A Study of Field-Oriented Control of a Permanent Magnet Synchronous Generator and Hysteresis Current Control for Wind Turbine Application

THESIS

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By

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ABSTRACT

Wind turbine has been popular in the area of renewable energy source. Wind turbine has shown the biggest growth in the past 10 years compared to other renewable sources. Permanent Magnet Synchronous Generator (PMSG) used as wind turbine generator. PMSG is suitable for the application due to its high efficiency, high torque-to-size ratio, and low maintenance requirement. The intermittent characteristic of wind requires a wind turbine to have good control system. This thesis discusses the Field Oriented Control (FOC) and Hysteresis Current Control (HCC) technique used to control the generator-side and grid-side respectively. In order to perform these controls, good understanding of the PMSG and electrical grid are required. In addition, reference frame theory and Space Vector Modulation are explained as supplement theories used for the Field Oriented Control. A MATLAB/Simulink simulation has been developed to simulate the control algorithms.
DEDICATION

To my parents and sister

Tonny Baktiono and Susilowati Halim

Evelyn Baktiono
ACKNOWLEDGMENTS

I would like to thank Dr. Ali Keyhani for his advice, patience, and understanding for the past two and a half years. I believed his guidance in during my Master degree has pushed me beyond my limits and gave me an invaluable experience. Dr. Keyhani’s kindness and patience in guiding me through my thesis development inspired me and helped me to persevere the tough times till the end. On top of that, I would like to sincerely thank Dr. Keyhani’s encouragements for me to met one of his colleague in Bandung, Indonesia. It gave me the precious opportunity to see the growth of renewable energy area in Indonesia, which I want to be a part with in the future.

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through my tough times. They never fail to fulfill my need and help me be what I am today.

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CHAPTER 1

INTRODUCTION

The thesis discusses the overall aspect of field oriented control of a Permanent Magnet Synchronous Generator (PMSG) and Hysteresis Current Control for wind turbine application. The following sections summarize the chapters in this thesis. Chapter 2 elaborates the development of wind energy in renewable world and its behavior impacted on the total power produced. Chapter 2 discusses wind turbine generators comparing PMSG with other type of generators and its operation. Chapter 4 introduces the control systems, which includes Field-Oriented Control and other supporting control techniques used to integrate the wind turbine generator to the power grid. Simulations and results are presented in Chapter 5. Last but not least, future works are presented in Chapter 6.

1.1 The World of Renewable Energy (Wind Energy)

Historically, energy utilization has been playing a fundamental part in the development of human civilization. Time and time again, it has proven that the growth of energy technology directly correlates to the economic growth of a society. [5] In today’s modern society, fossil fuel has been the main source of energy has been utilized as the main source of electricity to produce electricity. However, this type of energy source is deemed costly due to its unsustainable nature and environmental impact. [9] The
combustion of fossil fuel produces greenhouse gasses (mainly Carbon Dioxide) that traps the sun radiation in the atmosphere. These greenhouse gasses contain the reflected infra-red radiation, re-emitting them back to the earth’s surface. This recurring process leads to increase in overall temperature, which also known as Global Warming (Climate Change). [7]

Energy experts have actively promoted the usage of energy resources that are both sustainable and safe for the environment. The growth of renewable energy technology has shown a promising growth as an alternative energy resource or as a supplement towards the conventional electric generation. In particular, the wind energy has experienced the biggest growth in the past 10 years. [25] According to World Wind Energy Association, the installed capacity of wind turbine grew significantly 87 MW from 1997 to 2007. In the same light, United States federal researchers are confident that wind energy will be able to support 30% of electricity need for the nation with this rate of growth. [19]

Similar to the other renewable energy source, wind energy is pollution free. What sets it apart from the others is the competitive cost that it can offer to the industry, although some may find drawback in its erratic behavior. [14] The amount of energy obtained is determined by the speed of wind acting towards the wind turbine system. This restrains the usage of regular three-phase generators to directly generate the electricity. It limits the efficiency and the generator usage is limited in constant speed operating condition. [20] Nevertheless, the growth of power electronics enables variable speed
operating condition and increased turbine efficiency. Power converters are used to manipulate the generated electricity to match the power grid requirement.

1.2 Wind Turbine Generators (PMSG)

In order to generate electricity out of wind, a typical three-phase generator is needed. In chapter 3, synchronous and asynchronous generator is compared for their compatibility as wind turbine generator. For asynchronous (induction) generator, Squirrel Cage Induction Generator (SCIG) and Doubly Fed Induction Generator (DFIG) are compared, while Permanent Magnet Synchronous Generator (PMSG) represents the synchronous generator class.

Squirrel Cage Induction Generator is used as a fixed-speed wind turbine generator. The speed of SCIG remains close to constant, even when the wind speed changes. Thus, SCIG provides robustness and stability to the grid. The disadvantage of SCIG is that it requires reactive magnetizing current to operate as a generator. This means that SCIG requires more reactive power supplied to the rotor to produce more active power. The constant magnetizing current requirement causes several problems during transients, as well as operating in low power factor. Thus, efficiency of SCIG is low. [23]

Doubly Fed Induction Generator (DFIG), which is another type of induction generator, utilizes wound rotor as its rotor. As a wind turbine generator, DFIG’s rotor windings are connected through back-to-back voltage converter, which in charge of inducing voltage to the rotor, and its stator windings are directly connected to the grid. The power converter is responsible for controlling the rotor current injection when there
is a difference between mechanical frequency and electrical frequency. Compared to SCIG, although DFIG also requires magnetizing current, DFIG is able to control the reactive power. However, this capability may disrupt voltage stability in the case of weak grids. In addition to that, this type of generator requires slip rings to operate properly which has to be highly maintained. [23]

As for synchronous generator, Permanent Magnet Synchronous Generator (PMSG) has grown its popularity as wind turbine generator. PMSG in essence is more expensive and more complex than induction generators. However, PMSG does not require magnetizing current, which is the main problem of induction machines: to be fed into the rotor. Instead the permanent magnet can generate the magnetic field needed. This allows the generator to operate in high efficiency. On top of that, PMSG can be driven directly without gearbox with appropriate number of poles. Also, the replacement of rotor circuits with permanent magnet eliminates the usage of slip rings in PMSG. This means that the generator is nearly maintenance free, which is highly desirable for wind turbine applications. [23] Thus, PMSG is focused to be the generator for wind turbine application in the thesis.

In the later part of chapter 3, basic operation of Permanent Magnet Synchronous Machine is explained to gain better understanding. Important characteristics such as voltage, flux linkage, and torque equations are derived. Reference frame theory is also explained in order to transform the important characteristics into rotor reference frame representation, which is equivalent to the synchronous rotating reference frame. [24]
1.3 Control System of PMSG in Wind Turbine Application

In order to control Permanent Magnet Synchronous Generator (PMSG), a set of full-scale converter is used to connect to the grid. The set of full-scale converter consists of back-to-back voltage source converter, generator side converter and grid side converter connected through DC-link capacitor. This capacitor decouples the two converters, allowing two separate controls applied to the converters. [25] The grid side converter controls the power flow to maintain the DC-link voltage to be constant, while the generator side converter controls the torque and the speed of the PMSG. Chapter 4 describes the control technique of both converters and block diagram representation for the control system.

Field Oriented Control (FOC) method is applied to the generator-side converter to maintain the generator speed to operate at a desired speed. The reference speed used is assumed to operate at optimal speed to obtain the maximum power in a certain wind speed. Field Oriented Control is a method to decouple the torque producing and the magnetizing elements. In this way, the torque of an electric machine can be controlled independently causing easy implementation of an electric machine depends heavily on the ability to electric machine controller to control the torque. With the position of the machine obtained, Field Oriented Control allows a fast and precise control, leading to PMSG efficient performance. [25]

On the other hand, the grid side converter utilizes Hysteresis Current Controllers to maintain the DC link voltage to be constant by adjusting the power flow to the grid. The Hysteresis Current Controller compares the generated reference current to the actual
Based on the width of the hysteresis control, the output of the controller produces the right gate signal to for the rectifiers.

One of the textbook approaches to Field Oriented Control operation is further explained in Chapter 6 with mathematical model to give better understanding. Furthermore, mathematical model is presented for a better understanding. Detailed description of Hysteresis Current Controller and Space Vector Modulation is also discussed in this chapter.

1.4 Contribution of Authors

The author designed a full control system simulation for wind turbine equipped with PMSG. The control system simulation includes Field Oriented Control for the generator side controller and Hysteresis Current Control for the grid side controller. Space Vector Pulse Width Modulation is performed to generate pulses for the converters. The simulation is done through MATLAB/Simulink development environment. The results are evaluated as operated in variable wind speed operation.
CHAPTER 2

RENEWABLE ENERGY (WIND POWER)

Over the past few decades, fossil fuel has dominated the energy source market. The widespread use of this energy resource has quickly developed into an exploitation, which in turn led to a significant increase of carbon emission in the last 50 years. This momentous emission rate growth has been contributing to the acceleration on global warming process. As the awareness towards global warming increases, so does the demand for clean renewable energy. The thesis is focusing on utilizing wind energy as a mean of alternative energy that is sustainable. This chapter describes characteristics and nature of wind energy in context of electricity generation.

2.1 History of Energy

The word ‘energy’ originates from the ancient Greek word ‘energeia’, which means ‘activity’ or ‘operation’. [2] In modern days, energy is defined as “the ability to do work”. [1] At 1918, Amalie Emmy Noether, a German mathematician who is considered to be one of the most influential scientist, proved the existence of conservation law. The Noether’s theorem has become a fundamental tool of modern calculus variation and theoretical physics, including the law of conservation energy. [3] According to Noether’s theorem, the total amount of energy remains constant overtime in an isolated system. [3]
This means energy can either move within the system or be transformed to another type of energy.

In essence, the total amount of energy contained in an object is directly proportional to its mass. As the energy extracted from a matter, the mass of the system does not change as the transformation process takes place. Nevertheless, there may exist mechanistic limits of how much of the matter in an object may be transformed into types of energy or work on another system. This process of matter-transfer applies towards several types of energy, such as Electromagnetic energy, Kinetic energy, and Thermal energy. However, there are certain types of energy can be stored in a system without the presence of a matter, such as potential energy. Thermodynamics property, entropy, is best describing this transformation process by determining the amount of useful work available as energy transformed. [4] Thus, the attempt to extract the most useful work out of an energy source has always been the goal of humanity.

The effort of utilizing energies has become the essence of civilization development in the history of humanity. [5] It has been proved from time to time that the growth of energy technology is directly correlated to economic growth of a society. In early ages, wood has been the primary source of energy in ancient society in order to survive. The discovery of oil was not recorded until few centuries later at the banks of Euphrates Rivers, which marked the beginning of fossil fuel usage in human history. [6] Oil usage dated roughly 5000-6000 years back since the ancient Sumerians, Assyrians, and Babylonians. Coal, the next oldest fossil fuel used, has been around in China for
almost 3000 years. [6] The other well-utilized fossil fuel, natural gas, was discovered from Baku region (Azerbaijan), Iran around 6000-2000 years ago. [6]

In US modern society, Energy Information Administration (EIA) has categorized energy usage can into four sectors described in Figure 2.1.

![Figure 2.1 US Energy Consumption by Sector, 2009.][10]

According to Figure 2.1 also, EIA’s 2009 data showed that electricity held a significant role as an energy source in the three consumption sectors, excluding transportation. Not only electricity was popular due to its ability to be transmitted, but the technology has also grown towards electricity usage as the source of its power. The growth started as batteries, and eventually discovering electromagnetic induction. With electromagnetic induction, transmission of electricity became significantly less complicated. The use of copper wires, the greatest conductor material, enables electricity transfer from miles away with small loss. The development of electric motors further revolutionized the transmission of power.[18]
In 2009, British Petroleum (BP) collected sets of data recording the summary of energy usage in the world up until 2008.\[9\] From 1990 to 2008, electric generation has increased significantly by 170.26 percent. Even with the current growth rate of electric generation, as much as one thirds of world’s population does not have electricity. Considering the population growth rate and advancement of technology, demand of electricity is predicted to grow in an even faster rate.\[11\]

During recent industrialization period, electricity demand was massively supplied to the usage of fossil fuel. Fossil fuel was found to have high energy per weight ratio, which causes this vast usage of this source.\[5\] Since the discovery, fossil fuel has been consumed immensely in order to fulfill the rapid growth of energy demand. Figure 2.2 shows the world energy consumption growth from 1965 until 2008. The total energy consumed by the society increased by 348.2 percent compared to those back in 1965, with fossil fuels supplied most of the consumed energy portion.\[9\]
2.2 Fossil Fuel

Coals, oil, and natural gas, are materials considered as fossil fuels. The terminology of fossil fuels is used due to the total amount of time required to reproduce this energy source. The development process of fossil fuels requires over hundred millions of years.[1] In essence, fossil fuels are combustible animals and vegetations which remains buried underground and went through decomposition process without the presence of air. Hundreds millions of year ago, earth was filled with swamps, huge trees, and big leafy plants. These plants are the main component that forms the fossil fuel. The dead plants sank into the swamps creating spongy layers, called *peat*, covered with clay,
sand, and various materials. Over the time, sedimentary layers were formed and press
down the peat. Over hundreds millions of years the peat will form the fossil fuels that
exist today.[1]

The nature of reproduction time of fossil fuel made the energy source categorized
as non-sustainable (non-renewable). Considering fossil fuel rate of use, the resource
depletes faster than it is reformed. Figure 2.3 describes different reproduction rate of
energy sources available.

![Figure 2.3 Recovery rate of Energy Sources.[5]](image)

Considering the process required and the reproduction rate of fossil fuel, it is near
impossible for this energy resource to be renewed. As mentioned in previous sub-chapter,
the rapid industrial development requires more fossil fuel to be extracted. Figure 2.4
shows the trend of world oil production over the last 60 years.
According to the graph in Figure 2.4, the growth of oil production has reached plateau for the last several years. The data implies depletion in oil reserves, since the demand is higher than the ability to produce oil. Furthermore, the depletion rate increases quite fast in the last several years. Similar behavior was also observed in the other two fossil fuel sources: natural gas and coal. In 2002, Colorado River Commission of Nevada made estimation on the issue of fossil fuel usage.[11]
<table>
<thead>
<tr>
<th>Global Fossil Fuel Reserves</th>
<th></th>
<th>Natural Gas</th>
<th>Coal</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Petroleum</td>
<td>(Billion Barrels)</td>
<td>(Trillion Cubic Feet)</td>
</tr>
<tr>
<td>World Reserves (Jan 1, 2000)</td>
<td>1,017</td>
<td>5,150</td>
<td>1089*</td>
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<tr>
<td>World Potential Reserves Growth</td>
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<td>3,660</td>
<td>--</td>
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<tr>
<td>World undiscovered Potential</td>
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<td>--</td>
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<tr>
<td>YEARS OF RESERVES LEFT**</td>
<td>98</td>
<td>166</td>
<td>230</td>
</tr>
</tbody>
</table>

**Based on current levels of consumption and estimated total

*World Estimated Recoverable Coal

Table 2.1 World Fossil Fuel (Petroleum, Natural Gas, Coal) Assessment.[11]

Table 2.1 shows estimation on rate of production to consumption of fossil fuels reserves. The data was collected from U.S. Geological Survey of 2000 and Department of Energy International Energy Annual report in 1999. The estimation was made under the assumption that the consumption rate would remain constant as it was in 1999. Based on the estimation, they believe that all fossil fuels will be completely depleted by 2230, while oil reserves will all be consumed around 2100. However, several other studies indicated that the oil reserves come near to its end between 2050 and 2075.[11]

The reason that fossil fuels have a tremendous energy per unit weight property is due to hydrocarbon elements. These elements are mostly found in coal, and some in
many other fossil fuels. As a result, combusting fossil fuels produce Redox reaction resulting carbon dioxide and water. The great property of fossil fuel enables the development of large-scale industry. While this remains an attractive feature, fossil fuels usage also comes with its own price – particularly to the environment.

2.3 Global Warming

Global warming refers to the increase in average temperature of Earth’s surface. This process is caused by the increasing amount of greenhouse gas that builds up in the atmosphere, accelerating the greenhouse effect. Burning fossil fuels contributes a significant amount of carbon dioxide, one of the greenhouse gases. Many researchers also found this as the number one source of carbon dioxide production in modern culture. With the increase of carbon dioxide production, global warming process is accelerated.

2.3.1 Greenhouse Effect

Naturally, Earth makes use of greenhouse effect as one ways to maintain its temperature to be warm and livable for human being, which is accomplished by the greenhouse gasses exist in the atmosphere.
Figure 2.5 illustrates the overall process of greenhouse phenomenon. The process started as the heat radiation from the sun will be partly absorbed and partly reflected, both by the Earth and its atmosphere, back to outer space. Most of the Sun’s radiation, however, is absorbed by the earth’s surface and warms it. This radiation then will be re-emitted in all direction towards the outer space. The greenhouse gases then will trap this re-emitted infrared radiation, maintaining the temperature of the Earth at 60 degree of Fahrenheit.[7]

The greenhouse gasses are essentially gasses that exist in the atmosphere that have the capability to trap and emit heat. The most common greenhouse gases are water vapor, carbon dioxide, methane, nitrous oxide, and ozone. In regards to water vapor and carbon dioxide production is inevitable. This means, naturally, the Earth itself enhances
the greenhouse effect. However, some greenhouse gasses production is multiplied with the increasing usage of fossil fuels. Thus, further boosting the greenhouse phenomenon. Those affected greenhouse gases are:[8]

1. **Carbon Dioxide (CO₂)**: formed through combustion process of fossil fuels, solid waste, and wood products. Photosynthesis process of plants can reduce carbon dioxide.

2. **Methane (CH₄)**: formed through the production and transportation process of oil, coal, and natural gas. Agriculture, farms, and non-organic solid waste can also produce methane.

3. **Nitrous Oxide (N₂O)**: emitted through burning fossil fuels, agricultural, and industrial processes.

4. **Fluorinated gases**: industrial processes produce several strong greenhouse gases such as, hydrofluorocarbon, perfluorocarbons, and sulfur hexafluoride.

The Intergovernmental Panel on Climate Change’s (IPCC) report in 2007 (Figure 2.6) shows a drastic increase in carbon dioxide and methane concentration in the atmosphere for the past 50 years.
Figure 2.6 Atmospheric Concentration of Carbon Dioxide (in parts per million) and Methane (in parts per billion).

This extreme increase in CO2 and Methane causes an exponential rate of growth in temperature for the last 50 years. Over the past century itself, the average warming of the earth is around 1.3 degree Fahrenheit, shown in Figure 2.7. Even according to IPCC, during the last 30 years the rate of global warming has been three times as much as the warming rate for the past 100 years.[7] At this emission rate or more, the condition of the Earth’s climate will increase by 3 to 7 degree Fahrenheit steadily by 2100 and even greater warming afterwards.
Figure 2.7 Annual global surface temperature anomalies average from 1880 to 2007.[7]

Although such small temperature increase may seem insignificant, it will pose some serious effects in the long run. Earth’s water cycle, for instance, will be greatly affected by the phenomenon. Temperature increase causes more evaporation on the earth surface, resulting to more storms to be formed and dry the land even more. This will not only lead to more heat wave and cold snaps in certain area, but it will also increase floods occurrences in some area.[7]

However, the most concerning factor of global warming is the melting process of the polar ice sheets. Considering the vast volume of ice sheets, 1-2 degree of Fahrenheit will melt the ice sheets and increases the sea level quite significantly. The surface of these sea ices is responsible for reflecting back the sun and absorbs the heat on the darker region. Thus, it will maintain the climate for the wildlife exists there. Unlike floods that are temporary, the rise of sea level will be permanent. This poses a potential risk of environmental hazard that can harm the habitats and the cultures living inside.
Without the warming itself, IPCC predicted the sea level to increase from 6 inches to as much as 2 feet during this 21st century. With a significant ice sheet melts, the sea level can increase by 16 to 20 feet. Figure 2.8 shows IPCC’s prediction towards sea level in the next 90 years span. It shows a rapid increase of sea level trend from 1870 to 2009.

![Figure 2.8 Post and projected global sea level. [7]](image)

Furthermore, this rapid global temperature increase can be severe to the Earth itself and its inhabitants. The temperature increase worsens pollution like ozone and smog, which causes higher respiratory problems for younger children and older people. In addition, extinction problem can be a risk for several species, with low adaptation capability. Moreover, energy usage will be increased with the necessity of cooling down the temperature. This leads to an endless cycle of further fossil fuel that causes global warming.
2.4 Renewable Energy (Wind Energy)

With the growing awareness of global warming, energy experts increasingly promote the usage of clean and sustainable energy. In recent years, the society demand has gradually shifted towards clean and renewable energy. Those popular renewable sources are wind, sea, sun, biomass, etc.

According to the data collected by Ren21 in 2009, renewable sources contributed 16% of the global final energy consumption. The leading contributor was biomass with 10% followed by hydropower with 3.4%. Among all renewables, wind power capacity increased the most in 2010 with 39 GW. The total capacity is increased by 24% compared to that in 2009. [16] In the span of 10 years also, wind power experienced the most growth compared to other renewable sources.

![Figure 2.9 Global Cumulative Installed Wind Capacity 1996-2011. [17]](image)

Estimated from figure 2.9, wind energy is growing at the rate of 30% per year. A total of 238 GW wind power systems were installed by the end of 2011. Excluding hydropower, wind energy possessed the largest renewable capacities installed in the world. The growth
of this technology is determined mainly by China adding 50% of the total global installed wind power capacity in 2010.[16]

2.4.1 Advantage and Disadvantage of Wind Energy

The very essence of wind energy itself is pollution-free and inexhaustible energy source. Pollution-free means that in the process of converting the raw wind into usable energy, the system does not emit anything considered as pollution. As an energy source, wind energy is free and does not affected by the inflation of fuel cost. [10] Furthermore, wind farm is one of the fastest power systems to be built, compared to 8-10 years of nuclear power plant. [14] On top of that, the payback period of a wind farm can be as low as 6 to 8 months if placed in the right location. [19] With the cost of wind energy has come down by 85% from 20 years back, about 7 cents per kilowatt-hour. This price is comparable to those produced by coal or gas-fired power plants. Moreover, additional income for farmers from wind farms land leases and creating jobs vacancy will help the economy of a country. [19]

The drawback, however, wind occurrence is intermittent, almost close to unpredictable. This erratic behavior made wind power to be less desirable by the utility. This may cause voltage instability in weaker grids, due to rapid and reoccurring changes. In addition, wind turbine installation requires landscape altering. This leads to oppositions due to cultural reason or unique landscape condition. Furthermore, large tracts of land needed to generate large amount of electricity. For 100,000 MW wind farm, approximately 10,000 acres are needed. However, as the forecasting technology developed, the intermittent nature of wind is compensated. As the awareness to use clean
energy increases, less opposition has been given by the society towards the wind turbine.

2.4.2 Wind Power System Structure

Wind energy is extracted by using wind turbines. The turbines harnessed the kinetic energy from the wind and transformed it into rotational energy. Turbines technology has existed for several thousand of years, but only modernized in the last 50 years. Two different turbine types, VAWT (Vertical-Axis Wind Turbine) and HAWT (Horizontal-Axis Wind Turbine), have been developed. For wind turbine application, HAWT types are preferred.

The construction of Clipper Liberty wind turbine is used as an example to examine the system. The overall structure of the turbine is shown in Figure 2.10.

![Figure 2.10 Overall diagram of Clipper Liberty wind turbine structure.][15]
The top structure of the tower referred as *nacelle*. The *nacelle* itself consists of several important components of a wind turbine, including the generator. PCU (Pitch Control Unit) is the one responsible for controlling the pitch of the blade. In addition, 3-battery back-up unit installed serves as the emergency power supply for the hub should the system is down or there is no power supplied. This is essential to prevent the turbine from going out of control in unexpected conditions. To match the operating condition, these battery units designed to be robust towards highly vibrated environment and cold weather operations. [15]

The Clipper Liberty wind turbine is designed to have 2.5 MW power rating, with blades rotor diameter vary from 89 to 99 meter. The rotating blades are connected to drive shaft used to excite the generators intermediated with DGD (Distributed Generator Drive-train), a controller used for high torque low RPM wind turbine application. The drive-train has one input shaft and four high speed output shafts connected to the generators. Different to commercially available gearboxes, Clipper Liberty’s drive-train can split the load by a factor of 16, which is a significant advantage. This wind turbine uses slip rings application. Due to Yaw, connection from PCU and hub cannot be made with cables, thus slip ring used for all electrical communications. The slip ring also used for lightning protection and to distribute power to charge the pitch battery. On top of that, the system also installed with disk brake used to lock the blade in place. [15]

Clipper Liberty uses 4 independent permanent magnet generators for its turbine generation. Each Neodymium Iron Boron (Ne-Fe-B) generator rated at 660 kW at 1133 RPM. It has a low short-circuit current capacity and provides additional 3 to 4% more
efficiency than conventional doubly fed or wound rotor induction machines. These
generators are interconnected together to produce up to 2.5 MW electricity. The system is
initially derived its power from the grid to reach a certain RPM before it transitioned to
be self-powered. The power produced by the generator is converted to DC, distributed to
the bottom of the tower through bus bars, and inverted back to AC to be supplied to the
utility system. [15]

TCU (Turbine Control Unit) operates most of the major functions of the turbine
system. The main responsibility of this unit is to control the torque and the turbine speed.
Other than that, TCU also controls the Yaw, brake, motor, and fan. The yaw adjusts the
wind turbine to point to the wind flow. TCU also responsible for fault clearance, sensor
interface of the system, also act as tower vibration damping. [15]

The latest wind turbine technology developed by Clipper Liberty uses 80m hub
height steel tube tower. The tower itself divided into four steel tubular sections, also
known as ‘cans’, and assembled with bolted flanges. The bottom structure has 4.4m in
diameter and getting smaller and more flexible as the tower gets higher. Inside the tower,
cables are installed to carry the rectified current produced by the generators to the bus
bars and distributed down. The usage of bus bars is mainly due to its efficiency compared
to cables. [15]

At the bottom of the tower, GCU (Generator Control Units) received the rectified
current and invert it back to AC signal. IGBT-based inverters are used dedicated for each
generator. GCU also filters the controls 3rd and 5th harmonics of the signal to control the
resonance condition of the system. This particular function makes GCU holds the responsibility of controlling the currents. [15]

From the GCU, power is distributed by PDP (Power Distribution System). PDP ties all 4 inverters together and provides electrical protection for both the GCU and the entire wind turbine system. PDP dedicates a small portion of the produced power to maintain the turbine operation, while the rest goes to the utility system. The PDP unit also provides revenue metering and power quality metering. Before connected to the utilities, Pad Mounted Transformer step up the voltage from .69kV to 34.5kV. [15]

Safety operations, such as E-Stop, installed to the system, in case of unpredictable disruption occur. On top of that, turbine safety-loop system is implemented to protect the turbine from TCU, pitch system, or mechanical system failure. Lightning protection is crucial; due to the high risk of blades being struck. The blades are installed with 4 receptors connected to copper blade cap and conductors connected to blade main bearing lightning brushes. In addition, the nacelle also equipped with lightning rod. Double shielding for sensor wiring is performed. Finally, earth ground system, consisting of four 30-foot ground rods, copper ring, and interconnection with other turbines, is installed. [15]

2.4.3 Wind Power Calculation

Conventional wind turbine exploits HAWT type tubines in order to harness wind power. The generator embedded in the turbines extract kinetic energy contained in wind flows converts them to electrical power. Derived from kinetic energy equation, the wind
power amount per unit area is \( \frac{1}{2} \rho V^3 \). The cross-sectional area of wind turbine’s rotor \((\pi R^2)\) is used. [13]

\[
P = \frac{1}{2} \rho V^3 \quad (2.1)
\]

From wind power Equation 2.1, power coefficient representing performance of the wind turbine can be calculated. This power coefficient serves as a measure system in designing wind turbine’s rotor blades. Equation 2.2 describes the power coefficient components. [13]

\[
C_p = \frac{P}{\frac{1}{2} \rho V^3 A}
\quad (2.2)
\]

In essence, \( C_p \) can be understood as

\[
C_p = \frac{\text{Electricity produced by the wind turbines}}{\text{Total energy available in the wind}}
\]

In a perfect condition, where wind turbines have 100 percent efficiency, the rotor has to stop 100 percent of the wind. In order to achieve this goal, a stagnant solid disk rotor is required, from which no kinetic energy will be converted. [20] Applying Froude’s Momentum Theory to the system allows to find the ideal power of the turbine. Froude’s Momentum Theory model, also known as Actuator Disk Theory, assumes a 1-D analysis of an infinitely thin disk with area, \( A \), resulting in no resistance towards the air passing through. Another assumption on an even distribution of loading throughout the blade is made. This assumption refers to ignore viscous effect and compressibility of the blade. The reduced power coefficient factor is,

\[
C_p = 4(1 - a)^2 a
\]
Where,

\[ a = \text{factor accounting for the deceleration of wind through windmill rotor.} \]

Although ideal power equation theoretically can be achieved, however, the efficiency of wind power extracted by the turbines is not 100 percent. According to Betz’s law, a theory named after a German physicist Albert Betz in 1919, there is a limit to the maximum possible energy derived from a hydraulic wind engine, known as Betz’s limit. Betz limit stated that no more than 59 percent of the kinetic energy, contained in a steam tube that shares the same cross section as the disc, can be converted to useful work by the disc. The schematic of fluid flow (Figure 2.11) helps to contextualize the statement. Betz limit, that defines the magnitude of power coefficient, is known as Betz’s coefficient. [13]

![Figure 2.11 Schematic of fluid flow through a disk-shaped actuator.][13]

From conservation of momentum law, Betz proved the maximum power obtained at \( a = \frac{1}{3} \). This is achieved through taking derivative of the reduced power coefficient equation with respect to \( a \). And at maximum power, ideal power coefficient is \( 16/27 = 0.593 \). This shows that even in an ideal condition, windmill can only extract roughly 60% of the total power available. Furthermore, electricity transformation has a roughly 70%
efficiency. Applying the 70% efficiency of electric transformation brings down the $C_p$ to 41%. Wind turbine is considered good, in which power coefficient ranging from 35%-45%. [20]

The power coefficient $C_p(\lambda, \beta)$ itself is a function of the blade’s tip speed ratio $\lambda$ and the blade’s pitch angle $\beta$. In order to find the maximum power point at a certain wind speed, $\beta$ is set to zero. The tip speed ratio equation is given by.[20]

$$\lambda = \frac{\omega_r R}{v_w}$$

Where $\omega_r$ is the angular speed of the turbine, $R$ is the turbine radius, and $v_w$ is the velocity/speed of the wind. From this equation, the dynamic characteristic of the wind can be derived to be. [20]

$$\frac{d\omega_r}{dt} = \left(\frac{1}{J}\right) [T_m - T_L - F\omega_r]$$

The $J$ is the equivalent inertia of the system, $T_m$ is the torque developed by the wind turbine, $T_L$ is the generator torque or considered as a load in this system, and is the viscous friction coefficient. The target optimum power from a wind turbine is written as

$$P_{max} = K_{opt} \omega_{r_{opt}}^3$$

With

$$K_{opt} = \frac{0.5\pi \rho C_{p_{max}} R^5}{\lambda_{opt}^3}$$

$$\omega_{opt} = \frac{\lambda_{opt} v_w}{R}$$

(2.3)

Figure 2.12 shows the relation of turbine mechanical powers as a function of rotor speed in various wind speeds.
In order to achieve a maximum power at a certain wind speed, the turbine has to operate in an optimal rotor speed $\omega_{opt}$. From Equation 2.3, it is shown that the optimal rotor speed is directly proportional to the optimal tip speed ratio $\lambda_{opt}$. Thus, maintaining the turbine to operate at the optimal rotor speed is the desired.[20] The control system describes in Chapter 4 will maintain the rotor to operate at this desired speed.
CHAPTER 3

WIND TURBINE GENERATORS (PERMANENT MAGNET SYNCHRONOUS GENERATOR)

To extract the energy contained in the wind, wind turbines are needed to convert flowing air into electricity. For wind turbine application, any conventional three-phase generator will be able to serve this purpose. On top of the generator, power electronics used to manipulate the generated electricity to produce grid-compatible current. Throughout the years, researchers focusing on generators advancement, utilizing new technology for wind turbine application.

The generators discussed in this paper are classified into two types: asynchronous generator and synchronous generator. Asynchronous (induction) generators are compared with synchronous generators to evaluate the strengths and weaknesses of each generator in the light of wind turbine application. The asynchronous generator discussed includes Squirrel Cage Induction Generator and Doubly Fed Induction Generator. An in-depth study of Permanent Magnet Synchronous Generator is also done throughout the chapter. [23]
3.1 Squirrel Cage Induction Generators (SCIG)

Squirrel Cage Induction Generator (SCIG) is used for a fixed-speed wind turbine generator. The speed of an SCIG does not change more than a few percent, which mainly due to the generator slip caused by wind speed changes. This unique characteristic allows SCIG to provide robustness and stability to the system. On top of that, the structure of SCIG gives the mechanical simplicity to the turbine. However, Squirrel Cage Induction Generator required a gearbox to connect to the turbine and configured to be directly coupled to the grid. [23]

Wind turbines based on SCIG are typically equipped with soft-starter mechanism and installation for reactive power compensation. Similar to other induction generators, SCIG requires reactive magnetizing current. The reactive power has to be supplied either from the grid or power electronic system. Connecting the generator directly to the grid will allow the generator to derive the reactive power directly from the grid. However, this means that the fluctuation of wind the generator experience will directly transmitted to the grid. The steep torque characteristic of SCIG made the transients critical to the grid. The in-rush current of the generator can increase up to 7-8 times of the rated current. In weak grids, SCIG can cause severe voltage disturbances, therefore soft-starter mechanism is required. [23]

In general, SCIG presents robustness and stability to wind power system at normal operating condition. However, the magnetizing current, which is supplied from the grid, made the power factor of SCIG to be low at full load. This means SCIG requires
more reactive power from the grid in order to produce more active power. The amount of reactive power required by the generator then depends on the wind. [23]

In order to compensate this behavior, reactive power can be supplied from the grid or capacitors can be connected parallel to the generator. Despite of the approach, the electrical transients still become problematic towards the system. Without reactive power compensation, SCIG will cause instability to the grid voltage. When fault occurs, for instance, the wind turbine may speed up causing imbalance between electrical and mechanical torque. This means that when the fault clears, SCIG will draw a significant amount of reactive power from the grid, which leads to a further decrease voltage. [23]

3.2 Doubly Fed Induction Generators (DFIG)

Doubly Fed Induction Generator (DFIG) is the other type of induction generator that utilizes wound rotor, which windings mounted to a bidirectional back-to-back voltage converter. On top of that, DFIG stator windings are directly connected to the grid. The unique characteristic that differentiates DFIG with other induction machines is the ability to apply different voltages to its stator and rotor. In DFIG, the grid determines stator voltages and power converter externally induces rotor voltage. When there is a difference between mechanical and electrical frequency, the converter will inject rotor current to the system. The power converter of DFIG holds a critical role in the system, both in normal condition and fault condition. With this capability, DFIG can operate in a wide range of speed operation. [23]

The DFIG utilizes two power converters one on the rotor-side and the other on the grid-side and they are controlled independently. The rotor-side converter controls the
rotor current adjusting the active and reactive power. And the grid-side converter controls the DC-link voltage and maintains the converter to operate at unity power factor. In different operating conditions, power is either fed into or drove out of the rotor. In sub-synchronous condition, power flows into the rotor from the grid through the converter and vice versa in over-synchronous condition. In the stator, however, the power is fed to the grid in both conditions. [23]

The advantage of using DFIG is to have the ability to decouple active and reactive power control by controlling the rotor excitation current. DFIG also has the capability to control reactive power due to the presence of power converter that allows DFIG to be magnetized from rotor circuit on top of the grid. Moreover, DFIG is able to generate reactive power by itself, which then delivered through the grid-side converter to the stator. In normal operating condition where the grid-side converter operates in unity power factor, there is no reactive power exchange between the turbine and the grid. However, in weak grid, DFIG may supply and absorb reactive power in order to maintain voltage stability. Evidently, there has been a disadvantage of using DFIG, which is the necessity of slip rings. This will not only lead to maintenance problem, but also more cost in the long run. [23]

3.3 Permanent Magnet Synchronous Generator (PMSG)

Fundamentally, synchronous generator is much more complex than induction generator, and the cost of a synchronous generator is more expensive for a same size generator. However, one advantage of synchronous generator is that it does not required reactive magnetizing current in order to operate correctly. Instead, the magnetic field can
be generated from permanent magnet of the rotor. For wind turbine application, synchronous generator can be directly driven without gearbox with appropriate number of poles. Thus, despite of the cost and complexity, synchronous generator is desirable for wind turbine generator. [23]

The usage of Permanent Magnet Synchronous Generator (PMSG) for wind turbine generator has grown due to its self-excitation property. This characteristic allows PMSG to operate in high efficiency and high power factor. In essence, Permanent Magnet Synchronous Generator (PMSG) is a DC machine, whose rotor circuits replaced by permanent magnets. By substituting the rotor circuit, the structure of PMSM is significantly simplified. The DC supply, which requires for creating rotor flux, is no longer necessary. As a result, the size of Permanent Magnet Synchronous Machine is much smaller compared to DC machine. With smaller size, PMSM will have a higher moment of inertia, which means better reliability and higher power-to-size ratio. On top of that, brushes and slip rings will also be removed from the structure, which leads to less maintenance requirements. Thus, PMSG can generate power in any speed, even in low wind speed. [23]

The setup of PMSG, however, requires a full-scale power converter in order to control the voltage and frequency of the generated electricity. The usage of full-scale power converter adds the cost of PMSG application on top of the expensive permanent magnets. Other than that, magnetic materials of PMSG are also very prone to temperature variance. A significant increase in temperature, usually occur during faults, may lose its magnetic qualities. On top of that, during transients such as, machine starting,
synchronization, and voltage regulation, PMSG is incapable of providing steady voltage, which may lead to problems. The synchronous nature of the generator causes a stiff behavior in the case of an external short circuit, and if the wind speed is unsteady. [23]

For wind turbine application, small generator with high power-to-size ratio is demanded. A regular induction machines would not be a good choice because not only it has a bigger size, but it also requires quite a lot of maintenance. In induction machines, brushes and slip rings need to be replaced regularly. In wind turbine, where generators placed around hundreds of feet above the ground, maintenance is costly. By using permanent magnets instead of field windings, the PMSG does not require brush or slip rings. [22][24] This way PMSG satisfies the low maintenance requirement. The emergence of variable frequency power converter and microprocessor controller, PMSG can be designed to operate efficiently for Wind Turbine application. On top of that, PMSG can also be designed to have high power-to-size ratio by selecting powerful permanent magnets as the core of the rotor. As mentioned before, power density of PMSG is higher than that of induction machine at the same rating, due to no stator power dedicated for magnetizing current. Thus, PMSG application towards wind turbine is desirable. This chapter introduces the operation of PMSG describing a Permanent Magnet Synchronous Machine model for better understanding of its operation. [23] [24]

3.3.1 Basic Operation of Permanent Magnet Synchronous Machine
A typical two-pole three-phase PMSM is shown in Figure 3.1 above. The $as$, $bs$, and $cs$ axes are the stationary windings of the stator. The $as$-axis is obtained by applying the Right Hand Rule to $as$ and $as'$ windings. Respectively, the $bs$-axis and $cs$-axis are obtained using the same method. The cross-section representation of the current in the windings is viewed as a solid or crossed circle. In the picture, the $as$, $bs$, and $cs$ windings are pictured as crossed circles, which means that there is positive current flowing into the paper. On the contrary, the $as'$, $bs'$, and $cs'$ windings are pictured as solid circles depicting positive current going out of the paper. For analysis purposes, two additional axes are assigned in dealing with PMSM. $d$-axis is assigned to align with the north pole of the rotor’s permanent magnet and additional $q$-axis to be 90° ahead of the rotation. As the direction of the rotation is counterclockwise in the picture, the $q$-axis is 90°
counterclockwise ahead of the d-axis. The rotor speed of the PMSM is defined in angular velocity $\omega_r$. The rotor angle from the a-axis to the d-axis is indicated by $\theta_r$. The electromagnetic torque produced ($T_e$) is in the direction of increasing $\theta_r$ and the load torque ($T_L$) is in the other direction opposing $\theta_r$. This means that the electromagnetic torque produced is positive when the PMSM acts as a motor and negative when the machine acts as a generator. [24]

### 3.3.1 Voltage Equation of PMSM

Voltage equations for a regular two-pole three-phase PMSM, depicted in Figure 1, are derived into equations shown below. The voltage equations below, however, are derived from a round-rotor machine instead of salient-pole machine. [24]

\[
v_{as} = r_s i_{as} + \frac{d\lambda_{as}}{dt} \tag{3.1}
\]

\[
v_{bs} = r_s i_{bs} + \frac{d\lambda_{bs}}{dt} \tag{3.2}
\]

\[
v_{cs} = r_s i_{cs} + \frac{d\lambda_{cs}}{dt} \tag{3.3}
\]

The matrix form of these three equations is

\[
V_{abc} = R_s I_{abc} + p\lambda_{abc} \tag{3.4}
\]

Where,

\[
R_s = \begin{bmatrix}
r_s & 0 & 0 \\
0 & r_s & 0 \\
0 & 0 & r_s
\end{bmatrix} \tag{3.5}
\]

The voltages, currents, and flux linkage of Equation 2.4 can be represented in matrix form as shown below. This way the three voltage equations for three phases can be shortly written. [24]
\[(F_{abc})^T = [f_{as} f_{bs} f_{cs}]\]  \hspace{1cm} (3.6)

### 3.3.2 Flux Linkage Equation of PMSM

Similarly, flux linkage equations of this particular PMSM shown in Figure 3.1 are expressed as follows

\[
\lambda_{as} = L_{asas}i_{as} + L_{asbs}i_{bs} + L_{ascscs}i_{cs} + \lambda_{asm} \tag{3.7}
\]

\[
\lambda_{bs} = L_{bsas}i_{as} + L_{bsbs}i_{bs} + L_{bscs}i_{cs} + \lambda_{bsm} \tag{3.8}
\]

\[
\lambda_{cs} = L_{csas}i_{as} + L_{csbs}i_{bs} + L_{cscs}i_{cs} + \lambda_{csm} \tag{3.9}
\]

And the matrix representation of the flux linkage equations is

\[
\lambda_{abc} = L_S i_{abc} + \lambda'_m \tag{3.10}
\]

The fluxes \(\lambda_{asm}, \lambda_{bsm}, \) and \(\lambda_{csm}\) are the flux linkages, which were created as the permanent magnet sweeps over the \(as, bs,\) and \(cs\) windings. And, \(\lambda'_m\) is the matrix representation of these fluxes. Also, \(\lambda'_m\) is dependent to the position of the rotor or rotor angle \(\theta_r.\) [24]

\[
\lambda'_m = \begin{bmatrix}
\lambda_{asm} \\
\lambda_{bsm} \\
\lambda_{csm}
\end{bmatrix}
= \lambda'_m
\begin{bmatrix}
\sin \theta_r \\
\sin \left(\theta_r - \frac{2\pi}{3}\right) \\
\sin \left(\theta_r + \frac{2\pi}{3}\right)
\end{bmatrix} \tag{3.11}
\]

In the equation above, the magnitude of the permanent magnet’s flux linkage is represented by \(\lambda'_m.\) And the inductance matrix \(L_S\) are expressed as

\[
L_S = \begin{bmatrix}
L_{ts} + L_{ms} & \frac{1}{2} L_{ms} & \frac{1}{2} L_{ms} \\
-\frac{1}{2} L_{ms} & L_{ts} + L_{ms} & -\frac{1}{2} L_{ms} \\
\frac{1}{2} L_{ms} & -\frac{1}{2} L_{ms} & L_{ts} + L_{ms}
\end{bmatrix} \tag{3.12}
\]

Analyzing the matrix, the diagonal terms represent the inductances of the stator of each phase. This inductance consists of leakage inductance \(L_{ts}\) and magnetizing
inductance $L_{ms}$. Other terms in the matrix form represent the inductances caused by flux linkage from the other two phases. The displacement of assumed balance system causes these inductances to be $-\frac{1}{2} L_{ms}$, because each phase is displaced by 120° of the other ($\cos 120°$). [24]

3.3.3 Electromagnetic Torque of PMSM

With linearity assumption, electromagnetic torque of PMSM can be derived from the partial derivative of the co energy calculation. The electromagnetic torque then can be expressed as follows. [24]

$$T_e = \frac{p}{2} J_m \left[ (i_a - \frac{1}{2} i_b - \frac{1}{2} i_c) \cos \theta_r + \frac{\sqrt{3}}{2} (i_b - i_c) \sin \theta_r \right]$$  \hspace{1cm} (3.13)

In general, the sign representation of the electromagnetic torque is positive for motor action and negative for generator action. Knowing the electromagnetic torque $T_e$ equation, the speed of the rotor $\omega_r$ can be found through the motion equation of the machine. The equation is shown below

$$T_e = J \left( \frac{2}{P} \right) \frac{d\omega_r}{dt} + B_m \left( \frac{2}{P} \right) \omega_r + T_L$$  \hspace{1cm} (3.14)

Where $T_L$ is the load torque, $P$ is the number of pole of the rotor, $J$ is the moment of inertia, and $B_m$ to be the damping coefficient, such as friction. From solving the differential equation above, the speed of the rotor $\omega_r$ can be obtained. [24]

3.3.4 Reference Frame Theory

The study of electric machine is tightly dependent upon the reference frame theory. This theory simplifies all the major variables of an electric machine like voltage, current, flux, etc. The reference frame theory uses change of variables method to change
the reference from one reference frame to another. The purpose of applying this theory is to eliminate the time-varying inductances by transforming the variables, both of the stator and rotor, to a frame, which may rotate at any angular velocity or remain stationary. This arbitrary reference frame can be set to rotate in any the angular velocity. The two arbitrary reference axes are denoted by direct \((d)\) and quadrature \((q)\). The two axes are perpendicular towards each other and rotating in the same angular velocity \(\omega\). Reference frames, such as stationary, synchronously rotating, and rotor reference frame are all derived from this arbitrary reference frame by assigning different angular velocity for different frames. [24]

![Figure 3.11 Transformation of the Stationary Circuits to an Arbitrary Reference Frame](image)

**Figure 3.11 Transformation of the Stationary Circuits to an Arbitrary Reference Frame [24]**
The following describes a typical three-phase variables transformation from stationary circuits to an arbitrary reference frame as shown in Figure 3.2. The equation can be written as,

\[ f_{qd0s} = K_s f_{abcs} \]  \hspace{1cm} (3.15)

With

\[ (f_{qd0s})^T = [f_{qs} \ f_{ds} \ f_{0s}] \]

\[ (f_{abcs})^T = [f_{as} \ f_{bs} \ f_{cs}] \]

And

\[
K_s = \frac{2}{3} \begin{bmatrix}
\cos \theta_r & \cos \left( \theta_r - \frac{2\pi}{3} \right) & \cos \left( \theta_r + \frac{2\pi}{3} \right) \\
\sin \theta_r & \sin \left( \theta_r - \frac{2\pi}{3} \right) & \sin \left( \theta_r + \frac{2\pi}{3} \right) \\
\frac{1}{2} & \frac{1}{2} & \frac{1}{2}
\end{bmatrix} \]  \hspace{1cm} (3.16)

In this transformation, \( \theta \) in \( K_s \) is the angle produced by the integration of the angular velocity of the reference frame \( \omega \)

\[ \theta = \int_0^t \omega(\tau) \, d\tau + \theta(0) \]

The inverse transformation of equation 3.16 is:

\[
(K_s)^{-1} = \begin{bmatrix}
\cos \theta_r & \sin \theta_r & 1 \\
\cos \left( \theta_r - \frac{2\pi}{3} \right) & \sin \left( \theta_r - \frac{2\pi}{3} \right) & 1 \\
\cos \left( \theta_r + \frac{2\pi}{3} \right) & \sin \left( \theta_r + \frac{2\pi}{3} \right) & 1
\end{bmatrix} \]  \hspace{1cm} (3.17)

The transformation is basically trigonometric relations from one reference frame to another. There is nothing being reduced or added from the transformation. The arbitrary reference form is just another way to view the existing circuits. [24]
3.3.5 Commonly Used Reference Frame

Three commonly used reference frames are stationary, rotor, and synchronously rotating reference frames. As elaborated from the subsection before, the reference frames are differentiate from different value of angular velocity of the frame ($\omega$). Table 3.1 below shows the three commonly used reference frames. [24]

<table>
<thead>
<tr>
<th>Speed</th>
<th>Operation</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>Stationary circuit variables to stationary reference frame</td>
</tr>
<tr>
<td>$\omega_r$</td>
<td>Stationary circuit variables to rotor reference frame</td>
</tr>
<tr>
<td>$\omega_e$</td>
<td>Stationary circuit variables to synchronously rotating reference frame</td>
</tr>
</tbody>
</table>

Table 3.2 Commonly Used Reference Frame [24]

The Speed column states the speed of the reference frame and the Operation column describes the behavior of the reference frame. For instance, if the speed of the reference frame is 0, the stationary circuits are referred to the stationary reference frame, as shown in Figure 3.3. [24]
In this stationary reference frame, the transformation matrix $K_s$ is modified by setting $\theta$ equals to 0. $\theta$ is 0 because of the angular velocity of the frame $\omega$ is 0 and the initial $\theta(0)$ is also 0 in the transformation. This unique stationary reference frame is distinguished from others by adding superscript $s$ to transformation matrix representation. In this particular transformation, the transformation matrix $K_s^s$ is referred to the stationary reference frame application. The equation is given below. [24]

$$K_s^s = \frac{2}{3} \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & -\frac{1}{2}\sqrt{3} & \frac{1}{2}\sqrt{3} \end{bmatrix}$$  \hspace{1cm} (3.18)$$

In stationary reference frame, there are only two rows instead of three like transformation matrix to an arbitrary reference frame $K_s$. The third row if the transformation matrix
represents the 0 axis, which is not used due to balance set assumption. With the implementation of transformation matrix to equation below,

\[ f_{qds}^s = K_s f_{abcs} \]

Produce

\[ f_{qs}^s = f_{as} \quad (3.19) \]

\[ f_{ds}^s = -\frac{1}{\sqrt{3}}(f_{as} + 2f_{bs}) \quad (3.20) \]

Instead of using \( dq \)-axes like typical reference frame does, the stationary reference frame is usually represented in usual \( xy \)-axes. The purpose of this is to eliminate the confusion with the rotor or synchronously rotating reference frames as presented in Figure 3.4. In the stationary reference frame, \( f_{xs} \) is equal to \( f_{qs} \) and \( f_{ds} \) is negative of \( f_{ys} \). Therefore, the modified equation 3.19 and 3.20 can be rewritten as follows. [24]

Figure 3.13 Stationary Reference Frames Using xy Axis [24]
These equations will benefit in the rotor reference frame used for PMSM. It is not seldom to transform the stationary circuit variables into the $xy$ axis stationary reference frame first then use the position information $\theta_r$ to transform from the $xy$ axis frame to the reference frame fixed in the rotor. [24]

### 3.3.6 Rotor Reference Frame in PMSM

In order to further analyze the machine, reference frame theory will be used to simplify the analysis. Reference frame theory explains how to change the stationary circuits from stationary reference frame ($abc$ frame) to rotor reference frame. In dealing with PMSM, the rotor reference frame is the same as synchronously rotating reference frame. This condition only applies to synchronous machines, since the machine operates at synchronous speed, which means rotor’s angular speed is equal to that of the rotating stator flux. [24]

As mentioned before, the purpose of using reference frame of the rotor is to simplify the analysis process. With the rotor reference frame, time varying, $\theta_r$-dependent inductances can be eliminated. Instead, assigning $qd$-axes rotating at $\omega_r$ where the d-axis is aligned with the North Pole of the permanent magnet motor. To obtain the rotor reference frame, a transformation matrix $K^r_s$ is applied to the stationary circuits. [24]

\[
f^{r}_{qds} = K^r_s f_{abc}s
\]  

(3.23)
The superscript $r$ of the matrix indicates that it is the reference frame is a result of this transformation. This transformation matrix $K^r_s$ is also known as the Park’s transformation. [24]

$$K^r_s = \begin{bmatrix}
\cos \theta_r & \cos \left(\theta_r - \frac{2\pi}{3}\right) & \cos \left(\theta_r + \frac{2\pi}{3}\right) \\
\sin \theta_r & \sin \left(\theta_r - \frac{2\pi}{3}\right) & \sin \left(\theta_r + \frac{2\pi}{3}\right) \\
\frac{1}{2} & \frac{1}{2} & \frac{1}{2}
\end{bmatrix}$$

(3.24)

On the other hand, the inverse transformation matrix $(K^r_s)^{-1}$ is

$$(K^r_s)^{-1} = \begin{bmatrix}
\cos \theta_r & \sin \theta_r & 1 \\
\cos \left(\theta_r - \frac{2\pi}{3}\right) & \sin \left(\theta_r - \frac{2\pi}{3}\right) & 1 \\
\cos \left(\theta_r + \frac{2\pi}{3}\right) & \sin \left(\theta_r + \frac{2\pi}{3}\right) & 1
\end{bmatrix}$$

(3.25)

The purpose of having inverse transformations is to convert the existing qd components back to the stationary circuits. The following equation shows the process to convert back to stationary components. [24]

$$f^r_{abcs} = (K^r_s)^{-1}f^r_{qd0s}$$

Substituting the stationary components of equation 3.4 with their dq counterparts, voltage equation of the PMSM becomes

$$(K^r_s)^{-1}V^r_{qd0s} = r_s \frac{d}{dt}V^r_{qd0s} + p[(K^r_s)^{-1}][\lambda^r_{qd0s}]$$

(3.26)

Multiplying the equation with $K^r_s$ yields

$$V^r_{qd0s} = r_s I^r_{dq0s} + \omega_p \frac{d}{dt} \lambda^r_{qds} + p \lambda^r_{qd0s}$$

(3.27)

Where

$$\left(\lambda^r_{qds}\right)^T = [\lambda^r_{ds} \ -\lambda^r_{qs} \ 0]$$

(3.28)
To obtain the rotor reference flux linkage equations, Equation 3.10 is transformed applying the reference theory. The stationary elements from the equation are replaced by their dq representation and produced the following equation. [24]

\[
(K^r_s)^{-1}\lambda_{qd0s}^r = L_{ss}(K^r_s)^{-1}I_{qd0s}^r + \lambda_m^r
\]  

(3.29)

In the same manner, multiplying the equations with \( K^r_s \) becomes

\[
\lambda_{qd0s}^r = K^r_s L_{ss}(K^r_s)^{-1}I_{qd0s}^r + K^r_s \lambda_m^r
\]

(3.30)

Where

\[
K^r_s L_{ss}(K^r_s)^{-1} = \begin{bmatrix}
L_{ts} + \frac{3}{2}L_{ms} & 0 & 0 \\
0 & L_{ts} + \frac{3}{2}L_{ms} & 0 \\
0 & 0 & L_{ts} + \frac{3}{2}L_{ms}
\end{bmatrix}
\]

(3.31)

And

\[
K^r_s \lambda_m^r = \lambda_m^r \begin{bmatrix} 0 \\ 1 \\ 0 \end{bmatrix}
\]

(3.32)

Thus, the total flux linkage of the system in rotor reference is as follows.

\[
\lambda_{qd0s}^r = \begin{bmatrix}
L_{ts} + \frac{3}{2}L_{ms} & 0 & 0 \\
0 & L_{ts} + \frac{3}{2}L_{ms} & 0 \\
0 & 0 & L_{ts} + \frac{3}{2}L_{ms}
\end{bmatrix} \begin{bmatrix} i_{qs}^r \\ i_{ds}^r \\ 0 \end{bmatrix} + \lambda_m^r \begin{bmatrix} 0 \\ 1 \\ 0 \end{bmatrix}
\]

(3.33)

The total inductance of d-axis and q-axis is

\[
L_{ss} = L_{ts} + \frac{3}{2}L_{ms}
\]

Expanding the model of equation 3.27, the voltage equations can be derived to be.

\[
v_{qs}^r = r_s i_{qs}^r + \omega_r \lambda_{ds}^r + p \lambda_{qs}^r
\]

(3.34)
\[ v_{ds}^r = r_s i_{ds}^r - \omega_r \lambda_{qs}^r + p\lambda_{ds}^r \]  
(3.35)

\[ v_{qs}^r = r_s i_{qs}^r + p\lambda_{0s}^r \]  
(3.36)

And similarly, the expanded form of the flux linkage equation is [21][24]

\[ \lambda_{qs}^r = L_{ss} \lambda_{qs}^r \]  
(3.37)

\[ \lambda_{ds}^r = L_{ss} \lambda_{ds}^r + \lambda_{m}^r \]  
(3.38)

\[ \lambda_{0s}^r = L_{ss} \lambda_{0s}^r \]  
(3.39)

Combining the voltage equations and the flux linkage equations of the machine, voltage equations below are produced. [24]

\[ v_{qs}^r = (r_s + pL_{ss}) i_{qs}^r + \omega_r L_{ss} i_{ds}^r + \omega_r \lambda_{m}^r \]  
(3.40)

\[ v_{ds}^r = (r_s + pL_{ss}) i_{ds}^r - \omega_r L_{ss} i_{qs}^r \]  
(3.41)

\[ v_{0s}^r = (r_s + pL_{ss}) i_{0s}^r \]  
(3.42)

The matrix form of them can be written as

\[
\begin{bmatrix}
  v_{qs}^r \\
  v_{ds}^r \\
  v_{0s}^r
\end{bmatrix}
= \begin{bmatrix}
  r_s + pL_{ss} & \omega_r L_{ss} & 0 \\
  -\omega_r L_{ss} & r_s + pL_{ss} & 0 \\
  0 & 0 & r_s + pL_{ss}
\end{bmatrix}
\begin{bmatrix}
  i_{qs}^r \\
  i_{ds}^r \\
  i_{0s}^r
\end{bmatrix}
+ \begin{bmatrix}
  \omega_r \lambda_{m}^r \\
  0 \\
  0
\end{bmatrix}
\]  
(3.43)

Finally, electromagnetic torque of PMSM in rotor reference frame can be determined from the following equation.

\[ T_e = \frac{3}{2} \frac{P}{2} \lambda_{m}^r i_{qs}^r \]  
(3.44)

The electromagnetic torque of PMSM in rotor reference frame representation is very similar to that of the DC machine. Where the \( i_{qs}^r \) is the torque-producing component of the current, the change of this variable will directly correlated towards the electromagnetic torque. In the same way, \( i_{ds}^r \) is the magnetizing current. And lastly, \( \lambda_{m}^r \) is the constant permanent magnet flux of the PM machine. [21][24]
As mentioned before, the analysis of the PMSM is simplified in the rotor reference frame. The main reason is that in the rotor reference frame, PMSM behave like a DC motor. This means that each component can be decoupled, thus controlling one component does not affect the other. Furthermore, the control process of the system will be less complicated. [24]
CHAPTER 4

CONTROL SYSTEM DESCRIPTION

In wind turbine setup, control system holds a crucial role to determine the efficiency. Without a good control system, a big portion of the power produced is wasted. In order to control a wind turbine with Permanent Magnet Synchronous Generator (PMSG), a set of full-scale back-to-back voltage converter is used. The back-to-back converters are connected through a DC-link capacitor. The capacitor decouples the two converters, allowing separate controls being applied to each converter for simplicity. [25] The control systems are separated into generator-side controller and grid-side controller. Figure 4.1 depicts the overall system of PMSG based wind turbine system.

![Figure 4.14 PMSG based Wind Turbine System](image)
The chapter discusses the control systems used for a wind turbine equipped with PMSG as its generators. Field Oriented Control (FOC) method is applied to the generator-side converter. FOC controls the PMSG to operate at a desired speed. The reference speed used is assumed to operate at optimal speed at a certain wind speed. The grid-side controller utilizes Hysteresis Current Control to maintain the DC link Voltage at a constant by adjusting the power flow to the grid. PI controllers are used for both sides to compare the reference signal with the actual feedback signal supplied.

4.1 Generator Side Controller

The control system proposed to control wind turbine generator is Field Oriented Control (FOC). Field Oriented Control is a control technique developed for AC machine based on DC machine operation. The commutation of a DC machine is used to separate the rotor flux and the stator flux by 90°. As a result, a maximum electromagnetic torque is produced. Applying a similar approach, Field Oriented Controls is used to control the electromagnetic torque of the PMSG independently. The control technique decouples the stator currents into: torque-producing current and magnetizing current. By decoupling these components, the torque-producing current becomes independent from the other component, thus PMSG torque control becomes easier to manage. This implies to direct correlation between electromagnetic torque produced to the torque-producing current only. In order to perform this control, reference frame theory, introduced in Chapter 3, is necessary to view the machine variables in synchronous reference frame. [24]
4.1.1 Field Oriented (Vector) Control

The stator and rotor fluxes in PMSG can be described in vectors. The electromagnetic torque produced through the interaction of the two fluxes. The cross product of the rotor and stator fluxes produces the torque motion on the PMSG. Therefore, the maximum torque produced when the torque angle delta is at 90°, considering the cross product relationship. Equation 4.1 shows the function where the electromagnetic produced. [24]

\[ T_e = K\lambda_m I_s \sin(\delta) \]  

(4.45)

In Equation 4.1, Vector control is used to determine the electromagnetic torque, by controlling the stator MMF vector and the rotor flux vector. In Field Orientated Control (FOC), however, the two vector components are completely decoupled. Thus, the torque angle delta is exactly 90° and a completely decoupling of electromagnetic torque is achieved. Implementing FOC, the stator current \( I_{qs} \) in Equation 4.1 is no longer dependent to the rotor flux \( \lambda_m \). Therefore, the electromagnetic torque can be controlled by the stator current \( I_{qs} \), which also referred as torque producing current (Equation 4.2). As a result, controlling the electromagnetic current becomes much easier. [24]

\[ T_e = K\lambda_m I_{qs} \]  

(4.46)

Field Orientated Control in PMSG is formerly derived from a DC machine operation. Figure 4.2 compares a permanent magnet DC machine and a field-oriented PMSG. The commutation of a DC machine automatically does the field Oriented between the stator permanent magnet and the armature rotor flux. While in PMSG, the rotor flux \( \lambda_m \) is aligned to the d-axis of the machine and the torque producing current
$I_{qs}$ is aligned to the q-axis to produce complete decoupling of the torque producing elements. The difference is that DC machine vectors are fixed in space and the PMSG vectors are rotating in $\omega_r$ reference frame. [24]

![Diagram of DC machine and PMSG operation](image)

**Figure 4.15 DC machine and PMSG operation [24]**
Furthermore, considering the intermittent nature of a wind power, an efficient and fast control application is needed. Thus, Field Oriented Control is perfect fit for this application. [24]

4.1.2 Field Oriented Control in PMSG

Applying the Field Oriented Control to PMSG of the wind turbine system can be shown in Figure 4.2. The system consists of the PMSG itself, power converter equipped with PWM, current controller, and speed controller. [24] Field Oriented Control is a closed loop control, where controlling the stator current indirectly controls the electromagnetic torque of the machine. As mentioned in the previous subchapter, the control is performed in dq rotor reference frame. [25]

For simplicity purposes, constant angle control is performed for the turbine generator. The torque angle delta is maintained at 90°. This is achieved by setting the d-axis stator current to zero and the stator current only has the q-axis component. Thus, the torque only depends on q-axis stator current component, since the permanent flux and the torque angle constant. This q-axis stator current $i_{qs}$ is known as the torque-producing current. [25]

In synchronous machine, it is general convention that the North Pole of the permanent magnet aligned to the d-axis of the rotor reference frame. In order to know the position of the rotor, position sensor is installed to the generator to determine the state of the rotor. [24] A space vector diagram is presented in Figure 4.3. By controlling the stator current vector, the torque is kept as desired.
The $\delta$ is the torque angle and the $\theta_r$ is the load angle. The stator current vector is presented as $I_s = I_{sd} + jI_{sq}$. [25]
The algorithm of the control system is vividly described in Figure 4.4. In this particular control system, DC-link voltage, stator currents, and rotor position are measured as closed loop feedback signals. The rotor position is determined by the encoder mounted to the rotor. As desired, the d-axis stator reference current $I_{ds}^*$ is set to zero and q-axis reference current $I_{qs}^*$ is supplied through the speed regulator PI (Proportional Integral) controller. The d and q-axis current regulator produces $dq$ voltage signals. In order to decouples the current, to be independent from each other, $\omega_e \varphi_d$ is added, and $\omega_e \varphi_q$ is subtracted, at the current regulators output. The PWM (Pulse Width Modulation) used in this control system is SVM (Space Vector Modulation). The SVM
determines the duty cycle of the inverter that determines the DC-link voltage between the two inverters. [25]

The control algorithm explained above is derived based on Equation 4.3. By controlling the speed of the generator, torque-producing current is readjusted to either increase or decrease the electromagnetic torque to match the mechanical torque from the wind turbine.

\[ T_m - T_e = J \frac{2}{P} \frac{d\omega_r}{dt} \]  

(4.47)

Where,

- \( T_m \) – Mechanical torque input from the wind flowing
- \( T_e \) – Electromagnetic torque
- \( J \) – Moment of inertia

The PI controller used to compare the actual and reference signal, trying to bring the actual signal to the desired magnitude. Transformation blocks from stationary to rotor reference frame and from rotor reference frame to \( \alpha\beta \) reference is included. These transformation blocks is supplied with the rotor position angle \( \theta \). The assumption made for the control system is that speed reference \( \omega_r \) is obtained from Maximum Power Points Tracking algorithm. Thus, the control performed in Figure 4.3 is to maintain a constant speed in wind fluctuations. [25]
4.1.3 Current and Speed Regulators

In this subchapter, PI controllers implemented to regulate the currents and the speed. One PI controller is used for speed regulation and two PI controllers are used for currents regulation. The detailed subsystem is presented in Figure 4.5.

![Figure 4.18 q- and d- axis control loop structure [25]](image)

Where,

- \( \omega_r \) – Electrical speed in rot/min
- \( \omega_p \) – Electrical speed in rad/sec

According to Figure 4.5, the current loop is the inner loop, where the q-axis reference input is fed by the speed regulator’s output from the outer loop. The output of the speed PI controller is the difference between reference speed \( \omega_r^* \) and the measured speed \( \omega_r \). This produces q-axis reference current \( i_{qs}^* \). The current loop PI controllers process the error between reference currents \( i_{sq,d}^* \) and the measured currents \( isq,d \) and generate \( dq \) voltage output \( v_{sq,d} \). These \( dq \) output signals then decoupled from each other, explained in Equation 4.4 and 4.5 below. [25]
Equation 4.4 and 4.5 are the voltage equations of the stator. The two equations are coupled by the back-EMF of the other reference axis. In order to decouple the d and q-axis currents, the back-EMFs have to be compensated. Thus, the tuning process of the PI current controllers is less complicated. [25]

4.1.4 DQ to αβ reference Frame

Voltages with two phase orthogonal system (αβ reference) are required for the Space Vector Modulation (SVM) technique used in this control system. Figure 4.6 explains the transformation from dq-axis to αβ-axis. [30]

\[ v_{qs}^r = r_i i_{qs}^r + \omega_e \lambda_{ds}^r + p \lambda_{qs}^r \]  
\[ v_{ds}^r = r_i i_{ds}^r - \omega_e \lambda_{qs}^r + p \lambda_{ds}^r \]  
(4.48)

(4.49)

And the αβ reference transformation is explained in Equation 4.6 below:

\[ V_{\alpha} = V_d \cos(\theta_r) - V_q \sin(\theta_r) \]  
(4.50)
\[ V_p = V_d \sin(\theta_r) - V_q \sin(\theta_r) \]

4.1.5 **Permanent Magnet Synchronous Generator**

In this thesis, the control system is implemented to a 2.2 KW PMSG, which parameters of the machine are presented in Table 4.1. [25]

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Symbol</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nb. of Pole pairs</td>
<td>p</td>
<td>3</td>
<td>-</td>
</tr>
<tr>
<td>Frequency</td>
<td>f</td>
<td>87.5</td>
<td>[Hz]</td>
</tr>
<tr>
<td>Stator Resistance</td>
<td>( R_s )</td>
<td>1.906</td>
<td>[Ω]</td>
</tr>
<tr>
<td>d-axis stator inductance</td>
<td>( L_d )</td>
<td>30.31</td>
<td>[mH]</td>
</tr>
<tr>
<td>q-axis stator inductance</td>
<td>( L_q )</td>
<td>38.36</td>
<td>[mH]</td>
</tr>
<tr>
<td>Voltage constant</td>
<td>( K_e )</td>
<td>495.3</td>
<td>-</td>
</tr>
<tr>
<td>Moment of inertia</td>
<td>J</td>
<td>0.002</td>
<td>[kg m²]</td>
</tr>
<tr>
<td>Viscous friction</td>
<td>B</td>
<td>0.0028</td>
<td></td>
</tr>
</tbody>
</table>

**Table 4.3 PMSG parameters** [25]

4.1.6 **Converter**

Figure 4.5 shows the circuit diagram of a voltage source converter. A three phase converter utilizes 6 semiconductors (IGBTs) divided into three legs: a, b, and c, each leg consist of 2 switches. For this study, the switches are considered as ideal switches. Furthermore, each leg is designed to have only one switch can conduct at a time. [25]
The top switches are labeled as $S_a$, $S_b$, and $S_c$, while the bottom pairs are labeled as $S'_a$, $S'_b$, and $S'_c$. The switches can only have two values: 1 for conducting state and 0 for blocking state, and $S_a$ has an opposite value to $S'_a$. In order to get the desired output, duty cycles $D_a$, $D_b$, and $D_c$ are programmed. [25]

\[
V_{a0} = \frac{V_{DC}}{3} (2D_a - D_b - D_c)
\]
\[
V_{b0} = \frac{V_{DC}}{3} (-D_a + 2D_b - D_c)
\]
\[
V_{c0} = \frac{V_{DC}}{3} (-D_a - D_b + 2D_c)
\]

With,

$V_{a0}, V_{b0}, V_{c0}$ – phase voltages;

$V_{DC}$ – DC-link voltage.
And the DC link Current is,
\[ i_{DC} = [D_a \quad D_b \quad D_c]. \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} \]

Where,
\[ i_a, i_b, i_c – \text{line currents.} \ [25] \]

4.1.7 Space Vector Modulation

The Pulse Width Modulator used for the system is Space Vector Modulation (SVM). The modulation technique is based on the space vector representation of the voltage on the AC converter side. This PWM method has grown its popularity due to its simplicity in producing the duty cycles. [29] On top of that, SVM offers an accurate amplitude and frequency control, thus perfect for variable torque loads and large power drives. Furthermore, this space vector representation allows SVM to handle the modulation of all three phase simultaneously. [29]

For a three-phase application, 8 possible switching states are provided, including 6 active (non-zero) switching states and 2 zero switching states. Each active switching state represents a space vector in a 360° planes. The space vector voltage representation is obtained from voltage in \( \alpha \) and \( \beta \) reference frame. Equation 4.7 describes the components of reference voltage space vector \( \vec{V}^* \). [25]

\[ \vec{V}^* = v_\alpha + jv_\beta = \frac{2}{3} (v_{aref} + e^{j\frac{2\pi}{3}}v_{bref} + e^{-j\frac{2\pi}{3}}v_{cref}) \]  (4.51)

In which,
\( v_{aref}, v_{bref}, \) and \( v_{cref} \) are the phase voltages.
The 6 active switching states separate the 360° planes into 6 sectors, as depicted in Figure 4.6. The reference voltage $V^*$ is derived from conducting the two adjacent voltage vectors for the proper duration. Figure 4.6, for example, the reference voltage $V^*$ is located at sector 1, where the adjacent vectors are $V_1$ and $V_2$. In order to achieve state vector voltage $V_1$, state $[1 \ 0 \ 0]$ should conduct. The state $[1 \ 0 \ 0]$ is conducting when the upper switch of the first leg is turned on and the lower switches of the second and third leg are turned on. The switching frequency of the system is $T_{PWM}$ and $\alpha$ is the phase angle of the state vector voltage. [25] The maximum allowable magnitude of the state vector voltage $V^*$, for each angle $\alpha$, is $V_{DC}/\sqrt{3}$ before going to the over-modulation state.

![Figure 4.21 Space Vector Modulation sectors [25]](image_url)
Furthermore, the switching state required to produce $\bar{V}^*$ in Figure 4.8 is as follows: [0 0 0], [1 0 0], [1 1 0], and [1 1 1]. The switching sequence in Figure 4.7 is significant in order to reduce number of switching, which leads to lesser switching loss.

The zero states designed here are symmetrical. The zero states switching period in Figure 4.9 can be calculated as.

$$t_7 = t_0 = \frac{T_{PWM} - t_1 - t_2}{2}$$

Where, $t_0$, $t_1$, ..., $t_7$ are the durations of the applied vectors.

![Figure 4.22 Space Vector Modulation operation [25]](image)

The calculation of $\bar{V}^*$ in sector 1 is calculated as. [25]

$$\bar{V}^* = \bar{V}(100) \frac{t_1}{T_{PWM}} + \bar{V}(110) \frac{t_2}{T_{PWM}}$$

And,
The state vector voltage $\tilde{V}$ can be separated into $V \cos \alpha + jV \sin \alpha$. Substituting the real and imaginary part of the state vector, time duration $t_1$ and $t_2$ can be calculated.

\[
t_1 = \sqrt{3} \frac{V^*}{V_{DC}} T_{PWM} \sin \left( \frac{\pi}{3} - \alpha \right)
\]

\[
t_2 = \sqrt{3} \frac{V^*}{V_{DC}} T_{PWM} \sin \alpha
\]

The remaining sampling time after subtracting $t_1$ and $t_2$ is reserved for the zero state vectors $V_0$ and $V_7$. And the total of $t_1$ and $t_2$ should be less than or equal to the total sampling time $T_{PWM}$. Equation 4.8 to 4.9 describes the duty cycle calculations of the state vector in sector 1.

\[
D_a = \frac{t_1 + t_2 + t_o/2}{T_{PWM}} \quad (4.52)
\]

\[
D_b = \frac{t_2 + t_o/2}{T_{PWM}} \quad (4.53)
\]

\[
D_c = \frac{t_o/2}{T_{PWM}} \quad (4.54)
\]

The calculation of other sectors can be performed in the same manner. The phase voltage used in the system is 285V. [25]
4.2 Grid-side controller

The grid-side controller utilized three independent hysteresis current controllers to feed the gate signal of voltage converter. Hysteresis current control is an instantaneous feedback control that maintains the current in a specified band. The magnitude of the difference between reference current and actual current determines the switching signal generated for converters switches. [26] The hysteresis current control system is designed to complement the generator’s field oriented control by maintaining the DC-link voltage at a constant value. This DC-link voltage magnitude is adjusted by controlling the amount of current drawn to the electrical grid.

4.2.1 Grid-side Hysteresis Current Control

Hysteresis current control is designed as a non-linear feedback control system. The control system fixes the output current of the inverter instantaneously. Figure 4.10 depicts the operation of a hysteresis control.

![Figure 4.23 Hysteresis Control Operation](image)

Where,
\( \delta \) – the specified hysteresis band

\( u \) – Output of control signal

(the operation of the hysteresis control)

Based on the operations in Figure 4.8, the hysteresis controls the grid’s currents by keeping the current wave in the range of the defined hysteresis band. When the current wave reached the band limits, the hysteresis controllers generate a control signal (0 or 1), which defines the PWM gate signal. [28] The current controllers adjust the output current \( i \), tracking the current reference \( i^* \). Comparing the instantaneous currents on the grid with the reference signal, the controller adjusts the duty cycle of the PWM of the converter. This leads to a reduced error signal (delta). [27]

The implementation of hysteresis current control as the grid-side controller is shown in Figure 4.11.
In the system, DC-link voltage is maintained at 540 V. In order to control the voltage at a constant magnitude, the amount of currents injected to the electrical grid is adjusted. The error between reference voltage and actual voltage feed the PI controller to produce a multiplier to a unity three-phase current generator. The output current then compared to the actual current supplied to the electrical grid. The error difference between the two signals is connected to the hysteresis current control, which will produce the gate signal of the PWM.

As the DC-link voltage increases, reference currents $i_{abc}^*$ produced also increase. When the produced current is lower than the reference current, the converter connects the positive side of the DC-link source to the load, thus the current increases. On the contrary when the produced current is higher than the current reference the converter connects the negative side of the DC-link source to the load, which reduces the currents. With these two operations, the error of the current can be maintained within a certain fixed band. And Figure 4.12 shows the operation of the injected current with a hysteresis current control. [27]
Figure 4.25 Produced current with hysteresis current control

Compared to the classical current control based on PWM modulation, hysteresis current controller presents simplicity and robustness to the system, while the other may cause control delays, which leads to inaccurate control. Furthermore, the hysteresis current control has a good dynamic response. On top of that, this current control technique does not have tracking errors and independent from load parameter changes. [29] The drawback, however, the switching frequency varies. This may causes randomness towards the converters, which leads to a challenging converter. [29]
CHAPTER 5

SIMULATION & RESULTS

Having the controllers working properly, the Field Oriented Control and Hysteresis Current Controllers need to be tested. The control technique’s simulations are performed in discrete time domain under MATLAB/Simulink design environment. In order to have a fully functional and stable wind turbine system, both Field Oriented Control and Hysteresis Current Control are required to operate as they are designed. On top of that, the results of the simulations are analyzed to ensure the output signals are implementable in real condition application.

As mentioned in Chapter 4, the Field Oriented Control (FOC) is designed to control the generator speed to operate at a constant reference speed. The simulation is performed under the assumption of reference speed being supplied from Maximum Power Point Tracking (MPPT) controller. According to Figure 2.12 in Chapter 2, at a certain wind speed, there is a particular turbine speed $\omega_r = \omega_{opt}$, in which the generator transforms the maximum wind power into electrical power output. Thus, maintaining the generator speed at the specific turbine speed $\omega_{opt}$ is desirable. The generator used in this experiment is the pre-installed Simulink Permanent Magnet Synchronous Machine model rated at 2.2 kW. The PMSM parameters are described at Chapter 4, in Table 4.1.
In order to operate a wind turbine system efficiently, generator-side controller is not enough. While the generator-side controller maintains the speed to operate at an optimum speed, the DC-link capacitor voltage varies with the wind. As a result, wind variation causes the capacitor voltage to fluctuate. This fluctuation directly affects the electrical grid system, which leads to problems in weak grids. To prevent this problem, Hysteresis Current Control (HCC) is used as the grid-side controller. The HCC is designed to maintain the DC-link capacitor voltage at a constant magnitude by adjusting the power flow to the electrical grid. As the DC-link voltage rises, the controller increases the current supplied to the grid, which allows the DC-link to reduce back to the reference value.

This chapter discusses the simulations and results of both control techniques in different scenarios. These scenarios are constant torque condition, rising torque condition, and decreasing torque condition. The goal of the chapter is to show that the control techniques developed are working properly in these different operating conditions. The MATLAB/Simulink simulation block diagram can be found in Appendix A.

5.1 Generator operation at constant torque

The first test is done in a constant torque operation. The test case is built upon a scenario where constant wind flow moves the wind turbine, creating the input torques for the PMSG to generate electricity. The torque input is set at the rated torque. For a 2.2 kW PMSG with 87.5 Hz rating, the rated torque is calculated to be 12 Nm. Simulations
performed to demonstrate a working control system done by both the generator-side and
grid-side controllers.

![Developed Torque (N.m)](image)

**Figure 5.26 Developed Torque (N.m)**

Figure 5.1 shows the graph of the developed torque applied to Permanent Magnet
Synchronous Generator. The initial condition of the Permanent Magnet Synchronous
Machine is at rest. Thus, the early oscillations of the torque in Figure 5.1 are expected
due to machine starting up. During transients, the torque oscillates as much as 20Nm
peak-to-peak and stabilizes after roughly at 12Nm with a small ripple of 1.5Nm. This
developed torque drives and determines the speed of the generator.
The generator-side controller, Field Oriented Control, is designed to bring the generator speed to the reference speed. As described in Chapter 4, the control technique adjusts the magnitude of the electromagnetic torque, which compensates the speed of the generator. Inside the control system, three PI controllers are used to control the speed and the stator currents. The parameters used for these PI controllers are described in Table 5.1 below.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Speed Controller</td>
<td></td>
</tr>
<tr>
<td>Kp</td>
<td>0.038</td>
</tr>
<tr>
<td>Ki</td>
<td>0.8</td>
</tr>
<tr>
<td>Current</td>
<td>[-40, 40]</td>
</tr>
<tr>
<td>Saturation Limit</td>
<td></td>
</tr>
<tr>
<td>q-axis Current</td>
<td></td>
</tr>
<tr>
<td>Kp</td>
<td>3</td>
</tr>
<tr>
<td>Ki</td>
<td>10</td>
</tr>
<tr>
<td>q-axis Voltage</td>
<td>[-300, 300]</td>
</tr>
<tr>
<td>Saturation Limit</td>
<td></td>
</tr>
<tr>
<td>d-axis Current</td>
<td></td>
</tr>
<tr>
<td>Kp</td>
<td>15</td>
</tr>
<tr>
<td>Ki</td>
<td>45</td>
</tr>
<tr>
<td>d-axis Voltage</td>
<td>[-300 300]</td>
</tr>
<tr>
<td>Saturation Limit</td>
<td></td>
</tr>
</tbody>
</table>

Table 5.4 Generator-side controller parameters

Figure 5.2 shows the generator speed graph when Field Oriented Control is applied at a constant torque (wind speed) operating condition.
Figure 5.27 Field Oriented Control (Speed Controller)

Figure 5.2 shows the performance of Field Oriented Control when the generator is subjected to a constant torque input at 12Nm. The transient effect from the developed torque in Figure 5.1 carries over to the generator speed $\omega_r$. The speed shoots up as high as 585RPM at 0.5s. And the speed reaches its steady state at 2s following the reference speed defined $\omega_r^*$. The result can be improved by tuning the PI controller further.

For simplicity, phase a stator current $i_{sa}$ graph is shown in Figure 5.3 and as expected the current frequency and magnitude varies as the generator speed changes.
As the speed $\omega_r$ increases, the frequency of the stator current increase, while the magnitude varies with the torque. These behaviors are consistent with the Permanent Magnet Synchronous Machine’s operation. Furthermore, the current graphs show no DC offsets, as desired, since the offset can cause saturation to the machine.

The second control system, Hysteresis Current Control, maintains the DC-link voltage at 540V. The voltage reference was determined to feed the electrical grid at 208V 60Hz. The DC-link voltage is compared to the reference voltage and the error is processed through a PI controller, as discussed in Chapter 4. The PI controller parameters used in this Hysteresis Current Controller is described in Table 5.2 below.
<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kp</td>
<td>0.3</td>
</tr>
<tr>
<td>Ki</td>
<td>5</td>
</tr>
<tr>
<td>Hysteresis Band</td>
<td>0.005</td>
</tr>
</tbody>
</table>

Table 5.5 Hysteresis Current Control Parameters

The grid-side controller’s operation on the DC-link voltage is shown in Figure 5.4. In Figure 5.4, the DC-link voltage initially shoots up to 630V, due to transient operation of the machine. However, as the machine stabilizes, the DC-link voltage also reaches its steady state at 540V, which is the reference voltage.

Figure 5.29 Hysteresis Current Control (HCC) on Vdc
Lastly, the current and voltage supplied to the electrical grid are shown in Figure 5.5 below.

![Figure 5.30 Grid currents and voltage HCC](image)

Similar operation characteristic can be observed in the grid current signal. The start-up transients of the machine increased the current significantly and quickly stabilize at 0.1s. On the other hand, grid voltage signals remain constant at any value, as desired. Total
Harmonic Distortion study of the current is done to analyze the current signal. This study is performed through FFT analysis given in Simulink. At rated torque operation, the current THD is calculated to be 2.33%, where the signal at fundamental (60Hz) magnitude is 1.292.

5.2 Generator operation at 70% rated torque, step to rated torque

The second scenario is done in an increasing wind speed condition. To simulate this condition, the input torque is initially set at 70% rated torque and stepped up to rated torque. The initial torque magnitude is set at 8.5Nm and increased to 12Nm at 2.5s. In variable wind speed operation, both control techniques should be able to maintain the speed and the DC-link voltage to the reference value.

The speed control performed by the FOC in this test case is shown in Figure 5.6 below.

![Figure 5.31 Speed (70% stepped up to rated torque) FOC](image)

Figure 5.31 Speed (70% stepped up to rated torque) FOC
As designed, the Field Oriented Control prevents the speed from changing. At 70% rated torque, the initial speed jumps up to 590 RPM and settles down at 1.7s. When the step torque applied to the system, the speed accelerates to 545 RPM and quickly settles back after 0.75s. As mentioned before, the stator current’s magnitude increases directly proportional to the torque increase. Figure 5.7 describes phase a stator current $i_{sa}$ operation as the wind speeds up.

![Figure 5.32 Stator current phase a (70% stepped up to rated torque) FOC](image)

When the input torque increases, the DC-link voltage also increases. The Hysteresis Current Controller, then, increases the amount of current supplied to the grid.
in order to maintain the DC-link capacitor at 540V. The DC-link voltage operation is shown in Figure 5.8.

![Figure 5.33 DC-link voltage (70% stepped up to rated torque) HCC](image)

During transition, the DC-link voltage increased to 543V and forced back to the reference value 540V after 0.2s. Only the grid current operation is affected by the torque increase, while the voltage stays constant. Figure 5.9 describes the current operation when the torque is stepped up.
The grid current operation describes in Figure 5.9 behaves according to HCC designed. As disturbance introduced to the system, the current transitions fairly fast. The grid current stabilizes after 0.2s similar to DC-link voltage operation. Total Harmonic Distortion studies are performed for both grid current at 8.5Nm and 12Nm. The THD and fundamental magnitude of both condition is explained in Table 5.3 below.

<table>
<thead>
<tr>
<th>THD</th>
<th>Fundamental</th>
</tr>
</thead>
<tbody>
<tr>
<td>rated torque</td>
<td>2.40%</td>
</tr>
<tr>
<td>70% rated torque</td>
<td>4.27%</td>
</tr>
</tbody>
</table>

Table 5.6 Total Harmonic Distortion study (70% stepped up to rated torque)
The THD studies showed that the total harmonic distortion increases as the current magnitude decreases. At 70% of the rated torque, the grid current signal is still acceptable (below 5% THD).

5.3 Generator operation at 90% rated torque, step down to 60% rated torque

The last scenario is done at a decreasing wind speed operating condition. The test case is designed with a step down torque input from 90% rated torque to 60% rated torque. The input torque is set to step down from 10.8Nm to 7.2Nm at 2.5s. Again, the FOC and HCC are tested to fulfill their designed functions.

Figure 5.10 shows the FOC operation on generator speed control.

![Figure 5.35 Speed (90% to 60% rated torque) FOC](image-url)
Similar to previous simulation, the generator speed went down momentarily to 445RPM and increased back to the reference speed. In addition, Figure 5.11 depicts the decrease of the stator current magnitude as the input torque reduced.

![Phase a stator current (90% to 60% rated torque) FOC](image)

Figure 5.36 Phase a stator current (90% to 60% rated torque) FOC

The grid-side controller is able to maintain the DC-link voltage at 540V, described in Figure 5.12.
The DC-link voltage dips down to 536V and is able to be brought back to 540V. As described in previous subchapter, to maintain the DC-link capacitor voltage at constant, the current supplied to the grid has to be compensated in order to maintain the voltage. In this case, as the capacitor voltage decreases, the amount of current supplied to the electrical grid has to be reduced as well. This will slow down the discharge rate of the DC-link capacitor and allow the capacitor to be charged by the generator. Figure 5.13 shows the grid current operation as the torque input reduced from 90% to 70% of the rated torque.
In addition to the simulation results, total harmonic distortion studies are performed to the grid currents and the results are shown in Table 5.4 below.

<table>
<thead>
<tr>
<th>THD</th>
<th>Fundamental</th>
</tr>
</thead>
<tbody>
<tr>
<td>60% rated torque</td>
<td>4.77% 0.6213</td>
</tr>
<tr>
<td>90% rated torque</td>
<td>2.49% 1.283</td>
</tr>
</tbody>
</table>

Table 5.7 Total Harmonic Distortion study (90% to 70% rated torque)

It is shown that the current signal quality decreases as the torque reduced. However, even at 60% of the rated torque, the signal is maintained in a reasonable quality.
5.4 Conclusion of FOC and HCC simulation results

As designed, both the generator-side and the grid-side controllers work as they should in a 2.2kW wind turbine PMSG. The Field Oriented Control (FOC) used to control the generator-side is able to maintain the speed at reference point at all the three scenarios. In the same manner, the Hysteresis Current Control is able to control the DC-link voltage to operate at a constant 540V at every condition simulated. Furthermore, Total Harmonic Distortion calculation is made for the grid current signals, to determine the quality of the signals. It is shown that the system produces a reasonable signal, with 5% THD or less, when operated as low as 60% of the rated torque. This shows that the control systems designed produce good output signals from wind turbines with a 2.2kW PMSG.
CHAPTER 6

CONCLUSION & FUTURE WORKS

The thesis is developed on the Field Oriented Control (FOC) and Hysteresis Current Control (HCC) of a wind turbine. Wind, among other renewable sources, has the advantages of pollution-free and less expensive to implement. The wind energy sources can be harnessed through the usage of turbine technology. The turbine, then, is connected to a three-phase electric generator. Permanent Magnet Synchronous Generator is selected due to its high efficiency, high torque-to-size ratio, and low maintenance requirement. The detailed element of PMSG is discussed in Chapter 4.

Although wind energy has great potentials, the wind occurrence is intermittent and close to unpredictable. In order to develop an acceptable wind power system, control techniques have been the significant core of a wind turbine. The wind turbine system developed in the thesis utilizes FOC to control the generator-side and HCC for the grid-side system. The author has designed control algorithms for both side of the system. This chapter is written to give a brief summary of the whole thesis and future work proposal that may be taken to enhance the control system from this thesis.
6.1 Conclusion

Chapter 1 has introduced the topics discussed in the thesis. It started with a brief description of renewable energy resources, in which wind energy is selected to be the focal point of this thesis to further exposed. Wind turbine generators are then introduced to the reader with quick comparisons among three different generator types. Afterwards, the control techniques used in the system are introduced before the thesis finally moves on to the discussion of the Field Oriented Control and Hysteresis Current Control operations.

Chapter 2 gives introduction to different types of renewable energy resources as alternatives to fossil fuels. The chapter illustrates the growth of energy usage in yearly basis and describes how fossil fuels have become the main energy source all these times. The massive use of fossil fuel has caused global warming phenomenon, which also discussed in the chapter. Renewable energy, specifically wind energy, is used in order to reduce the usage of fossil fuels. The wind power system and wind power analysis concludes this chapter.

In chapter 3, the main focus is on the wind turbine generators. The chapter specifically focused on Permanent Magnet Synchronous Generator (PMSG). PMSG is compared to Squirrel Cage Induction Generator (SCIG) and Doubly Fed Induction Generator (DFIG) in the light of wind turbine generator application. PMSG thrives due to its advantage of high-efficiency, low torque-to-size ratio, and low maintenance requirement. A complete machine operation description is discussed in this chapter. In addition, reference frame theory is explained in this chapter.
Further in chapter 4, the control system developed to regulate the wind turbine is introduced and explained in details. The chapter starts with field oriented comparison between DC machine and PMSG. Field Oriented Control is discussed and implemented as the generator-side controller to maintain the DC-link voltage at constant value. FOC is implemented in order to simplify the generator control. The generator signals, such as, voltage, current, flux linkage, are transformed into $dq$ representation. In addition, decoupling process is performed to separate the torque producing component from magnetizing component. This way, adjusting the control system is easier to do. On the electric grid-side, Hysteresis Current Control is introduced to control the power flow supplied to the grid. Thus, the DC-link capacitor voltage is adjusted.

Finally, chapter 5 shows the simulation and results of the control system. It is shown that the system is controllable in three different operation conditions. The simulations are done in constant torque input, step up torque condition, and step down torque scenario. It is also shown that the output current signal produced, in different torque inputs, has a relatively good quality with a low total harmonic distortion values.

6.2 Future works

The field oriented control of PMSG using the position sensor has been a relatively mature field. Further enhancement may involve the usage of sensorless Field Oriented Control. Tuning the PI controller also becomes a challenge of itself. On the other hand, the hysteresis current control used for the grid-side controller has been common. The variable switching frequency from hysteresis current controller may cause the converter protection to be challenging. The usage of Space Vector Modulation may be a good
solution for the system. However, other non-linear control technique such as fuzzy logic or sliding mode control may significantly improve the performance of the system.
BIBLIOGRAPHY


Appendix A: MATLAB/Simulink Block Diagram
A.1 GENERAL REPRESENTATION

Electrical Grid
3-phase
(208V, 60Hz)

Grid-side Controller

Vdc_link+

Vdc_link

Vdc_link-

Isa

Isb

Is_c

PMSG_Bus signal

Permanent Magnet
Synchronous Machine
(2.2kW, 87.5Hz)

PMSM

T_load

actual speed

load_torque

[1_abc]

speed_ref

[N]

[N]

[N]

[N]

[N]

[N]

[N]

[N]

[N]

[N]

[N]
A. 2 GENERATOR-SIDE CONTROLLER
A.2.1 SPEED AND CURRENT CONTROLLER
A.2.2 DECOUPLING BLOCK

A. 3 GRID-SIDE CONTROLLER
A.3.1 HYSTERESIS CURRENT CONTROLLER