



بسم الله الرحمن الرحيم

**Sudan University of Science and Technology**  
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# **Proposed Voltage Control of Doubly Fed Induction Generator Connected to the Grid**

**منهجية التحكم في الجهد للمولد الحثي مزدوج التغذية  
المتصل بالشبكة**

**A Thesis Submitted in Partial Fulfillment for the Requirements of  
the Degree of M.Sc. in Electrical Engineering (Power)**

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## الآية

قال تعالى:

{قَالُوا سُبْحَانَكَ لَا عِلْمَ لَنَا إِلَّا مَا عَلَّمْتَنَا إِنَّكَ أَنْتَ الْعَلِيمُ الْحَكِيمُ}

صدق الله العظيم

سورة البقرة الآية (32)

# DEDICATION

To all you who came helpful, to the people who made this project an experience worth living, for you I am grateful...

# ACKNOWLEDGMENT

Firstly, i thank Allah almighty for His blessings and for providing me with the strength, power and the patience to succeed.

My words of thanks go to my supervisor **Dr. Zaki eldeen Mohammed Eltayeb Elhassan**; I thank him for his continuous guidance, unlimited support, grateful efforts, continuous encouragement and scientific insight during this project.

Finally, I would like to thank all the people who supported my project. Foremost have been my family who encouraged me to work hard and to continue this work and my colleagues for their kindness and support.

# **ABSTRACT**

The wind energy is one of the fastest growing renewable sources, it is improvement and conversion technology has led to a fast development of wind power generation in recent years. Accordingly, this thesis deals with vector control of doubly fed induction generator (DFIG) connected to the grid. Control of (DFIG) based wind turbines needs to pay special attention to the distorted voltage operation scenario. Apart from the normal operation of the wind turbine, the designed control must be prepared to tackle problematic situations derived from grid voltage disturbances. These grid voltage disturbances can be of different natures (voltage dips, imbalances, harmonics, etc.) depending on the characteristics of the electric grid itself vector control has been simulated using MATLAB Simulink. Simulation results are presented to validate the proposed controllers. The performance analysis of a (DFIG) driven by a wind turbine has been described. The dynamic equation of (DFIG) has been considered and the results show that DFIG performance proved to be more reliable and stable when connected to grid side with the proper converter control systems.

## المستخلص

تعد طاقة الرياح واحدة من أسرع مصادر الطاقة المتجددة نمواً، وقد أدى الإهتمام بها والتحسين المتواصل عليها في السنوات الأخيرة إلى تطور سريع في مولدات طاقة الرياح. وتركز هذه الدراسة على التحكم الاتجاهي لتوربينات الرياح القائمة على المولد الحثي ذو التغذية المزدوجة (DFIG). وتحتاج المولدات الحثية ذات التغذية المزدوجة إلى اهتمام خاص لعملية التحكم في المبدل لتفادي حدوث أي تشوه في الجهد. ويغض النظر عن طرق التشغيل التقليدية لتوربينات الرياح يجب الأخذ في الاعتبار عند تصميم نظام التحكم أن يعالج المشاكل الناتجة من اضطرابات جهد الشبكة والتي يمكن أن تحدث في شكل (إنخفاض شديد في الجهد، إختلال في التوازن، التوافقيات، ...الخ). وبالإعتماد على خصائص الشبكة الكهربائية تم عمل برنامج محاكاة بإستخدام برنامج الماتلاب للمولد الحثي ذو التغذية المزدوجة عن طريق التحكم الاتجاهي. وتم عرض النتائج وتحليل الأداء لنظام التحكم الاتجاهي ووفقاً لذلك وجد أن نظام التحكم الاتجاهي للمولد الحثي ذو التغذية المزدوجة أنه نظام أكثر موثوقية وإستقراراً.

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# LIST OF SYMBOLS

Acceleration	$A$
kinetic energy	$E$
Mass	$M$
work done	$W$
Distance	$S$
Force	$F$
Initial velocity of the object.	$U$
velocity wind	$v_w$
Power	$P$
mass flow rate	$\frac{dm}{dt}$
the area	$A$
density of air	$P$
actual mechanical power	$P_w$
upstream wind velocity at the entrance of the rotor blades	$v_u$
downstream wind velocity at the exit of the rotor blades	$v_d$
ratio of wind speed	$A$
radius of the turbine	$R$
site elevation	$H_m$
mechanical torque	$T_m$

## LIST OF ABBSERVATION

Doubly-Fed Induction Generator	DFIG
Vertical Axis Wind Turbine	VAWT
Horizontal Axis Wind Turbine	HAWT
Alternating Current	AC
Direct Current	DC
Squirrel Cage Induction Generator	SCIG
Wound Rotor Induction Generator	WRIG
Permanent Magnet Generator	PMSG
Voltage Source Converters	VSC
Rotor-Side Converter	RSCs
Grid-Side Converters	GSCs
Field Orientation Control	FOC
Insulated Gate Bipolar Transistors	IGBTs

**CHAPTER ONE**  
**INTRODUCTION AND THESIS STRUCTURE**

# CHAPTER ONE

## INTRODUCTION AND THESIS STRUCTURE

### 1.1 Background:

The expansion of power generation and transmission has been severely limited due to limited resources and environmental restrictions as the power demand has increased substantially. Nowadays wind energy is widely used as non-pollutant energy and promising renewable energy resources in the world for electrical power generation. Wind power is abundant, renewable, widely spread, clean, an alternative to fossil fuels, rapidly growing source of energy and produces no greenhouse gas emissions during operation. Advantages of wind power can make it as lucrative source of power for both utility-scale and small, distributed power generation applications.

Wind turbines produce electricity using the power of the wind to drive an electrical generator. Wind passes over the blades, generating lift and exerting a turning force. The rotating blades turn a shaft inside the nacelle, which goes into a gearbox. The gearbox increases the rotational speed to that which is appropriate for the generator, which uses magnetic fields to convert the rotational energy into electrical energy. The power output goes to a transformer, which converts the electricity from the generator at around 700 to the appropriate voltage for the power collection system, typically 33 kV. Wind turbine is having two types. One is fixed speed wind turbine and another one is variable wind turbine. The most common type of wind turbine is the fixed-speed wind turbine with the induction generator directly connected to the grid. However this system has a number of drawbacks. The reactive power and, therefore, the grid voltage level cannot be controlled. Most of the drawbacks of fixed wind turbine are avoided when variable-speed wind turbines are

used. These turbines improve the dynamic behavior of the turbine and reduce the noise at low wind speeds. But in variable speed wind turbine power electronics converter is needed which makes the variable speed operation possible. Basically, a wind turbine can be equipped with any type of three-phase generator, such as synchronous generator and asynchronous generator. Out of these, doubly fed induction generator which is type of asynchronous generator is more preferable because of its several advantages. The DFIG technology allows extracting maximum energy from the wind for low wind speeds by optimizing the turbine speed, while minimizing mechanical stresses on the turbine during gusts of wind. The optimum turbine speed producing maximum mechanical energy for a given wind speed is proportional to the wind speed. Another advantage of the DFIG technology is the ability for power electronic converters to generate or absorb reactive power, thus eliminating the need for installing capacitor banks as in the case of squirrel-cage induction generator. Some researchers believe that the DFIG should be used only for the purpose for which it has been installed, i.e., supplying active power only.

## **1.2 Problem statement:**

Control of DFIG based wind turbines needs to pay special attention to the distorted voltage operation scenario. Apart from the normal operation of the wind turbine, the designed control must be prepared to tackle problematic situations derived from grid voltage disturbances. These grid voltage disturbances can be of different natures (voltage dips, imbalances, harmonics, etc.) depending on the characteristics of the electric grid itself. DFIG has suffered from voltage fluctuations when it used in wind power connected to grid and this behavior led to unstable voltage in power system. However, this research addressed the DFIG voltage stability problem in power system.

### **1.3 Methodology:**

The following methodology has been adapted in order to carry out research work:

- Study and analysis DFIG driven by wind turbine and connected to the grid .
- Adopted vector control method with proposed control of DFIG connected to the grid.
- Be familiar with wind turbine behavior and simulation with perfect parameters control.
- Simulate the model system of wind power using DFIG with full converter control using Matlab Simulink.

The simulation result most confirm with available result in literature.

### **1.4 Objectives:**

The aim of this thesis is achieve voltage control of power grid when wind power based on DFIG added into the system.

Also software in power system analysis and simulation which widely used in power could Matlab Simulink.

### **1.5 Thesis lay-out:**

Thesis is organized as follow:

The literature of this thesis is written and ordered in chapter two. However, in chapter three the DFIG mathematical model with vector control method has presented. Moreover, chapter four which is a main core of this research shows the thesis simulation model and the result with perfect presentation. Finally, conclusion and recommendations appended in chapter five.

# **CHAPTER TWO**

## **LITERATURE REVIEW**



# **CHAPTER TWO**

## **LITERATURE REVIEW**

### **2.1 Wind power system:**

This known to all that the burning of fossil fuels are having a vital influence on the global climatic conditions. Effective changes in the climatic condition will require deep reduction in the emission of greenhouse gases. The electricity systems are viewed as easier to transfer to low carbon energy source than most of the challenging sectors of an economy such as surface and air transport. Hence the significant use of cost-effective and reliable low carbon electricity generation sources, in addition to demand-side measures are becoming the most important objective of energy policies in many countries. Over the past decades, wind energy has been accounted for the fastest rate of growth among any form of electricity generation with its development stimulated by concerns over the climatic changes, energy diversities and security of supply by many policy makers. The maximum energy that can be taken out from the 0-100 meters layer of the atmosphere has been approximated to be around 10 12 kWh per year, which is having the same potential as hydro-electric generation [1].

#### **2.1.1 Advantages of using wind energy:**

1. It is a clean source of energy .no emission of greenhouse gas so no problem of ozone layer depletion.
2. It can be harnessed easily and having its availability in abundance.
3. It is simply a different form of solar energy which is caused by the non-uniform heating of earth surface and revolution of earth.

4. Its price is very less costing around 3-4 cents kwh so it will also help in developing the rural area where wind is available in abundance by making wind mills in farm and ranches [1].

### **2.1.2 Modern wind turbines fall into 2 basic groups:**

- a. Vertical Axis Wind Turbine (VAWT).
- b. Horizontal Axis Wind Turbine (HAWT) [2].

In a VAWT, the shaft is mounted on a vertical axis perpendicular to the ground – like an eggbeater. VAWT's are always aligned with the winds; as such adjustment is not necessary when the wind direction changes. Some of the disadvantages of the VAWT are that it cannot start moving by itself, it needs a boost from its electrical system to get started. Also, instead of a tower, it typically uses guy wires for support, so rotor elevation is lower. Lower elevation means slower wind due to ground interference, which contributes to lower efficiency. All equipment is at ground level for easy installation and servicing; but that means a larger footprint for the turbine, which is a big negative in farming areas. This design is rarely used in large wind farms.

In a HAWT, the shaft is mounted horizontally, parallel to the ground. HAWTs need to constantly align themselves with the direction of the wind. This type of turbine uses a tower as a base and the components are at an optimum elevation for wind speed. As such, each tower takes up very little space since almost all of the components are up in the air. Most large modern wind turbines are horizontal-axis turbines [2].

## **2.2 Wind turbine architectures:**

Wind Turbines are classified according to their drive train as follows:

### **2.2.1 Fixed speed turbines:**

Fixed-speed wind turbines are designed to achieve maximum efficiency at a particular speed. This implies that regardless of the wind speed, the rotor speed is fixed and determined by the gear ratio, generator

design and the grid frequency [3]. These devices consist of an induction generator connected directly to the grid. It must be mentioned here that as induction machines consume reactive power, and produce high transient currents while energizing, an installation of compensation capacitors along with soft starter unit is necessary. Fixed speed wind turbines are considered to be simple, robust, reliable and cheap devices. However, limited power quality control, uncontrollable reactive power consumption and mechanical stress are the disadvantages of fixed speed wind turbines [4].

### **2.2.2 Variable speed turbines:**

Variable speed wind turbines are designed to obtain maximum efficiency over a wide range of wind speeds. These devices keep the generator torque to a constant level and the variations in the wind speed are absorbed by the changes in the generator speed. They are typically equipped with an induction or a synchronous generator and connected to the grid via power electronic interface [3].

The advantages of variable speed wind turbines are increased energy capture, improved power quality and lower mechanical stress. The disadvantages are complex structure, losses in power electronics and a higher cost [4].

## **2.3 Types of generators basically:**

A wind turbine can be equipped with any type of three-phase generator. Today, the demand for grid-compatible electric current can be met by connecting frequency converters, even if the generator supplies alternating current (AC) of variable frequency or direct current (DC) [5].

**Several generic types of generators may be used in wind turbines:**

### **1- Asynchronous (induction) generator:**

- Squirrel cage induction generator (SCIG).
- wound rotor induction generator (WRIG).

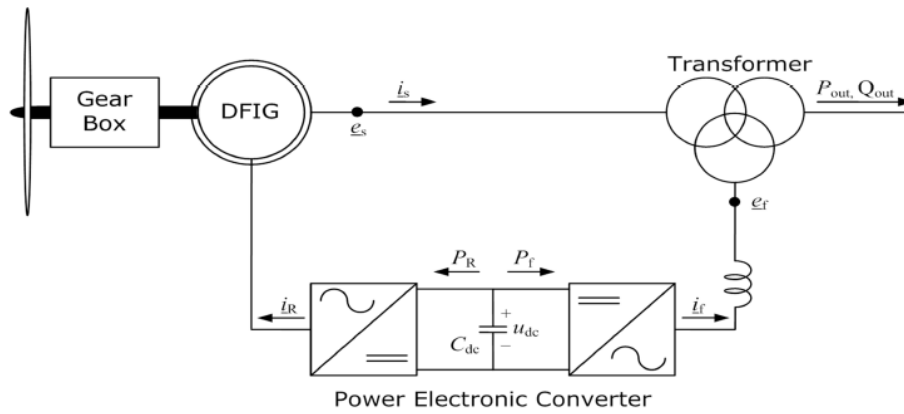
- OptiSlip induction generator (OSIG).
- Doubly-fed induction generator (DFIG).

## 2- Synchronous generator:

- wound rotor generator (WRSG).
- Permanent magnet generator (PMSG) [5].

Currently the most popular variable-speed wind turbine configurations are as follows:

Doubly Fed Induction Generator (DFIG) Wind Turbine  
wind turbine is shown schematically in Figure 2.1.



**Figure 2.1: General topology of a DFIG wind turbine**

It uses a Wound Rotor Induction Generator (WRIG) with slip rings to take current into or out of the rotor winding and variable-speed operation is obtained by injecting a controllable voltage into the rotor at slip frequency [6].

The rotor winding is fed through a variable-frequency power converter, typically based on two AC/DC IGBT-based voltage source converters (VSC) linked by a DC bus. The power converter decouples the network electrical frequency from the rotor mechanical frequency, enabling variable-speed operation of the wind turbine. The generator and

converters are protected by at voltage limits and an over-current ‘crowbar’.

A DFIG system can deliver power to the grid through the stator and rotor, while the rotor can also absorb power, depending on the rotational speed of the generator [4].

## 2.4 Mathematical formulation of turbine model:

Under constant acceleration ( $a$ ), the kinetic energy ( $E$ ) of an object having mass ( $m$ ) and velocity  $v$  is equal to the work done ( $W$ ) in displacing that object from rest to a distance ( $s$ ) under a force ( $F$ ), i.e. ( $E = W = Fs$ ). According to Newton’s second law of motion [7].

$$F = ma \tag{2.1}$$

Thus, the kinetic energy becomes:

$$E = mas \tag{2.2}$$

From kinematics of solid motion, ( $v^2 = u^2 + 2as$ ) where  $u$  is the initial velocity of the object. This implies that  $\left(a = \frac{v^2 - u^2}{2s}\right)$ . Assuming the initial velocity of the object is zero, we have that  $\left(a = \frac{v^2}{2s}\right)$ . Hence from equation (2.2) we have that [7]:

$$E = \frac{1}{2}mv^2 \tag{2.3}$$

This kinetic energy formulation is based on the fact that the mass of the solid is a constant. However, if we consider wind (air in motion) as a fluid, both density and velocity can change and hence no constant mass.

For this reason Reccab et. al formulate the kinetic energy law with a factor of  $\left(\frac{2}{3}\right)$  instead of  $\left(\frac{1}{2}\right)$ .

In this paper we shall assume that the density of air does not vary considerably even with variation in altitude or temperature and use the kinetic energy law in the form of equation (2.3). Hence the kinetic energy (in joules) in air of mass ( $m$ ) moving with velocity  $v_w$ (wind) can be calculated from equation (2.3) above. The power  $P$  in the wind is given by the rate of change of kinetic energy, i.e.

$$P = \frac{dE}{dt} = \frac{1}{2} \frac{dm}{dt} v_w^2 \quad (2.4)$$

But mass flow rate  $\left(\frac{dm}{dt}\right)$  is given by  $\left(\frac{dm}{dt} = \rho A v_w\right)$  where  $A$  is the area through which the wind in this case is flowing and  $\rho$  is the density of air. With this expression, equation (2.4) becomes [7]:

$$P = \frac{1}{2} \rho A v_w^3 \quad (2.5)$$

The actual mechanical power  $P_w$  extracted by the rotor blades in watts is the difference between the upstream and the downstream wind powers, i.e.

$$P = \frac{1}{2} \rho A v_w (v_u^2 - v_d^2) \quad (2.6)$$

where ( $v_u$ ) is the upstream wind velocity at the entrance of the rotor blades in (m/s) and ( $v_d$ ) is the downstream wind velocity at the exit of the rotor blades in (m/s). We shall see later that these two velocities

give rise to the blade tip speed ratio. Now from the mass flow rate, we may write [7]:

$$\rho A v_w = \frac{\rho A (v_u + v_d)}{2} \quad (2.7)$$

$$\begin{aligned} P_\omega &= \frac{1}{2} \left[ \rho A \left\{ \frac{v_u}{2} (v_u^2 - v_d^2) + \frac{v_d}{2} (v_u^2 - v_d^2) \right\} \right] \\ &= \frac{1}{2} \left[ \rho A \left\{ \frac{v_u^3}{2} - \frac{v_u v_d^2}{2} + \frac{v_d v_u^2}{2} - \frac{v_d^3}{2} \right\} \right] \\ &= \frac{1}{2} \left[ \rho A v_u^3 \left\{ \frac{1 - \left(\frac{v_d}{v_u}\right)^2 + \left(\frac{v_d}{v_u}\right) - \left(\frac{v_d}{v_u}\right)^3}{2} \right\} \right] \end{aligned} \quad (2.8)$$

$$P_\omega = \frac{1}{2} \rho A V_u^3 C_p$$

Where

$$C_p = \frac{\left(1 + \frac{v_d}{v_u}\right) \left(1 - \left(\frac{v_d}{v_u}\right)^2\right)}{2} \quad (2.9)$$

The expression for  $(C_p)$  in equation (2.9) is the fraction of upstream wind power captured by the rotor blades.  $(C_p)$  is often called the Betz limit after the Germany physicist Albert Betz who worked it out in 1919. Other names for this quantity are the power coefficient of the rotor or rotor efficiency. The power coefficient is not a static value. It varies with tip speed ratio of the wind turbine.

Let  $(\lambda)$  represent the ratio of wind speed ( $v_d$ ) downstream to wind speed ( $v_u$ ) upstream of the turbine, i.e.

$$\lambda = \frac{v_d}{v_u}$$

$$\lambda = \frac{\text{blade tip speed}}{\text{wind speed}} \quad (2.10)$$

$(\lambda)$  is called the tip speed ratio of the wind turbine. The blade tip speed in metres per second can be calculated from the rotational speed of the turbine and the length of the blades used in the turbine, i.e. [7]:

$$\text{blade tip speed} = \frac{\text{angular speed of turbine } (\omega) \times R}{\text{wind speed}} \quad (2.11)$$

where  $R$  is the radius of the turbine and  $\omega$  is measured in radian per second.

Substitution of equation (2.10) into equation (2.99) leads to:

$$C_p = \frac{(1 + \lambda)(1 - \lambda^2)}{2} \quad (2.12)$$

Differentiate  $(C_p)$  with respect to  $(\lambda)$  and equate to zero to find value of  $(\lambda)$  that makes  $(C_p)$  a maximum, i.e.

$$\frac{dC_p}{d\lambda} = \frac{(1 + \lambda) \cdot (-2\lambda) + (1 - \lambda^2) \cdot 1}{2} = 0 \quad (2.13)$$

yielding  $(\lambda = -1)$  or  $(\lambda = \frac{1}{3})$ . Now  $(\lambda = \frac{1}{3})$  makes the value of  $(C_p)$  a maximum. This maximum value is  $(\frac{16}{27})$ . Thus the Betz limit says that no wind turbine can convert more than  $(\frac{16}{27})$ , (59.3%) of the kinetic energy



of the wind into mechanical energy turning a rotor, i.e ( $C_{pmax} = 0.59$ ). Wind turbines cannot operate at this maximum limit though. The real world is well below the Betz limit with values of (0.35 – 0.45) common even in best designed wind turbines.

If the rotor of a wind turbine turns too slowly most of the wind will pass through the openings between blades with little power extraction. If on the other hand the rotor turns too fast, the rotating blades act as a solid wall obstructing the wind flow again reducing the power extraction. The turbines must be designed to operate at their optimal wind tip speed ratio ( $\lambda$ ) in order to extract as much power as possible from the wind stream. Theoretically the higher the ( $\lambda$ ) the better in terms of efficient operation of the generator [7]:

There are disadvantages however. High ( $\lambda$ ) causes erosion of leading edges of the blades due to impact of dust or sand particles found in the air. This would require use of special erosion resistant coating material that may increase the cost of energy. Higher ( $\lambda$ ) also leads to noise generation, vibration, reduced rotor efficiency due to drag and tip losses and excessive rotor speeds can lead to turbine failure.

Other factors that impede complete energy conversion in a complete turbine system are things such as gearbox, bearings, number and shape of blades etc. Only (10– 30%) of the power of the wind is ever actually converted into usable electricity. Air density ( $\rho$ ) is another flow input quantity at the rotor system. ( $\rho$ ) is a function of both air pressure and temperature. When air pressure increases ( $\rho$ ) increases. When air temperature decreases  $\rho$  increases. This is in accordance with the equation of state [8]:

$$P = \rho RT \quad (2.14)$$

where ( $R$ ) is the gas constant. Both temperature and pressure decrease with increasing elevation. Hence site location is important as elevation has major effect on power generated as a result of air density variation. At atmospheric pressure, ( $P_{\text{atm}} = 14.7\text{psi}$ ), temperature is ( $T = 600F$ ) and density is ( $\rho = 1.225\text{kg/m}^3$ ). Temperature and pressure both vary with elevation. This affects the air density. propose the following relation [8]:

$$\rho = \rho_0 e^{-\frac{0.297}{3048} H_m} \quad (2.15)$$

where ( $H_m$ ) is site elevation in metres. At high elevations the air density corrections can be important [8].

**CHAPTER THREE**  
**MATHEMATICAL MODEL**

# CHAPTER THREE

## MATHEMATICAL MODEL

### 3.1 Introduction:

The DFIG wind energy system is widely accepted in today's wind energy industry. The DFIG is essentially a wound rotor induction generator in which the rotor circuit can be controlled by external devices to achieve variable speed operation. A typical block diagram of the DFIG wind energy system is shown in Figure 2-1. The stator of the generator is connected to the grid through a transformer, whereas the rotor connection to the grid is done through power converters, harmonic filters, and the transformer.

The power rating for the DFIG is normally in the range of a few hundred kilowatts to several megawatts. The stator of the generator delivers power from the wind turbine to the grid and, therefore, the power flow is unidirectional. However, the power flow in the rotor circuit is bidirectional, depending on the operating conditions. The power can be delivered from the rotor to the grid and vice versa through rotor-side converter (RSCs) and grid-side converters (GSCs). Since the maximum rotor power is approximately (30%) of the rated stator power, the power rating of the converters is substantially reduced in comparison to the (WECS) with full-capacity converters. With variable speed operation, a (DFIG) wind energy system can harvest more energy from the wind than a fixed-speed (WECS) of the same capacity when the wind speed is below its rated value. The cost of the power converters and harmonic filters is substantially lower than that in the (WECS) with full-capacity converters. The power losses in the converters are also lower, leading to improved overall efficiency. In addition, the system can provide leading

or lagging reactive power to the grid without additional devices. These features have made the DFIG wind energy system one of the preferred choices in the wind energy market [7].

### 3.2 Operating principle:

Once the speed of the rotor exceeds that of the rotating magnetic field of the stator (synchronous speed), a current is induced in rotor windings. With increase in the rotor speed, power is transferred to the stator via electromagnetic mechanism, and is then supplied to the electric grid through the stator terminals. The induction generator speed varies with the load torque. The difference between the rotational speed of the rotor and the synchronous speed of the stator flux is measured in percentage and is called the slip of the machine. The rotor and grid side converters allow the slip control of the DFIG. The slip power is regained for higher rotational speeds and sent to the grid, accounting for a more efficient operation. For reduced speed of the rotor, the ratings of the converters are similarly rated with lower ratings in comparison with the generator. This accounts for reduction of the system costs and losses [9].

For generation of power the mechanical torque being applied at the rotor is positive and also since the speed of the flux in the stator-rotor air gap is positive and constant( for constant frequency of grid), therefore slip sign accounts for the sign of power output from the rotor terminals. ( $C_{\text{rotor}}$ ) and ( $C_{\text{grid}}$ ) help in the production or absorption of the reactive power; they are used 15 for the control of reactive power or the voltage at the grid terminals. Pitch control can be employed for limiting the power output of the generator at higher speeds of wind [9].

$$P_m = T_m * \omega_r \quad (3.1)$$

$$P_s = T_{em} * \omega_s \quad (3.2)$$

Neglecting losses in generation,

$$J \frac{dw_r}{dt} = T_m - T_{em} \quad (3.3)$$

At steady state, for constant speed generation,

$$T_m = T_{em} \quad (3.4)$$

$$P_m = P_s + P_r \quad (3.5)$$

Therefore,

$$P_r = P_m - P_s = T_m \omega_r - T_{em} \omega_s$$

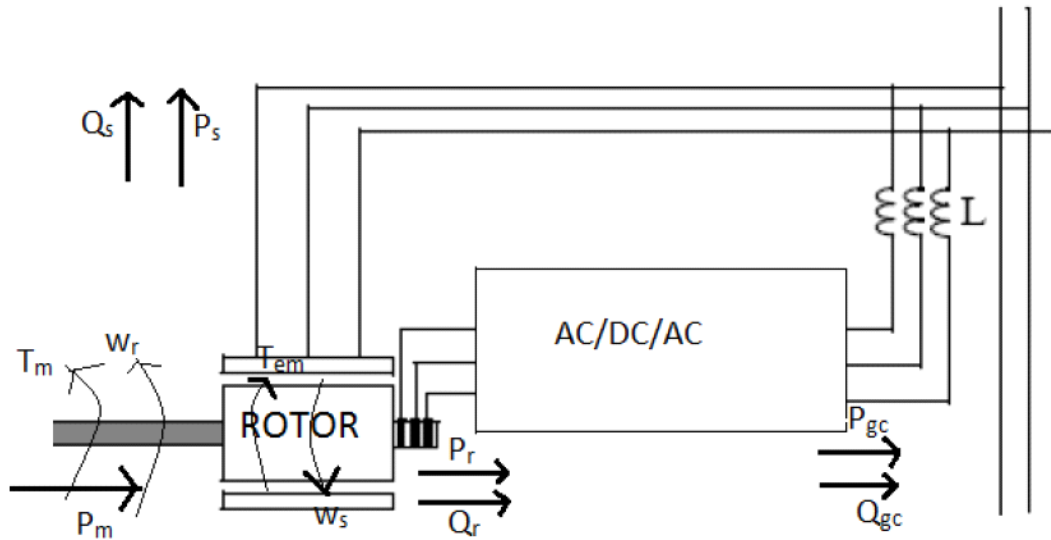
$$P_r = T_{em} (\omega_r - \omega_s) = \frac{T_{em}}{\omega_s} \omega_s (\omega_r - \omega_s)$$

$$P_r = (\omega_s T_{em}) \left( \frac{\omega_r - \omega_s}{\omega_s} \right)$$

$$\therefore P_r = -sP_s$$

Where slip

$$s = \frac{\omega_s - \omega_r}{\omega_r}$$



**Figure 3.1: A wound-rotor, doubly fed induction generator**

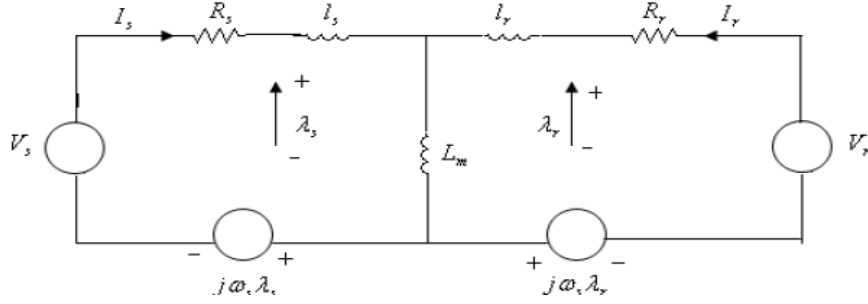
Usually the magnitude of slip  $s$  is below 1, so  $(P_r)$  is small compared to  $(P_s)$ , the mechanical torque  $T_m$  is positive (during generation), synchronous speed  $(\omega_s)$  is positive and fixed (for constant frequency at grid), and therefore the sign of  $(P_r)$  depends on the sign of slip. It's positive when slip is negative (for rotational speeds above the synchronous speed) and negative when slip is positive (for rotational speeds below the synchronous speed).

During super synchronous mode,  $(P_r)$  is sent to the (DC) link capacitor which raises the (DC) voltage. During sub synchronous mode,  $(P_r)$  is extracted from the capacitor lowering the (DC) voltage. The grid converter then extracts or delivers the grid power to keep the dc voltage fixed. During steady state,  $(P_{gc})$  is equal to  $(P_r)$ , also the turbine speed can be found out from  $(P_r)$  extracted by or fed to  $(C_{rotor})$ . The phase sequence of AC voltage produced by  $(C_{rotor})$  depends on rotor speed and is positive when rotor speed is less than synchronous speed and negative when rotor speed exceeds the synchronous speed. The magnitude of the frequency of this (AC) voltage is slip times the frequency of the grid [9].

### **3.3 Mathematical model:**

It is well known that a DC drive has excellent dynamic performance, as it is possible to decouple the stator magnetic flux and electromagnetic torque of the drive. The vector control, also known as Field Orientation Control (FOC), of induction machines emulates the DC drive control. In this section a dynamic model of DFIG and its control have been presented using the generator convention. The DFIG modeling and control have been carried out in the well-known coordinate systems using Park's transformation for both three-phase to two-phase and two-phase to three-phase axes transformation. The stator and rotor windings of a three-phase induction machine are represented by two sets of orthogonal fictitious coils (4, 5). The model is based on the commonly

known as „Park model“. The equivalent circuit of a DFIG in an arbitrary reference frame rotating at synchronous speed is shown in Figure 2 [10].



**Figure 3.2: Equivalent circuit of DFIG in an arbitrary reference frame rotating at synchronous speed.**

According to the Figure 3.2, the stator and rotor fluxes  $\lambda_s$  and  $\lambda_r$  are represented by equation (3.6) [11].

$$\lambda_s = (l_s + L_m)i_s + L_m i_r = L_s i_s + L_m i_r \quad (3.6)$$

$$\lambda_r = (l_r + L_m)i_r + L_m i_s = L_m i_s + L_r i_r$$

The stator and rotor voltage in reference frame are expressed by equation (3.7) [12]:

$$V_s = R_s i_s + j\omega_s \lambda_s + \frac{d\lambda_s}{dt} \quad (3.7)$$

$$V_r = R_r i_r + j(\omega_s - \omega_r)\lambda_r + \frac{d\lambda_r}{dt}$$

The equivalent stator magnetizing current  $i_m$  is defined as;

$$\lambda_s = L_s i_s + L_m i_r = L_m i_m$$



There for

$$i_m = \left( \frac{L_s i_s}{L_m} + i_r \right) \quad \text{and}$$

$$i_s = \frac{L_m}{L_s} (i_m - i_r)$$

**Substituting s i in r gives**

$$\lambda_s = \frac{L_m^2}{L_s} i_m + L_r i_r \left( 1 - \frac{L_m^2}{L_s L_r} \right)$$

Now substituting the values of  $\lambda_s$ ,  $i_s$  and  $\lambda_r$  in equation (3.7) give

$$V_s = R_s i_s + L_m \frac{di_m}{dt} + j\omega_s \lambda_s$$

$$V_r = R_r i_r + \sigma L_r \frac{di_r}{dt} + \frac{L_m^2}{L_s} \frac{di_m}{dt} + j(\omega_s - \omega_r) \lambda_r$$

Where

$$\sigma = 1 - \frac{L_m^2}{L_r L_s}$$

If stator voltage  $V_s$  and  $\lambda_s$  are assumed to be constant, then

$$\frac{di_m}{dt} = 0$$

**And**

$$V_s = R_s i_s + L_m \frac{di_m}{dt} + j\omega_s$$

$$V_r = R_r i_r + \sigma L_r \frac{di_r}{dt} + j(\omega_s - \omega_r)$$

The above set of equations for stator and rotor voltages in d - q coordinates can be written as shown in equation (3.8) [12].

$$\begin{aligned} V_{ds} &= R_s i_{ds} - \omega_s \lambda_{qs} + \frac{d\lambda_{ds}}{dt} \\ V_{qs} &= R_s i_{qs} + \omega_s \lambda_{ds} + \frac{d\lambda_{qs}}{dt} \\ V_{dr} &= R_r i_{dr} - s\omega_s \lambda_{qr} + \frac{d\lambda_{dr}}{dt} \\ V_{qr} &= R_r i_{qr} + \omega_s \lambda_{dr} + \frac{d\lambda_{qr}}{dt} \end{aligned} \quad (3.8)$$

The subscripts d and q indicate the direct and quadrature axis components of the reference frame, where s and r represent stator and rotor quantities, respectively. The decomposition into d - q coordinate systems is required for the control [10]. The flux linkages can be further calculated using the following relations shown in equation (3.9) [12]:

$$\begin{aligned} \lambda_{ds} &= (l_s + L_m) i_{ds} + L_m i_{dr} = L_s i_{ds} + L_m i_{dr} \\ \lambda_{qs} &= (l_s + L_m) i_{qs} + L_m i_{qr} = L_s i_{qs} + L_m i_{qr} \\ \lambda_{dr} &= (l_r + L_m) i_{dr} + L_m i_{ds} = L_r i_{dr} + L_m i_{ds} \\ \lambda_{qr} &= (l_r + L_m) i_{qr} + L_m i_{qs} = L_r i_{qr} + L_m i_{qs} \end{aligned} \quad (3.9)$$

The rotor slip is defined by equation (3.10).

$$s = \frac{\omega_s - \omega_r}{\omega_s} \quad (3.10)$$

Also the electromagnetic torque developed is given by equation (3.11).

$$T_e = n_p(i_{qr}\lambda_{ds} - i_{dr}\lambda_{qs}) \quad (3.11)$$

It can also be written in terms of rotor current as

$$T_e = n_p \frac{L_m}{L_s}(\lambda_{dr}i_{qr} - \lambda_{qr}i_{dr})$$

The equations for active and reactive power in d and q axes are expressed by equation (3.12) [1].

$$\begin{aligned} P_s &= V_{ds}i_{ds} + V_{qs}i_{qs} \\ Q_s &= V_{qs}i_{ds} - V_{ds}i_{qs} \end{aligned} \quad (3.12)$$

Normally a medium to high power generator is used in wind farms; therefore the stator resistances can be neglected. The stator voltage along d - q axis from equations (3.3) will reduce to equation (3.13) [12].

$$V_{ds} = -\omega_s\lambda_{qs} + \frac{d\lambda_{ds}}{dt} \quad (3.13)$$

$$V_{qs} = \omega_s\lambda_{ds} + \frac{d\lambda_{qs}}{dt}$$

In vector control method, which is used to achieve independent control of active and reactive power, the stator flux vector is aligned with d -axis which gives the following equation (3.14).

$$\begin{aligned} \lambda_{ds} &= \lambda_s = L_s i_{ds} + L_m i_{dr} \\ \lambda_{qs} &= L_s i_{qs} = L_m i_{qr} = 0 \end{aligned} \quad (3.14)$$

The stator voltage in DFIG, which is a variable-speed constant-frequency generator, remains constant. Moreover the three-phase sinusoidal voltage is transformed into d – q synchronous reference frame. This gives the relation as shown in equation (3.15) [10].

$$V_{ds} = 0 \quad (3.15)$$

$$V_{qs} = V_s$$

From equations (3.13), (3.14) and (3.15), the stator active and reactive power can be obtained as shown in equations (3.16) and (3.17) respectively [12].

$$P_s = V_s \frac{L_m}{L_s} i_{qr} \quad (3.16)$$

$$Q_s = \frac{V_s \lambda_s}{L_s} - \frac{V_s L_m}{L_s} i_{dr} \quad (3.17)$$

From equations (3.16) and (3.17), it can be concluded that the delivered power depends directly on the d and q components of rotor currents except that for the reactive power there is second term, which represents power needed to magnetize the machine.

Also, the electromagnetic torque is proportional to the  $i_{qr}$  as shown in equation (3.18) [12].

$$T_e = n_p \frac{L_m}{L_s} \frac{V_s}{\omega_s} i_{qr} \quad (3.18)$$

### 3.4 Transformation from three-phase to two –phases axes:

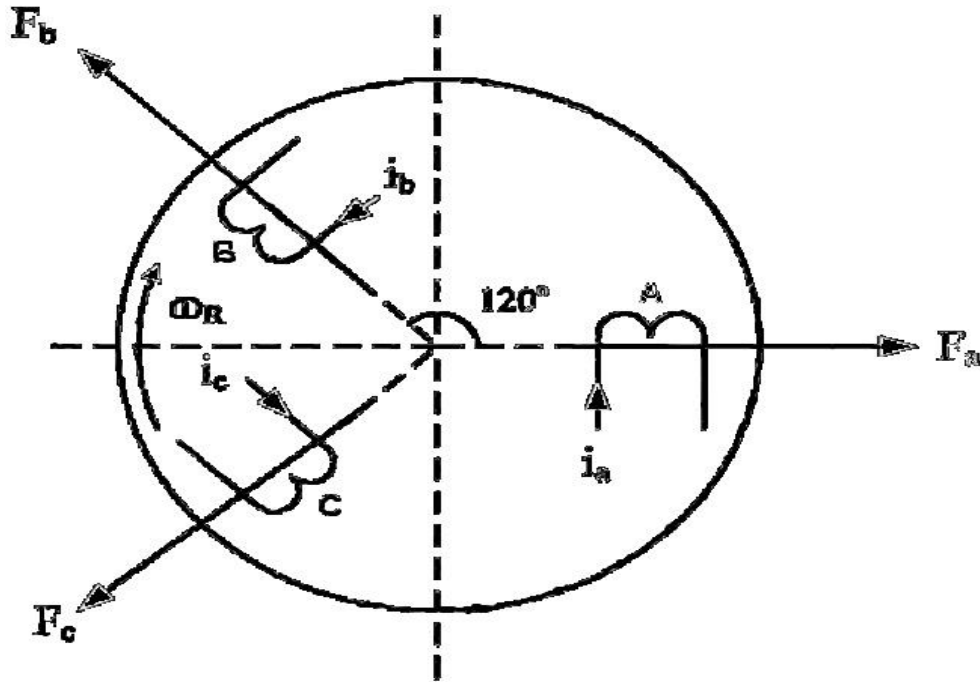


Figure 3.3: Rotating 3-phase balanced windings

In this section it is shown how a three-phase rotating system can be transformed into a two-phase rotating system [13]. It is also shown how the stationary two-phase system can be obtained which is the basic principle control of DFIG. The transformation is carried out based on the principle of invariance of power so that the power in one set of variables is same as power in the new set of variables. A symmetrical 2-pole, three-phase winding on the rotor is represented by three coils A, B and C each of  $N$  effective turns and mutually displaced by  $120^\circ$  as shown in Figure 3.3. Maximum values of (mmfs)  $F_a$ ,  $F_b$  and  $F_c$  are shown along their respective phase-axes. The combined effect of these three mmfs results in a constant magnitude mmf, which rotates at constant velocity depending on the poles and frequency [12].

Let the three-phase currents be given by equation (3.19).

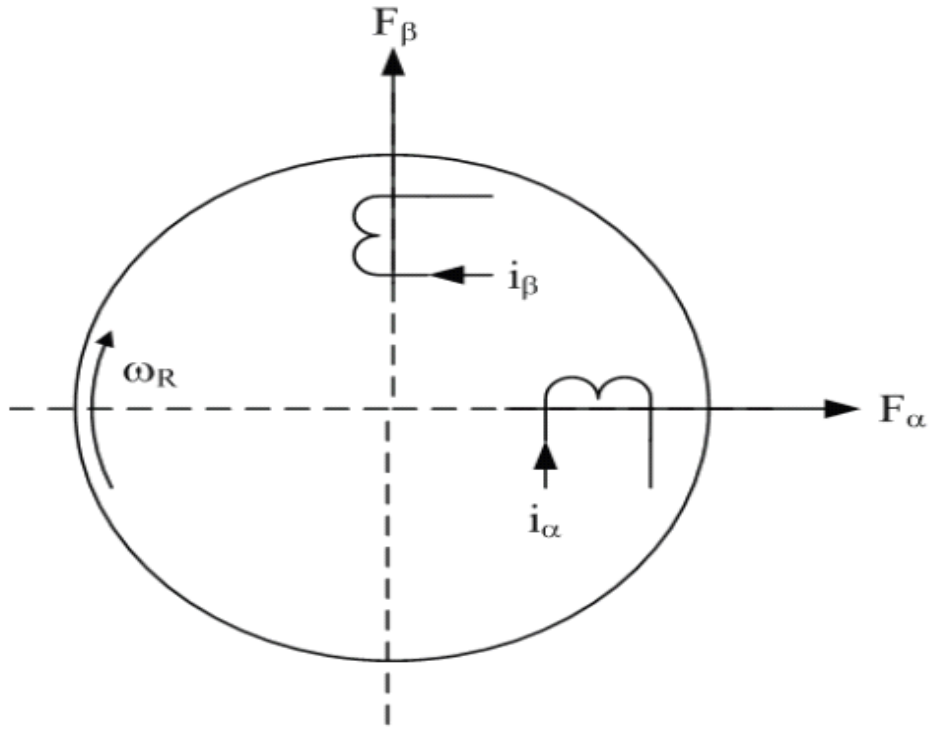
$$i_a = I_m \cos(\omega t)$$

$$i_b = I_m \cos\left(\omega t - \frac{2\pi}{3}\right) \quad (3.19)$$

$$i_c = I_m \cos\left(\omega t - \frac{4\pi}{3}\right)$$

Then these current will produce an mmf of a constant magnitude rotating with respect to the three-phase winding at the time.

In Figure 3.4 a balanced two-phase winding is represented by two orthogonal winding coils a, b on the rotor. The axes of A and a are taken to be coincident for the convenience in transformation [12].



**Figure 3.4: Rotating 2-phase balanced windings**

Let the two- phase currents be given by equation (3.20),

$$i_\alpha = I_m \cos \omega t$$

$$i_\beta = I_m \cos\left(\omega t - \frac{\pi}{2}\right) = I_m \sin(\omega t) \quad (3.20)$$

Flow in the two-phase windings, the result will be an mmf of constant magnitude  $I N$  revolving with respect to the two-phase winding at the time frequency of the phase currents. The mmfs of three-phase and two-phase systems can be equated in magnitude to achieve the transformation. Now both the magnitude of currents and number of turns of two-phase systems are changed to obtain identical transformation for voltage and current.

Let the number of per-phase turns in two-phase winding be as times the per-phase turns of the three-phase winding. Then for equal mmfs,  $i$  should be equal to  $i_a$  which can be proved by resolving the 3-phase mmfs along  $\alpha$ -axis as shown in equation (3.21) [12].

$$i_\alpha \sqrt{\frac{3}{2}} N = N [i_a \cos(0^\circ) + i_b \cos(120^\circ) + i_c \cos(240^\circ)] \quad (3.21)$$

$$i_\alpha = \sqrt{\frac{2}{3}} \left( i_a - \frac{1}{2} i_b - \frac{1}{2} i_c \right)$$

And similarly  $i$  is given by equation (3.22).

$$i_\beta = \sqrt{\frac{2}{3}} \left( 0 + \frac{\sqrt{3}}{2} i_b - \frac{\sqrt{3}}{2} i_c \right) \quad (3.22)$$

To obtain a square matrix a zero sequence current which does not produce any rotating mmf can be added in a convenient form and complete result can be represented as shown in equation (3.23).

$$\begin{bmatrix} i_\alpha \\ i_\beta \\ i_0 \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \\ \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} \quad (3.23)$$

The above transformation also applies to voltage or flux [12].

### 3.5 Transformation from rotating axes to stationary axes

The rotating two-axes with rotating phasors and stationary space phasors in stationary axes are shown in Figures 3.5 and 3.6 respectively. Rotating axes are aligned along d , q axes by taking angle 0 at time t = 0 [12].

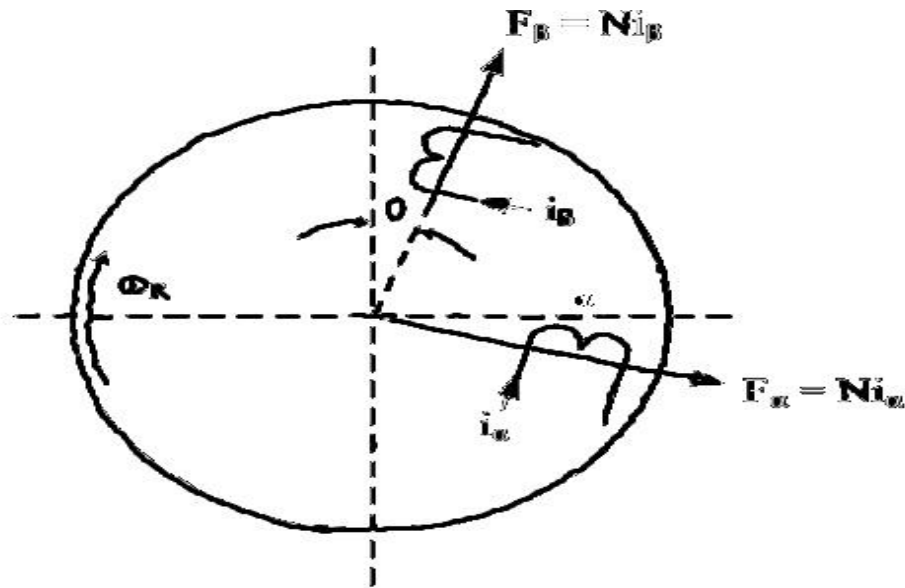
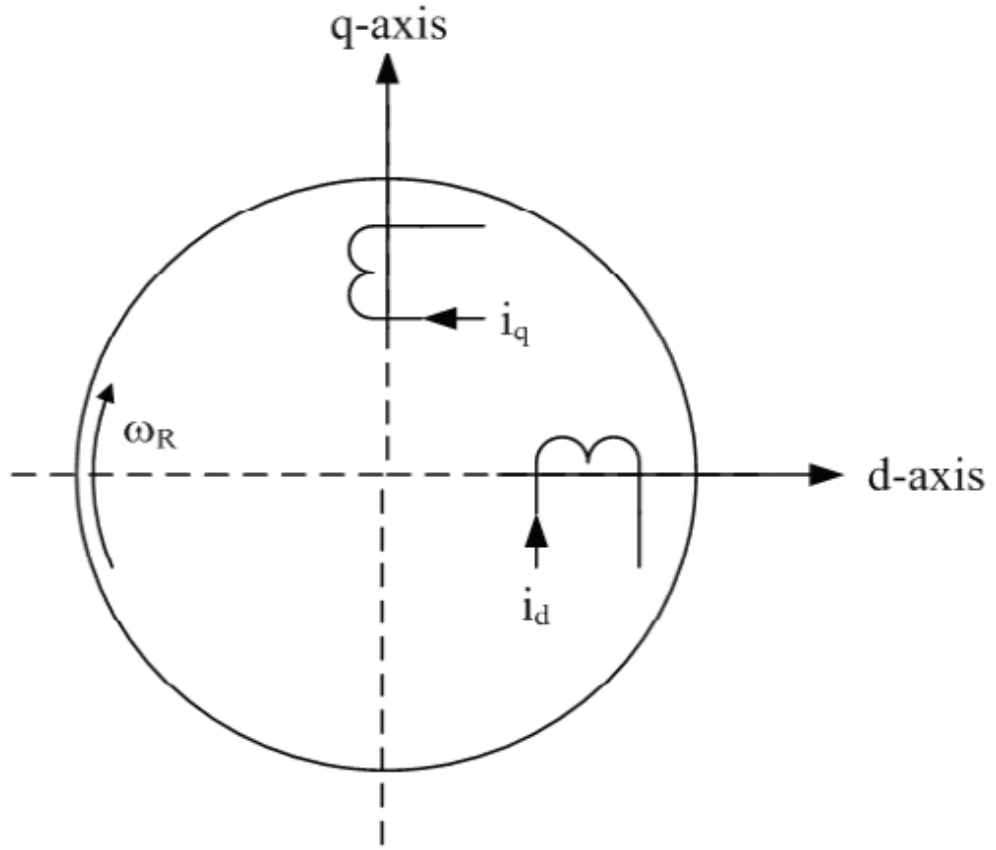


Figure 3.5 Rotating axes of 2-phase windings





**Figure 3.6: Stationary d , q axes of 2-phase windings**

Assuming the same effective number of turns in  $\alpha$  ,  $\beta$  and d , q axes, mmfs  $F_\alpha$  and  $F_\beta$  can be resolved along d and q axes, it gives the relationship as follows [12]:

$$F_d = F_\alpha \cos \theta + F_\beta \sin \theta$$

Therefore currents along d and q axes are given by equations (3.24) and (3.25).

$$i_d = i_\alpha \cos \theta + i_\beta \sin \theta \tag{3.24}$$

similary

$$i_q = -i_\alpha \sin \theta + i_\beta \cos \theta \quad (3.25)$$

The equations (3.24) and (3.25) in matrix form are expressed as shown in equation (3.26).

$$\begin{bmatrix} i_d \\ i_q \end{bmatrix} = \begin{bmatrix} \cos \theta & \sin \theta \\ -\sin \theta & \cos \theta \end{bmatrix} \begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} \quad (3.26)$$

The transformation from rotating three-phase system to two-phase rotating system and two-phase rotating system to two-phase stationary system can be carried out from equations (3.18) and (3.21). With the help of these relations the transformation from three-phase rotating system to two-phase stationary system can be obtained by substitutions and taking the inverse transformation will give the relation as shown in equations (3.27) and (3.28) [12].

$$\begin{bmatrix} i_d \\ i_q \\ i_0 \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} \cos \theta & \cos \left( \theta - \frac{2\pi}{3} \right) & \cos \left( \theta - \frac{4\pi}{3} \right) \\ -\sin \theta & -\sin \left( \theta - \frac{2\pi}{3} \right) & -\sin \left( \theta - \frac{4\pi}{3} \right) \\ \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} \quad (3.27)$$

**And**

$$\begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} \cos \theta & -\sin \theta & \frac{1}{\sqrt{2}} \\ \cos \left( \theta - \frac{2\pi}{3} \right) & -\sin \left( \theta - \frac{2\pi}{3} \right) & \frac{1}{\sqrt{2}} \\ \cos \left( \theta - \frac{4\pi}{3} \right) & -\sin \left( \theta - \frac{4\pi}{3} \right) & \frac{1}{\sqrt{2}} \end{bmatrix} \begin{bmatrix} i_d \\ i_q \\ i_0 \end{bmatrix} \quad (3.28)$$

## **3.6 Converter**

### **3.6.1 Rectifiers and inverters**

The electronic devices can be used in the rectifying as well as in the inverting mode.

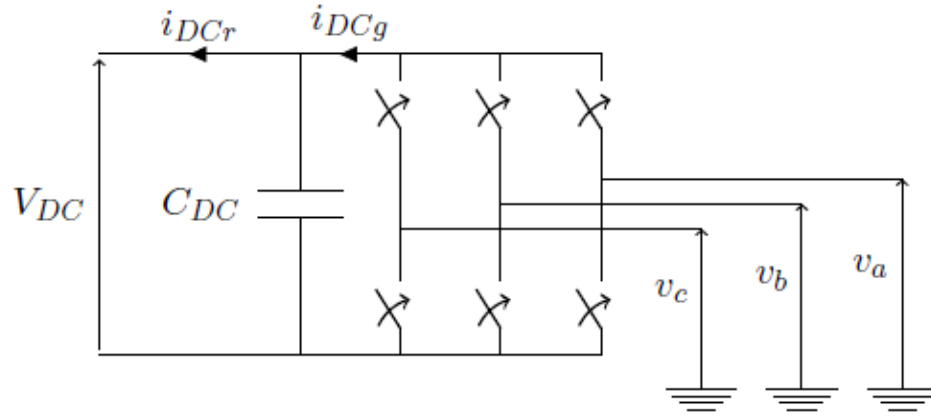
Diode is very common device to be used in uncontrolled rectifier, because of its “Modeling, Simulation & Control of Induction Generators Used in Wind Energy Conversion” simplicity, low cost and low losses. However it is non-linear in nature hence generates harmonic currents and allows only a unidirectional power flow. Back to back connected converters are widely used in three-phase frequency converter. The back to back converter is a bidirectional power converter consisting of two pulse-width modulated (PWM) converters. The capacitor connected in back to back arrangement decouples the control of the two converters and maintains the grid side DC link voltage constant. The basic concept of DFIG control is that the rotor frequency changes with the change in speed and the direction of rotor power flow changes from super-synchronous to sub-synchronous speeds. The power electronic converters accomplish this very conveniently. The power electronics converter compensates the difference between mechanical and electrical frequencies by injecting a rotor current with a variable frequency, thus electrical and mechanical frequencies are decoupled. This feature results in maximum energy extraction and noise reduction at low wind speeds. Converter can also work as an active element in power system making active and reactive power flow controllable. It can be used as a local reactive power source in case of weak grid and also improves the power quality by reducing the flicker level and limit the short-circuit power. The grid-side converter in DFIG can perform as Static Compensator (STATCOM) to support LVRT condition. In modern variable speed wind generator systems Insulated Gate Bipolar Transistors (IGBTs) are typically used [12].

### 3.6.2 Converter models

The DFIG is generally used with two back-to-back PWM converters as shown in figure 2.1. The grid-side controller is used to keep the DC-link voltage constant and to make the grid side run at unity power factor, so that no reactive power is flowing between the rotor and the grid. The rotor-side controller allows to control stator voltage and stator active power [14].

### 3.6.3 Supply-side converter

The supply side can be modelled as in figure 3.7.



**Figure 3.7: Grid-side model**

The grid-side converter is supplied with three phase-voltages coming from the grid. Assuming a symmetrical grid, voltages  $v_a$ ,  $v_b$  and  $v_c$  can be written as [15].

$$v_a = V_s \sin(\omega_g t + \phi_g) \quad (3.29)$$

$$v_b = V_s \sin\left(\omega_g t + \frac{2\pi}{3} + \phi_g\right) \quad (3.30)$$

$$v_c = V_s \sin\left(\omega_g t - \frac{2\pi}{3} + \phi_g\right), \quad (3.31)$$

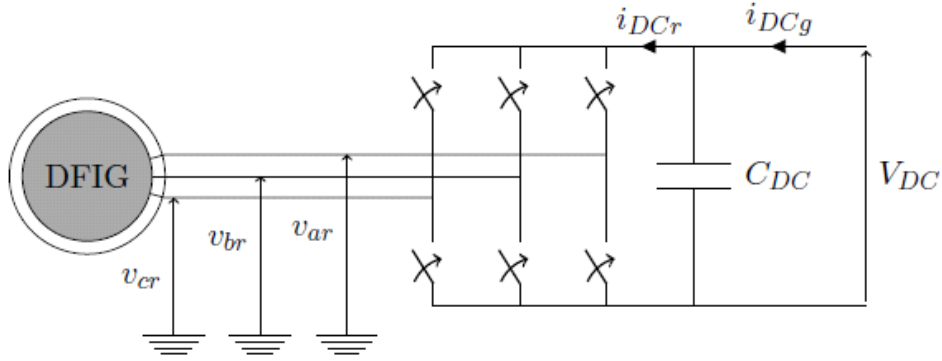
Where  $\phi_g$  is the phase of voltage  $v_a$ ,  $\omega_g$  is the electric frequency of the grid and  $V_s$  is the RMS stator voltage.

The PWM converter switches the transistors on and off according to a control signal it receives from the controller. The controller delivers the PWM modulation depth,  $P_{m1}$ , as a control signal. The modulation depth relates the grid voltage magnitude  $V_s$  to the dc-voltage  $V_{DC}$  [15]:

$$V_s = P_{m1} \frac{\sqrt{3}V_{DC}}{2\sqrt{2}} \quad (3.32)$$

### 3.6.4 Rotor-side converter

The rotor side can be modelled as in figure 3.8 [15]:



**Figure 3.8: Rotor-side model**

The quantities  $v_{ar}$ ,  $v_{br}$  and  $v_{cr}$  are the three rotor phase-voltages defined by

$$v_{ar} = V_r \sin(\omega_r t + \phi_{gr}) \quad (3.33)$$

$$v_{br} = V_r \sin\left(\omega_r t + \frac{2\pi}{3} + \phi_{gr}\right) \quad (3.34)$$

$$v_{cr} = V_r \sin\left(\omega_r t - \frac{2\pi}{3} + \phi_{gr}\right) \quad (3.35)$$

Where  $\phi_{gr}$  is the phase of voltage  $v_{ar}$  and  $V_r$  the RMS rotor voltage. The converter sets the rotor voltage according to the PWM modulation depth,  $P_{m2}$ , delivered by the controller. The RMS rotor voltage magnitude  $V_r$  can be expressed in terms of dc-link voltage as

$$V_r = P_{m2} \frac{\sqrt{3}V_{DC}}{2\sqrt{2}} \quad (3.36)$$

In the  $d_q$ -reference frame, this means that

$$v_{dr} = P_{md} \frac{\sqrt{3}V_{DC}}{2\sqrt{2}}, \quad (3.37)$$

$$v_{qr} = P_{mq} \frac{\sqrt{3}V_{DC}}{2\sqrt{2}}. \quad (3.38)$$

where  $P_{md}$  and  $P_{mq}$  are the modulation depth's components [15].

### 3.7 Vector control of the DFIG

DFIG can be controlled by controlling rotor side converter and grid side converter. VC can be used for both. The objective of the Vector control for RSC is to regulate stator active power  $P_s$  and reactive power  $Q_s$  independently. The overall (RSC) control scheme using Vector control. To describe the control scheme, the general park's model of DFIG is used. Using the conventions in static stator oriented reference frame, voltage vector equations are written as [16]:

$$V_s = R_s i_s + \frac{d\varphi_s}{dt} \quad (3.39)$$

$$V_r = R_r i_r + \frac{d\varphi_r}{dt} - j\omega\varphi_r \quad (3.40)$$

$$\varphi_s = L_s i_s + L_m i_r \quad (3.41)$$

$$\varphi_r = L_m i_s + L_r i_r \quad (3.42)$$

The vector control scheme consists of two series of two PI controllers. The active and reactive power error signals are given to the

two different PI controller which gives direct rotor current  $I_{rd}^*$ , and quadrature current  $I_{rq}^*$  respectively. These two signals are compared with the generator currents,  $I_{rd}$  and  $I_{rq}$  and the error signal is given to the other two PI controllers. The output of these controllers is rotor voltage  $V_{rd}$  and  $V_{rq}$  respectively [16].

From rotor voltage equations

$$V_{rd} = R_r i_{rd} + \sigma L_r \frac{di_{rd}}{dt} \quad (3.43)$$

$$V_{rq} = R_r i_{rq} + \sigma L_r \frac{di_{rq}}{dt} \quad (3.44)$$

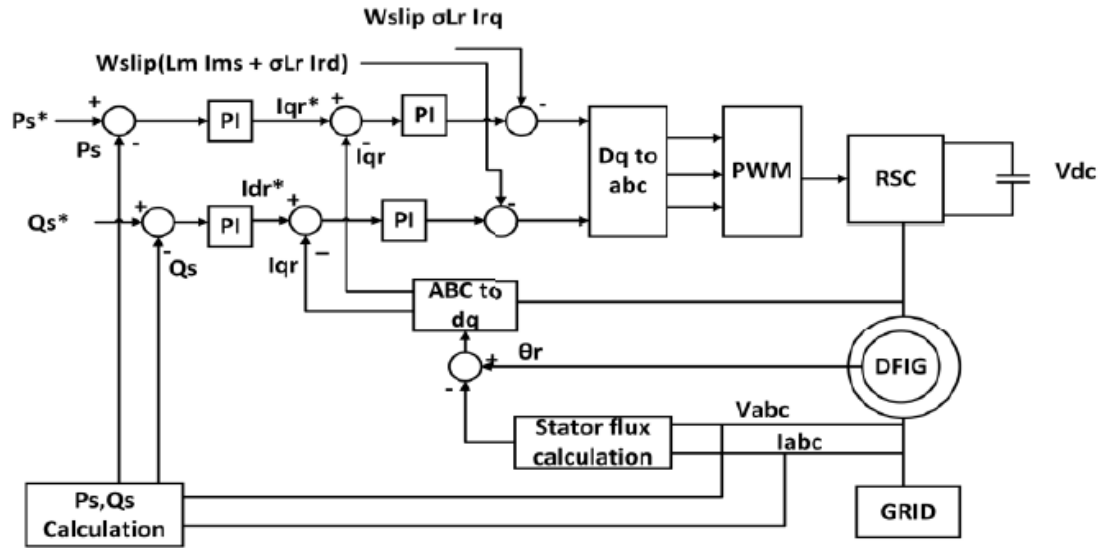
Where,  $\sigma$  is the leakage factor defined as,

$$\sigma = 1 - \frac{L_m^2}{L_s L_r} \quad (3.45)$$

To ensure good tracking of rotor d-q axis currents, compensation terms are added to  $V_{rd}$  and  $V_{eq}$

$$V_{rd}^* = V_{rd} - w_{slip} \sigma L_r i_{rq} \quad (3.46)$$

$$V_{rq}^* = V_{rq} + w_{slip} (\sigma L_r I_{rd} + L_m i_{rd}) \quad (3.47)$$



**Figure 3.9: Vector control structure for DFIG**

The voltage signals are given to the PWM generator which gives pulses to the rotor side converter.

The proposed vector control of DFIG in wind power application is verified using MATLAB/SIMULINK software [16].



# **CHAPTER FOUR**

## **RESULTS AND DISCUSSION**

# CHAPTER FOUR

## RESULTS AND DISCUSSION

### 4.1 Simulation results and discussion

In this section, the simulation of DFIG under vector control method by using MATLAB software is presented. To verify vector control performance, the behavior of DFIG wind turbine has been simulated. The RSC is used to regulate rotor current, and the GSC is responsible for adjusting the DC link voltage. Series results under constant wind speed has been obtained from the MATLAB program to describe the behavior of the system under vector control method.

From the results, the DFIG has gotten strongly operation with stable performance, constant speed and fixed DC link voltage. Furthermore the output power of the DFIG is more linear, stable and safety transient response with smooth recovery values under constant speed.

Also the DFIG vector control has achieved stability without adding any FACTs.

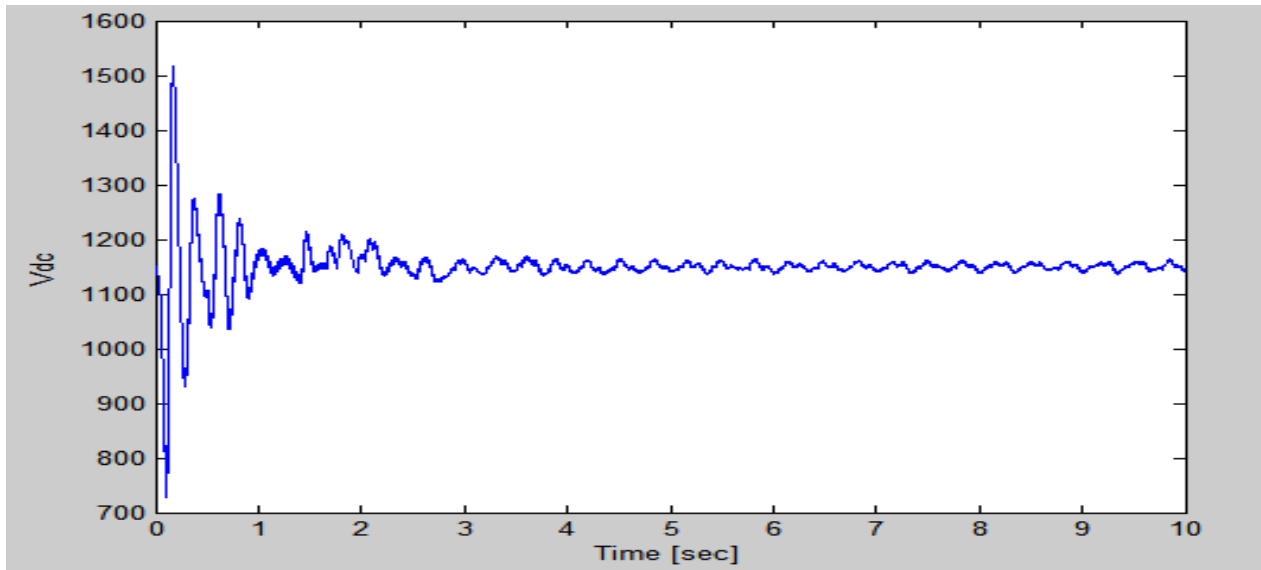
The most simulation results have smooth curves with fewer ripple that means this method is implemented in adequate techniques control to provide and enhance the control system.

The system consist of DFIG, transformer, transmission lines and grid network. The DFIG wind turbine voltage and rated power are 575 V and 1.5 MW. The machine speed is set as value 0.9 pu and three phase fault occurs in 2 – 2.11 sec.

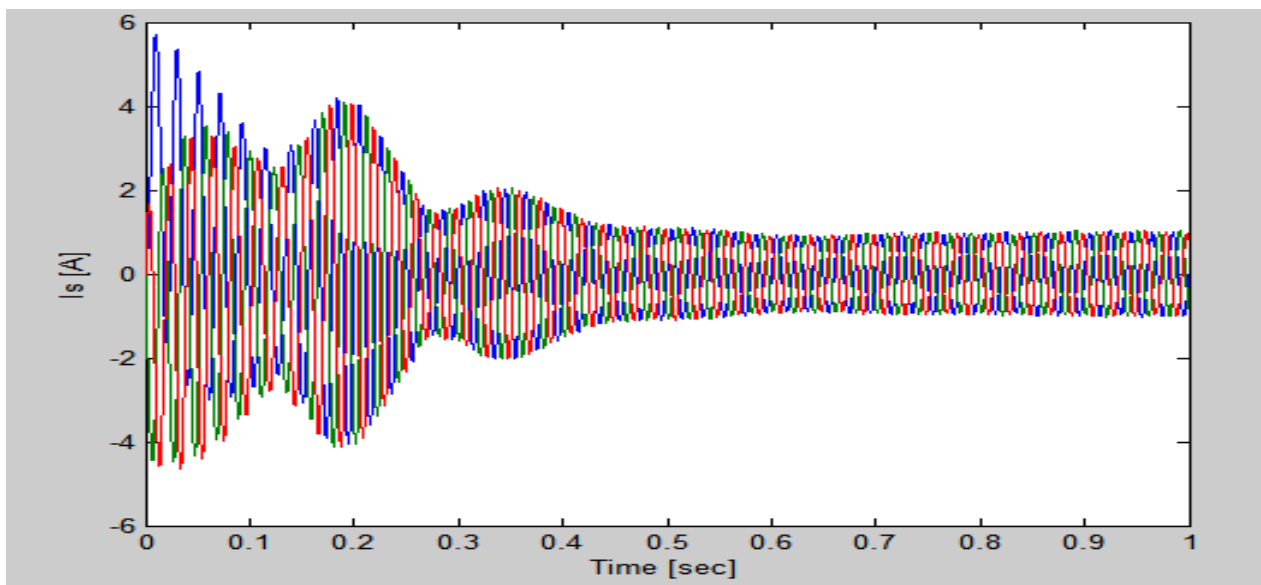
The DFIG use two back to back converter regulate the rotor current, and GSC is responsible for adjusting the DC link voltage.

The crowbar is applied to protect the rotor against over current during dynamic operation.

The model studied specification data and control parameters are listed in table I and II in appendix.

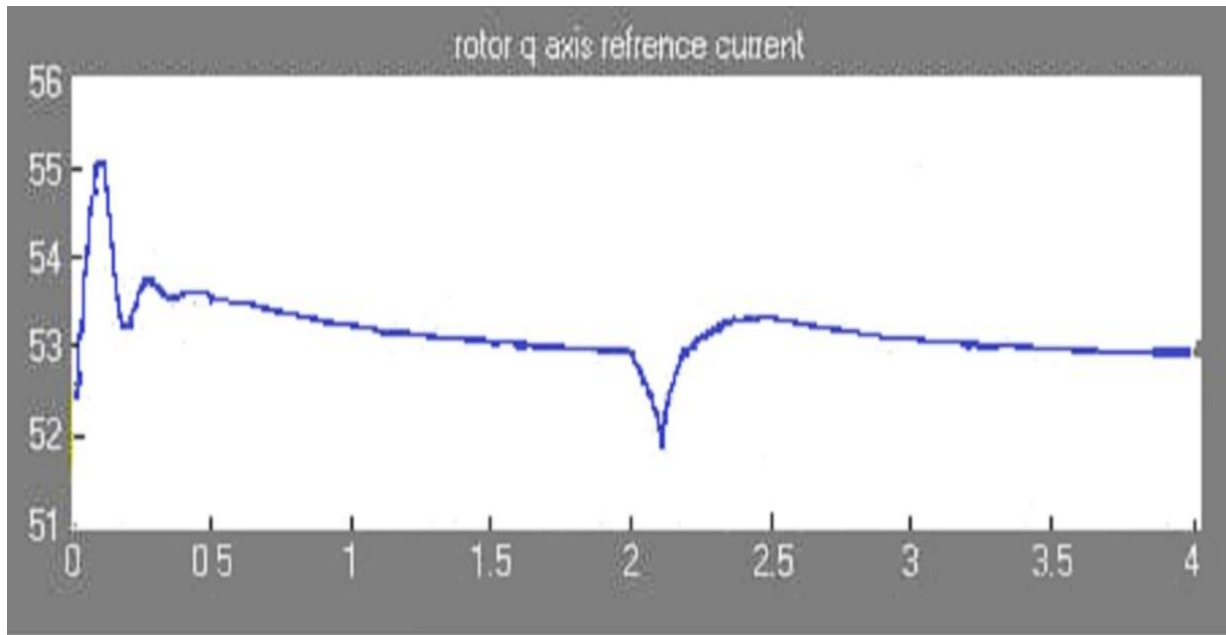


**Figure 4.1:  $V_{dc}$**



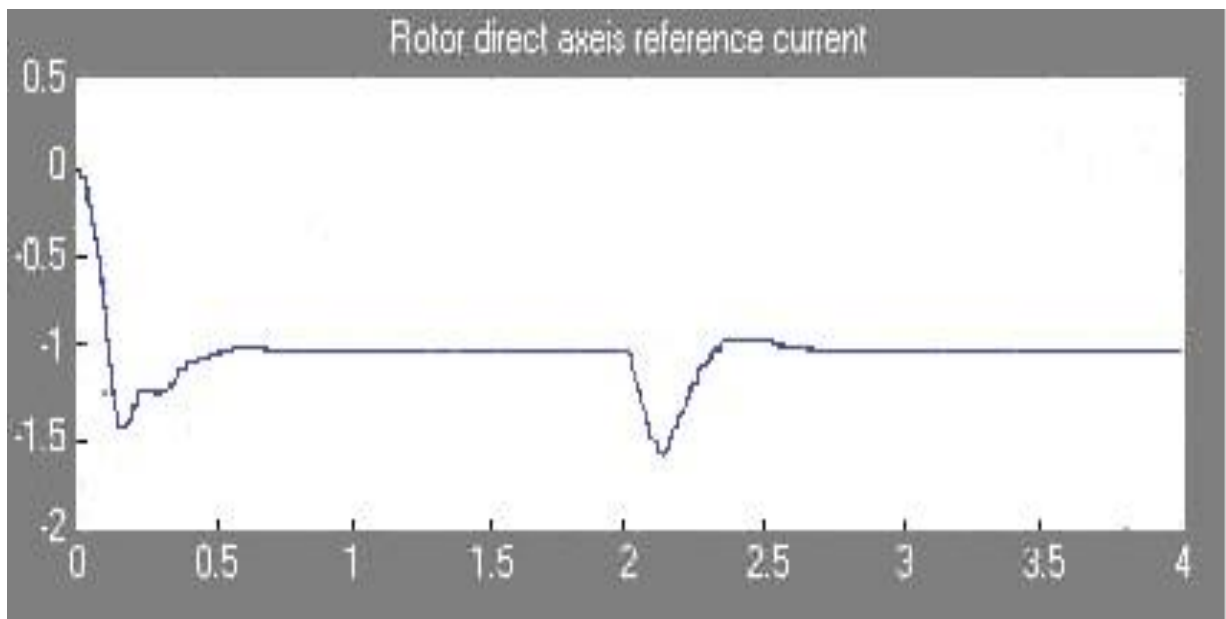
**Figure 4.2: stator three phase current**

Figure 4.1 shown the the  $V_{dc}$  has almost constant value in steady state and safety dynamic response durin abnormal system operation.



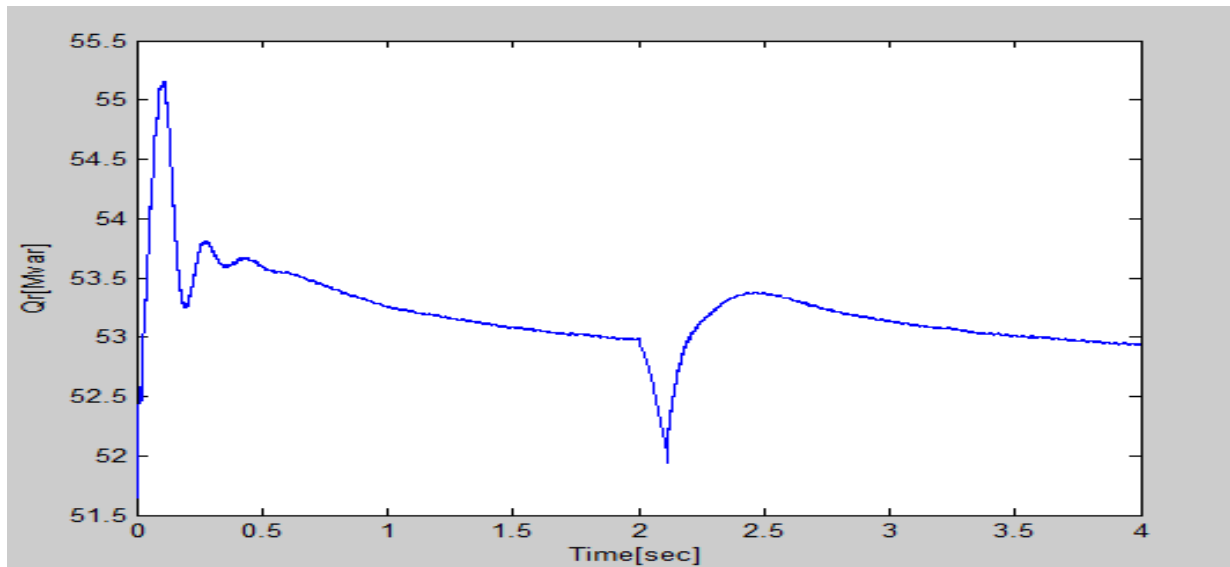
v

**Figure 4.3: rotor q axis reference current**

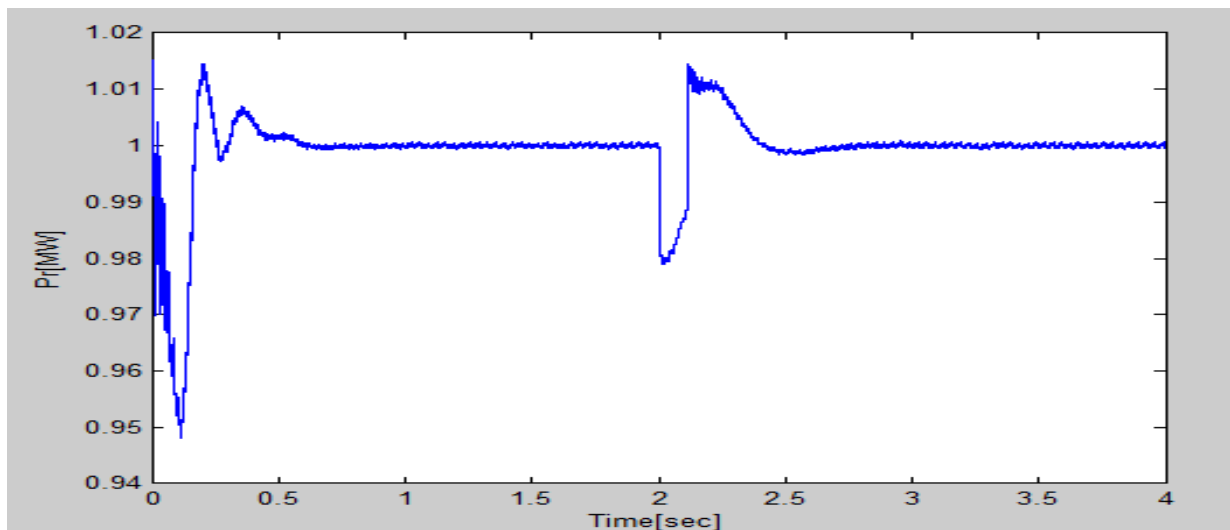


**Figure 4.4: rotor direct axis reference current**

Figure 4.3 and figure 4.4 shown the RSC converter parameter ( $I_{rq}$  and  $I_{rd}$ ) respectively, which are mainly controlled reactive and real power respectively and rotor currents shown respectively. So active power is controlled by  $I_{rq}$  component, and reactive power is controlled by  $I_{rd}$  component of vector.



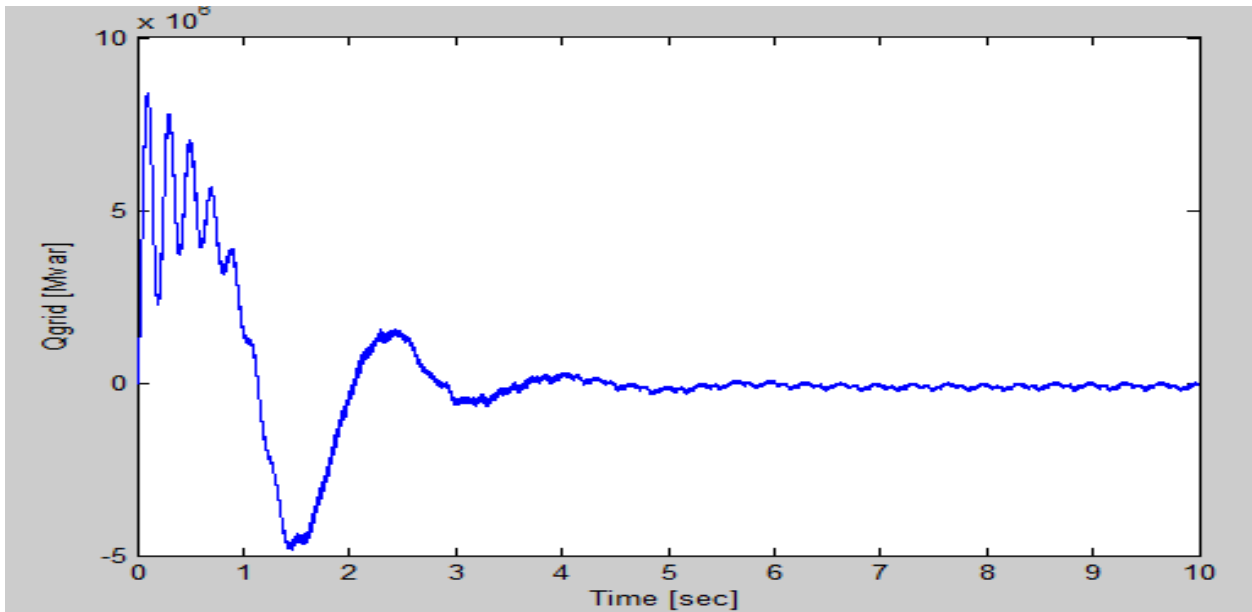
**Figure 4.5: rotor reactive power**



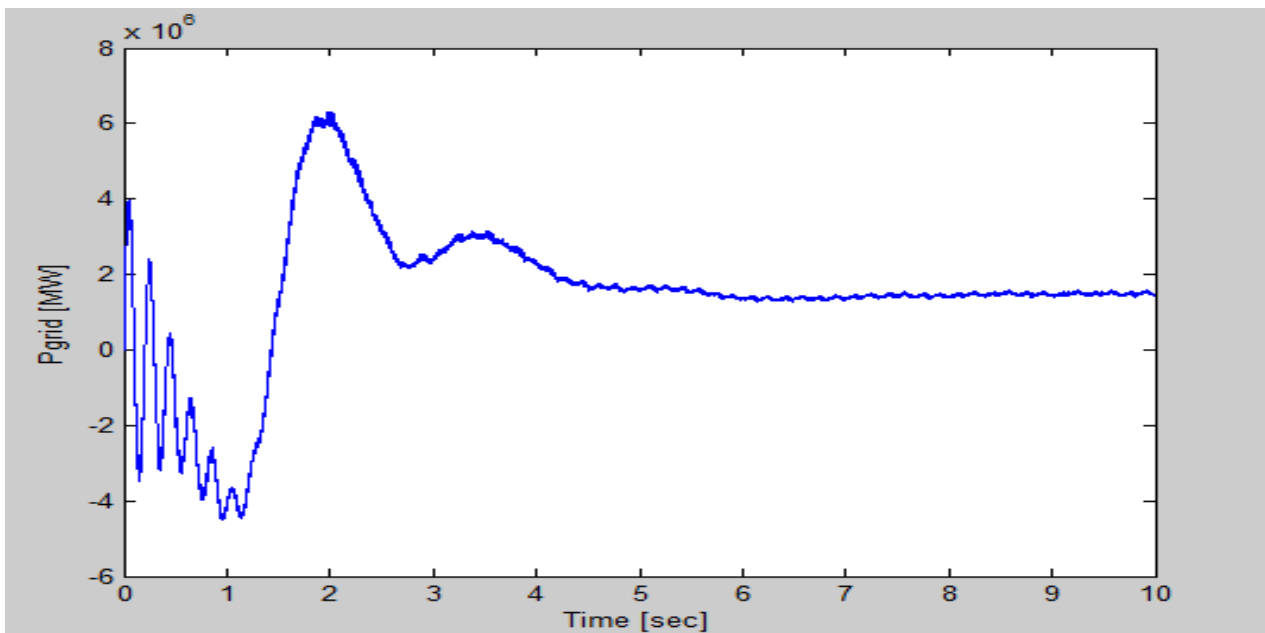
**Figure 4.6: rotor active power**

Figure 4.5 shown the rotor reactive power(  $Q_r$ ) response is better, and Figure 4.6 shown the rotor real power (  $P_r$ ) has better response and fewer ripple.

The machine side provides good decoupling between active and reactive powe.



**Figure 4.7: grid reactive power**



**Figure 4.8: grid active power**

The grid reactive and real power are displayed in figs 4.7 and 4.8, respectively.

Referring to fig 4.7, the reactive power forced to zero values to keep the voltage at stable value, which ensure the unity power factor (PF).

Finally  $P_g$  has better value and good steady state response.

## **CHAPTER FIVE**

# **CONCLUSIONS AND RECOMMENDATIONS**

# CHAPTER FIVE

## CONCLUSIONS AND RECOMMENDATIONS

### 5.1 Conclusions

The performance analysis of a doubly-fed induction generator driven by a wind turbine has been described. In this thesis, dynamic equation of doubly fed induction generator has been given. Especially, Generated power, DC voltage, wind speed, pitch angle and grid side voltages are identified using MATLAB simulation model. Due to the advances in power electronics, it advantaged to use the doubly fed induction generator system with fixed speed connected to the electrical grid through an AC-DC-AC converter for improving the efficiency of the power conversion. Considering the results it can be said that DFIG proved to be more reliable and stable system when connected to grid side with the proper converter control systems.

Vector control is the use of a two-phase transformation to break a system down into orthogonal components for easier control. For three-phase machines, this can be seen as the transformation of three-phase real quantities to complex rotating quantities in a fixed frame (space vectors) and then transformed as orthogonal components in a rotating frame (the d-axis and q-axis).

The d-axis and q-axis, while a fictional mathematical abstraction, can be thought of in a physical sense as actual rotating windings. This allows an equivalent, simpler representation of a three-phase machine as a two-phase machine. Control and analysis can be done more easily, intuitively in degree frame.

The doubly fed induction generator is found to have the least output power variation and the fastest response of the three control



techniques simulated. Moreover, the additional complexity of the system enables an overall system power factor control, to help operate the system at close to unity power factor.

## **5.2 Recommendations**

The recommendation of future work of this thesis is related to doubly fed induction generator such as several benefits, such as better efficiency, rating of the converter is less, cost efficient, loss of those converter is minimum, easy power factor correction, possibility of four quad, ant active and reactive control and better utilization factor.

So for all above the recommendation can be written as below:

- Explanation and analysis the multi-type control of grid connected DFIG to obtain power system stability control.
- Study a hybrid control between any two controls like voltage and frequency coordinated control in DFIG based on the wind turbine.
- Study the paralleling DFIG simplified voltage control.

## References

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## **Appendices**

# Appendices

## Appendix A:DFIG parameters data:

**Table I: Wind turbine parameters.**

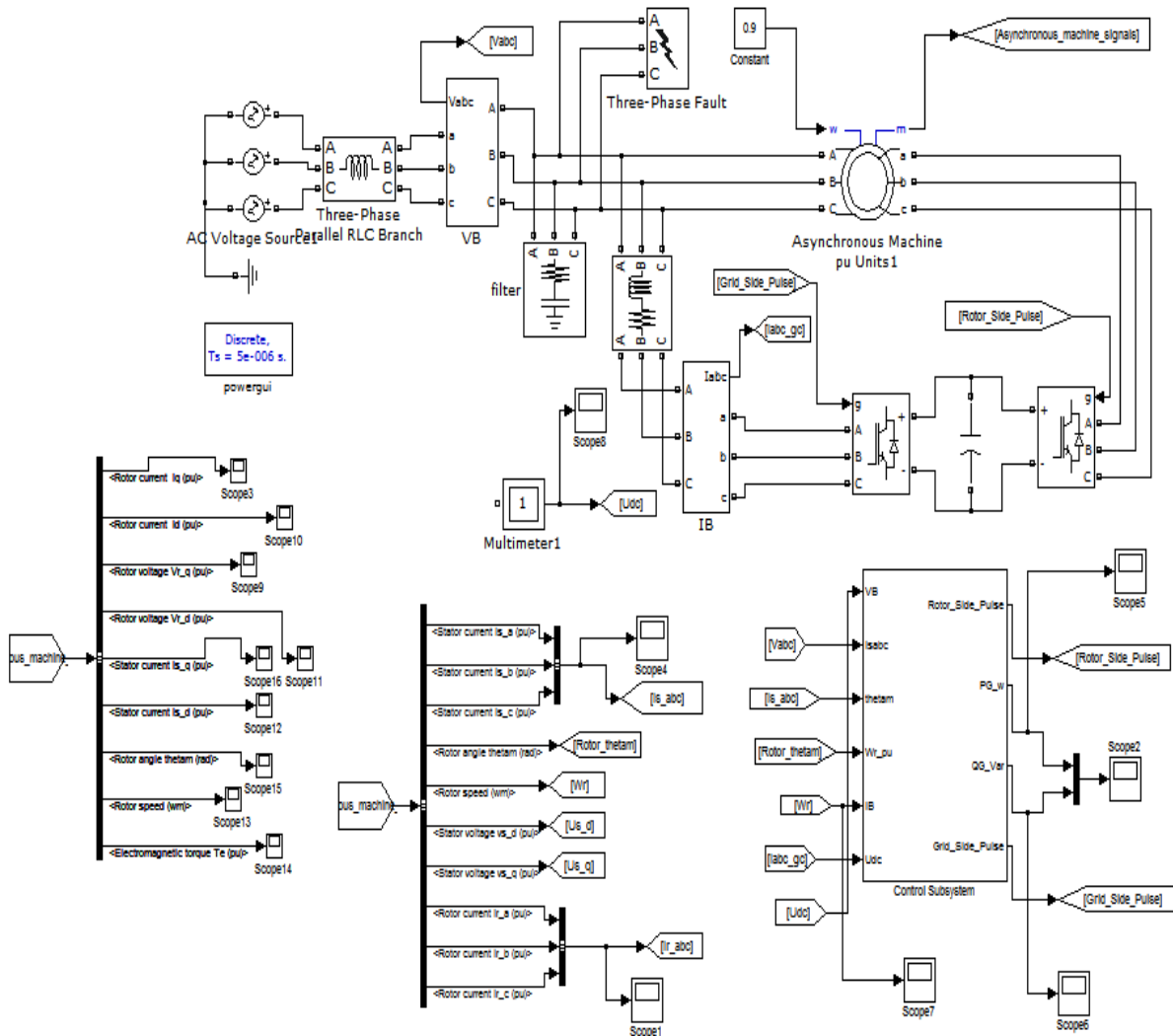
<b>Wind turbine</b>	
<b>Rated power, <math>P_m</math></b>	<b>2.0 MW</b>
<b>Rotor radius, R</b>	<b>40 m</b>
<b>Air density, <math>\rho</math></b>	<b>1.229 kg/m<sup>3</sup></b>
<b>Gearbox ratio</b>	<b>60</b>
<b>Gearbox efficiency</b>	<b>0.97 pu</b>
<b>Average wind speed, <math>V_w</math></b>	<b>11.42 m/s</b>

**Table II: DFIG parameters**

<b>1.5 MW DFIG</b>	
<b>Rated power</b>	<b>1.5 MW</b>
<b>Rated Voltage</b>	<b>575 V</b>
<b>Rated frequency</b>	<b>50 Hz</b>
<b>Number of pole pairs, P</b>	<b>3.0</b>
<b>Stator winding resistance, <math>R_s</math></b>	<b>0.023 p</b>
<b>Rotor winding resistance, <math>R_r</math></b>	<b>0.016 p</b>
<b>Stator leakage inductance, <math>L_{LS}</math></b>	<b>0.18</b>
<b>Rotor leakage inductance, <math>L_{Lr}</math></b>	<b>0.16</b>
<b>Magnetizing inductance, <math>L_m</math></b>	<b>2.9 pu</b>

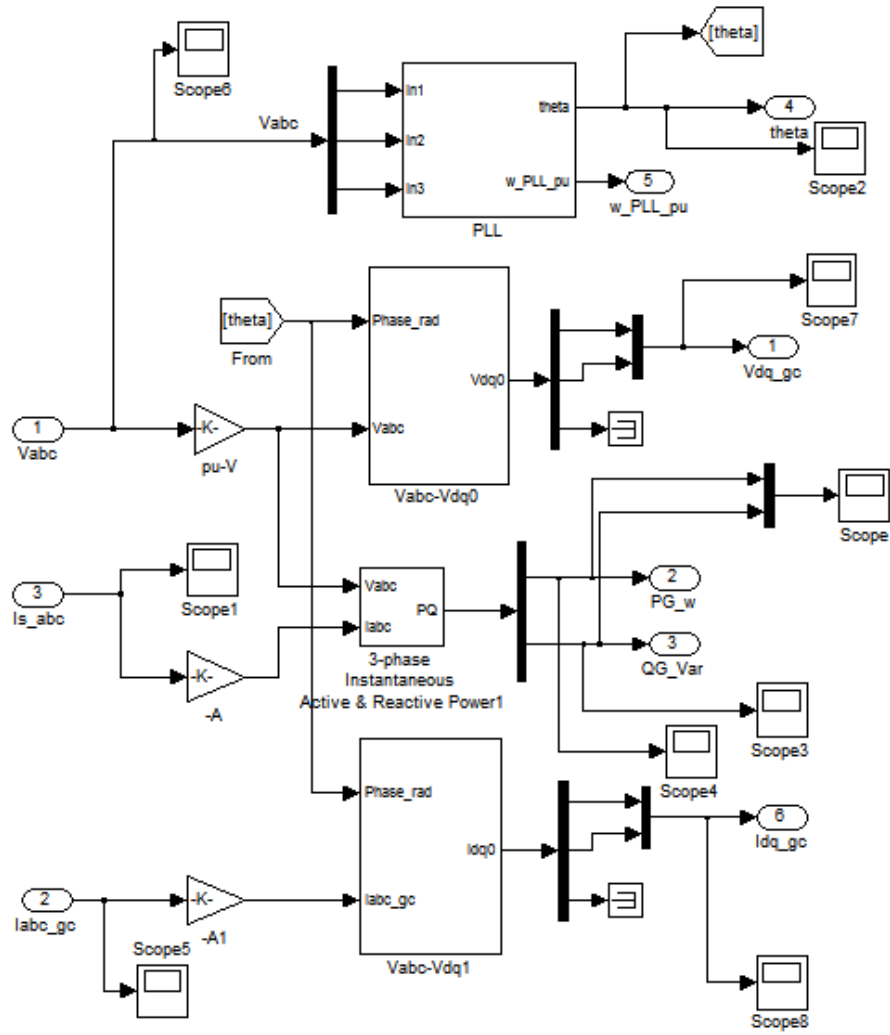
## Appendix B: Simulation Models of DFIG:

### Doubly-Fed Induction Generator Model



(a) Main page of DFIG





(e) P&Q model