T.C.
ISTANBUL AYDIN UNIVERSITY
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GRID VOLTAGE-ORIENTED VECTOR CONTROL FOR THE GRID SIDE CONVERTER OF THE WIND TURBINE DOUBLY-FED INDUCTION GENERATOR

MASTER'S THESIS

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Department of Electrical & Electronic Engineering

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ONAY FORMU

DECLARATION

I hereby declare with respect that the study “Grid Voltage-Oriented Vector Control for the Grid Side Converter of the Wind Turbine Doubly-Fed Induction Generator”, which I submitted as a Master thesis, is written without any assistance in violation of scientific ethics and traditions in all the processes from the Project phase to the conclusion of the thesis and that the works I have benefited are from those shown in the Bibliography. (14/7/2021)

Wafa K. Abukweik

FOREWORD

First, I would like to express my endless gratitude to God for being who I am right now and helping me to find patience, strength within myself to complete this thesis.

I would also like to thank my family not only for encouraging me to go abroad for a master's degree but also for teaching me to chase my dreams and never give up.

I feel very fortunate to have Prof. Dr. MEHMET EMIN TACER as my supervisor and want to express my appreciation for guiding me within the whole research process in a patient and effective manner.

Prof. Dr. MEHMET EMIN TACER is not only professional in his field, but a person with a great heart that keeps encouraging me.

Finally, I would like to acknowledge the important contribution of Istanbul Aydin University to my life, not only from an academic perspective but helping to meet great people that inspire, challenge, support and motivate me.

July 2021 Wafa K. Abukweik

GRID VOLTAGE-ORIENTED VECTOR CONTROL FOR THE GRID SIDE CONVERTER OF THE WIND TURBINE DOUBLE-FED INDUCTION GENERATOR

ABSTRACT

Wind energy currently plays a major role in the energy industry, and other fields such as economics, science, and research. With the daily developments in wind turbine systems that have worked on global problems such as global warming, unemployment, and the economy of countries, these systems have become indispensable. According to "Global Wind Reports 2019" only in 2019, 60.4 GW of wind energy were installed. This makes the total global wind energy in 2019 more than 651 GW. Wind Turbine converts kinetic energy into mechanical energy using the rotor then from mechanical into electrical using the generator. One of the generators that are widely used in MW scales wind turbines is the doubly fed induction generator (DFIG). This thesis presents control method which is called the grid voltage-oriented vector control method that is used to control a grid side converter (GSC) of the DFIG. This control method is capable to regulate the power flow of the rotor side circuit and maintaining a unity power factor for overall system through feeding reactive power to the DFIG. The used mathematical model is presented in d-q reference frame. The study is validated through simulation using software MATLAB/Simulink, studies including a modeling, control, and simulation on a 2 MW on-grid doubly fed induction generator wind generation system. The aim of this thesis is to validate the operation of the model by obtaining a constant value for the DC link voltage at different wind speeds and reactive power values. The DC link voltage performance results of the MATLAB/ Simulink model will be presented and analyzed.

Keywords: Control of wind turbines, grid side converter GSC, doubly fed induction generator DFIG, grid voltage-oriented vector control.

RÜZGÂR TÜRBİNİ ÇİFT BESLEMELİ İNDÜKSİYON JENERATÖRÜ ŞEBEKE YAN KONVERTÖRÜ İÇİN ŞEBEKE VOLTAJI EKSENLİ VEKTÖR KONTROLÜ

ÖZET

Rüzgâr enerjisi günümüzde özellikle enerji sektöründe ve ekonomi, bilim ve araştırma gibi diğer alanlarda son derece önemli rol oynamaktadır. Rüzgâr türbini sistemlerindeki gelişmeler küresel ısınma, işsizlik ve ülke ekonomileri gibi küresel meseleler açısından gerekli olmuştur. Küresel Rüzgâr Raporu 2019 yılı sayısına göre, yalnızca 2019 yılında olmak üzere, dünyada toplam 60.4 GW rüzgâr enerjisi kurulumu gerçekleştirilmiştir. Aynı yıl için dünya geneli toplam rüzgâr enerjisi kurulu gücü 651 GW seviyesine ulaşmıştır. Rüzgâr türbini kinetik enerjinin mekanik enerjiye dönüştürüldüğü bir sistemdir. Sistem bu işi ise rotor kullanarak yapmakta, devamında ise mekanik enerjiden jeneratör kullanarak elektrik enerjisi üretmektedir. MW kapasiteli rüzgar türbinlerinde yaygın kullanılan jeneratörlerden birisi de çift beslemeli indüksiyon jeneratörüdür (DFIG). Bu araştırmada, çift beslemeli indüksiyon jeneratörü şebeke tarafı konvertörünü kontrol etmek için kullanılan şebeke voltajı eksenli vektör kontrolü metodu hakkında kapsamlı bilgi sunmak amaçlanmıştır. Bahsedilen kontrol metodu rotor tarafı devresinin güç akışını regüle etmek ve tüm sistem için DFIG'ye reaktif güç besleyerek tek güç faktörü sağlamak için kullanılmaktadır. Bunun için d-q referans çerçevesi için bir matematiksel model sunulmuştur. Araştırmanın geçerliği MATLAB/Simulink yazılımı kullanılarak yapılan simülasyon ile test edilmiştir. Simülasyon çalışmaları modelleme, kontrol ve 2 MW şebeke bağlantılı çift beslemeli indüksiyon jeneratörü rüzgâr üreteç sistemi kurgularını içermiştir. Bu şekilde, farklı rüzgâr hızı ve reaktif güç değerlerinde DC bağlantılı voltaj için sabit bir değer elde etmek için işletme modeli geçerliğini sınamak hedeflenmiştir. MATLAB/Simulink modelinin DC bağlantı voltajı performansı sonuçları sunulmuş ve analiz edilmiştir.

Anahtar kelimeler: Rüzgâr türbini kontrolü, şebeke bağlantılı konvertör GSC, çift beslemeli jeneratör DFIG, şebeke voltajı eksenli vektör kontrolü

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ABBREVIATIONS

RSC : Rotor side converter

GSC : Grid side converter

DFIG : Doubly fed induction

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I. INTRODUCTION

A. Background

Society needs energy mainly in his daily life and can be obtained from several sources including conventional and renewable sources.

The energy crisis has led to an increase in interest in alternative energy. In 1887 when wind energy was first used to produce electricity. Uses of the wind are many, including, it is used nowadays to generate energy, it has been used since ancient times in villages to grind grain by converting wind into mechanical energy using windmills, and it was used in ancient times to transport water and move sailing ships. that a windmill found in Afghanistan around 200 BC (Kaldellis & Zafirakis, 2011).

The advantages of wind energy including, it is clean, does not end and free. The main component of the wind turbine is a rotor or blades that converts wind energy into mechanical energy, and the wind kinetic energy works to move the blades, where these blades rotate a shaft that leads from the rotor axis to the generator, and then the generator converts this rotational energy Into electricity that is then stored in batteries or transferred to household or utility company power grids. (Deshmukh). This thesis is in on-grid mode. The chosen wind turbine is variable speed horizontal axis wind turbine, triple blade, offshore, upwind. This project focuses on DFIG that simply is a variable speed generator. The advantages of DFIG including, it is cheap, generate power even at low speed of wind, the power factor can be controlled, and the frequency of DFIG is constant and it does not change with the speed. This led us to main advantage of this generator which is lower cost and high efficiency.

B. Thesis Purpose

As can be concluded from the Betz coefficient that the losses almost % 59.25 of the power of the wind facing the turbine, meaning that the turbine only benefits from almost % 40 of the wind power. Therefore, methods have been developed to control the turbine so that it makes the most of the wind power possible.

II. LITERATURE REVIEW

Recently, there have been many studies about wind energy history, power generation of wind energy and control methods and technology of wind turbines. John Kaldellis , and Dimitrios Zafirakis mentioned a review of the wind energy, issues, performance, and history and according to his studies and the world needs for clean energy they expected by 2030 about 1 TW of wind energy will be enough (Kaldellis & Zafirakis, 2011). Nilaj Deshmukh explained in his studies the performance and the advantages of wind turbines compared to the fossil fuels (Deshmukh). Hermann – Josef Wanger introduced an overview on the basic concepts of wind energy (Wanger, 2018). John Fletcher discussed DFIG in detail and introduces in his book in ch.14 the DFIG operation, construction, and control methods (Fletcher, 2010). Wenping Cao, Ying Xie, and Zheng T provides brief reference guide for wind turbine generation systems and various topologies of adjusted speed generators (Cao, Xie, & T). Bnan Al – Qallab explained the concept of betz limit which says that power gained by the wind turbine is only 59.25% from the wind power, and this percentage is called Betz coefficient or Betz limit. Simply, out of every 100 units, the wind turbine benefits from 40 units only (Al-Qallab, 2019). The goal of this literature review is to compare three control methods that are implement on DFIG.

A. Grid voltage oriented vector control (Proposed method)

Controlling grid circuit the DFIG using this method is not complicated process, the DFIG is used in Mega scale wind turbine farms so it must be controlled. In the study by Mohammad Sleiman and Bachir Kedjar that deals with the Simulink, control, and modelling of DFIG for MPPT under nonlinear load and sudden wind speed variations and from the graphs can be resulted that the DFIG is one of the most efficient solutions to capture MPPT from the available wind energy, also losses in converters are reduced because the total power fraction is handled by the converter. (Sleiman & Kedjar, 2013). Wei Zhang and Yi Ruan were carried out a mathematical model of

GSC based on DFIG using switching functions to analyze their operating characteristics and the result was sinusoidal input currents with adjustable power factor and better static and dynamic characteristics as well as constant DC voltage can be obtained by the GSC (Zhang, 2012). Wiley provided the control schemes and block diagrams of the induction machine on MATLAB Simulink in his book. This book has been followed to implement the control scheme on MATLAB Simulink and from the graphs in this work can be resulted that in an open loop system, dc bus voltage fluctuation or ripple is large. For solving this problem there are two solutions (Wiley, 2011):

- one of the solutions is increasing the DC link capacitor size that is difficult to apply.
- And by suitable control a constant DC voltage value has been obtained.

B. Stator flux-oriented vector control

It is used for controlling stator circuit. Md Arifujjaman, Tariq iqbal, and J.E Quaicoe were carried out the associated control strategy and the dynamic modeling of DFIG (Md). Another investigation was carried out by MAishwaray Devi R studied the regulation of the active power and reactive power to achieve the independent control of the wind power and the DFIG reactive power, so he studied the power regulation of an on-grid wind energy at different wind speeds, and the from the graphs can be noticed the following (Devi, 2014):

- At different wind speeds, the control system obtained the maximum power and it has been achieved in milliseconds.
- The GSC and RSC change their function as converters and inverters automatically during the change between sub and super synchronous modes.

C. Static Kramer drive system

This method is applied for controlling the circuit of the rotor of the induction motor speed, which works through injecting voltage into the phase voltage to the circuit of the rotor and by this changing two factors will be controlled which are the resistance of the rotor and induction motor speed, and it can be applied just if the speed of the drive is lower than the synchronous speed. According to Amr Amin the mathematical models of this method are difficult to understand or can be applied for only steady-state analysis because it is applied on the rotor side, a mathematical model based on the reference frame theory and from the graphs or the Lab tests can be confirmed the validity of this model and verify that this model is not ignoring the commutation overlap angle effect. (Amin, 1999).

III. WIND TURBINE SYSTEM

A. Types of Energy?

Two types of energy, renewable and non-renewable, due to the damage caused by non-renewable energy and the continuous increase in global temperature due to global warming. So, research again began on developing renewable energies.

B. Wind Energy

Nowadays wind energy is used to generate electricity from it by using wind turbines and to get rid of conventional energy sources.

The advantages of wind energy are it used to produce reliable, affordable, and clean energy.

Figure 1 Strong wind.

C. What is Wind Turbine?

A wind turbine is a system designed to convert the wind's kinetic energy into mechanical energy using the rotor then from mechanical into electrical using the generator.

Wind turbine systems produce reliable, affordable, and clean energy. It can be used in many applications like electricity generation for buildings and standalone systems, etc.

D. Horizontal Axis Wind Turbine

Nowadays many types of wind turbines are used (Wanger, 2018). In general, what makes designing this type of turbine difficult is that the generator and gearbox are placed over the tower, which makes the design here complicated and expensive. It is considered one of the most modern turbines as research and developments are based on this model.

Among the advantages of this type of the following, its efficiency is high, its structure is characterized by strength and durability, and it is resistant to shocks and windstorms, it produces high output power, produces less noise, and has fewer negative impacts on the environment compared to other types, it looks beautiful for the environment. It reduces the cost of materials needed to design the turbine, which also reduces its weight.

The disadvantages of this system including, its rotation is slow due to the heavyweight of the blades and the cost of transporting and installing it, and its components are also expensive.

Figure 2 Horizontal axis wind turbine.

E. Components of Horizontal Axis Wind Turbine

There are fixed and other moving parts in the turbine. Mostly the moving parts are those that need constant maintenance, while the fixed parts are manufactured so that they last for many years that extend with the life of the turbine so that they are resistant to moisture, rust and various weather conditions, and this increases the cost of the turbine. As seen in figure below the components of the wind turbine.

The rotor includes blades, the hub, the low-speed shaft (main shaft), bearings and the biscuit.

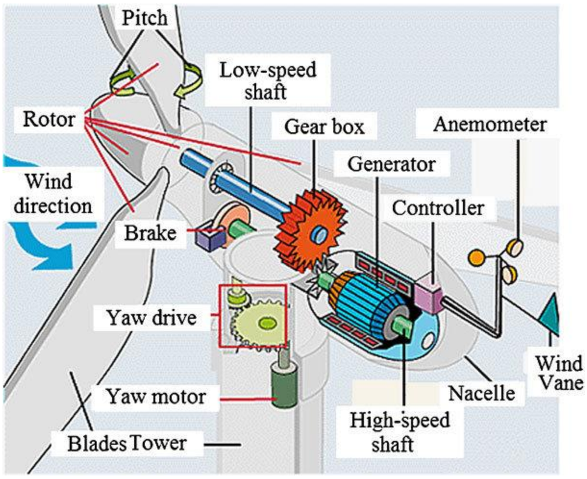


Figure 3 Components of the wind turbine (Magdi, 2012).

1. Tower

Its function holds and supports the rotor and nacelle and achieves the desired height.

2. Nacelle

It is the house or box that contains the turbine components and is placed in the turbine at the top of the tower. There is also wind vane and anemometer above it.

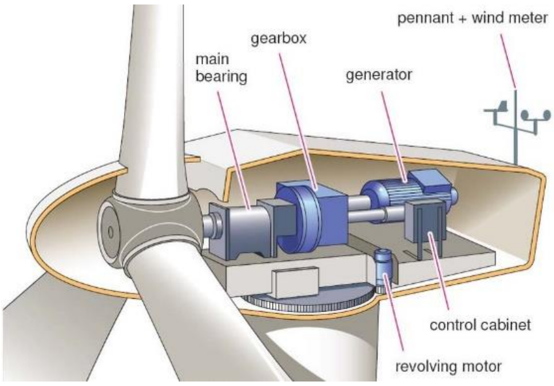


Figure 4 Nacelle of the wind turbine (Benbouzid & Amirat, 2008).

3. Hub

The part on which the blades are installed, and we can consider it the head of the turbine and the most part subjected to pressure, and this is why it is manufactured from very strong materials that are resistant to different weather conditions such as iron of all kinds either welded or cast and steel. It also carries the main shaft of the turbine, which is connected to the drive train. The hub contains the blade bearings, pitch system, and internals.

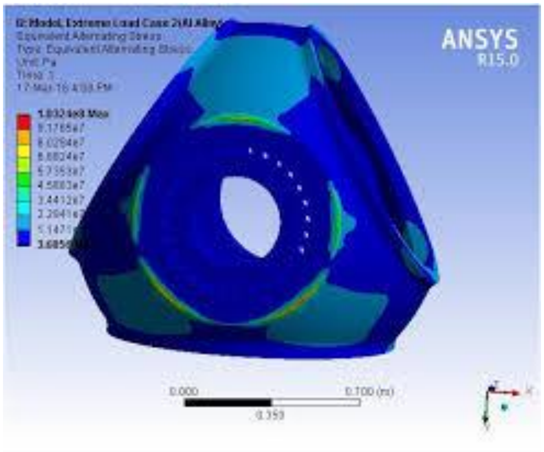


Figure 5 Hub of the wind turbine (S. Ravikumar, 2017).

4. Low-Speed Shaft

It is the shaft which is between the rotor and the gearbox.

5. Gearbox

The turbine's gearbox is made from high-quality aluminum alloys, cast iron ,and stainless steel.

In the turbine, it increases the speed as the speed enters the gearbox through the main shaft at slow speed and high torque, and in the high-speed shaft it is low torque and high speed. It is connected between the generator shaft and the slow-speed shaft to increase the rotational speed.

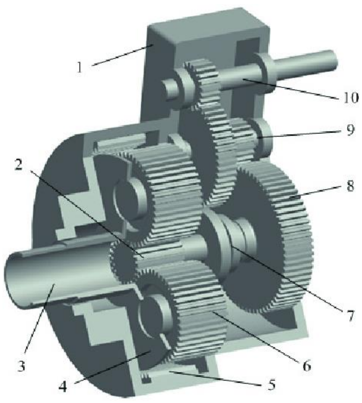


Figure 6 Gearbox of the wind turbine.

6. High-Speed Shaft

It rotates at high speed and low torque according to the capacity of the generator and the speed it needs to generate electricity.

7. Bearing

That holds the shafts and allows it to rotate.

8. Safety Brake

The turbine will not be able to rotate at high speeds because this will cause great pressure on the blades and accidents such as blade breakage, fire and explosion may occur. Therefore, the turbine must be stopped when it reaches its maximum permissible speed since after the turbine reaches the maximum permissible speed it produces the highest possible energy. However, if the speed is above the permissible speed then the generation efficiency will decrease.

If the brakes are used in the following cases: if the turbine reaches a dangerous speed, in the event of an electrical malfunction, and In the event of a breakdown of an electric supply.

There are two types of brakes: The primary brake and backup brake stops the turbine if the primary fails.

Figure 7 Brake of the wind turbine.

9. Generator

The output from the gearbox is transmitted to the generator set via the high-speed shaft which characterized by low torque and high speed.

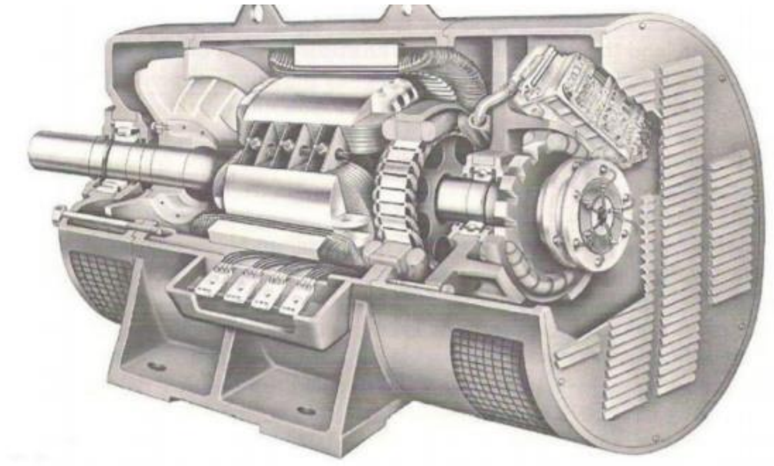


Figure 8 Generator of the wind turbine (Cao, Xie, & T).

10. Electronic Controller

A device that controls the entire turbine and its functions are as follows, it gives an order to the yaw drive or yaw system to rotate the nacelle when the wind vane gives a signal to the controller, then it gives an order to the pitch controller to change the pitch angle of the blades, and it gives a command to stop the turbine according to the speed sensors if it exceeds the permissible speed.

11. Anemometer

A device used to measure wind speed has been explained previously.

12. Wind vane

A device used to measure wind direction and When the wind vane gives a signal to the controller, then it gives an order to the pitch controller to change the pitch angle of the blades to be facing the wind. Also, it gives an order to the yaw drive or yaw system to rotate the nacelle.

13. Yaw Drive

It is located at the base of the nacelle and works with the aim of being able to change the rotor direction of the turbine.

The yaw system is responsible for directing the turbine towards the wind in the normal condition and directing it away from the wind in case of danger.

F. Induction Motor (Asynchronous motor)

An electric motor which converts the electrical to mechanical energy. It consists of the rotor and stator.

The advantages of induction motors are characterized by having simple designs, inexpensive, highly efficient, and rarely maintenance.

It is called an induction motor because the required rotor voltage and current are provided by induction from the stator winding. The rotor is not connected electrically to any source of supply.

1. Principle of Operation

The Induction motor work as a motor and generator.

Rotational speed (n) is what determines whether it works as a motor or as a generator.

NS: (Synchronous speed) It is the speed that separates the operation of the induction motor as a motor or as a generator.

If the rotational speed of the generator reaches a speed at maximum possible speed as a generator, then the generator will automatically shut down because it will become out of control.

In the wind turbines, before the wind comes, the induction motor works as a motor, then when the wind comes and the speed increases, then the gearbox increases the speed to a speed greater than the speed of synchronous speed, then it starts to work as a generator, and when it reaches point A as in the figure below which represents the maximum possible speed as a generator, it stops working automatically because it will become out of control.

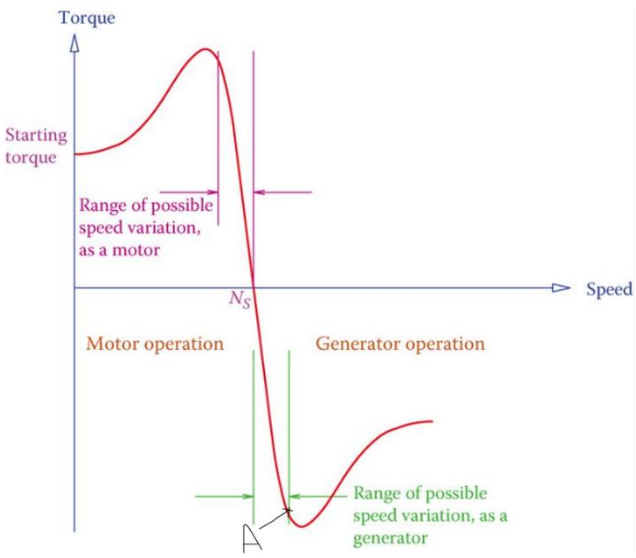


Figure 9 Speed-torque characteristic curve of a three-phase induction motor (Sue, 2011).

2. Wound Rotor Induction Motor

It is a type of induction motor. Nowadays it is used in wind turbines. The Active and Reactive power are needed, as follows:

Active / Real power: [W] fed from the generator to the grid.

Reactive power: [VAR] needed for excitation of the generator and it's fed from the grid to the generator.

Wound rotor induction motor consists of rotor, stator, slip ring brushes, and wires.

From the stator, there are 3 wires connected to the transformer or to the grid, and from the rotor, there are 3 wires that connected to the converter through slip rings and brushes holding them at the end of the rotor's wires. The brushes are holding the slip rings, so the brushes do not rotate but the slip ring rotates.

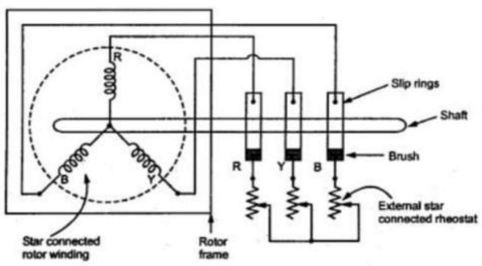


Figure 10 Stator and rotor of Wound rotor induction motor.

G. Betz Limit

In this model, Newton's laws of mechanics will be applied. It is assumed here that the wind flow is axial and concentrated towards the rotor and that the winds are not dispersible.

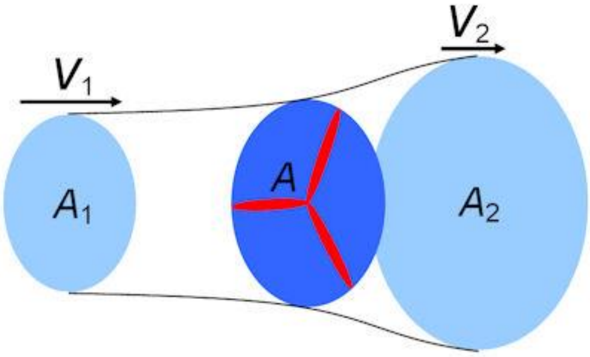


Figure 11 Wind affected area in a wind turbine.

$$\text{Energy} = \text{Power} \times \text{Time} \quad \textbf{(3.1)}$$

The power produced by the turbine is given by the following equation:

$$P = \frac{1}{2} \times m \times v^2 \quad \textbf{(3.2)}$$

$$= \frac{1}{2} \times m \times (v_1^2 - v_2^2) \quad \textbf{(3.3)}$$

Where, v_1: The wind speed before hitting the turbine. v_2: The wind speed after the turbine.

And the mass m is equal to:

$$m = \rho \times A \times v \quad \textbf{(3.4)}$$

Where, ρ : Density of the air. A: Swept rotor area. V : Wind speed.

Average speed of the wind turbine rotor is given by:

$$v_{avg} = \frac{1}{2} \times (v_1 + v_2) \quad \textbf{(3.5)}$$

When substituting equation 5 into kinetic power equation the result is:

$$P_{kin} = \frac{1}{2} \times \rho \times A \times (v_1^2 - v_2^2) \times v_{avg}$$

$$= \frac{1}{2} \times \rho \times A \times ((v_1 + v_2)/2) \times [v_1^2 - v_2^2]$$

$$= \frac{1}{4} \times \rho \times A \times [v_1^3 - v_2^3 - v_1 \times v_2^2 + v_1^2 \times v_2]$$

$$= \frac{1}{4} \times \rho \times A \times v_1^3 \times [1 - \left(\frac{v_2}{v_1}\right)^3 - \left(\frac{v_2}{v_1}\right)^2 + \left(\frac{v_2}{v_1}\right) \qquad \textbf{(3.6)}$$

To find the point at which the maximum power is achieved, the equation 6 with respect to v_2 is derived.

$$dP_{kin}/ dv_2 = \frac{1}{4} \times \rho \times A \times [(-3) \times v_2^2 - 2 \times v_1 \times v_2 + v_1^2] = 0$$

$$= (-3) \times v_2^2 - 2 \times v_1 \times v_2 + v_1^2 = 0$$

$$= (3 \times v_2 - v_1) \times (v_2 + v_1) = 0$$

$$3 \times v_2 - v_1 = 0 \rightarrow\rightarrow\rightarrow v_2 = \frac{1}{3} \times v_1 \qquad \textbf{(3.7)}$$

When substituting v_2 into P_{kin} equation, the following is concluded:

$$P_{kin} = (0.5925) \times \frac{1}{2} [\rho \times A \times v_1^3]$$

$$P_{kin} = 0.5925\, P_{wind} \qquad \textbf{(3.8)}$$

Where, P_{kin} : The wind turbine kinetic power. P_{wind}: Power of the wind.

The power a turbine gains from wind power is influenced by rotor space, the length of the blades, and wind speed: wind speed is the most influential factor because it is raised to the power of 3 v^3.

The number 0.5925 means that the power gained by the wind turbine is only 59.25% from the wind power, and this percentage is called Betz coefficient or Betz limit. Simply, means that out of every 100 units, the wind turbine benefits from 40 units only.

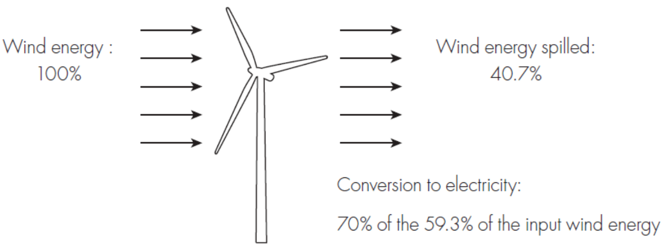


Figure 12 Effect of Betz coefficient (Al-Qallab, 2019).

H. The Mechanical Power of Wind Energy

The energy in the wind is defined as the kinetic energy expended in the wind per unit time. This can be described by:

$$P_o = \frac{1}{2}\rho A V_o^3 \qquad \textbf{(3.9)}$$

However, the power that can be used for something useful is limited by a factor called "Betz Coefficient" or "Betz Limit" that is 0.592 or 59.2% . As can be concluded from the Betz coefficient that the losses almost $\%\ 59.2$ of the power of the wind facing the turbine, meaning that the turbine only benefits from almost % 40 of the wind power.

The turbine out maximum power is described by:

$$P_m = \frac{1}{2}\rho C_p A V_o^3 \qquad \textbf{(3.10)}$$

Where C_p is the power coefficient that determined by TSR tip speed ratio and pitch angle. The figure below shows the $C_p - \text{TSR}$ curve at variable values of pitch angle.

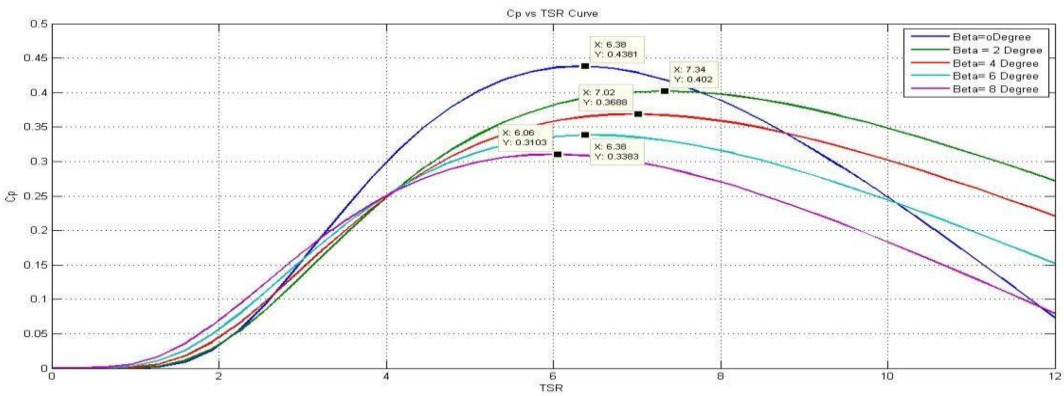


Figure 13 Cp vs TSR curve.

As can be concluded from the above figure, when the value of pitch angle increases, the C_p optimum value will decrease. The maximum power can be achieved by operating the turbine at the C_p optimum value and lowest value of pitch angle which is zero. The stall control is to turn off the generator of when the speed of the wind is more than the allowable limit.

Now important definitions in wind turbine system will be defined. Cut-in speed is the minimum wind speed required to start producing power from the wind turbine.

According to the previous equations between this speed and rated speed the wind turbine power varies with cube of wind speed. The output power remains constant between the rated speed and cut-out speed. The cut-out speed, at this wind speed the wind turbine will be turned off automatically by using different methods.

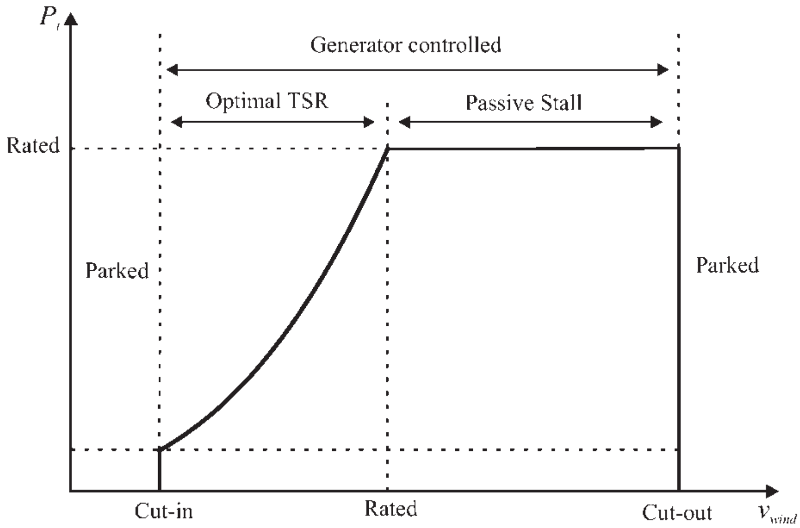


Figure 14 Cut-in, rated, and cut-out wind speed.

I. Control Methods of Horizontal Variable-Speed Wind Turbine

The wind turbine which is used here converts mechanical energy to electrical energy by using the DFIG. The generated wind turbine mechanical power can be given by:

$$P_m = \frac{1}{2}\, \pi\, \rho\, R^2\, C_P\, (\lambda\, \beta)\, v_\omega^3 \qquad \textbf{(3.11)}$$

$$\lambda = \frac{\Omega_t\, R}{v_\omega} \qquad \textbf{(3.12)}$$

Where P_m : Mechanical power , ρ: Air density , R: Blade radius , C_P: Performance coefficient

λ: Tip speed ratio , β: Pitch angle , Ω_t: Rotor shaft speed , v_ω: wind speed

In General, C_P is a nonlinear function of the β and λ that can be given by:

$$C_P\,(\lambda, \beta) = C_1 \left(\frac{C_2}{\lambda_i} - C_3\, \beta - C_4\right) e^{\frac{-C_5}{\lambda_i}} + C_6\, \lambda_i \qquad \textbf{(3.13)}$$

And , $$\lambda_i = \left[\frac{1}{(\lambda + C_7\, \beta)} - \frac{C_8}{(\beta^3 + 1)}\right]^{-1} \qquad \textbf{(3.14)}$$

The turbine control methods that will be discussed including, pitch angle control, yaw angle control, control of generator speed and grid voltage-oriented vector control.

1. Pitch Angle Control System

Basically, there are two essential forces on the blade that cause movement in the blade, the forces are lift force and drag force. In figure below the forces acting on the blades are seen.

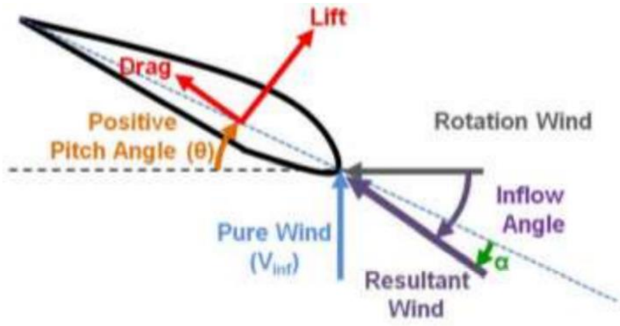


Figure 15 Force acting on the blades.

Here we use a wind turbine with 3 blades. There is a hydraulic motor for each blade to control the pitching of the blade. The three hydraulic motors move at the same time with the same movement. One-pitch control is applied for all three hydraulic motors. When the power of the turbine reaches the rated power, the mechanical power delivered to the generator must be limited.

2. Yaw Angle Control System

Basically, the upwind turbine which faces a wind direction uses this control system. Yaw angle control system: A mechanical geared system with a motor rotates the turbine to face the wind. There is a sensor to detect the wind direction.

IV. DOUBLY FED INDUCTION GENERATOR

A. Introduction

The WRIM is used in DFIG. The DFIG application is in a wind turbine. The reason to call it DFIG is as follows: Doubly fed because it is fed from two sides or from two power sources. Hence, the it is fed from the stator and rotor.

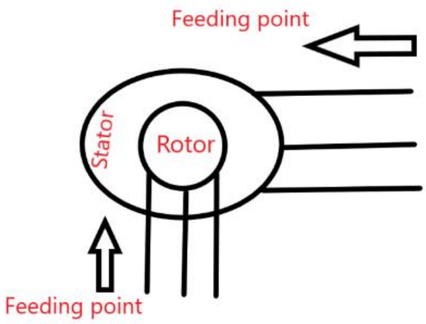


Figure 16 Feeding points DFIG.

An induction because of the principle of its operation is induction. Generator because it works as a motor as well as a generator.

From the scheme of the DFIG it is shown that DFIG is a variable speed fixed frequency generator, which means the frequency is constant and does not depend on the generator speed and determined in the DFIG by the grid, which is the electricity company.

The DFIG scheme consists of Stator and rotor. The stator is directly connected with grid. The rotor is connected with grid through the back-to-back $AC - DC - AC$ frequency converter. The advantages of DFIG including, it is cheap, generate power even at low speed of wind, the power factor can be controlled, and the frequency of DFIG is constant and it does not change with the speed. The configuration is shown below.

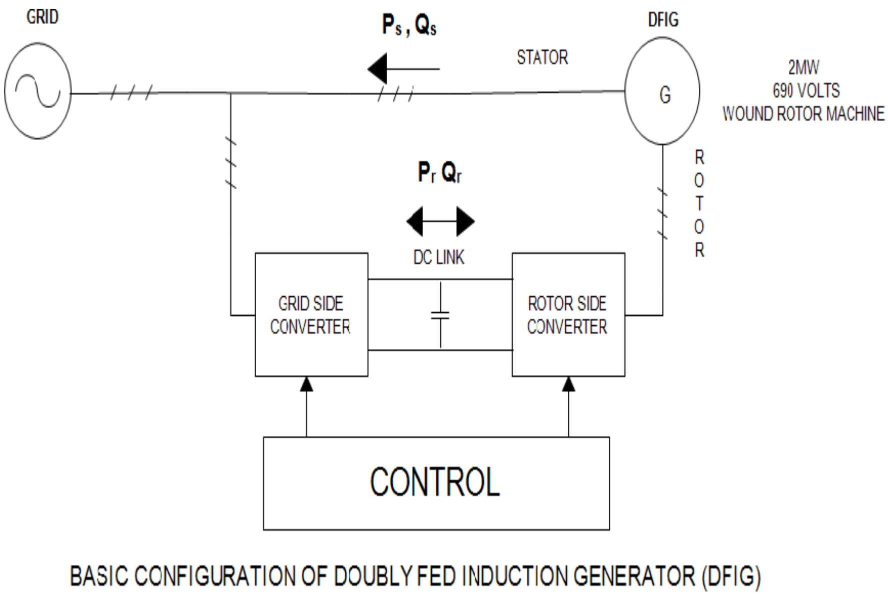


Figure 17 The configuration of DFIG.

As can be shown from the above figure, the power flow in the stator is unidirectional that means it is fed from one side which is from the stator to grid. Also, it can be noticed that the power flow in the rotor is bidirectional which mean it is fed from two sides either from rotor to the grid or from grid the rotor. Because of the wind fluctuation the deviation in power is managed through the rotor.

B. Construction of DFIG

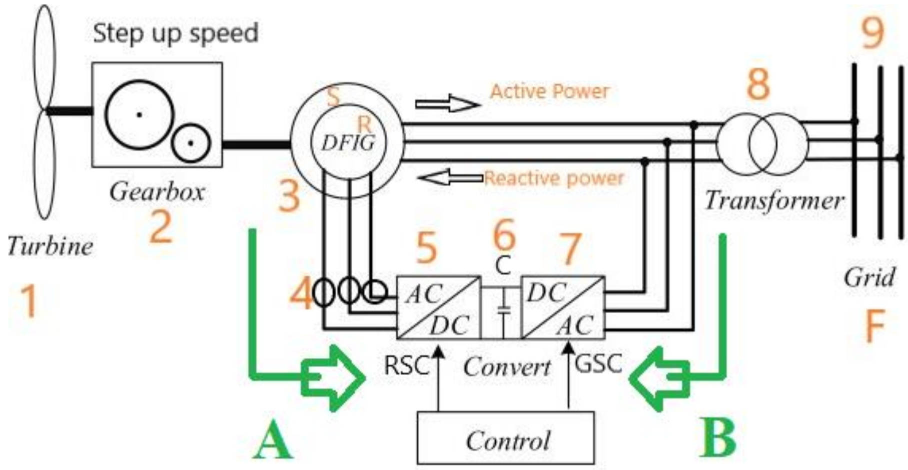


Figure 18 DFIG schematic (Torkaman, 2018) (Wiley, 2011).

The main shaft rotates at low-speed high torque. Then the gearbox function is to step up the high-speed shaft rotational speed at high speed and low torque. The numbered parts in the pi are as follows:

1)) The turbine's main shaft.

2) Step up gearbox to increase the rotational speed.

3)) Wound rotor induction motor which mainly consists of rotor and stator. From the stator, there are 3 wires which are connected to the grid. The rotor has 3 wires which are connected to the converter by slip rings and brushes at the end of it.

4)) The slip rings and brushes which needed at the end of the rotor's wires.

5)) RSC: It stands for Rotor Side Converter. It is called by this name because it is at the rotor side.

6)) DC link: it is used as a filter to remove the ripple present in the DC signal.

7)) GSC: It stands for Grid Side Converter. It is called by this name because it is on the grid side.

C. The Principle of Operation of DFIG

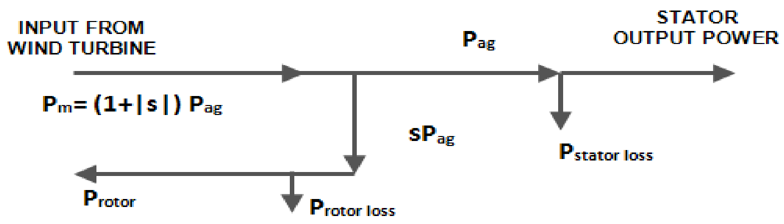
Simply, the principle of operation of DFIG is the speed of the rotor varies though, through the suitable adjustment of the frequency of the rotor it is still can be got a constant value of the frequency of the stator as can be noticed from the equation below that describes the DFIG stator frequency:

$$f_{Stator} = \frac{\text{Rotor Speed} \times \text{Number of Poles}}{120} \pm f_{Rotor} \quad \textbf{(4.1)}$$

If the generator is running at speed higher than the synchronous speed (η_S) that is called super synchronous mode, that means power flow in rotor circuit is fed from rotor side to grid side. At this mode to remain or keep the frequency of the rotor constant, a negative frequency component $(-f_{Rotor})$ must be added. $(-f_{Rotor})$ means that power is flowing from the rotor to the grid. Also, if the generator is running at speed less than the η_S a positive frequency component $(-f_{Rotor})$ must be added to remain the f_{Stator} constant. However, when the generator is running at a η_S the f_{Rotor} is zero that means a constant dc is fed to the rotor. In that case, it can be said that DFIG is acting as a synchronous generator. DFIG nowadays is used in Mega scale projects, the operation modes of it are sub and super synchronous (Fletcher, 2010).

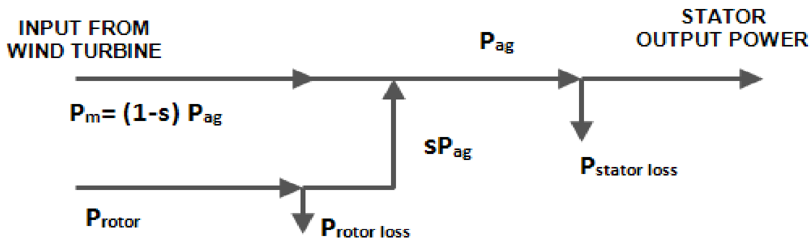
More simply, When the wind turbine's speed is higher than the η_S the energy and speed of the rotor increases. In this case the DFIG control scheme helps to remain the speed and output frequency of the rotor constant by extracting the extra power and fed it to the grid.

However, in sub synchronous the power is flowed from the grid side to the rotor side. This mode appears if the rotor tries to decrease its speed, then power is fed to the rotor and it does the work of the motoring to maintain its speed at η_S. The path of the power of DFIG in both modes is describes in the figures below.



POWER FLOW IN DFIG DURING SUPER SYNCHRONOUS MODE OF OPERATION

Figure 19: Super synchronous mode in DFIG.



POWER FLOW IN DFIG DURING SUB SYNCHRONOUS MODE OF OPERATION

Figure 20 Sub synchronous mode in DFIG.

D. Modelling of DFIG

A normal DFIG is a Wound rotor induction generator which consists of rotor and stator circuit (Devi, 2014). The components of the stator circuit are a balanced $3-$ phase winding located in $120\,°$, a stator frame, and a laminated stator core including stator slots embedded inside. Distributed winding in nature, insulated and located in stator slots. The components of the rotor circuit are three-phase insulated windings, rotor, and rotor slots. They are connected to one end of them to form a star connection and on the other side are connected by slip rings. The component of the converter is a 2 level full bridge converters connected through a dc link bus. The first level is the RSC and the second level is the GSC. The RSC and GSC according to the mode sub or synchronous mode might act either as inverter or rectifier. If GSC acts as inverter, then the RSC will act as rectifier and the opposite is true. IGBT switches are used for this function. The figure below shows the 6 IGBT's in the RSC and the 6 IGBT's in the GSC. The RSC and GSC in DFIG can work as inverter and rectifier. IGBT stands for Insulated Gate Bipolar Transistor. The IGBT is controlled by the gates. The RSC and GSC are controlled by the 6 IGBT.

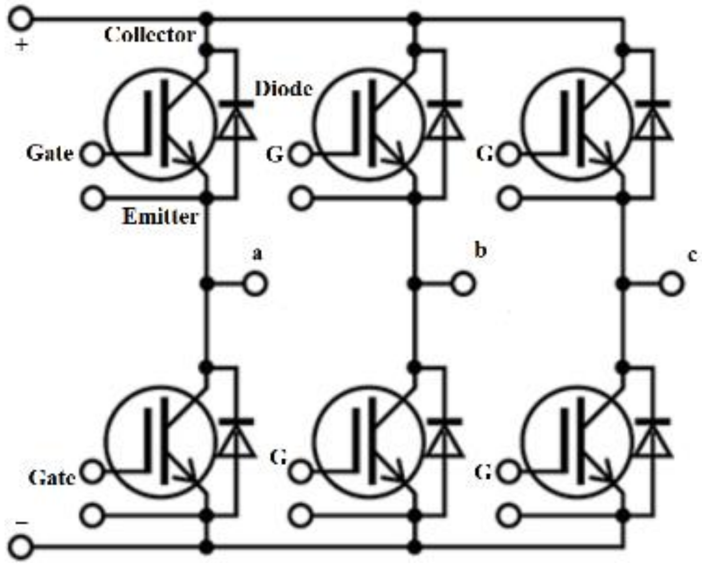


Figure 21 IGBT's construction.

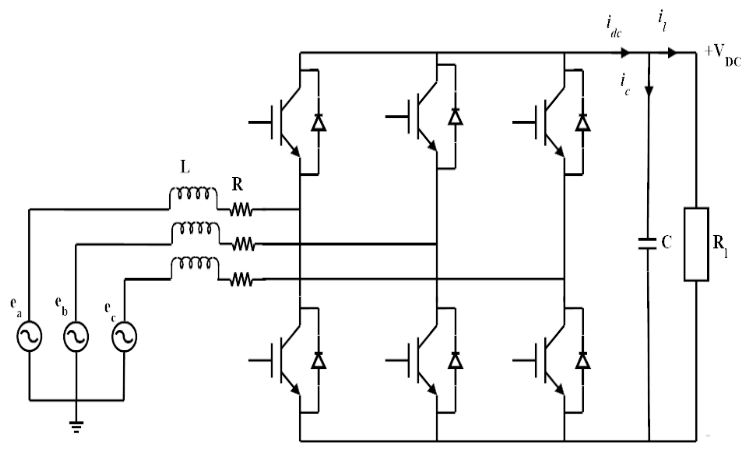


Figure 22 Full bridge converter 2 level with IGBT.

If DFIG is connected to a balanced $3-\text{phase}$ source, a rotating magnetic field will be generated in the stator circuit and a magnetic field will be created in the rotor side because of the power fed to rotor side. By rotating reference frame, the magnetic fields are described in the following equations:

$$\phi_{ds} = L_{ss}\, i_{ds} + L_m i_{dr} \quad \textbf{(4.2)}$$

$$\phi_{qs} = L_{ss}\, i_{qs} + L_m i_{qr} \quad \textbf{(4.3)}$$

$$\phi_{dr} = L_{ss}\, i_{dr} + L_m i_{ds} \quad \textbf{(4.4)}$$

$$\phi_{qr} = L_{ss}\, i_{qr} + L_m i_q \quad \textbf{(4.5)}$$

Also, the voltage of the rotor and the voltage of the stator in rotating reference frame are described below:

$$V_{ds} = R_s\, i_{ds} + \left(\frac{d\phi_{ds}}{dt}\right) - \omega_s\, \phi_{qs} \quad \textbf{(4.6)}$$

$$V_{qs} = R_s\, i_{qs} + \left(\frac{d\phi_{qs}}{dt}\right) - \omega_s\, \phi_{ds} \quad \textbf{(4.7)}$$

$$V_{dr} = R_r\, i_{dr} + \left(\frac{d\phi_{dr}}{dt}\right) - (\omega_s - \omega_r)\phi_{qr} \quad \textbf{(4.8)}$$

$$V_{qr} = R_r\, i_{qr} + \left(\frac{d\phi_{qr}}{dt}\right) + (\omega_s - \omega_r)\phi_{dr} \quad \textbf{(4.9)}$$

Another important definition is the emf rotation that occurs because of the rotation of the axis. In the stator circuit, the magnetic field speed, and the synchronous speed (ω_s) equal to each other. But in a rotor circuit, the rotating axis speed is the relative speed between the stator rotating magnetic field of the stator and the rotor and it is represented by $(\omega_s - \omega_r)$.

The stator reactive power and active power are shown below:

$$P_s = 3/2\left(V_{ds} \times i_{ds} + V_{qs} \times i_{qs}\right) \quad \textbf{(4.10)}$$

$$Q_s = 3/2\left(V_{qs} \times i_{ds} - V_{ds} \times i_{qs}\right) \quad \textbf{(4.11)}$$

E. Power Control Schemes of DFIG

Control the power converter of the rotor side circuit of DFIG is essential and through RSC and GSC, the whole DFIG is being controlled. By applying the vector control method on RSC and GSC the control process is simpler, faster, and more efficient. The advantage of it is the response first, also reactive power and active power could be controlled separately.

The process of the vector control scheme is as follows. In the first step, the 3 phase quantities are transformed into 2 mutually orthogonal frames of reference. In the second step, by separately controlling these two components, separate control is achieved.

1. Control of RSC

The importance of control the RSC is to control the reactive power and the active power of the stator side separately (Md) (Devi, 2014). A stator flux-oriented vector control scheme is applied for this purpose. To apply this scheme first there are assumptions as shown below.

>The stator voltage drop across the resistance is neglected because the stator resistance value is very low in value.

> The frequency and amplitude of the stator and the grid voltage are assumed to be constant.

>The q-axis rotates $90\,^{\circ}$ ahead of the d-axis at synchronous speed in the direction of rotation.

>The stator flux vector is aligned with the stator $d-$axis.

Those assumptions mathematically are represented as shown below:

$V_{ds} = 0 \qquad V_{qs} = V_s$

$\phi_{ds} = \phi_s \qquad \phi_{ds} = 0$

The P and Q will be as shown below:

$$P_s = \frac{3}{2}\left(V_{qs} * i_{qs}\right) \tag{4.12}$$

$$Q_s = \frac{3}{2}\left(V_{qs} * i_{ds}\right) \tag{4.13}$$

Hence, the reactive power and active power of the stator are controlled in a separate manner if the $d-$axis and $q-$axis components separately of current being controlled.

2. Control of GSC

The aim of controlling the GSC is to regulate the voltage across the DC link and to compensate for reactive power at the grid (Sleiman & Kedjar, 2013). The grid voltage-oriented vector control scheme is used for this purpose by aligning the $dq-$axis in the direction of grid voltage.

F. Modelling of GSC

In DFIG 70% of the energy flows in the path of the active power that is from the stator towards the grid, and only 30% of the energy is in the direction from the rotor to the grid. This means the converter sizing is only 30% in size, the power converter is usually rated at 25-30% of the generator power rating (Bedoud, Ali-rachedi, Bahi, Lakel, & Grid, 2015). Control of DFIG is an essential matter that cannot be neglected. It keeps the generator parameters, such as speed, reactive power, active power, and DC bus voltage near-optimal values.

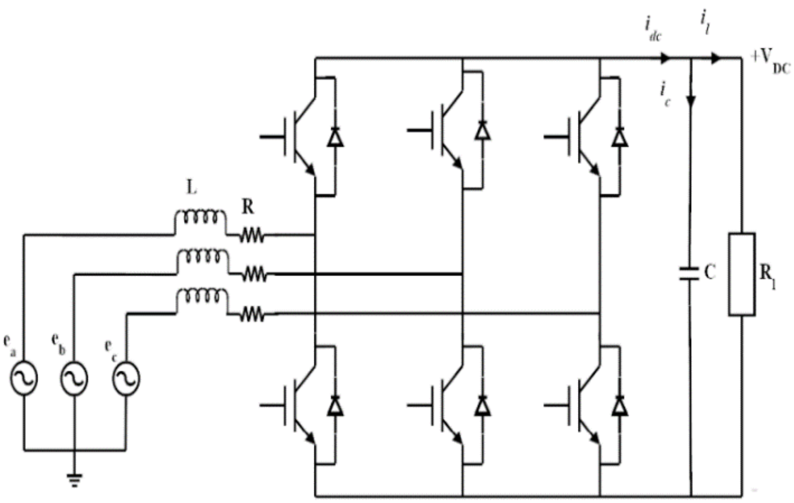


Figure 23 GSC configuration.

As shown in figure above the GSC circuit is supplied by a three-phase circuit.

In the middle between the RSC and GSC, there is a DC-link that includes a capacitance C feeding to a resistance R. Capacitance C which has two functions, it works as a filter and feeding the resistance R, also it can supply or feed limited reactive power.

The dynamic model of GSC in dq rotatory reference frame is described as follows:

$$L_g \frac{didg}{dt} = V_{dg} - R_g i_g - V_{dc} + \omega_g L_g i_{qg} \quad \textbf{(4.14)}$$

$$\text{and, } L_g \frac{diqg}{dt} = V_{qg} - R_g i_g - V_{dc} + \omega_g L_g i_{qg} \quad \textbf{(4.15)}$$

Also, the active and reactive power associated with GSC are described as follows:

$$P_g = \frac{3}{2} \left(V_{dg}\, i_{dg} + V_{qg}\, i_{qg} \right) \quad \textbf{(4.16)}$$

$$Q_g = \frac{3}{2} \left(V_{qg}\, i_{dg} - V_{dg}\, i_{qg} \right) \quad \textbf{(4.17)}$$

V. PROPOSED METHOD AND SIMULATION

A. Vector Control Scheme

As shown in figure below, the rotating reference frame dq axis will be rotated along the voltage of the grid. However, ($V_{dg} = V_g$) and $V_{qg} = 0$. That will change the power equations as shown below:

$$P_g = \frac{3}{2}\left(V_{dg}\, i_{dg}\right) \quad \textbf{(4.18)}$$

$$Q_g = -\frac{3}{2}\left(V_{dg}\, i_{qg}\right) \quad \textbf{(4.19)}$$

Where, V_g is the full grid voltage. There are 2 control loops for the GSC control as shown in figure below.

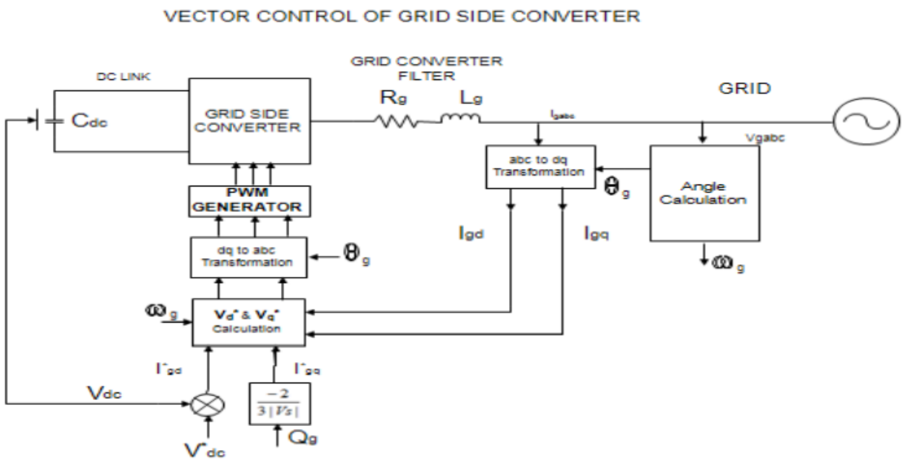


Figure 24 GSC control scheme (Zhang, 2012).

The DC bus voltage control loop was developed based on the power balance principle on both sides of the GSC. So mathematically can be described as shown:

$$V_{dc}\, i_{dc} = V_{dg}\, i_{dg} + V_{qg}\, i_{qg} \quad \textbf{(4.20)}$$

As the $d-$axis of the reference frame is oriented to the grid that will makeV_{qg} and $i_{qg} = 0$. So, the above equation will be:

$$V_{dc}\, i_{dc} = V_{dg}\, i_{dg} \quad \textbf{(4.21)}$$

But, $\mathrm{i_{dc} = i_c + i_1 = C\,\frac{dVdc}{dt} + i_1}$ **(4.22)**

After substitution into the equation:

$$\frac{\mathrm{dV\,dc}}{\mathrm{dt}} = \frac{\mathrm{V_{dg}\,i_{dg}}}{\mathrm{C\,V_{dc}}} - \frac{\mathrm{i_1}}{\mathrm{C}} \quad \textbf{(4.23)}$$

$\mathrm{V_{dc}}$ can be controlled through $\mathrm{i_{dg}}$ in case $\mathrm{i_1}$ is used as a disturbance. In this case as can be seen in figure above the DC link voltage and reference DC link voltages are compared. The DC link voltage reference value from the following:

$$\mathrm{V_{dc,min}} \geq \sqrt{3}\,\mathrm{V_{gm}}\ \text{(For SVPWM Switching)} \quad \textbf{(4.24)}$$

To get the reference value of $\mathrm{i^*_{gd}}$ the difference between the voltages is calculated then fed to a PI controller. Also, the reference value of $\mathrm{i^*_{gq}}$ is got through the $\mathrm{Q_g}$. The reference value $\mathrm{i^*_{gd}}$ and the reference value of $\mathrm{i^*_{gq}}$ are compared with the grid current dq − original values ($\mathrm{i_{gd}}$ and $\mathrm{i_{gq}}$).

The resulting signal is fed back to the PI controllers to get the reference values of $\mathrm{V^*_{gq}}$ and $\mathrm{V^*_{gq}}$. The resulting signals are then turn into $\alpha\beta$ − reference frame and finally fed to a space vector pulse width modulation (SVPWM) to generate the control pulses.

B. Simulation Figures

The figure below shows grid voltage-oriented vector control scheme block diagram which has been implemented on MATLAB Simulink.

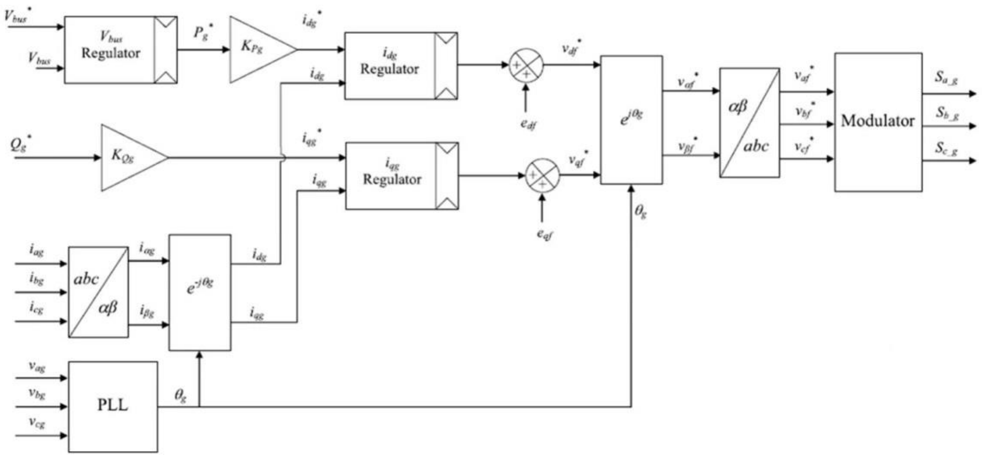


Figure 25 Grid voltage oriented vector control block diagram (Wiley, 2011).

Why it is important to convert from dq to alpha-beta?

When you are working in abc system in that case you have 2 parameters the time and the angle so we can't analyze that's why we have to change from abc to dq and from dq to alpha-beta.

The figure below shows general control scheme with values on MATLAB.

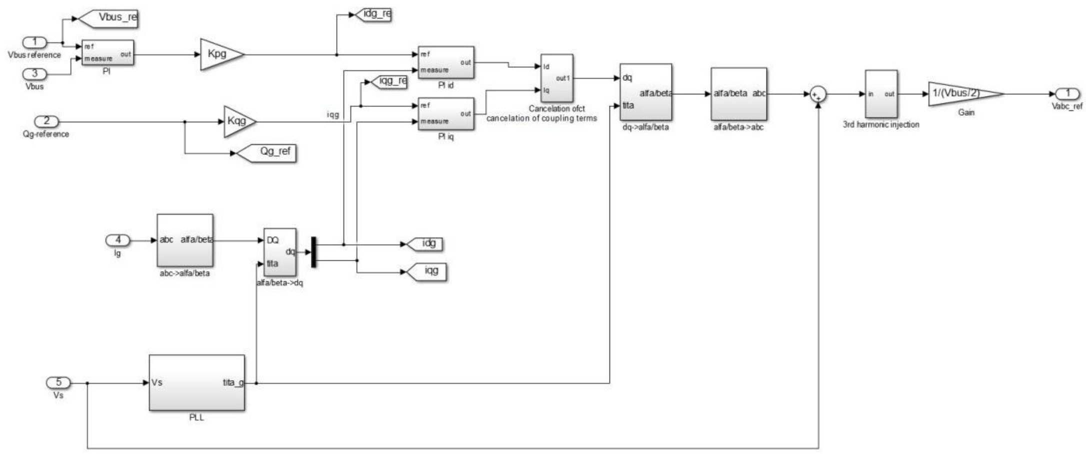


Figure 26 General control scheme block diagram.

The figure below shows PI block contents. This is the PI contoller for the dc bus voltage where $\mathrm{Kp_v}$: propotional gain $= -1000$, $\mathrm{ki_v}$: interrupt gain $= -300000$

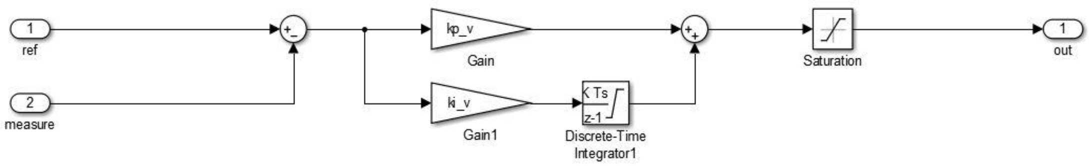


Figure 27 PI block.

The figure below shows PI controller for the idg (d-axis component grid current).

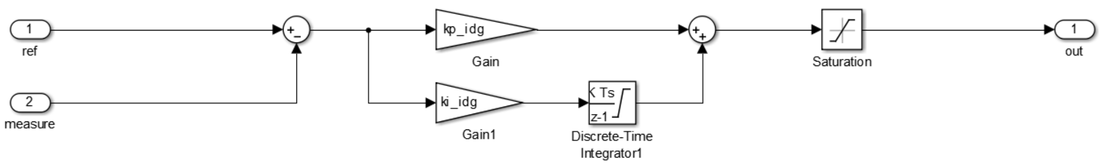


Figure 28 PI controller for the idg.

The figure below shows PI controller for the iqg (q-axis component grid current).

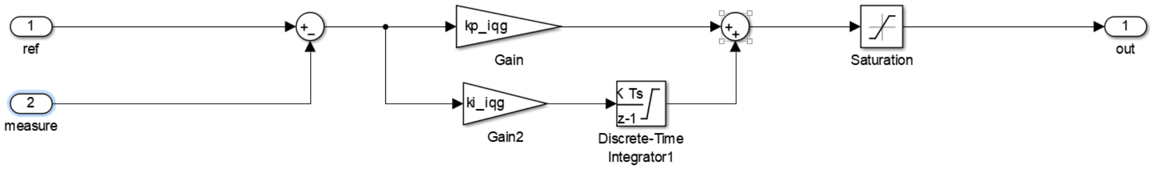


Figure 29 PI controller for the iqg.

The figure below shows the 3d harmonic injection and this allow to increase 15 percent of the output voltage and the gain has been used after it because also the output Vabc – ref must be normalized (Normalizing according to our dc bus voltage at the converter)

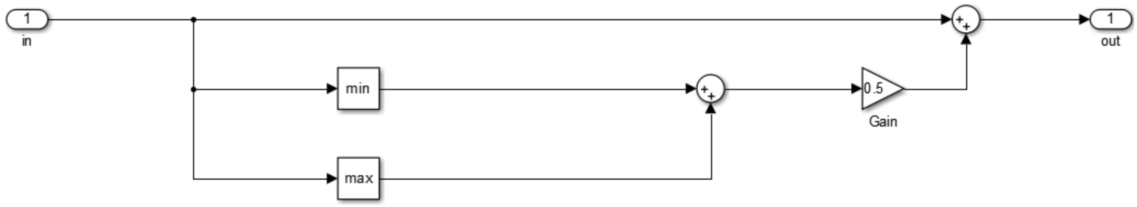


Figure 30 PI third harmonic injection.

C. Simulation Results

Tables 1 , 2, 3, and 4 show the MATLAB Simulink used parameters for stator and rotor side.

Table 1 Rotor parameters refereed to the stator side.

Values with symbol	Name
f = 50	% Stator frequency (Hz)
Ps = 2e6	% Rated stator power (W) (Active Power)
n = 1500	% Rated rotational speed (rev/min)
Vs = 690	% Rated stator voltage (V)
Is = 1760	% Rated stator current (A)
Tem = 12732;	% Rated torque (N.M)
p=2	% Number of pole pair
Vr = 2070;	% Rated rotor voltage (non-reached)(V)
Rs = 2.6e-3;	% Stator resistannce (ohm)
Lsi = 0.087e-3;	% Leakage inductance (stator & rotor) (H)
Lm = 2.5e-3;	% Magnetizing inductance (H)
Rr = 2.9e-3;	% Rotor resistance referred to stator (ohm
Vbus = 1150;	% DC de bus voltage referred to stator (V)

Table 2 GSC parameters.

Values with symbol	Name
Cbus = 80e-3;	% DC bus capacitance
Rg = 20e-6;	%Grid side filter's resistance
Lg = 400e-6;	% Grid side filter's inductance
beta=0;	% Pitch angle

Table 3 PI regulations parameters.

Values with symbol
kp_v = -1000;
ki_v = -300000;

Table 4 Three blade wind turbine model parameters.

Values with symbol	Name
N = 100;	% Gearbox ratio
Radio= 42;	% Radius
ro= 1.225;	% Air density
beta=0;	% Pitch angle

The performance of grid side and rotor side converter is shown in results below.

The values of V_{wind} (the wind speed) and Q_g (reactive power at the grid) are the simulation inputs.

Table 5 The input parameters.

Values with symbol	Name
Vwind = 7.5	% Wind Speed (m/s)
Qg = 0	% Reactive Power (VAR)

The performances of RSC and GSC are shown in the graphs below.

During the start up the grid side converter and rotor side converter reaches their stable operation point.

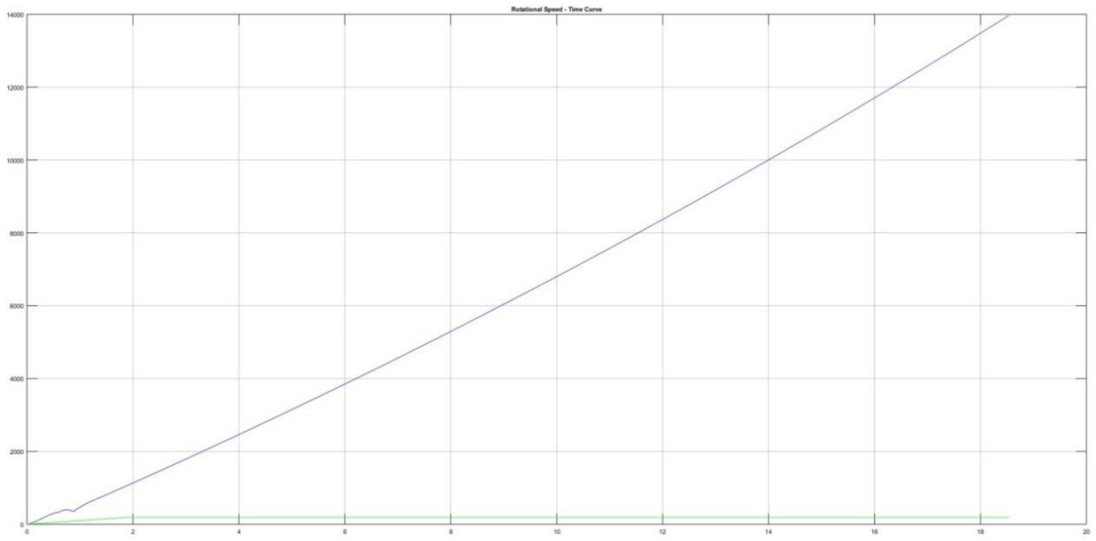


Figure 31 Rotational speed of the generator.

Figure above represents the rotational speed of the generator and as expected it increases continuously. Control at RSC working to it's optimal rotational speed value according to the wind speed that we have set.

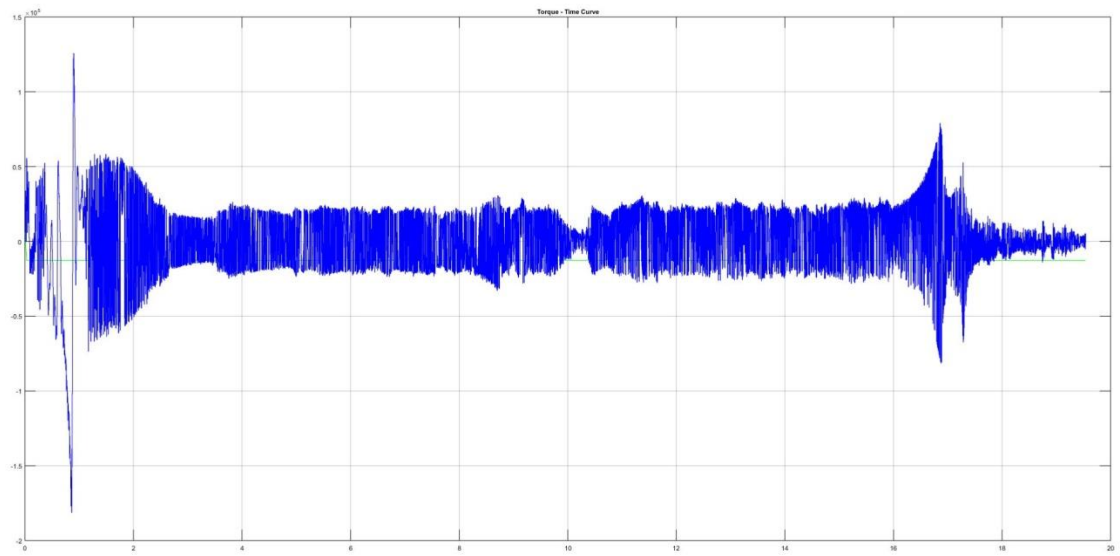


Figure 32 Torque of the generator.

Figure above represents the torque, and it is obvious that it is working properly.

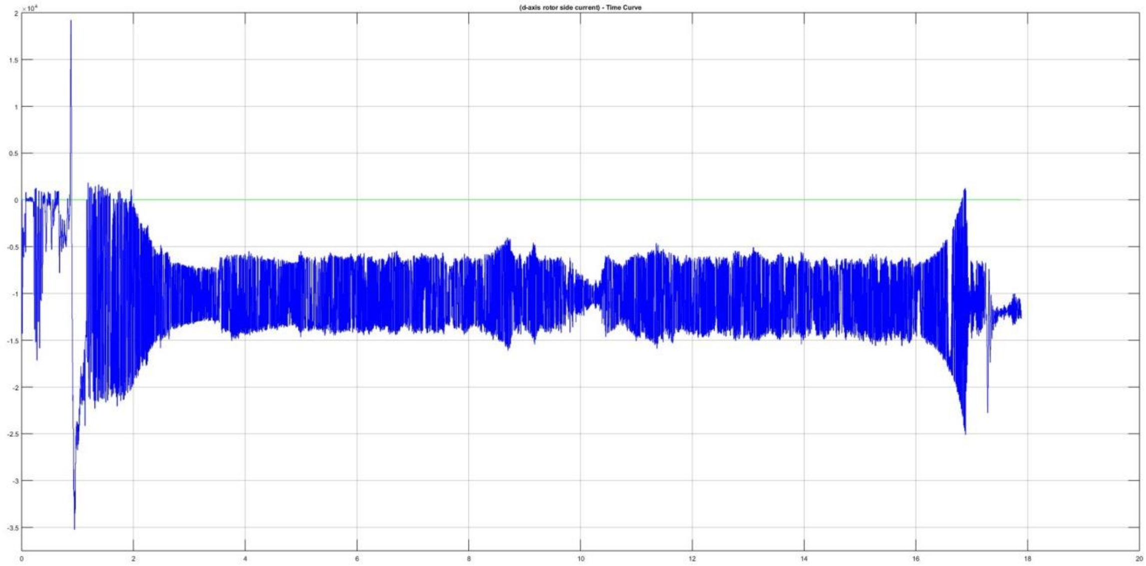


Figure 33 d-axis current in the rotor side converter.

This figure above represents the d-axis current in the rotor side converter, and it is working properly.

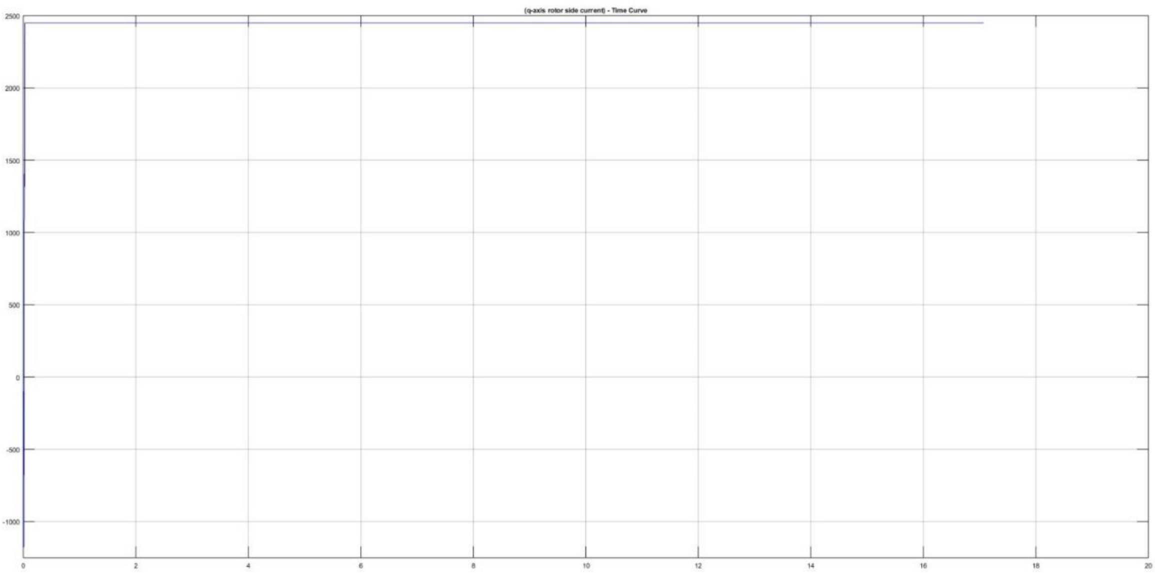


Figure 34 q-axis current in the rotor side converter.

This figure above represents the d-axis current in the rotor side converter, and it is working properly.

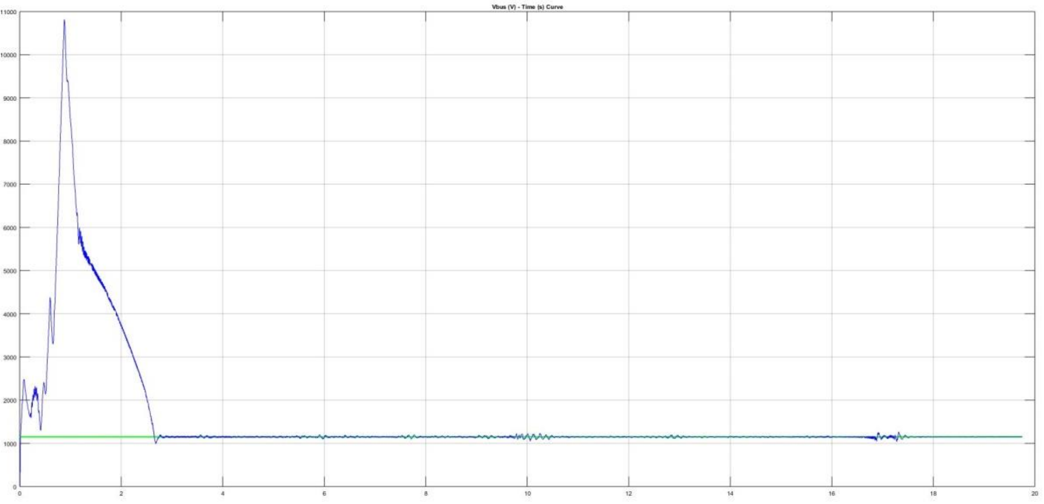


Figure 35 DC-link voltage.

The figure above shows that in an open-loop system, dc bus voltage fluctuation or ripple is very large. After implementing the grid voltage-oriented vector control by suitable control of the converter a constant DC voltage value has been achieved. The green line represents the DC link voltage which is 1150 v in the ideal case, and the blue line represents the DC link that has been got.

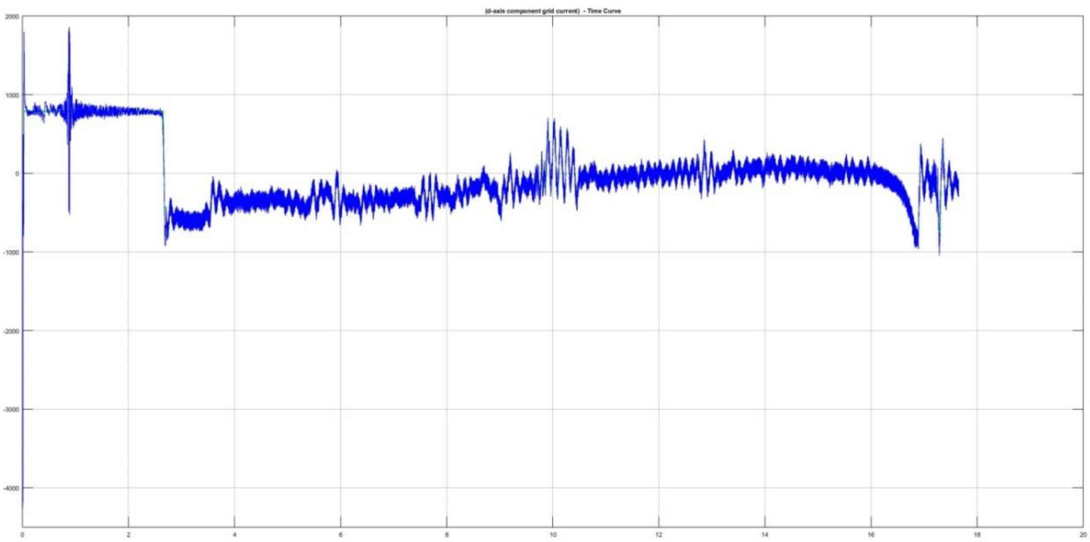


Figure 36 The d-axis component grid current.

The figure above represents the performance of the idg which is the d-axis component grid current from minimum power to maximum power and the it is obvious that the system is running.

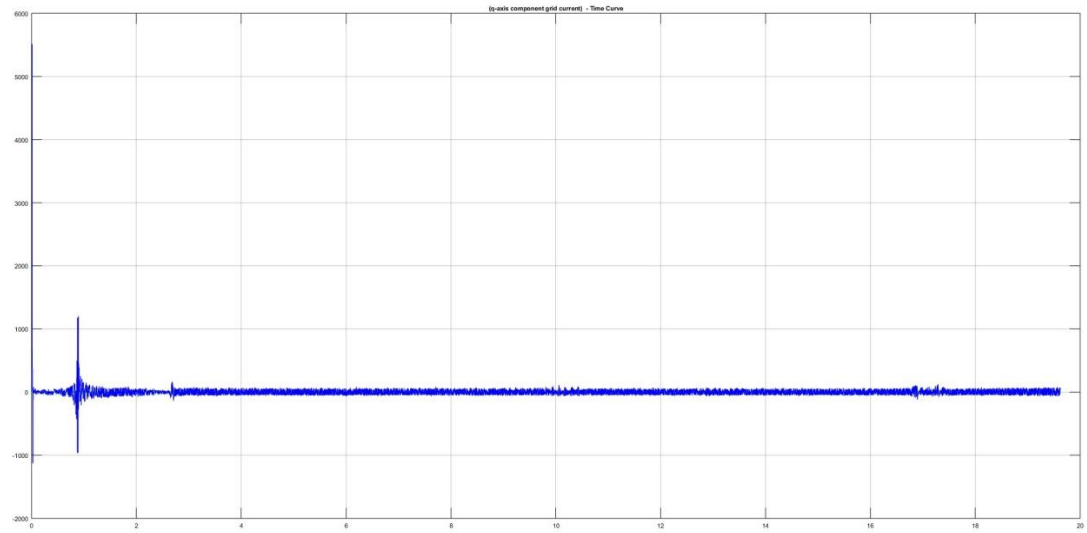


Figure 37 The q-axis component grid current.

The figure above represents the performance of the iqg which is the q-axis component grid current and it starts to run as can be noticed from the curve after a few seconds.

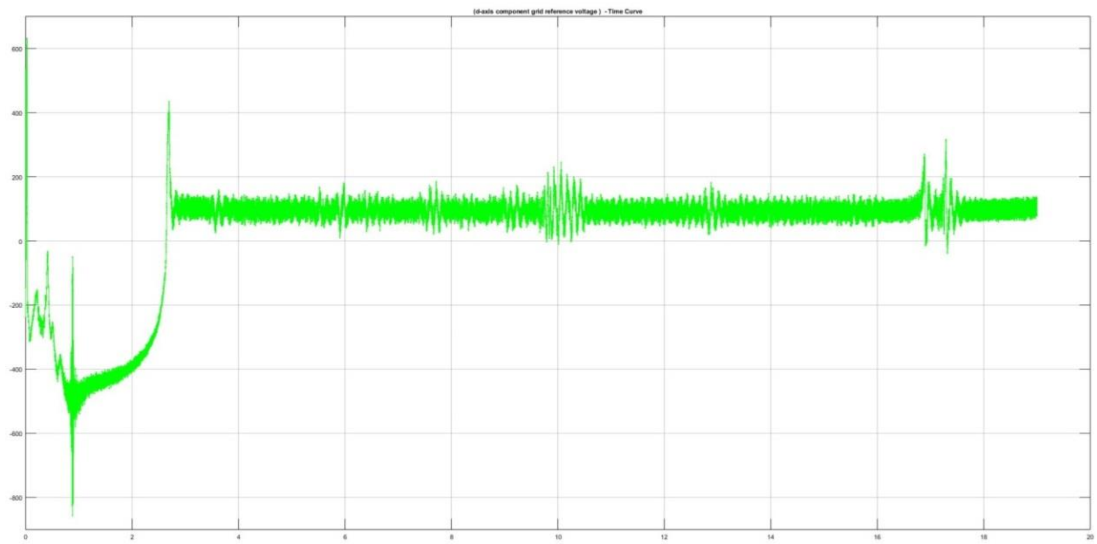


Figure 38 The d-axis component grid reference voltage.

The figure above represents the vdg which is the voltage reference, and it is a very small voltage because we are using a feedback voltage of the grid.

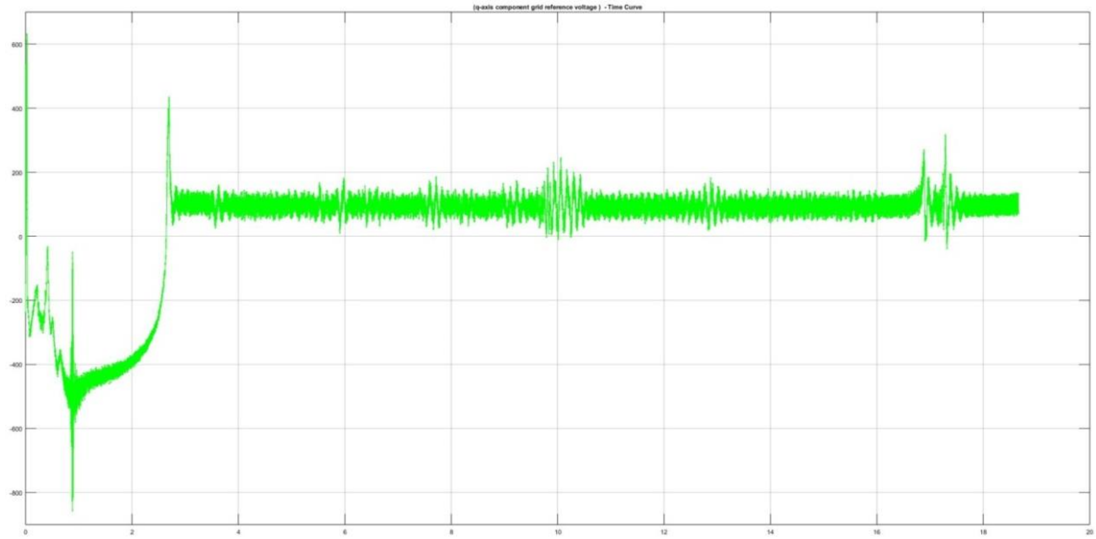


Figure 39 The q-axis component grid reference voltage.

In the figure above represents the vqg which is the voltage reference, and it is a very small voltage because we are using a feedback voltage of the grid.

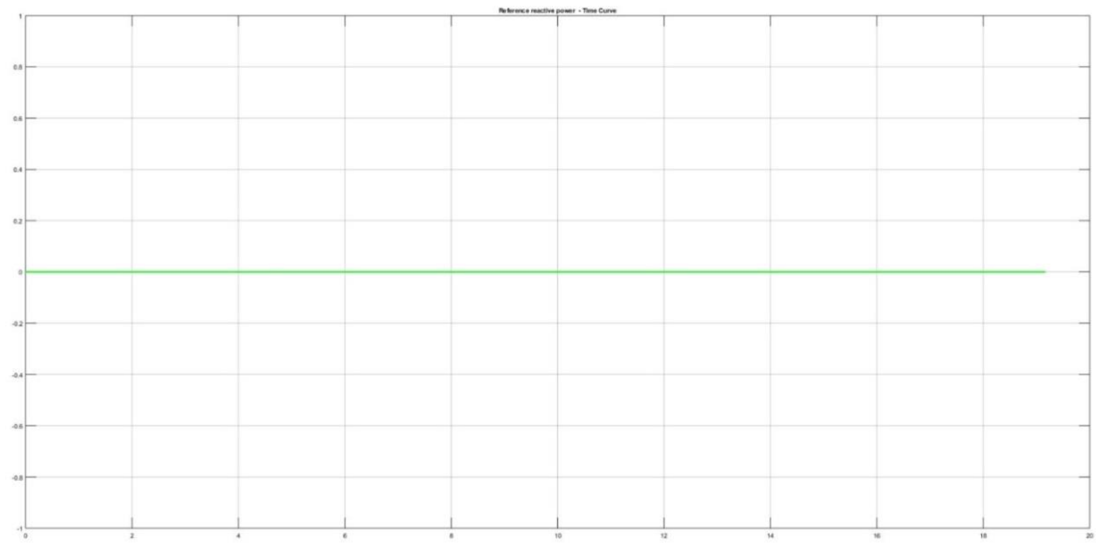


Figure 40 The reference reactive power of the grid.

The figure above represents the reference reactive power of the grid which is set at zero.

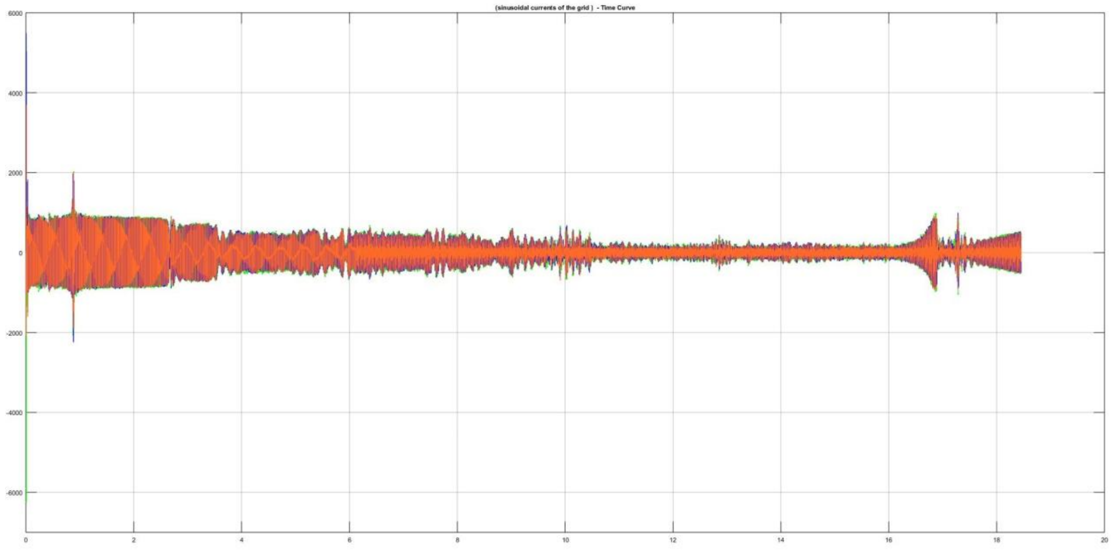


Figure 41 The sinusoidal currents of the grid (Ig).

This curve represents the Ig which is the sinusoidal currents. sinusoidal currents are evenly sine wave alternating currents with a frequency of 50 Hz.

D. Simulation Results Notes

The results in the graphs can be explained in the following two scenarios. In the first scenario, a constant DC voltage value must pass through the GSC for effective power flow. From the DFIG parameters, it shows that the ideal DC link voltage value is 1150 v and after implementing the control scheme the 1150 v has been achieved. Second scenario, the control scheme is applied also to maintain a unity power factor for the overall system by feeding reactive power to the DFIG.

VI. CONCLUSION AND FUTURE WORK

A. Conclusion

The modeling, control, and simulation of an on-grid 2000 KW DFIG has been carried out in this thesis. The proposed method is capable to solve the DFIG problems which include regulating the power flow in the rotor side and maintaining a unity power factor for overall system. From the DC link voltage performance results, the aim of this thesis has been achieved which is to validate the operation of the simulation model by obtaining a constant value for the DC link voltage at different wind speeds and reactive power values. Sleiman, M., & Kedjar, B studied the oriented vector control techniques on the DFIG under sudden wind speed variations. For this purpose, I studied it under constant and not sudden speed variations different cases to check the performance of the system at each speed separately and got results which are the 2 back-to-back voltage source converters is capable to compensate for grid reactive power, and the DFIG has been operated at unity power factor while delivering maximum power to the grid.

B. Future Work

In the future a high efficiency DFIG with energy storage could be applied. Moreover, it is important in other field which uses the same type of generator with energy storage applications, smart systems, and hybrid systems.

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RESUME

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