space phasor modulus $|i_{m_s}|$. Following, the equations are given by

$$ q_s = L_s i_s + L_m i_r e^{i\theta_r} = L_m i_{m_s} \quad (26) $$

$$ i_{ms} = \frac{L_s}{L_m} i_s + i_r e^{i\theta_r} \quad (27) $$

$$ i_{ams} = \frac{L_s}{L_m} i_{as} + i_{Dr} \quad \text{where} \quad i_{Dr} = i_{ar} \cos \theta - i_{br} \sin \theta \quad (28) $$

$$ i_{\beta ms} = \frac{L_s}{L_m} i_{\beta s} + i_{Qr} \quad \text{where} \quad i_{Qr} = i_{ar} \sin \theta + i_{br} \cos \theta \quad (29) $$

$$ i_{ms} = \sqrt{i_{ams}^2 + i_{\beta ms}^2} \quad (30) $$

$$ \rho_s = \arctan \frac{i_{\beta ms}}{i_{ams}} \quad (31) $$

4) Expression of rotor current components $i_{Dr}$ and $i_{Qr}$ in the rotating reference frame aligned to the stator flux-linkage space phasor. These new rotor current components $i_{dr}$ and $i_{qr}$ are calculated by the following equations:

$$ i_{dr} = i_{Dr} \cos \rho_s + i_{Qr} \sin \rho_s \quad (32) $$

$$ i_{qr} = -i_{Dr} \sin \rho_s + i_{Qr} \cos \rho_s \quad (33) $$

5) Considering (16) and (17), it is possible to decouple the cross coupling between the $d$ and $q$ components of rotor current, $-\omega_{\text{slip}} \sigma L_r i_{qr}$ in $v_{dr}$ and $\omega_{\text{slip}} \sigma L_r i_{dr}$ in $v_{qr}$, in the control law used. Furthermore, it is feasible to include a feed-forward compensation term $\omega_{\text{slip}} L_2$
ML_{lims} \text{ in the control law that will compensate for the tracking error caused by variations of the back electromotive force (EMF).}

6) In order to implement the control loop, two identical PI controllers are used. Internal mode control (IMC) is used to design the controller [28].

### 3.3.3 Power controller

The stator power can be controlled in cascade with current if the current dynamics are set to a much faster speed than the power dynamics. The steps followed by the designed control algorithm are summarized as follows.

1) Calculation of stator voltage space phasor modulus \(|v_s|\).
2) Expression of stator current components, \(i_{as}\) and \(i_{bs}\), in the rotating reference frame aligned to the stator flux linkage space phasor.
3) Implementation of a PI controller to provide the power control loop in order to generate the reference rotor current component. A limiter and an antiwindup compensator must be included in this controller.

### 3.5 Simulation results

To verify the theoretical analysis, DFIG is modeled in Simulink, and simulation results are provided in Figure 3-3 and Figure 3-4.
Figure 3-3. Generator output power (W)

Figure 3-4. Generator torque (Nm)
3.6 Conclusion

Doubly-fed induction generators (DFIGs) have a number of advantages over other types of generators when used in wind turbines. In this chapter, the main advantages of DFIGs for wind turbines are mentioned and discussed how DGIGs contribute to the cost reduction, reliability improvement, and load reduction. In order to link an DFIG model to FAST in a SIMULINK environment, the model must be expressed in time domain. This thesis develops the time-domain modeling and simulation of DFIGs with the associated control blocks. The conventional induction generator in FAST or SIMULINK is replaced with the DFIG model which offers many advantages in floating offshore wind turbines.
Chapter Four

Structural control of floating offshore wind turbines

Recently, several researchers have investigated control approaches to reduce the motion and loads of floating offshore wind turbines. These approaches do not utilize structural control techniques; instead, the existing wind turbine control system, pitch and yaw control, is modified to improve the damping of problematic motions and loads on the floating support structure. While these approaches are shown to be effective, they suffer from two critical drawbacks. First, reducing the platform motion and the tower loads usually comes at the expense of increased blade pitch actuator usage, power variability, and blade root fatigue loads. Second, for some floating models, these new control methods yield load reductions that, while large in a relative sense, still result in a structure that experiences unacceptably large absolute loads, and, therefore offshore turbine designs that may not be viable [1], [3]. It is desirable to produce even larger load and motion reductions for floating offshore turbines, so alternative control methods, such as structural control approaches used in civil engineering, may be needed.
Structural control is the civil engineering discipline that uses dynamic systems to reduce acceleration and loading in buildings and bridges due to wave and earthquake forcing. There are many different designs for the systems used to accomplish this goal, ranging from massive pendulums to precisely controlled servomotor mass dampers. For over twenty years, numerous large-scale active and passive structural control systems have been implemented for civil structures [1]. The following section will outline passive, semi-active, and active structural control.

4.1 Passive structural control

The simplest type of structural control devices are passive, which use no power to operate. As the structure vibrates, some of the vibrational energy is transferred to the mass of the structural control device and dissipated by the damper.

4.1.1 Passive tuned mass dampers

The most common passive structural control device is the tuned mass damper (TMD). This device utilizes a mass on an ideally frictionless track. The TMD mass and the main structure are connected via a spring and dashpot. In the ideal form of the TMD, both of these components are linear and have a constant spring and damping constant. The mass and spring are tuned to a system frequency that causes loading, which results in the TMD mass vibrating at this frequency. The damper then dissipates energy from the whole system in the form of heat. The theory is simple, but tuning the spring and damping constants optimally can be difficult. Even for an idealized one degree of freedom structure, the optimal tuning for the spring and damper is dictated by a complex
function. For structures with more degrees of freedom and nonlinearities, like an offshore wind turbine, there is no analytical solution currently available for the optimal tuning and numerical approaches must be used. Figure 4-1 shows a diagram of a tuned mass damper. [1]- [4]

![Figure 4-1: Schematic of a passive TMD](image)

4.1.2 Other passive structural control designs

Alternative passive devices have been utilized besides the simple mass on a track. These include tuned liquid dampers (TLDs), tuned liquid column dampers (TLCDs), and pendulum dampers. Tuned liquid dampers use the sloshing of a fluid to provide a force on the structure, and TLCDs improve upon this idea by using two attached vertical columns of liquid with an orifice between them to provide the damping force [1]. The difference between the heights of the two liquid columns provides an equivalent spring force, and the fluid passing through the orifice provides a damping force. Pendulum
dampers use the swinging of a large pendulum tuned to a certain frequency to provide a counter-force to structural accelerations as shown in Figure 4-2.

Figure 4-2: Schematic tuned liquid column damper [1]

Among many control strategies, semiactive control technology is particularly useful for reducing the capital and maintenance costs, eliminating the external energy dependence and increasing the reliability and robustness of the system. The specific characteristics of floating offshore wind turbines require new methodologies and tools for the modeling and design of control systems and some innovative control devices for dynamic load mitigation. One of the most visible and effective methods is to place a tuned liquid column damper (TLCD) on top of the structure. The use of TLCDs in mitigating vibrations within civil engineering structures has also been extensively studied. Yalla and Kareem [9] presented an approach to compute the optimum head loss
coefficient for a given level of wind or seismic excitation in a single step without resorting to iterations.

![Schematic of combined structure-LCD system](image)

**Figure 4-3: Schematic of combined structure-LCD system [3]**

The objective of the control design is to reduce the structure response when subject to disturbances such as strong winds and waves. The goal is to keep the structure response as small as possible with a low control effort.

### 4.2 Semi-active structural control

Semi-active mass damper (SAMD) utilizes a damper that can change its damping constant during operation. This ability can be used to tune the mass damper on the fly and can result in better performance compared to passive TMDs with a minimal energy investment when compared to active dampers. The damper in these systems can take the
form of an electrorheological (ER), magnetorheological (MR), or fluid viscous damper. The ER and MR dampers use either an electric or magnetic field to change the viscosity of the fluid in the damper. The fluid viscous damper uses a controlled valve to vary the viscous resistance through the damper orifice. Figure 4-4 shows the diagram of a controllable valve damper.

![Diagram of controllable valve damper](image)

**Figure 4-4. Diagram of controllable valve damper**

### 4.3 Active structural control

Active structural control devices use a controlled actuator in order to apply forces to the mass and structure and potentially have an even greater impact on structural acceleration than passive and semi-active systems. Active systems can operate over a wider frequency band and can apply higher forces to the structure by way of the actuator.

#### 4.3.1 Active mass damper

An active mass damper (AMD) consists of a mass and an actuator, which can be actively controlled to apply a force to the mass and an equal and opposite force on the structure. Since there is no physical spring and damper in this system, the actuator must
provide all of the forces to the mass damper. There is also the potential to destabilize the system and add energy to the structure if the control scheme is not well designed.

4.3.2 Hybrid mass damper

The HMD combines the TMD and AMD, and features a tuned mass, spring, and damper system as well as an actuator. With the addition of an actuator, the HMD gains the potential for improved performance over a passive system. Examples of installed HMDs utilizing servomotor and hydraulic actuators can be found in the literature. Both the AMD and HMD can add energy to the system, thus there is a potential for instability. The HMD, however, includes a passive system, so it can still provide load reduction with no actuation power.

4.4 NREL 5 MW turbine and platform models

The wind turbine model is this project is the NREL 5 MW wind turbine. This turbine was used in FAST simulations in this study. The turbine is a three bladed, upwind, variable speed, pitch controlled turbine, with a 126 m rotor diameter and a 90 m hub height. This turbine model is widely used by many other researchers as a reference turbine. A barge-type floating support structure is used in this investigation. The ITI Energy barge is a large, 40m × 40m ×10m barge with eight catenary mooring lines. More details of the ITI Energy barge are given by Jonkman in [7]. Table 4.1 shows a summery description of the NREL 5 MW wind turbine.
Table 4.1: NREL 5 MW turbine properties

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rating</td>
<td>5 MW</td>
</tr>
<tr>
<td>Rotor Orientation, Configuration</td>
<td>Upwind, 3 blades</td>
</tr>
<tr>
<td>Rotor, Hub Diameter</td>
<td>126 m, 13 m</td>
</tr>
<tr>
<td>Hub Height</td>
<td>90 m</td>
</tr>
<tr>
<td>Cut-In, Rated, Cut-Out Wind Speed</td>
<td>3 m/s, 11.4 m/s, 25 m/s</td>
</tr>
<tr>
<td>Rotor Mass</td>
<td>110,000 kg</td>
</tr>
<tr>
<td>Nacelle Mass</td>
<td>240,000 kg</td>
</tr>
<tr>
<td>Tower Mass</td>
<td>347,460 kg</td>
</tr>
<tr>
<td>Length</td>
<td>61.5 m</td>
</tr>
<tr>
<td>Overall Mass</td>
<td>17,740 kg</td>
</tr>
<tr>
<td>Second Mass Moment of Inertia</td>
<td>11,776,047 kgm²</td>
</tr>
<tr>
<td>First Mass Moment of Inertia</td>
<td>363,231 kgm</td>
</tr>
</tbody>
</table>

4.5 FAST-SC(structural control) code overview

FAST-SC is a modified version of the NREL code FAST, and was developed by Dr. Matthew Lackner at the University of Massachusetts Amherst in 2009 and has been modified through 2013. FAST-SC was created in order to model additional degrees-of-freedom (DOFs) in wind turbines, specifically structural control (SC) devices. A basic description of the FAST SC code, which provides the source code and supporting files for other users, is presented in the following. In developing FAST-SC, it is assumed that:

1. Two independent single degree of freedom TMDs are modeled.
2. The two TMDs are located in the nacelle of the turbine and translate in the nacelle frame of reference.
3. One TMD, labeled TMDX, translates in the fore-aft direction (the x-axis in the nacelle frame of reference), while the other, labeled TMDY, translates in the side-to-side direction (the y-axis in the nacelle frame of reference).
4. Each TMD consists of a mass, a spring, and a damper. The total force on the mass produced by the spring and damper also has an equal and opposite force on the nacelle. An active force can be commanded to act on the TMD, which in turn exerts an equal and opposite force on the nacelle, creating the active control force.

5. Each TMD system also has two ‘‘stops,’’ which are spring dampers that only engage when the position of the TMD exceeds a user-specified stop position.
A simple schematic of the TMDX configuration is shown in Figure. 4-6, which indicates that TMDX oscillates in the axial direction in the turbine nacelle and that the spring, damper, and active force actuator connect the TMD mass to the nacelle and so generate forces between these two bodies. The TMDY has a similar configuration, in the side–side direction. The external active control force is denoted by f.

Several early publications describe the theoretical background and practical implementation for modeling structural control in FAST, which resulted in the “FAST-SC” code. FAST-SC can model two independent TMDs with a user-defined mass, spring stiffness, damping, and translation direction. Earlier investigations defined the TMDs as translating in the fore-aft and side-side directions exclusively, but any arbitrary rotation of the TMD translation direction about the vertical axis is possible. The TMDs can be located in the nacelle or the platform, which is useful in the case of floating offshore wind turbines. The FAST-SC code can run with the FAST Simulink interface for semi-active and active control,
with the spring stiffness, damping, and external force input for each TMD commanded in Simulink.

### 4.6 Conclusion

In this chapter, the various structural control techniques which can reduce the loads in floating offshore wind turbines are discussed and compared in terms of performance, and complexity. FAST-SC (Structural Control) which is a modified version of the NREL code FAST, and was developed by Dr. Matthew Lackner at the University of Massachusetts Amherst, is discussed in detail. FAST-SC was created in order to model additional degrees-of-freedom (DOFs) in wind turbines, specifically structural control (SC) devices. The structural control techniques can be modeled in MATLAB environment, and added to the MATLAB simulations performed in chapter 2, and the results can be compared with the FAST-SC.
Chapter Five

New Bidirectional Converter for Floating Off-shore Wind Turbines

5.1 Introduction

Due to the variability of wind speed, wind turbine output power can be highly variable. Power fluctuations from the wind turbine may cause severe power quality problems when connected to the grid. The large variability in wind turbine output power can adversely impact local loads that are sensitive to pulsating power, posing a challenge to the extensive use of wind power. The rapid growth of the wind power and its immense potential as a future energy source encourages us to find a way to smooth the variable wind power. Energy storage technologies can be used to improve the quality of the wind power [47], [48].

A power quality conditioner with the ultracapacitor to smooth the variable wind turbine output power is introduced in [46]. The short term storage capabilities of the ultracapacitor can be used effectively to smooth the wind power to minimize rapid power
excursions that may damage sensitive local loads. The power conditioner mainly consists of power converters to shape the injected current at the point of common coupling. The conditioner is based on a single phase shunt Voltage Source Inverter (VSI) connected between the grid interconnection point and the ultracapacitor. The shunt VSI injects or absorbs active power from the line to smooth the variable wind power by charging or discharging the ultracapacitor. The ultracapacitor is connected to the DC link through a DC-DC converter. Traditionally, the VSI DC link voltage is maintained relatively constant by the shunt inverter control. In this application, we use a bidirectional DC-DC converter to maintain the DC link voltage. The bidirectional DC-DC converter acts in buck mode during discharge of the DC link and in boost mode during charging to maintain the voltage of the DC link in order to provide good controllability of the VSI. The VSI controller calculates the compensating active power, which is then synthesized by using the bipolar pulse width modulation (PWM) switching sequence. The reference signal to the shunt inverter controller is obtained from a low pass filter, which has a large time constant. The fluctuating wind power is passed through the low pass filter to get the smoothed reference value. The conditioner ensures that smooth power is available at the grid interconnection point [46].

5.2 Power quality conditioner

As shown in Figure 5-1, the power quality conditioner consists of a shunt inverter and a bidirectional DC-DC converter. The voltage source inverter acts as a shunt active filter compensating the active power of the wind turbine. The VSI is connected to the line through an RL filter which reduces the unwanted harmonics. The shape of the output current of the conditioner depends on the inductor value. The value of the resistor and the
inductor determines the damping in the circuit. On the other side, the VSI is connected to the DC link capacitor. The DC-DC converter with the ultracapacitor is used to reduce the size of the DC link capacitor and to maintain the voltage of the DC link relatively constant as the ultracapacitor discharges and charges. The bidirectional DC-DC converter charges the ultracapacitor in buck mode by reducing the voltage of the DC link. In the other direction, it acts in boost mode, discharging the ultracapacitor to increase the voltage of the DC link. The power conditioner injects or absorbs active power from the line through the filter to smooth the variable wind turbine output power. The DC link acts

Figure 5-1: Power quality conditioner [46]
as the voltage source for the VSI. The primary objective of the conditioner is to inject a current at the point of common coupling (PCC) so that the current supplied to the grid is relatively smooth. The smoothed current is obtained by passing the (measured and scaled) wind turbine current through a low pass filter that is tuned to provide the appropriate high-frequency cutoff. The ultracapacitor is charged and discharged rapidly to supply the required current while holding the DC link constant. Note that the reference current is not a constant, but rather a slowly varying current. If the reference current were held constant, this would imply that the electrochemical capacitor would have infinite ability to charge and discharge. By allowing the reference current to slowly vary, the energy supplied to the grid will track the energy supplied by the wind turbine [46].

5.2.1 DC-DC bidirectional converter

The two primary components of the power conditioner are the shunt inverter to control the injected current and the DC-DC converter to regulate the DC link voltage and control the ultracapacitor injected current. The topology of the bidirectional DC-DC converter is shown in Figure 5.2. The bidirectional DC-DC converter acts a buck converter in one direction and as a boost converter in the other direction [10]-[13]. Power MOSFETS are used as the switching devices in the circuit. The operation of the converter is controlled by the DC link voltage and the voltage of the ultracapacitor. The main purpose of the bidirectional DC-DC converter is to maintain the voltage of the DC link relatively constant at a reference value. The DC link capacitor is used as an intermediate element between the DC-DC converter and the inverter.
The DC-DC converter operating modes can be divided into four modes:

- **Mode 1**: The DC-DC converter acts in buck mode when the DC link voltage \( V_{dc} \) is greater than the reference value \( V_{ref} \). In this mode, the DC-DC converter controls the current to charge the ultracapacitor.

- **Mode 2**: The DC-DC converter acts in boost mode when the DC link voltage \( V_{dc} \) falls below the reference value. In this mode, the ultracapacitor discharges.

- **Mode 3**: When the ultracapacitor is fully charged, the DC-DC converter shuts down to avoid damaging the ultracapacitor.

- **Mode 4**: When the ultracapacitor is fully discharged, the conditioner shuts down until the wind turbine produces sufficient current to resume charging of the ultracapacitor.
5.2.2 Ultracapacitors

Ultracapacitors are electrochemical double layer capacitors that have unique characteristics when compared with other energy storage devices. Ultracapacitors have high energy density and large time constants as well. Although multiple time-scale models of ultracapacitors have been developed, a simple ultracapacitor model, such as the one in Fig. 3 containing only one RC branch, was used in the simulation of the converter system. This model is composed of an equivalent series resistor (ESR) and a capacitor (C) [5]. The ESR represents the ohmic losses in the ultracapacitor. Higher order ultracapacitor models are essential for simulation studies in which the timescale of interest is on the order of microseconds. In the current application, the timescale of interest is on the order of minutes; therefore the single RC branch model is sufficient to capture the ultracapacitor behavior of interest.

The benefits of using ultracapacitors are quite extensive. Ultracapacitors have low losses while charging and discharging. They have a very low ESR, allowing them to deliver and absorb very high currents and to be charged very quickly, making them well suited for energy buffer applications. Ultracapacitors are highly efficient components even at very high currents. The characteristics of the ultracapacitor allow it to be charged and discharged at the same rates, something most batteries cannot tolerate. Ultracapacitors have a wide voltage window and can be deeply discharged. The energy storage mechanism of an ultracapacitor is a highly reversible process. The process moves charge and ions only. It does not make or break chemical bonds like batteries. Therefore, the ultracapacitor is capable of millions of cycles and many years of continuous duty with minimal change in performance. These advantages make ultracapacitors well suited for
power quality conditioning applications. The power conditioner was constructed using two series-connected Maxwell ultracapacitor modules of 165F nominal capacitance and rated voltage 48.6V.

5.2.3 Shunt inverter

A full-bridge IGBT based inverter topology is used in this application. The full-bridge inverter consists of four switching devices. The gating signals for the IGBTs are obtained through the pulse width modulation controller. Anti-parallel diodes are connected across the power IGBTs to protect the devices and to provide the power flow in the reverse direction. The voltage source inverter connected in shunt to the line acts as a current source, injecting or absorbing the compensating current from the line. The shunt inverter is connected to the line through a series interference RL filter, which reduces the unwanted harmonics. The filter provides smoothing and isolation from high frequency components. On the downstream side, the full-bridge inverter is connected to the DC link. The injected current is in phase with the line voltage to produce a unity power factor [46].
The VSI operates in the following two modes:

**Mode 1:** When the wind turbine power is greater than the reference value, the converter acts like a rectifier, drawing active power from the line and charging the DC link capacitor.

**Mode 2:** When the wind turbine power is less than the reference value, the converter acts like a VSI injecting active power into the line by discharging the DC link capacitor.

Figure 5-3: Shunt inverter circuit [46]
The variable wind power is passed through a low pass filter to get a smoothing reference signal for the inverter controller. The output of the low pass filter is given to the shunt inverter controller as the reference value [9].

5.3 New bidirectional converter for FOWTs

As mentioned before, the bidirectional DC–DC converters are increasingly being used in many power related systems, including power quality conditioner, hybrid electric vehicle (HEV) [49], fuel cell vehicles (FCV) [50]–[52], satellites, renewable energy systems, and Uninterruptible Power Supplies (UPS) [53]. In power quality conditioner applications, a bidirectional DC–DC converter that manages energy and power flow between the DC bus and energy storage allows the use of low-voltage battery and high-voltage inverter-motor drive. Bidirectional power flow enables the energy capture of regenerative brake and energy release during startup, accelerating, and hill climbing. In renewable energy applications, a bidirectional DC–DC converter is used to transfer the renewable energy to the capacitive energy source when the DC bus voltage is high while delivering energy to the load when the DC bus voltage is low [54]. Bidirectional converters are divided into two main groups Non-isolated Bidirectional Converters (NIBDCs) and Isolated Bidirectional Converters (IBDCs). In applications where a high voltage ratio is not needed or the input and output do not need to be grounded simultaneously, non-isolated bidirectional converters are preferred due to their simple structure, lower cost, small size, and ease of control. NIBDCs, which are the focus of this study, are derived by combining basic converters. The resulting converters are buck-and-boost, buck/boost, SEPIC/Zeta, and Cuk/Cuk NIBDCs. In order to dramatically reduce the reactive components' size and cost, high efficiency operation of NIBDCs is desirable.
However, in a hard switching converter, as the switching frequency increases switching losses and electromagnetic interference increase. To alleviate this problem, there are several techniques, such as Zero-Voltage-Transition (ZVT) / Zero-Current-Transition (ZCT) techniques, coupled-inductor, interleaving, and multi-resonant or quasi-resonant techniques, that can be applied to the hard switching NIBDCs to significantly increase their efficiency. Each of the abovementioned techniques has its own drawbacks when applied to a BDC in terms of current stress, voltage spike, cost, complexity, and variable frequency control [67]. To make the converter operate at very high frequencies, GaN HEMTs, which are new promising power devices, can be applied to the converters to further reduce the switching losses. Gallium Nitride (GaN) power transistors are fast emerging as potential replacements for silicon power MOSFETs because of their superior on-state conduction and high-frequency switching performances.

5.4 A survey on existing NIBDCs

5.4.1 Soft-switched NIBDCs with ZCT/ZVT techniques

In soft-switched NIBDCs with ZCT/ZVT techniques, using some auxiliary passive or active elements, ZVT or ZCT is provided for the semiconductor devices, which leads to a significant reduction in switching losses. To avoid complexity in ZVT and ZCT BDCs, it is desirable to share auxiliary elements to provide soft switching in both power flow directions.

Several ZVT/ZCT NIBDCs have been previously proposed. In [55]-[58], the idea of auxiliary circuits introduced previously in [59] and [60] are employed resulting in a reduced number of elements. However, in [55] and [56], the auxiliary switches are turned
off under hard switching. In [57], soft switching is lost for operating duty cycles higher than 0.5. In [58], all the switches are gated in a switching cycle which leads to higher switching losses and complexity of the control circuit. Another non-isolated ZVT BDC is proposed in [61] which uses the previously proposed auxiliary circuit in [62]. In [61], all switches are soft switched and the duty cycle is not limited. However, two split input voltages are required by means of inserting two equal capacitors between the input line and ground. In order to balance the capacitors, the auxiliary circuit is applied twice in a switching cycle resulting in a more complex control and increased switching losses. In [63], a combination of ZVT buck [59] and ZVT boost [64] converters is used, but this converter suffers from a high number of circuit elements. In [66], a split voltage is necessary to sufficiently reset the snubber inductor, \( L_x \), during the main switch conduction interval. Complexity is another issue in [66] when taking into account the required control and drive circuitry.

### 5.4.2 NIBDCs with coupled inductors

A coupled Inductors technique is applied in the applications where the low-side DC voltage source is much lower than the high-side voltage source. This technique allows the converter to have a steep voltage conversion ratio and prevents the converter duty cycle from becoming too narrow (in buck mode) or too wide (in boost mode). Note that either type of extreme duty cycle would lead to the converter components and have undesirable voltage and current peak stresses [67]. Several coupled inductor NIBDCs have been previously proposed with focus on reducing the switching losses with a minimum number of auxiliary switches.
5.4.2.1. Coupled-inductor NIBDCs with two auxiliary switches

In [68], ZVT is achieved for the switches. The presence of coupled inductors provides significant reduction in the converter volume, since all the converter inductors are implemented on a single core. In this converter, there is almost no extra voltage spike or current stress on the switches, making it suitable even for medium power applications. However, complexity is an issue with this converter when taking into account the required control and drive circuitry, as this converter suffers from four switches. Also, the auxiliary switches must be unidirectional, adding cost. In order for the converter to operate with ZVT in a wide range of duty cycles, the coupled inductors must be designed carefully, otherwise ZVT is lost.

5.4.2.2. Coupled-inductor NIBDCs with one auxiliary switch

In [67], using a common active clamp circuit, ZVS turn-ON of both switches is achieved. It can operate with a continuous inductor current, fixed switching frequency, and steep conversion ratio. The stress on the switches is very low as well. Compared to [68], this converter has fewer switches. However, there is still one auxiliary switch for which the soft switching condition is not guaranteed. Although the converter turn on is under "true ZVS", the converter is turned off under "almost ZVS". For low power applications, this converter does not show a good performance and the converter efficiency dramatically drops. Therefore, it is not a good choice.
5.4.2.3. Coupled-inductor NIBDCs without auxiliary switches

Compared to the converters in [67] and [68], there is no auxiliary switch in the introduced converter in [69]. The proposed converter can operate with ZVS, fixed switching frequency, and a ripple-free inductor current in buck and boost modes. A very simple auxiliary circuit which consists of an additional winding to the main inductor and an auxiliary inductor provides ZVS function and cancels out the ripple component of the inductor current. In boost mode, the switch $S_2$ acts as a boost switch and the switch $S_1$ acts as a boost diode. In buck mode, $S_1$ acts as a buck switch and $S_2$ acts as a buck diode. An additional winding $N_s$ to the main inductor and auxiliary inductor $L_s$ are added and the filter capacitor $C_f$ is split into $C_{f1}$ and $C_{f2}$. This auxiliary circuit provides ZVS function and cancels out the ripple component of the main inductor current regardless of the direction of power flow. The main features of this converter are listed below:

1. ZVS of the power switches is always achieved regardless of load condition.
2. The reverse recovery problem of the anti-parallel diode of the switches is solved.
3. The ripple-free current characteristics are provided in low voltage side regardless of load condition, which reduce the voltage ripple and increase the lifetime of the battery.
4. The number of auxiliary elements is minimized.
5. There is no current or voltage stress on the power switches.
6. Compared with the previously introduced soft switched NIBDCs, in which at least three switches are used, no extra switches are used in this converter.
5.4.2.4. **Interleaved soft-switched NIBDCs**

An interleaving technique can be applied to the bidirectional DC-DC converters where several identical bidirectional DC-DC converters are connected in parallel, which solves the current ripple problem, and makes a suitable option for batteries and ultracapacitors to increase their lifetime [58-60]. However, the multi-channel interleaved structure has many components and its control algorithm is complex [69]. In [70], an interleaved ZVS bidirectional converter is introduced. The main advantages of the converter are as follows:

1. The use of CoolMOS as the main switch under zero-voltage soft switching condition.
2. Multiple-phase legs for current sharing to reduce the conduction loss.
3. Coupling inductors between each two-phase legs to cancel the magnetic flux ripples and to reduce effective rms current of both inductor and switches so that the conduction loss is further reduced.
4. The use of output capacitance of the device to achieve zero voltage soft switching for the entire load range.

The proposed multiphase interleaved complimentary-switching-type converter in [71], has the following main features:

1. Zero voltage switching and thus high efficiency at heavy load conditions.
2. Interleaving phase-leg currents to eliminate the ripple current going into the sensitive voltage source.
3. Compact inductor size with discontinuous conduction mode operation.
4. Compact bus capacitor size with ripple cancellation.

5.4.2.5. Quasi or multi-resonant NIBDCs

Quasi- or multi-resonant converters that have high-switch peak voltage stresses are difficult to control and implement [72] and [73]. These converters are especially ill-suited for coupled-inductor converters that already have high switch peak voltage stresses due to the presence of the coupled inductors.

In [74], a new family of multi-resonant bidirectional converters is introduced. In the proposed bi-directional converters, instead of using two independent auxiliary circuits for each main switch, the same components with a single auxiliary switch are used to provide soft commutation at both modes of converter operation. In addition, the soft switching range in the proposed converters is not dependent on the duty cycle and the auxiliary circuit is applied only once in each switching cycle, which leads to a simple control circuit. The main drawback of this converter is that the inductor current has a lot of ripple with a very high peak, because it must flow in both directions during each switching cycle. This results in very high turn-off losses that take away from the improvement in efficiency due to the ZVS turn on and additional filtering is needed to reduce voltage ripple.

5.5 Proposed soft-switched NIBDC

The proposed converter shown in Figure 5-4 is composed of two main switches, $S_1$ and $S_3$, two auxiliary switches, $S_2$ and $S_4$; a main inductor, $L$; two auxiliary resonant inductors, $L_{r1}$ and $L_{r2}$; and the resonant capacitor, $C_r$. To analyze the converter, it is assumed that DC bus voltage, battery and inductor L current are constant in a switching
cycle. $V_{in}$ is DC bus voltage, $V_o$ is the battery voltage, and $I_o$ is inductor L current. The proposed bi-directional converter has several properties which enhance its performance. Soft switching conditions, reduced switching losses due to fewer switches, no transformers, and lower weight and volume are the most important properties of the proposed converter. It has four distinct operating intervals during a switching cycle in buck mode, and six intervals in boost mode. The operation of the converter in both buck and boost modes is discussed below. To simplify the theoretical analysis, all elements are assumed to be ideal, and the converter is operating in steady state condition.

![Figure 5-4: Proposed soft-switched bidirectional converter](image)
5.5.1 Buck mode

In buck mode, $S_1$ and $S_2$ are the main and auxiliary switches, respectively. During this mode, $S_3$ and $S_4$ are off. Prior to $t_0$, the auxiliary switch $S_2$ turns off and the $C_r$ voltage reaches $-V_{C_{r_{\text{max}}}}$. The key waveforms of the converter in buck mode are shown in Figure 5-5. The proposed converter has four operating stages in this mode, as depicted in Figure 5-6. The buck mode intervals are illustrated as follows:

*Interval 1 $[t_0-t_1]$: In this interval, both $S_1$ and $S_2$ are off, and the output current is provided by body-diode of $S_3$. 

*Interval 2 $[t_1-t_2]$: At $t_1$, $S_1$ is turned on. $C_r$ and $L_{r_1}$ form a half-cycle resonance through $S_1$ and the anti-parallel diode of $S_2$. This resonance forces $D_3$ current to decrease in a sinusoidal fashion. As a result, both $S_1$ turn-on and $D_3$ turn-off are under ZCS condition. 

$C_r$ voltage and $L_{r_1}$ current equations during this interval are as follows:

$$V_{C_{r_{\text{r}}}}(t) = -V_{C_{r_{\text{max}}}} \cos(\omega_0(t - t_1))$$

$$I_{L_{r_2}}(t) = I_L + \left(\frac{V_{C_{r_{\text{max}}}}}{Z_0}\right) \sin(\omega_0(t - t_1))$$

where

$$Z_0 = \sqrt{\frac{L_{r_1}}{C_r}}$$

$$\omega_0 = \frac{1}{\sqrt{L_{r_1}C_r}}$$
**Interval 3 [t_2-t_3]:** At \( t_2 \), the resonance between \( C_r \) and \( L_{r1} \) completes after the half-cycle resonance. This operating stage is identical to the switch-on stage of the PWM buck converter.

**Interval 4 [t_3-t_4]:** This interval starts with turning the switch \( S_2 \) on. By turning this switch on, a resonance starts between \( C_r \) and \( L_{r1} \). After a half-cycle, \( C_r \) voltage reaches \(-V_{c_r}^{max}\). This resonance forces the \( S_1 \) current to decrease in a sinusoidal fashion and to turn off under ZCS condition.

\[
V_{c_r}(t) = V_{c_r}^{max} \cos(\omega_0(t - t_3))
\]  

\[
I_{Lr1}(t) = \left(\frac{V_{c_r}^{max}}{Z_0}\right) \sin(\omega_0(t - t_3))
\]  

Figure 5-5. Converter theoretical waveforms in buck mode of operation
5.5.2 Boost mode

In boost mode, $S_3$ and $S_4$ are the main and auxiliary switches, respectively. During this mode, $S_1$ and $S_2$ are off. To simplify the analysis, the input current and output voltage are considered constant, and the circuit is operating at steady state condition. The proposed converter has six operating stages in this mode. The main theoretical...
waveforms of the proposed converter in boost mode are shown in Figure 5-7, and the equivalent circuit for each operating interval is shown in Figure 5-8. The boost mode intervals are as follows:

**Interval 1 \([t_0-t_1]\):** At \(t_0\), \(S_3\) turns on. The main inductor \(L\) current flows through \(L_{r2}\) and \(S_3\). \(L_{r2}\) is being charged linearly. \(S_3\) turn-on is approximately ZCS.

![Converter theoretical waveforms in boost mode of operation](image)

Figure 5-7. Converter theoretical waveforms in boost mode of operation
Figure 5-8. Equivalent circuit for each operating interval of the proposed converter in boost mode, (a) [t₀-t₁], (b) [t₁-t₂], (c) [t₂-t₃], (d) [t₃-t₄], (e) [t₄-t₅], and (f) [t₅-t₆]
**Interval 2 \([t_1-t_2]\):** At \(t_1\), \(L_{r2}\) current reaches \(I_L\), and \(L_{r1}, L_{r2}\) and \(C_r\) form a resonance through \(S_3\) and \(D_4\). The relations of \(C_r\) voltage and \(L_{r2}\) current are as follows:

\[
V_{Cr}(t) = V_{Cr}^{\text{max}} \cos(\omega_0(t - t_1))
\]

\[
I_{Lr2}(t) = I_L + \left(\frac{V_{Cr}^{\text{max}}}{Z_0}\right) \sin(\omega_0(t - t_1))
\]

where

\[
Z_0 = \sqrt{\frac{L_{r1} + L_{r2}}{C_r}}
\]

\[
\omega_0 = \frac{1}{\sqrt{(L_{r1} + L_{r2})C_r}}
\]

**Interval 3 \([t_2-t_3]\):** At \(t_2\), \(C_r\) current reaches zero and the resonance stops. During this interval, the main inductor \(L\) charges by constant current \(I_L\). This operating stage is identical to the switch-on stage of the conventional PWM converter.

**Interval 4 \([t_3-t_4]\):** This stage starts with turning on \(S_4\). \(L_{r1}, L_{r2}\) and \(C_r\), continue to resonate until \(L_{r1}\) current reaches zero at \(t_4\).

**Interval 5 \([t_4-t_5]\):** At \(t_4\) resonance stops. \(C_r\) Charges linearly by constant current \(I_L\) until it reaches \(V_0\) at \(t_5\). \(C_r\) voltage relation is as follows:

\[
V_{Cr}(t) = V_{cr}(t_4) + \left(\frac{I_L}{C_r}\right)(t - t_4)
\]
Interval 6 \([t_5-t_6]\): When \(C_i\) voltage reaches \(V_{in}\), \(D_1\) turns on under ZVS condition. During this interval energy is transferred to output. At \(t_6\), \(S_3\) is turned on again, starting another switching cycle.

5.6 Simulation and experimental results

PSpice circuit simulator was used to provide simulation results for the proposed converter to verify the theoretical analysis. A simple FET circuit simulation model, introduced in our previous work, [75], for high-frequency silicon power MOSFETs, was used in this study; this model is applicable to both GaN power transistor as well as silicon trench power MOSFET used in this study. The model is built around MOSFET M1 and other parasitic resistors and capacitors are connected externally, as shown in Figure 5-9. A LEVEL 3 SPICE MOSFET model was used for M1. This model accurately represents both the static and switching characteristics of power FETs; model parameters were extracted from the static and switching measurements. The simulation and experimental results are depicted in Figure 5-10 and figure 5-11, respectively. It can be observed that soft switching is provided for all the switches at both turn-on and turn-off modes. The converter parameters are shown in Table 1. The converter efficiency curve is shown in Figure 5-12 and Figure 5-13, and is compared to the GaN hard switching BDC, Si soft switching BDC, and Si hard switching using PSpice software. The efficiency comparison is done with the same parameters. It can be observed from Figure 5-12 and Figure 5-13 that the efficiency of the proposed GaN soft switching converter is higher than the others, as expected.
Figure 5-9. circuit simulation models for (a) GaN power transistor and, (b) silicon power MOSFET.
Figure 5-10. Simulation results: Voltage (continuous line) and current (broken line) simulation results of (a) switch $S_1$ (without body diode), (b) switch $S_3$ (without body diode)
Figure 5-11. Experimental results: Gate signal (orange line), voltage (green line), and current (purple line) waveforms of (a) switch $S_1$, and (b) switch $S_3$, respectively.
Figure 5-12. Efficiency comparison of the proposed GaN soft-switched converter with GaN hard-switched and Si hard-switched bidirectional converter in boost mode.

Figure 5-13. Efficiency comparison of the proposed GaN soft-switched converter with GaN hard-switched and Si hard-switched bidirectional converter in buck mode.
5.7 Converter control

Figure 5-14 shows the block diagram of the converter control circuit. The converter operation mode is determined by the enable signal Venable. When Venable is low, the BDC operates in boost mode and when Venable is high, the BDC operates in buck mode. The overall control block diagram consists of two main control blocks namely the PWM controller block and the adapting block. The PWM controller block includes a conventional PWM controller which is applied to BDCs. This control block consists of two feedback loops, the outer voltage loop and inner current loop. Since the converter input current is not constant, a low pass filter is applied to the inductor current to estimate the average current. The adapting block plays the role of adapting the output pulse of PWM controller to the proposed converters. The control method of the proposed converter is on the basis of the SOC of the battery. The SOC of the battery would be adjusted to match the power demand of the load. In buck mode, the bi-directional converter charges the battery. In boost mode, the bi-directional converter discharges the battery to balance its voltage. With this strategy, when the SOC of the battery is below 80 %, the bi-directional converter acts as a buck converter and charges the battery. Alternatively, if the SOC is more than 80%, the bi-directional converter acts as a boost converter and discharges the battery. Using MATLAB/SIMULINK software, the simulation results of the battery in both buck and boost modes are shown in Figure 5.15.
Figure 5-14. Block diagram of the converter control circuit
Figure 5.15 Simulation results of the converter control in (a) buck mode where the SOC is less than \( \text{SOC}_{\text{ref}} \), and (b) boost mode where the SOC is greater than \( \text{SOC}_{\text{ref}} \).
5.8 Conclusion

A power quality conditioner with the ultracapacitor is used to smooth the variable wind turbine output power. The conditioner is based on a single phase shunt Voltage Source Inverter (VSI) connected between the grid interconnection point and the ultracapacitor through a bidirectional converter to maintain the DC link voltage. The bidirectional DC-DC converter which is the focus of this chapter acts in buck mode during discharge of the DC link and in boost mode during charging to maintain the voltage of the DC link in order to provide good controllability of the VSI. In this chapter, a new high efficient DC/DC bidirectional converter for power quality conditioner systems in floating offshore wind turbines is introduced which benefits from soft switching techniques. The operation and control of the converter is discussed in detail and verified by simulation and experimental results.
Chapter Six

Conclusion and Future Work

In this thesis a system-level modeling approach was used to develop a wind turbine system simulation tool in the MATLAB/Simulink environment for application to offshore wind turbines. This tool was used to study floating offshore wind turbines to assess methods to reduce the cost and increase the reliability of floating offshore turbines. Different structural control methods that can be applied to floating offshore wind turbines were introduced and compared. Additionally, doubly-fed induction generators were proposed to be incorporated in an offshore wind turbine. These generators were modeled in the Simulink environment and used in wind turbine simulation studies. Finally, a new high efficiency buck and boost bidirectional converter was proposed for power conditioner applications for floating offshore wind turbines. A detailed discussion of the operation of each converter and their merits and demerits for wind turbines was included. Simulation results using PSpice were presented for this power conditioner application to verify the device’s theoretical assessment. Finally, a 500 W prototype of the converter at 100 kHz is built where the experimental results are in excellent agreement with the theoretical analysis and simulation results.
This work can be extended in several ways. First, the modeling of a floating offshore wind turbine can be improved by incorporating more complex, representative models of the system. The simulation results can be further verified by comparing them with other simulation tools as well as experimental results. Structural control can be applied to the floating offshore wind turbines benefiting from DFIGs running in the Simulink environment. Additionally, the proposed DC-DC converter can be improved, and the number of elements and the device’s voltage and current stress can be reduced.


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