MODELING OF DOUBLY-FED INDUCTION GENERATORS CONNECTED TO DISTRIBUTION SYSTEM BASED ON eMEGASim® REAL-TIME DIGITAL SIMULATOR

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ABSTRACT

This study is aimed to model and develop a stable test bed for a wind farm composed of six doubly-fed induction generators (DFIGs) connected to a distribution system based on the OPAL-RT’s eMEGASim® real-time digital simulator. The system in this research consists of a 9 MW wind farm, an average SimpowerSystems® DFIG wind turbine, connected to a 13.8 kV IEEE 14 bus distribution network.

A Simulink model was designed and built using SimPowerSystem Simulink of Matlab R2011a. Most of existing studies on the simulation relevant to wind power mainly focus on off-line simulation. Therefore, the model has been rebuilt on the RT-LAB environment based on the OPAL-RT’s eMEGASim® real-time digital simulator to test the wind farm performance at the same rate as actual time. After running the model on eMEGASim® real-time digital simulator, some studies such as three-phase to ground fault and voltage sag have been made to test the response of the model.
ACKNOWLEDGEMENTS

In the name of God, Allah the merciful,

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LIST OF ABBREVIATIONS

A, Cross-Sectional Area of the Wind That Crossed the Blades
AC, Alternating Current
\( \beta^\circ \), Blade Pitch Angle
\( C_p \), Power Coefficient
\( CO_2 \), Carbon Dioxide
COTS, Commercial-Off-the-Shelf
DC, Direct Current
DFIG, Doubly-Fed Induction Generators
\( E_{DC_{actual}} \), Actual DC Link Voltage
\( E_{DC_{ref}} \), Voltage Reference Point Value
\( f_s \), Stator Side Frequency
GSC, Grid Side Converter
HAWT, Horizontal-Axis Wind Turbine
HIL, Hardware-in-the-Loop
\( l_{dref} \), d-Axis Rotor Current
\( l_{qref} \), q-Axis Rotor Current
IEEE, Institute of Electrical and Electronics Engineers
IGBT, Insulated-Gate Bipolar Transistor
KV, Kilo Volt
$MVAR$, Megavolt Ampere Reactive

$MW$, Mega Watt

$\eta_e$, Efficiency of Electrical Generator

$\eta_m$, Overall Mechanical Efficiency of Transmission

$P_{\text{actual}}$, Actual Active Power of Generator

$P_{\text{Available}}$, Power Available

$P_e$, Electrical Power Output

$PI$, Proportional – Integral

$P_m$, Power of Wind Turbine Rotor

$PM$, Permanent Magnet

$P_{\text{net}}$, Net Power

$P_r$, Rotor Power

$P_{\text{ref}}$, Power Reference Point Value

$P_s$, Stator Power

$PS$, Pure Simulation

$pu$, Per Unit

$PWM$, Pulse-Width Modulation

$\rho$, Air Density

$R$, Blade Radius of Wind Turbine

$RCP$, Rapid Control Prototyping

$RSC$, Rotor Side Converter

$RTS$, Real Time Simulation

$RT-LAB$, Real-Time Laboratory
$s$, second

$S$, Slip of Machine

$T_s$, Step Size

$V$, Wind Speed

$V_{q_{\text{ref}}}$, q-Axis Stator Voltage

$\text{VAWT}$, Vertical-Axis Wind Turbine

$\text{WTG}$, Wind Turbine Generator

$\omega_s$, Synchronous Speed

$\omega_r$, Rotor Angular Speed

$\text{WECS}$, Wind Energy Conversion System

$\text{WG}$, Wind Generator

$\lambda$, Tip Speed Ratio.
CHAPTER 1
INTRODUCTION

Background to the Study

In recent years, global warming has become the center of attention due to its negative impact on the environment. However, many studies have been made to reduce the emissions of carbon dioxide ($CO_2$) which is the main cause of greenhouse gases emission. According to these studies, using biofuel as the source for generating electricity is the primary source of $CO_2$ emissions in the world. The $CO_2$ emissions from the electricity generation sector is approximately 40% worldwide, followed by transportation, industry, and other sectors as shown in Fig. 1.1 [1].

![Figure 1.1 Sources of $CO_2$ emissions by sector.](image)
The studies also emphasized the need to migrate towards a more efficient method of generating electricity to reduce the impact of global warming issues. Integrating renewable energy into the electricity generation sector could save the world from a serious problem due to greenhouse gases produced from power plants.

The adaptation of reliable renewable energy into the power grid has dramatically developed in recent years to become more reliable with better power generation quality. Figure 1.2 depicts the projection of the annual growth rates of energy consumption by energy source from 2005 to 2035 as determined by the U.S. Energy Information Administration's International Energy Outlook 2011 [2]. Figure 1.2 illustrated that the amount of global hydroelectric and other renewable electric generating capacity will rise 2.7% per year through 2035 (2,372 gigawatts), more than any other electricity generating source, because of the higher oil costs and climate change concerns which encourage to switch to cheaper and cleaner generating fuels [2].

![Figure 1.2 Global installed power generation capacity by energy source [2].](image)
As shown in figure 1.3, wind power is one of the fastest growing renewable energy worldwide between 2010 and 2035. By 2020, wind power would account for more than 12% of the world's total installed capacity.

![Figure 1.3 Global installed power generation capacity by renewable source [2].](image)

The mechanical nature of wind energy has allowed the use of several types of wind generator (WG) such as squirrel cage induction generator (fixed speed), wound-rotor induction generator with adjustable external rotor resistance, doubly-fed induction generator, and induction machine with full converter interface [3] [4]. The last three types are classified as variable-speed wind turbines which are preferable over traditional fixed speed wind turbines due to their higher energy yields, extracting power in a perfect way, lower power fluctuations, and less mechanical stress [5] [6].

The doubly-fed induction generators (DFIG) are currently the most popular wind generators in the market among variable-speed wind turbines because of their high energy
efficiency and controllability [6]. The general shape for the DFIG is that the DFIG stator side is connected to the grid directly while the rotor windings are connected to the grid via AC/DC/AC IGBT power converter. The rotor side comparing to the stator side transfers one-third ($1/3$) of the output power to the grid. Therefore, the converter rating is lower than the generator rating [6].

The impact of penetration small scale of the wind turbine generators on the power system stability is minimal. Unlike the conventional design of a power distribution system, WGs are designed to be in close proximity to the load. Doing so, this design attracted many benefits to the existing grid system, such as; reducing power losses from the line, increasing the reliability of the grid, and reducing the cost of operation. However, when the penetration of the small scale the wind turbine generators increases, the dynamic performance of power system can be affected [4].

Therefore, a virtual plant model is needed to investigate and test the impacts of the integration of wind farms into a power system under different conditions to overcome any problem that might happen on a physical plant. One of the means to build a virtual plant model is to use the simulation tool. Most of existing studies on the simulation pertinent to wind power mainly focus on off-line simulation which has to go through a long research period with low accuracy. By contrast, an advanced real-time simulation platform, the Real-Time Laboratory (RT-LAB) developed by Opal-RT technologies has the functions of real-time simulation, which can shorten the research period and give results that come close to the physical system [7].

**Purpose of Thesis**

The main aim of this thesis is to model and develop a stable test bed for an average DFIG wind farm connected to an electrical distribution system based on eMEGASim® real-time digital
simulator. After building the model based on eMEGASim® real-time digital simulator, some studies such as three-phase to ground fault and voltage sags have been made to test the model.

Report Outline

This thesis consists of five chapters. In chapter 1, the background to the study has been reviewed. Chapter 2 shows general theoretical perspective of wind turbines in general and focuses more in depth on the DFIG wind turbine. In chapter 3, the thesis presents an overview of real time simulation and gives the most important steps that must be used to model and execute the Simulink model under the RT-LAB environment. Chapter 4 presents a detailed 13.8 kV distribution system with a wind turbine model in the configuration. Moreover, it describes in details the system model using a real time simulation system and the result of the simulation system case studies. Finally, the conclusion and suggestions for future studies are presented in chapter 5.
CHAPTER 2
REVIEW OF LITERATURE

Introduction to Wind Energy Conversion System

Wind energy conversion system (WECS) is the overall system that converts the wind energy into useful electrical power through a mechanical power. The WECS consists of three major aspects: aerodynamic, mechanical and electrical aspect. The major parts included in the mechanical and the electrical power conversion of a typical wind turbine system are shown in figure 2.1 [8].

Figure 2.1 Block diagram showing the components of WECS connected to grid.

Modern wind turbines are generally classified into two basic groups: the horizontal-axis wind turbines (HAWT) and the vertical-axis wind turbines (VAWT). Currently, most of the wind turbines using in the market are from HAWT type. It named HAWT because its shaft rotates on an axis parallel to the ground level. The HAWTs are divided into downwind horizontal axis wind
turbines and upwind horizontal axis wind turbines. As shown in figure 2.2, the rotor blades of the downwind turbines are stroked by wind from the back side. On the other hand, the rotor blades of the upwind turbine are facing the wind directly. This type requires a complex yaw control systems to keep the blades facing into the wind, but it operates more smoothly and delivers more power comparing to the other type. For these reasons, the majority of modern wind turbines are from the upwind type. Therefore, most of the technologies described in this thesis are related to three blades upwind horizontal axis wind turbines (HAWTs).

![Diagram of Downwind and Upwind Turbines](image)

Figure 2.2 Downwind turbine and upwind turbine.

Basic Components of a Wind Turbine

The main mechanical and electrical components of a wind turbine system are shown in figure 2.3. A typical HAWT made up of the following parts: rotor, drive train, nacelle, main-frame, tower and foundation. The rotor is formed by blades and hub and this part is responsible
to extract the wind energy and convert it into mechanical energy. For drive train, it is formed by brakes, low-speed shaft, gearbox, electrical generator, and high-speed shaft. This group is using the mechanical energy from the rotor and converts it into electricity through the electrical generator. For nacelle and main-frame, they are formed by housing, bedplate, and yaw system. Also, the transformer and power electronics converters can be added to last group if possible. The yaw system is used to allow the rotor facing the wind direction to extract maximum power.

Figure 2.3 Typical HAWT components [8].

Wind Turbine Generators

At the present time, there are four types of construction modes wind turbine generators (WTGs) used currently in the market, based on the grid connection:

- Squirrel cage induction generator.
- Wound-rotor induction generator with adjustable external rotor resistance.
- Doubly-fed induction generator.
- Induction machine with full converter interface.

As shown in figure 2.4, the squirrel cage induction generators (asynchronous generators) are directly connected to the grid through a step up power transformer. These types of the generators are also known as a constant or fixed speed wind generators because they are operated with less than 1% variation of rotor speed [6] [15]. Moreover, the squirrel cage induction generators always consume reactive power. Therefore, the capacitor bank connected close to the generators to compensate the reactive power consumption in order to achieve a unity power factor. Thus, these generators are undesirable in the large wind turbines due to their limitation in power capture.

![Figure 2.4 A fixed speed asynchronous wind generator.](image)

In wound-rotor induction generator with adjustable external rotor resistance as illustrated in figure 2.5, the variable rotor resistance control is used to control the output power. These types of generators give a better performance by extracting power in a perfect way comparing to the
previous types. Therefore, the main goal of the rotor resistance controller is to obtain the operating point with maximum possible wind power extraction without exceeding the machine limits [6] [15].

Figure 2.5 Wound rotor induction wind generator with external rotor resistance.

In conventional (singly-fed) induction generators, when the generator rotor rotates due to the prime mover, the static magnetic field created by the dc current fed into the rotor windings rotates at same speed as the rotor [31]. As a result of changing magnetic flux, this will induce the three-phase voltage at the stator side. Same operating principles can be applied in a DFIG except that the dc current fed into the generator rotor winding is not static as in the conventional induction generator, but it is creating using three-phase current with adjustable frequency via the power converter [31]. The doubly-fed induction generators (DFIGs) are the most popular wind generators due to their high energy efficiency and controllability [6]. As shown figure 2.6, the DFIG stator side connected to the grid directly via a power transformer and the rotor windings connected to the grid via AC/DC/AC IGBT power converter and a power transformer. This
converter comparing to the stator side transfers one-third \((1/3)\) of the output power to the grid. Therefore, the converter rating is lower than the generator rating [6].

Figure 2.6 Doubly-fed induction generator.

For full converter induction machine as shown in figure 2.7, the induction machine is connected to the grid directly through fully rated power converters and a power transformer. As seen in figure 2.7, the power electronics converters handle the entire output power of the generator. Thus, it provides a wide range of speed and operates at unity power factor because there is no reactive power exchange with the grid via the rotor or machine side converter. The machine side converter is used to control the generator torque loading at a particular speed, while the grid-side inverter is operated to maintain the \(DC\) bus voltage constant [10]. For the induction machine, there are two types; wound field and permanent magnet synchronous machine.
Permanent magnet synchronous machine is often used in wind turbines which use a permanent magnet (PM).

![Diagram of wind turbine generator system]

Figure 2.7 Induction machine with full converter interface.

After giving an overview of wind turbine generators, the advantages and disadvantages of these generator types are summarized in table 1 [6] [8].
Table 2.1 The Advantages and Disadvantages of Wind Turbine Generators.

<table>
<thead>
<tr>
<th>Generator Types</th>
<th>Advantages</th>
<th>Disadvantages</th>
</tr>
</thead>
<tbody>
<tr>
<td>Squirrel cage induction generator</td>
<td>• Simplicity.</td>
<td>• Not support any speed control (low efficiency).</td>
</tr>
<tr>
<td></td>
<td>• Low cost.</td>
<td>• Low power factor.</td>
</tr>
<tr>
<td></td>
<td>• Robustness.</td>
<td>• Need a reactive power compensator.</td>
</tr>
<tr>
<td></td>
<td>• Not support any speed control (low efficiency).</td>
<td>• High mechanical stress.</td>
</tr>
<tr>
<td>Wound-rotor induction generator with adjustable external</td>
<td>• Variable speed.</td>
<td>• Limited variable speed (middle efficiency).</td>
</tr>
<tr>
<td>rotor resistance</td>
<td>• Fast control.</td>
<td>• Low power factor.</td>
</tr>
<tr>
<td></td>
<td>• Low harmonics.</td>
<td>• Need a reactive power compensator.</td>
</tr>
<tr>
<td>Doubly-fed induction generator</td>
<td>• Active and reactive power controllability (Decoupled).</td>
<td>• Existence of brush/slipring.</td>
</tr>
<tr>
<td></td>
<td>• Reduced capacity of power electronics.</td>
<td>• High losses on gearbox.</td>
</tr>
<tr>
<td></td>
<td>• Lower losses.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• Lower power electronics cost.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• Compact size.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• Less mechanical stress.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• Smooth grid connection.</td>
<td></td>
</tr>
<tr>
<td>Induction machine with full converter interface</td>
<td>• Variable speed.</td>
<td>• Higher power electronics cost.</td>
</tr>
<tr>
<td></td>
<td>• Less mechanical stress.</td>
<td>• Higher losses.</td>
</tr>
<tr>
<td></td>
<td>• Smooth grid connection.</td>
<td>• Large size.</td>
</tr>
<tr>
<td></td>
<td>• Operates at unity power factor.</td>
<td>• High losses on gearbox.</td>
</tr>
<tr>
<td></td>
<td>• No Reactive power exchange.</td>
<td></td>
</tr>
</tbody>
</table>
Theory of wind turbines

As mentioned at the beginning of this chapter that the main role of the wind turbines is to extract energy from the wind. Therefore, the power available ($P_{Available}$) that can be extracted from the wind is given by [8, 12, 13, 21]:

$$P_{Available} = \frac{1}{2} \cdot \rho \cdot A \cdot V^3$$  \hspace{1cm} (2.1)

where

$\rho$ is the air density ($kg/m^3$).

$A$ is the cross-sectional area of the wind crossed the blades ($m^2$).

$V$ is the wind speed ($m/s$).

A perfect wind turbine cannot extract all the power available in the wind. The power actually captured by the wind turbine rotor ($P_m$) is defined by the power coefficient $C_p$ (or efficiency coefficient) which is the ratio between the power extracted and the available power in the wind [8, 12, 13, 14, 21]:

$$C_p = \frac{P_m}{P_{Available}}$$  \hspace{1cm} (2.2)

The maximum theoretical value of the efficiency coefficient ($C_{p,\text{max}}$) is 0.593, which is commonly known as the Betz limit. Actual efficiency coefficient is less than this limit due to various aerodynamic and mechanical losses. By substituting equation (2.1) into equation (2.2), it will give the mechanical power that can be extracted by the wind turbine which is a function of the power coefficient ($C_p$) and the available wind power:

$$P_m = \frac{1}{2} \cdot C_p \cdot \rho \cdot A \cdot V^3 = \frac{1}{2} \cdot C_p \cdot \rho \cdot \pi \cdot R^2 \cdot V^3$$  \hspace{1cm} (2.3)
Generally, the power coefficient \((C_p)\) is a function of tip speed ratio \((\lambda)\) and blade pitch angle \((\beta^o)\) [8, 12, 13, 14, 21]. As illustrated in figure 2.8, there is a maximum value for the power coefficient with respect to tip speed at various values of the pitch angle \(\beta^o\). The tip speed ratio is given by:

\[
\lambda = \frac{\omega_r \cdot R}{V}
\]

(2.4)

where

\(\omega_r\) is rotor angular speed \((\text{rad/s})\).

\(R\) is the blade radius of the wind turbine \((m)\).

Figure 2.8 Characteristics function of \(C_p\) vs. \(\lambda\), at various pitch angle values [8].

Figure 2.9 shows the mechanical power versus the rotating speed of the generator with no blade pitch angle control \((\beta = 0^o)\) at various wind speeds. It is observed that the operation of the
wind generator must follow a specific point of the rotor speed for each wind speed to maximize the mechanical power to get the maximum value of the wind power coefficient \( C_{p,max} \). Thus, the maximum mechanical power that can be continuously extracted from the low and the medium wind can be achieved by control the rotate speed of the generator to tracking the maximum power point (MPP tracking control or MPPT) for each wind speed as depicted by dotted line in figure 2.9 [8] [18].

Figure 2.9 Mechanical power versus rotor speed curves [18].

The aerodynamic torque captured by the rotor of the wind turbine is described as [15]:

\[
T_r = \frac{P_m}{\omega_r} = \frac{1}{2} \cdot C_p \cdot \rho \cdot A \cdot V^3
\]  \hspace{1cm} (2.5)

In large wind turbines, the mechanical power \( P_m \) expressed in equation 2.3 is not
directly connected to the generator, but is usually coupled through a transmission or gear box. Thus, as shown in figure 2.10, the electrical power output \( P_e \) that is connected to the grid or auxiliary circuits can be expressed as:

\[
P_e = \eta_m \cdot \eta_e \cdot \frac{1}{2} \cdot C_p \cdot \rho \cdot A \cdot V^3
\]

where

- \( \eta_m \) is the overall mechanical efficiency of the transmission.
- \( \eta_e \) is the overall efficiency of the electrical generator.

![Diagram of wind electrical system](image)

Figure 2.10 Wind electrical system.

**Wind Turbine Power Curves Characteristics**

Each wind turbine performance can be estimated by the power curve which is usually given by the manufacturer of the wind turbine. The power curve, which is the function of the estimated power output to wind speed, is used to measure the total wind power protection by the wind turbine. There are three distinct points to any power curve of a variable-speed variable-pitch wind turbine as illustrated in figure 2.11 [11, 13, 18]:

- Cut-in wind speed (2-4 m/s): the blades start to rotate and consequently the wind turbine generator begins to generate power to supply the load.
• Rated wind speed (11 – 20 m/s): after the wind speed increasing above the cut-in speed point, the wind turbine generator starts to produce more power which is proportional to the cube of the wind speed. By increasing the wind speed further, the output power of the generator will increase until the wind speed reaches the rated wind speed at which the output power of the generator is regulated to its rated power.

• Cut-out or furling wind speed (20 – 25 m/s): at some point when the wind increase above the rated wind speed range in which the wind turbine must be shut down to avoid mechanical damage due to the high wind speed. This is achieved by adjusting the blade pitch angle and by using brakes.

Figure 2.11 Wind turbine power curve characteristics [11]
The doubly-fed induction generator is widely used in wind power generation due to its high energy efficiency and controllability [6]. This generator converts the wind energy into useful electrical power through wound rotor induction machine. As shown in figure 2.12, the DFIG-based WECS basically consists of a wound rotor induction machine, wind turbine with drive train system, rotor side converter (RSC), grid side converter (GSC), DC-link capacitor, and coupling transformer. The wound rotor induction machine stator winding is connected to the grid directly through a three-phase power transformer while the rotor winding is connected to the grid via AC/DC/AC IGBT power converter and a three-phase power transformer by slip rings and brushes, hence the term ‘doubly-fed’. The stator side of the DFIG is connected to the grid with fixed frequency \( f_s \) and voltage, whereas the rotor side supplies a variable frequency which is controlled by the power converters before connecting to the grid. Because only part of the real power flows through the rotor circuit, these power converters are used to handle a fraction (25-30\%) of the total power to accomplish independently full control of the real and the reactive power of generator [18] [19].

Thus, the losses in the power converters can be reduced because these converters handle less than 30\% of the generator rated power. The control system controls the real and reactive power by changing the current flowing in the rotor winding to extract the maximum possible power from the wind. Therefore, the power of the rotor can be connected to the grid at the rated frequency by interposing the converters.
Figure 2.12 Components of DFIG-based WECS.

The active power of the stator is always flowing to the grid, independently of the operation state, whereas the machine operates as motor (sub-synchronism operation) when absorbing power, while the machine operates as a generator (hyper-synchronism or super-synchronous operation) when supplying power. By neglecting the power losses, the relation between the rotor power ($P_r$) and the stator power ($P_s$) through the slip ($S$) is given by [13]:

$$P_r = -S \cdot P_s$$  \hspace{1cm} (2.7)

where $S$ is defined as the slip of the machine which is given by:
\[
S = \frac{\text{Synchronous Speed } (\omega_s) - \text{Rotor Speed } (\omega_r)}{\text{Synchronous Speed } (\omega_s)}
\] (2.8)

Therefore, the net power \( P_{net} \) that is generated from both stator and rotor side can be expressed as [13]:

\[
P_{net} = P_s + P_r = P_s - S \cdot P_s = (1 - S) \cdot P_s
\] (2.9)

When the slip \( S \) is negative, the machine will operate in the hyper-synchronous (supersynchronous) operation state (as a generator), while the machine will operate in the sub-synchronous operation state (as a motor) when the slip \( S \) is positive, i.e. the rotor speed is slower than the synchronous speed. By this configuration, the wound rotor induction generator delivers directly the 2/3 of its rated power to the grid through the stator windings, while it delivers 1/3 of its rated power through the rotor windings via the converters [13].

Control Methods

The control system in the wind turbines plays an important role to control and extract the maximum energy from available wind while protecting the wind turbine components. Overall the power can be controlled by the following methods; the generator speed, blade angle adjustment, and yaw adjustment [16] [17]. The generator speed control is the most effective way to extract the maximum power from a low wind speed by using the power electronic converters as it will be discussed in the next section [16] [17]. For blade angle adjustment control, the pitch angle adjustment is used to stall and furl the wind turbines as shown in figure 2.13 (A). By stalling a wind turbine, this will increase the angle of attack, which causes the flat side of the blade to face
further into the wind. In contrast, Furling works by decreasing the angle of attack, causing the edge of the blade to face into the wind. Therefore, when fully furl turbine blades is made, this will stop the wind turbine completely. Pitch angle adjustment is a very effective way to limit output power by changing aerodynamic force on the blade at high wind speeds. For the yaw control, it is used to rotate the entire wind turbine to face the wind direction as shown in figure 2.13 (B).

(A) Pitch adjustment

(B) Yaw adjustment

Figure 2.13 Pitch adjustment and yaw adjustment [16].

In other words, the pitch angle control and controlling the synchronous speed of the generator are the most effective in the wind turbines control system as shown in figure 2.14, which is depicted a system-level layout of a wind energy conversion system [16].
Figure 2.14 System-level layout of a wind energy system.

**Power Converter models**

The AC/DC/AC converter consists of two back-to-back PWM converters as shown in Figure 2.12. The power converter is divided into two components: the rotor-side converter (RSC) and the grid-side converter (GSC) with a DC link capacitor between them in order to keep the voltage variations in the dc-link voltage small. Both of these converters are Voltage-Sourced Converters equipped with IGBTs and diodes to synthesize an AC voltage from a DC voltage source, which enable a bi-directional power flow [10] [18]. The Voltage-Sourced Converter is used to convert the AC voltage source into the DC voltage source and vice versa.

**Rotor-Side Converter Control for DFIG**

The rotor-side converter controller is used to control independently the stator voltage (or reactive power) and output active power of the wind turbine [10] [18]. The generic control loop is illustrated in figure 2.15. Since the converter operates in a stator-flux $qd$-reference frame, the
rotor current is decomposed into an active power \((q\text{-axis})\) and a reactive power \((d\text{-axis})\) component. When the wind speed changes, the active and reactive (or voltage) power of the generator will also change. As shown in figure 2.15, Actual active power of the generator \((P_{\text{actual}})\) is compared with reference point value \((P_{\text{ref}})\) which is determined by the wind speed. The difference between these two values will go to a Proportional Integral (PI) controller which is used to generate the required value of q-axis rotor current \((I_{q\text{ref}})\). Likewise, a PI controller of the reactive power side is used to generate the required d-axis rotor current \((I_{d\text{ref}})\). The two outputs of both \(PI\) controllers are transformed from the \(q\text{-}d\) frame into the \(abc\) frame to obtain the required value of rotor currents. Then, \(I_{ar\_ref}, I_{br\_ref}\) and \(I_{cr\_ref}\) are algebraically summed with, \(I_{ar\_act}, I_{br\_act}\) and \(I_{cr\_act}\) respectively. The last result is obtained as a result of generation and demand quantities. The triggering pulses would control the IGBT switches in the rotor-side converter and that will enhance the stability of entire system by sustaining the frequency and voltage within permissible tolerances [19] [20].

Figure 2.15 Rotor-side converter control system [19].
Grid-Side Converter Control for DFIG

The role of the grid-side converter is to control the DC-link voltage by maintaining it constant and it is also used to generate or absorb reactive power. The DC link voltage is used as well, with the $q$-$d$ reference frame oriented along the stator currents and stator voltages, enabling independent control of the active and reactive power flowing between the grid and the converters. The decoupling and compensation procedures of a typical grid-side converter control are illustrated in Figure 2.16. The actual DC link voltage ($E_{DC_{actual}}$) is compared with reference point value ($E_{DC_{ref}}$) as shown in figure 2.16. The difference between these two values will go to two PI controllers which are used to generate the required value of $d$-axis stator voltage ($V_{d_{ref}}$). Similarly, the difference between the actual reactive power ($Q_{actual}$) and reference value ($Q_{ref}$) will go to another two PI controllers to generate the required value of the $q$-axis stator voltage ($V_{q_{ref}}$). These desired $q$-$d$ voltages ($V_{d_{ref}}$ and $V_{q_{ref}}$), the outputs of both PI controllers, are transformed from the $q$-$d$ frame into the $abc$ frame to fire the IGBTs [19]. Therefore, a typical grid-side converter control is illustrated in Figure 16.
Figure 2.16 Grid-side converter control system[19].
CHAPTER 3
REAL TIME SIMULATION

Real Time Simulation Environment

The Real time simulation (RTS) has been around for a while and it has been used in many engineering fields. Real time simulation technology can be defined as a computer model building from a real physical system that can be run in the computer at the same rate as actual time [22]. Therefore, the RTS brought many advantages for engineers such as cost avoidance, increase quality, complete physical testing, reuse of simulator, more tests in the lab, early faults detection, increase productivity, and less test on the site.

Real-time system configurations can be classified into three applications categories as shown in figure 4.1 [23] [24].

- Rapid control prototyping (RCP)
- Hardware-in-the-loop (HIL)
- Pure Simulation (PS)
In RCP application, a real-time simulator is used to implement a plant controller model and connect to a physical system via input and output of the simulator ports. This application category gives many advantages which are faster to implement, more flexible and easier to debug [23]. On contrast, HIL is used to test real controllers connected to a simulated plant model. The simulated plant model is usually cost less and more stable than a real plant. Beside the advantages mentioned above, HIL allows testing a model with less cost and without risk. In PS application, a real-time simulator is used to implement both controller model and a virtual plant model as illustrated in figure 3.1 [23] [24].

**RT-LAB™ Overview**

The software used in this study is *RT-LAB™* (Workbench) Version: v10.5.5.301. *RT-LAB* is a distributed real-time platform that enables engineers and researchers to run Simulink dynamic models at real-time with hardware-in-the-loop (HIL), at low cost, high accuracy and a very short time.
Its scalability allows the developer to add computing power where and when it is needed. It is flexible enough to be applied to the most complex simulation and control problem, whether it is a Real-Time Hardware-in-the-Loop application or for speeding up model execution, control and test. Embedded device in a real-time system is given a predetermined amount of time (1 ms, 5 ms, or 20 ms) to read input signals, such as sensors, to perform all necessary calculations, such as control algorithms, and to write all outputs, such as analog/digital outputs. The model is solved by fixed-step solvers within fixed intervals called step size ($T_s$) as shown in figure 3.2.

![Figure 3.2 Proper choices for time step simulation.](image)

As shown in figure 3.3, overrun occurs when a predetermined time step is too short and cannot perform the process of the simulation. To overcome this overrun, the time step should be increased to omit this interference with next interval. But, increasing time step decreases the accuracy of the results [25].
Figure 3.3 Improper choices for time step simulation.

**Hardware Details**

The simulator used in this study is *OP5600* real-time digital simulator and this simulator is used to demonstrate the real-time performance of an average model of wind farm connected to distributed network. It is built using low cost, high availability commercial-off-the-shelf (*COTS*) components that includes advanced monitoring capabilities and scalable input/output and processor power.

The *eMEGASim®* simulator contains a powerful real-time target computer equipped with 12-3.3 *GHz* processor cores running Red Hat Linux real-time operating and two user-programmable FPGA-based *I/O* management options available, powered by the Xilinx Spartan-3 or more powerful *Virtex-6 FPGA* processor. Available expansion slots accommodate up to 8 signal conditioning and analog/digital converters modules with 16 or 32 channels each for a total of fast 128 analog or 256 discrete or a mix of analog and digital signals [26].

It releases as a single target that can be networked into a multiple-target *PC* cluster or for complex applications capable of implementing large models with more than 3000 *I/O* channels.
and a time step below 25 micros. This also allows including hardware-in-loop (HIL) testing, complex power grids, micro-grids, wind farms, hybrid vehicles, more electrical aircrafts, electrical ships and power electronic systems can be simulated with time step as low as 10 microseconds or less than 250 nanoseconds for some subsystems in order to increase the accuracy. In addition, it offers versatile monitoring on the front panel through RJ45 to mini-BNC connectors [26]. The front and back views of OP5600 real-time digital simulator are depicted in figure 3.4.

![Figure 3.4 OP5600 real-time simulation target view.](image)

(a) Front View (b) Back View

**ARTEMIS**

**ARTEMiS** is an add-on Blockset that optimize Simulink models, created using the SimPowerSystems, by extending the range of time step to achieve both speed and accuracy of the real time simulation. The many advantages are offered by The **ARTEMiS** Plug-in to SimPowerSystems Blockset [27]. One of these advantages is Real-time computational capability which means providing faster simulations. Furthermore, **ARTEMiS** uses stable integration methods that are free from the numerical oscillations that often affect the standard SimPowerSystems blockset fixed-step integration methods such as trapezoidal or Tustin. Finally,
ARTEMiS comes with specialized models for real-time simulation such as ARTEMiS Distributed Parameter Line and ARTEMiS Stublines that enables distributed simulation of power systems on several CPUs or cores of standard PCs using RT-LAB. The ARTEMiS plug-in is especially designed to work in the RT-LAB real-time environment and shall prove very effective in helping the typical user reach its real time objectives [27].

RT-LAB Modeling

Any Simulink model can be implemented in RT-LAB environment by performing the flowing steps. The block diagram of the Simulink model must be modified by regrouping the model into subsystems and inserting OpComm blocks. In RT-LAB, all the subsystems must be named with a prefix identifying their function [25]. The prefixes are console subsystem (SC_), master subsystem (SM_) and slave subsystem (SS_). For console subsystem (SC_), there is at most one in each real-time simulated model. It contains all user interface blocks, such as scopes, displays, switches and gains, and this subsystem will run asynchronously from the other subsystems. Each master and slave subsystem in RT-LAB is represented by a core to perform their processes in efficient and fast way. In the RT-LAB model, there is always one master subsystem in each model; however, slave subsystem only needed when computational elements must be distributed across multiple cores. Master subsystem (SM_) and slave subsystem (SS_) contain all the computational elements of the model, the mathematical operations, the input and output blocks, and the signal generators. After grouping the model, OpComm blocks must be added to enable and save communication setup data. All inputs of subsystems must first go to OpComm block before being used.
Execute the Model under RT-LAB

To start simulation execution of the Simulink model under the RT-LAB, the following steps are generally required [28] [32]:

- Double-clicking on RT-LAB icon on your desktop.
- From Open Model button select the RT-LAB Simulink model file.
- Select the edit target platform, and then click on the Compile button. This automatically starts the following processes on the screen:
  - The model will divide into smaller groups for each subsystem.
  - C-code will generate for all the generated groups.
  - Code compilation for the various subsystems for real-time execution.

At the end of this step, an executable file is generated for each subsystem of the model. Each file is executed by a Target Node as previously assigned.

- After the model is compiled, click on the Assign nodes button to bring up the list of executables. Each executable can then be assigned to a node in the system.
- Click on the Load button to load the executable files.
- Click on Execute button to start the simulation process on the windows host.
- From the Console Subsystem file, the result of the simulation can be seen.
CHAPTER 4
MODELING, CASE STUDY AND SIMULATION RESULTS

Model Construction

The AC distribution system that is used in this study is the IEEE 14 bus system. As shown in figure 4.1, it consists of 14 buses, 20 distribution lines, 2 synchronous generators, 3 synchronous condensers, and 11 loads. The distribution voltage of the system is 13.8 KV and its nominal frequency is 60 Hz. The IEEE 14 bus system was built and developed using MATLAB/SIMULINK software where the data of IEEE 14 bus system is shown in appendix A [29]. At bus 8, the synchronous condenser was replaced with a 9 MW wind farm adopted from SimPowerSystems™ Simulink. This wind farm consisting of six 1.5 MW wind turbines is connected to a three-phase power transformer to export power to a 13.8 kV grid through bus 8. The wind turbine used in this study is an average model of doubly-fed induction generators (DFIGs) which consist of wound rotor induction generators and AC/DC/AC IGBT-based PWM converters. The stator windings are connected directly to grid with a fixed 60 Hz frequency while the rotor is fed at variable frequency through the grid side converter and the rotor side converter. The wind speed used in this model is maintained constant at 15 m/s. The total loads were intentionally reduced to make the wind farm contribute more than 20% of the total power. The control system uses a torque controller in order to maintain the speed at 1.2 pu, while the reactive power generated by the wind turbine is regulated at 0 Mvar [32].
Figure 4.1 Single line diagram of the IEEE 14 bus distribution system.
According to the \textit{OPAL-RT} instructions mentioned in chapter 3, the IEEE 14 bus system with a wind farm is divided into 7 sections beside the console subsystem as shown in figures 4.2 and 4.3. “SM\_Section\_A” consists of the swing bus, bus 2, one load and one synchronous generator. The subsystem “SS\_Section\_B” and “SS\_Section\_C”, each one has two buses, two loads, one transformer, and one synchronous condenser. The subsystem “SS\_Section\_D” has two buses and one load. The “SS\_Section\_E” has the wind farm (9 MW) which is consists of six DFIG wind turbines (1.5 MW for each) connected to the grid via a distributed transformer through the bus 8. Finally, two buses on the subsystem “SS\_Section\_F” and three buses on “SS\_Section\_G” and each bus on these subsystems has one load. After grouping the model, The “StubLine” block from the ARTEMiS block library is used as distribution lines, and OpComm block has been added to enable and save communication setup data as mentioned in chapter 3. The final look of the model in the RT-Lab environment is shown in figures 4.3. In addition, the view layouts of the model’s subsystems used in this study are presented in appendix B.
Figure 4.2 Single line diagram of model configuration.
IEEE 14-bus Network with A Wind Farm
13.8 kV Transport Network with 14 buses, 20 distribution lines, 2 synchronous generators, 2 synchronous condensers, 11 loads, and 6 wind turbines

Figure 4.3 Simulink implementation of IEEE 14 bus with the wind farm in the RT-LAB environment.
Model Testing

After modeling the system in the *RT-LAB* environment, the system has been studied in the steady state by using the *OP5600* real-time digital simulator with a time step of 50 µs. After executing the model by following the steps in chapter 3, it is found that the voltage of the system at each bus is almost 1 pu as seen in figure 4.4, showing the per unit voltages for some of the system buses (bus 1, 2, 4, 5, and 10 respectively).

As illustrated in figure 4.5, the output active power of the wind farm is 9 MW while the output reactive power is maintaining at 0 MVar. Furthermore, the turbine speed is 1.2 pu of generator synchronous speed while the dc voltage is keeping 1150 V due to the control strategy made in the grid side converter. After getting acceptable results, this indicates that the system is stable and working correctly in the steady state. Therefore, the main objective of this thesis is achieved.
Figure 4.4 Per unit voltages at bus 1, 2, 4, 5, and 10 respectively.
Figure 4.5 Wind farm parameters under steady state operation: (A) Active power of the wind farm, (B) Reactive power of the wind farm, (C) Turbine speed, and (D) The DC voltage (Page 41 – 42).
(C) Turbine speed.

(D) The DC voltage.
Power Curve

As mentioned in chapter 2, the power curve is the function of the estimated power output to wind speed and this curve is used to measure the total wind power protection by the wind turbine. Thus, the model has been tested at different wind speeds to measure the output power of wind turbine generator as shown in table 4.1. After drawing the data in the table 4.1 by using Matlab as illustrated in figure 4.6, the power curve of each wind turbine generator used in this study is very similar to the theoretical power curve mentioned in chapter 2. At 4 m/s which is known as the cut-in wind speed, the wind turbine generator starts to generate electricity. By increasing the wind speed further, the output power will increase proportional to the cube of the wind speed until the wind speed reaches the rated wind speed at which the output power of the wind turbine generator is regulated to the rated power (1.5 MW). At cut-out wind speed which is 20 m/s, the wind turbine will shut down.

![Power Curve](image)

Fig. 4.6 Power curve of each wind turbine generator used in the study.
Table 4.1 Output Power of Each Wind Turbine Generator with Different Wind Speed.

<table>
<thead>
<tr>
<th>Wind Speed (m/s)</th>
<th>Output Power (MW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.000</td>
<td>0.000</td>
</tr>
<tr>
<td>3.000</td>
<td>0.000</td>
</tr>
<tr>
<td>4.000</td>
<td>0.016</td>
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<tr>
<td>5.000</td>
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</tr>
<tr>
<td>6.000</td>
<td>0.165</td>
</tr>
<tr>
<td>7.000</td>
<td>0.288</td>
</tr>
<tr>
<td>8.000</td>
<td>0.423</td>
</tr>
<tr>
<td>9.000</td>
<td>0.595</td>
</tr>
<tr>
<td>10.00</td>
<td>0.810</td>
</tr>
<tr>
<td>11.00</td>
<td>1.073</td>
</tr>
<tr>
<td>12.00</td>
<td>1.377</td>
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<tr>
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<td>1.500</td>
</tr>
<tr>
<td>20.00</td>
<td>1.500</td>
</tr>
</tbody>
</table>

Model Validation

Some investigations have been made to test the validity of the developed model under the three-phase to ground fault and voltage dip.

Performance of the Wind Farm under Three Phase to Ground Fault

In this part, the impact of the three-phase to ground fault on the wind farm terminal has been studied. Initially, three-phase to ground fault occurred on the line between the wind farm and bus 8 of the IEEE 14 bus system for 5 cycles during the period 10 s (600/60 s) to 10.083 s (605/60 s). The results of this simulation are illustrated in figure 4.7.
When the fault occurred during $t = 10$ s to $t = 10.083$ s, the wind farm output active power increased to 11.3 MW and then reduces to 0 MW in 1 cycle. Moreover, the wind farm started to generate reactive power until the fault is cleared. For the turbine speed, it decreased slightly and then increased suddenly up to 1.235 pu of the generator synchronous speed. In addition, the dc voltage increased gradually from 1150 V to 2040 V during fault period. Finally, the voltage at bus 8 sagged to almost 0 V during this period.

After the fault cleared at $t = 10.083$ s, the wind farm output active power recovered and back to 9 MW in less than 2 s. However, the wind farm started to absorb reactive power for 1.5 cycles before returned back to 0 MVar. For the turbine speed, it started to fluctuate for almost 4 s until getting back to its nominal value 1.2 pu of the generator synchronous speed. For the dc voltage, it reduced until recovering after 3 cycles and back to 1150 V. Lastly, the voltage at bus 8 retrieved after 1.5 cycles.

![Wind Farm Active Power](image)

(A) Active power of the wind farm

Figure 4.7 Wind farm parameters under three phase to ground fault: (A) Active power of the wind farm, (B) Reactive power of the wind farm, (C) Turbine speed, (D) The DC voltage, and (E) Bus 8 voltage (page 45 – 47).
(B) Reactive power of the wind farm.

(C) Turbine speed.
(D) The DC voltage.

(E) Bus 8 voltage.
Performance of the Wind Farm under the Voltage Dip

In this section, the response of the steady state operation of the DFIG wind farm has been investigated in case of the whole system voltage dip by programming the generators to reduce their voltage to 0.5 pu at t = 10 s (600/60 s) and to recover after 10.083 s (605/60 s). As seen in figure 4.8, when the voltage decreased to 0.5 pu at 10 s, the wind farm parameters started to oscillate due to this disturbance. After 10.083 s by a few seconds, the wind farm returned back to its normal operation through the control system.

Figure 4.8 Wind farm parameters under voltage sag: (A) Active power of the wind farm, (B) Reactive power of the wind farm, (C) Turbine speed, (D) The DC voltage, and (E) Bus 8 voltage (page 48 – 50).
(B) Reactive power of the wind farm.

(C) Turbine speed.
(D) The DC voltage.

(E) Bus 8 voltage.
CHAPTER 5
CONCLUSION AND FUTURE WORK

Conclusion

A stable test bed for an average DFIG wind farm connected to an electrical distribution system based on eMEGASim® real-time digital simulator has been modeled and developed. In addition, tests were done on the performance of DFIG models on the OP5600 simulator with a time step of 50 µs. Moreover, the three-phase to ground fault and voltage sag were introduced to observe and test the dynamic response of the model. It is observed that when the fault and the voltage sag occurred at 10 s, the wind farm parameters started to oscillate and they returned back to their normal operation after 10.083 s by a few seconds as expected.

Future Work

The test bed that has been modeled by using real time digital simulator provides a useful platform for future studies for those who have an interest in wind power and also useful for education and academic works. It can be used to implement and develop various studies such as interaction of wind farm with an energy storage system, interaction of model with a solar system, applying protection system technology and developing new advanced control schemes.
REFERENCES


APPENDIX A

IEEE 14-BUS TEST SYSTEM (GENERAL)
Table A.1: Bus Data

<table>
<thead>
<tr>
<th>Bus Number</th>
<th>P Generated (p.u.)</th>
<th>Q Generated (p.u.)</th>
<th>P Load (p.u.)</th>
<th>Q Generated max. (p.u.)</th>
<th>Q Generated min. (p.u.)</th>
<th>Bus Type*</th>
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<tbody>
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<td>0.000</td>
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*Bus Type: (1) swing bus, (2) generator bus (PV bus), and (3) load bus (PQ bus)
Table A.2: Impedance Data

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<th>From Bus</th>
<th>To Bus</th>
<th>Resistance (p.u.)</th>
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<th>Line Charging (p.u.)</th>
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APPENDIX B

DETAILED VIEW LAYOUTS OF THE MODEL’S SUBSYSTEMS
The model layout of subsystem section A
The model layout of subsystem section B
The model layout of subsystem section C
The model layout of subsystem section D
The model layout of subsystem section E
The model layout of subsystem section F
The model layout of subsystem section G
The model layout of subsystem Console section
VITA

I am Mohammad Altimania, from Saudi Arabia. In March 2010, I completed my Bachelor of Science Degree in Electrical Engineering from Qassim University. During my study, I did two Summer Training one of them in Saudi Aramco Company (Saudi Arabian Oil Company) for two months in 2007 and the other one in Saudi Electricity Company for also two months in 2009. In May 2010, I joined the Department of Electrical Engineering, college of Engineering, at Tabuk University as a teaching assistant which enables me to pursue my higher studies in the Electrical Engineering field. I started the MS Electrical Engineering program at the University of Tennessee at Chattanooga in Fall 2012. After graduation, I am planning to complete my study to get a Ph.D. in electrical engineering.