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Research Article

Power Quality Improvement for Grid Connected Wind Energy Generation System by Implementation of DFIG scheme

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Abstract

The doubly fed induction generator (DFIG) is used in most of the wind energy conversion system (WECS), due to its numbers of advantage for fulfilling the condition of variable speed and running above the synchronous speed. This characteristic will avoid harming the wind turbine mechanism, this system is very good when the actuated wind speed is above the rated speed. In this paper, we will present the contribution of wind power system in mitigation of power Emergency, to analysis the performances of different types of generators used in wind form, solutions to improve the Power quality of Grid connected wind energy generation system, and to generate a constant frequency from the variable speed operation of the shaft using the traditional PI. Implementing DFIG will allow constant amplitude and frequency at stator even if the wind speed is varying i.e., variable speed constant frequency operation. It also helpful to generate even at lower wind speed. It is applicable on a speed range of ± 30% around the synchronous speed.It uses a reduced rated AC/DC/AC bidirectional converter (25-30% of total rating), by implement the above controllers in MATLAB/SIMULINK.

Keywords—*The Doubly Fed Induction Generator (DFIG); Wind Energy Conversion System (WECS); PI regulator; Vector Control with the field-oriented control; variable speed constant frequency operation.*

I INTRODUCTION

Nowadays, big efforts are utilised to minimise the impact of electricity Production on the environment. The search for a clean and renewable energy has accepted much attention throughout the world [1]. The wind power is considered as one of the most Promising sources of renewable technologies due to the non-toxic pollution or minimal global warming emissions, made that technology one of the Virtuous and most feasible source of energy.

The DFIG is an attractive choice for wind power Production because of their great number of advantages [2] such as variable speed, constant frequency, active/reactive power controllability [3] and reduced mechanical stresses [4]. The use of DFIG is becoming more and more common for power generation as it is suitable for the implementation of advanced features required for grid integration [5].The application of artificial intelligence techniques power

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electronics and control systems has been growing as Pt controller [6]. In this paper, PI control is applied in order to improve the behaviour of the DFIG under disturbances.

This paper is organized as follows. Firstly, in section II discuss how wind energy has gained importance in the recent years and also latest trend in wind energy conversion system structure. In section III how wind energy conversion model developed. After that in section IV includes the mathematical model of DFIG system for steady state as well as dynamic state of the generator. In section V discussed the methodology used for wind energy conversion system like PI controller system as well as pitch-controlled system with block diagrams. Also presenting results of the PI controlled system presented in this section. Finally in section VI result, conclusion and future scope will discuss.

Electricity Production through wind energy has been well Acknowledge as environmentally friendly, socially favourable, and economically competitive form any applications. Wind energy is one of the fastest-emerging renewable alternatives for the electrical supply around the earth. The success of the mechatronics system is aMajor step. Since the design of the power converter is highly subjected to on the characteristics of the turbine, developing at stabled for the wind turbine system is required. The dynamic part of the wind turbine system is composed of a wind turbine, a transmission, and a generator. Because the dynamic characteristic of the wind turbine is depending on the operating environment that is usually tested in a wind tunnel, it is not suitable to refine the design of the electrical part in the field test. Therefore, an emulator that can duplicate the characteristics of the dynamic part of a wind turbine under the testing environment would be helpful to facilitate the design process.

The role of the wind turbine emulator in assisting the design of WECS. A wind turbine separates the most extreme measure of energy from the wind while working at an ideal rotor speed, which again depend upon speed of wind. The ideal rotor speed differs because of the variable idea of the wind speed. Development shows that variable speed activity of the rotor brings about a higher energy creation comparison with a framework working at consistent speed. Sharp edges are utilized to remove power from the wind. By working the cutting edges at ideal tip speed proportion, most extreme measure of energy can be extricated from the variable speed wind turbine.

Configurations of WECS

Configurations of WECS Generators and power converters are the main electrical components of a WECS.

A.Fixed speed WECSwithout power converters:

I In this method the gear box is used to match the speed of wind turbine and generator for delivering the rated power at rated speed. During the system start-up, heavy in-rush current is limited using a soft starter and later it is bypassed by a switch. For compensating the reactive power drawn by the induction generator, a three-phase capacitor bank is installed

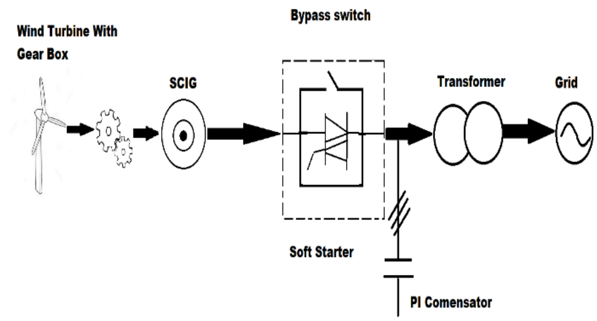


Figure 1: Fixed speed WECS without power converters interface [8].

B. Variable speed WECS

Variable speed WECS Variable speed WECS systems are classified into two types based on the power rating of the power electronics converter, such as Minimise capacity converters and maximum capacity converters. Due to the use of these power converters, decoupling between the generator and grid can be made automatically.

Variable speed reduced capacity converters are designed only with wound rotor induction generators, since rotor currents can be controlled on rotor side for variable speed operation without the need for total power in power system.

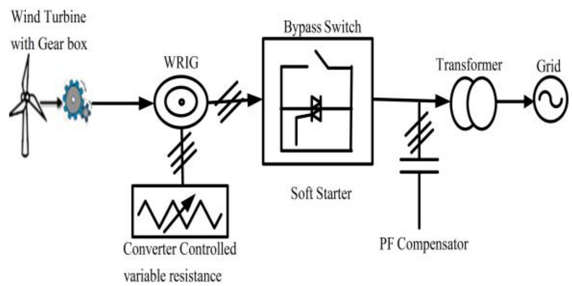


Figure 2: Variable speed WECS with variable rotor resistance[8]

Reduced capacity converters are again classified into two types such as wound rotor induction generator with variable rotor resistance and doubly fed induction generator (DFIG) with rotor converter and Wound rotor induction generators is shown in Fig. 1.2 with a variable resistance in the rotor circuit.

Variable speed operation of the turbine is achieved by varying the rotor resistance which affects the torque/speed characteristics of generator. The rotor resistance is varied with the help of power converter

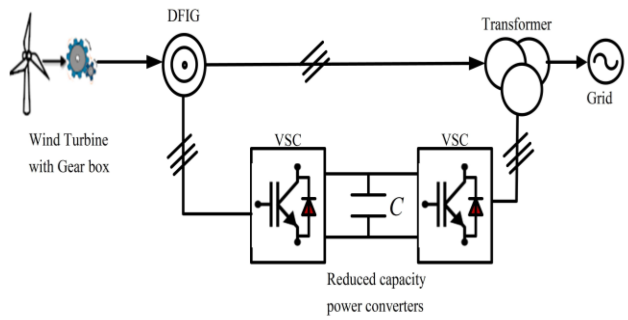


Figure 3: Variable speed WECS with reduced power capacity converters[8]

The speed of WRIG can be increased only 10 % above the rated synchronous speed of the generator.

The speed of WRIG can be increased only 10 % above the rated synchronous speed of the generator, In Fig. 1.4, DFIG WECS is shown, where 4 variable resistances in the rotor circuit is replaced by power converters and there are no power compensation and soft starter. The power in the rotor circuit processes only slip power, that is only 30 percent of the rated power of the generator. Due to reduction in the power capacity, the cost of converter equipment is less compared to the full capacity converters.

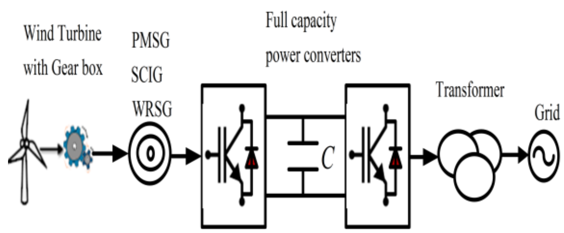


Figure 4: Variable speed WECS with full capacity converters[7]

III MODEL OF WIND SPEED

The Virtue of converting wind to other useful energy forms depend on the efficiency with which the rotor interacts with the wind flow.

Kinetic energy contained in wind is given by: -

$$E = 0.5v^2 \qquad (1)$$

Where m is the rate of flow of air and v2 is the speed of wind.

Taking into account a wind rotor of cross-sectional area A exposed to the wind flow equation (3.1) is given by: -

$$E = 0.5AV\rho v^2 \qquad (2)$$

Where AV denotes the volume flow and AVρ represents the mass flow. V is the volume of air accessible to the rotor. Hence power, can be expressed as

$$P = 0.5A\rho v^3 \qquad (3)$$

From equation (3), we find that factors affecting the power available in the wind stream are the area of the wind turbine rotor, density, and the wind velocity. However, the wind velocity effect is more due to its cubic relationship with the power.

1. MAXIMUM AMOUNT OF ENERGY TO BE EXTRACTED

Wind turbine cannot extract the power given in equation no (3) completely from the wind. Only a section of its kinetic energy is transformed to the rotor, while the remaining air leaving the wind turbine is carried away. Therefore, real power formed by a rotor will be decided according to the energy transferred that would take place from the wind speed to the rotor. This efficiency is defined as the power coefficient. Hence power coefficient of the rotor can be defined as the fraction of actual power developed by the rotor to the theoretical power available in the wind [13].

$$C_p = \frac{2P_0}{\rho A v^3} \qquad (4)$$

Where P_o is the power developed by the turbine.

The thrust force experienced by the rotor can be expressed as

$$F = \frac{1}{2}\rho A v^3 \qquad (5)$$

So rotor torque expressed as

$$T = \frac{1}{2}\rho A v^2 R \qquad (6)$$

Where, R is the rotor radius.

Figure 5 shows the power extracted by air.

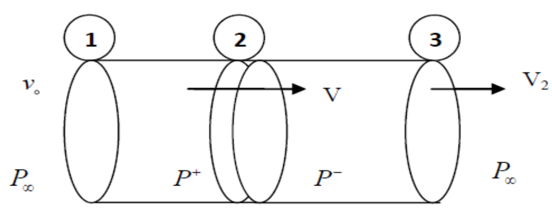


Fig. 5. Power contained in wind[7]

If surface 2 allows the air through it without any hindrance, then results is v=v0 and v2=v0 and therefore the power extracted is zero. If surface 2 allows a very large hindrance like wall, then all the v0 is stopped near the surface 2 and so power extracted is zero again. So in the both cases we got zero output power. Let we have one axial interference factor ‘a’. When a=0, it offers no interference and if a=1, then there is complete blockage.

In between there should be some value of a, at which it should be maximize. Therefore, a is defined in terms of v and v0 as,

$$v = v_0(1 - a) \qquad (7)$$

Where if a=0, v=v_0

If a=1, v=0

$v_0(1-a) = \frac{1}{2}(v_0 + v_2)$ (8)

$v_2 = v_0(2-1 = 2a)$ (9)

Maximum amount of power extracted will be equal to drop in kinetic energy of the air.

So power extracted

$P_0 = \frac{1}{2}\rho A v(v_0^2 - v_2^2)$ (10)

Substituting the value of v and v2 in equation (3.10), we get

$P_0 = \frac{1}{2}\rho A v_0(1-a)[v_0^2 - v_0^2(1-2a)^2(11)$

$P_0 = \frac{1}{2}\rho A v_0^3(4a - 8a^2 + 4a^3)$ (12)

$\frac{dP_0}{da}=0$

$$\frac{dP_0}{da} = \frac{1}{2}\rho A v_0^3(4 - 16a + 12a^2)$$

$\frac{1}{2}\rho A v_0^3(4 - 16a + 12a^2)=0$

$4 - 16a + 12a^2 = 0$

$$a = 1/3$$

Therefore, maximum power can be extracted when a=1/3

So that from equation (7)

$$v = v_0(1 - 1/3)$$

$v = \frac{2}{3}v_0$ (13)

Hence, we can say that maximum power can be extracted only when speed goes to 2/3 rd of v_o.

So substituting the value of a=1/3 in the equation of (12),

$P_0 = \frac{1}{2}\rho A v_0^3(4.(\frac{1}{3}) - 8(1/3)^2 + 4(\frac{1}{3})^3)$ (14)

$P_0 = \frac{1}{2}\rho A v_0^3(\frac{16}{27})$ (15)

Where $\frac{1}{2}\rho A v_0^3$denotes the power contained in the wind and the value 16/27 represents the maximum possible efficiency.

The connection between the mechanical power and the wind speed passing through the turbine rotor can be given by the equation,

$P_m = \frac{1}{2}\rho A v_0^3 C_p$ (16)

$P_m = (\frac{1}{2}\rho\pi R^2 v_0^3)C_p$ (17)

Where P_m is the mechanical output power, $\frac{1}{2}\rho A v_0^3$ is the power contained in wind and is $C_p$is the power coefficient of the wind turbine and is the function of the pitch angle, β and the tip speed ratio λ.

2. WIND ENERGY CHARACTERISTICS

Wind energy is another form of kinetic energy as it flows in air. It can be converted into electrical energy through power conversion mechanism. The wind turbine extracts kinetic energy from the swept area of the blades as shown in the Figure (3.2) [15]. The power in the air flow can be calculated is by:

$$P_{air} = \frac{1}{2\rho A v} \qquad (18)$$

Were

ρ=air density (approx. 1.225 kgm−3),

A= area swept by the rotor,

v = Up wind free mean wind speed

When wind power is transmitted to the wind turbine rotor than it is reduced by the factor called the power coefficient and power coefficient is given by the formulae given below in the equation (19).

Power Coefficient, Cp:

$$C_p = \frac{P_{Mechanicalpower}}{P_{air}} \qquad (19)$$

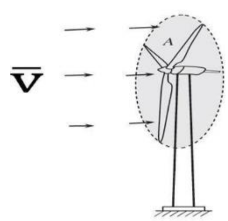


Figure 6: Area Swept by Wind Turbine Blades[8]

The maximum value of Cp is called Betz limit. Then it is given as

$$P_{\text{Mechanical power}} = C_p P_{air} = \frac{1}{2\rho A v} \qquad (20)$$

For getting the maximum wind power, there is need of higher wind speed, a longer length of blades so that large area is swept under them, and a higher air density. Because of this even a small variation in wind speed it can result in great change in the power due to the fact that the wind power output is proportional to the cubic of wind speed.

IV MATHEMATICAL MODELLING OF DFIG

DFIG is also called doubly fed induction asynchronous machine (DFIAM) with wound rotor construction. Recently, DFIAM has become more popular WECS as it provides variable speed operations.

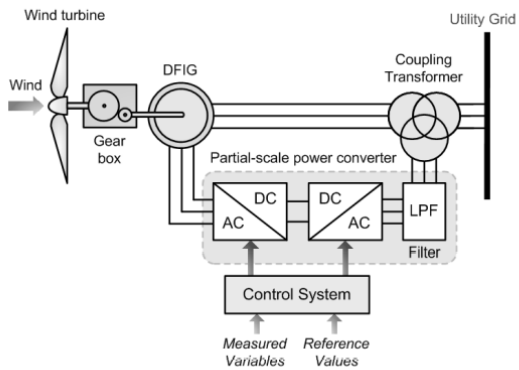


Figure 7. DFIG-based wind energy conversion system scheme[8]

The power control equipment is required to provide active and reactive power compensation during load/demand fluctuations [14].

DFIG have control options from stator as well as rotor side. A blade pitch angle control mechanism is also need to regulate and increase mechanical power output of the wind turbine under various wind speed range. Pitch angle controller actuates on the basis of error signal between reference wind turbine speed and generator measured speed [15].

1. ADVANTAGES OF DFIG:

a) 70% of power is transmitted directly through stator side with Flexible AC Transmission system (FACTs) devices like Static Synchronous Compensator (STATCOM) installed at PCC[16].

b) The rest of the 30% power is delivered to the grid with the help of power electronic converter connected to rotor side with rating about 25%-30% of DFIG's power rating in comparison with fixed speed synchronous generator [17].

In this section, the mathematical DFIG is developed in mainly two reference frames such as rotor and stationary frame using first order differential equations. The steady state and dynamic response of the DFIG are study for different operating conditions. Also, Inertia emulation model for DFIG is derived for frequency support.

A. STEADY STATE MODEL OF DFIG

The steady state model of three phase DFIG machine is derive from an equivalent circuit diagram as shown in Figure 8 (a) and 8(b).In this the mutual reactance X m is mentioned onto stator voltage supply source Vs side and the simplified model of the induction machine is as shown in Figure 8 (b). To obtain the torque equation from the equivalent circuit, the rotor current Ir is expressed as follows

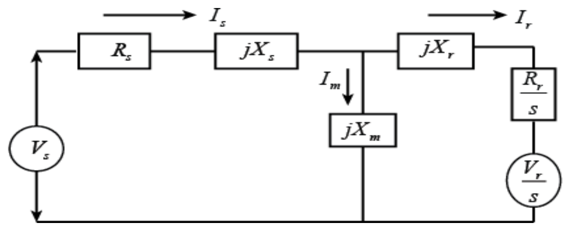


Figure 8(a) Equivalent Circuit of DFIAM with injected rotor voltage[11].

I_r=((V_S-V_r)/S_{slip})/((R_s+R_r/S_{slip})+j(X_{ls}+X_{lr}))

Where,

V_s and $V_r$stator and rotor per phase steady state voltages

X_{ls}, X_{lr} stator and rotor leakage reactance, R_s and R_r are stator and rotor resistance. S_{slip} is slip factor.

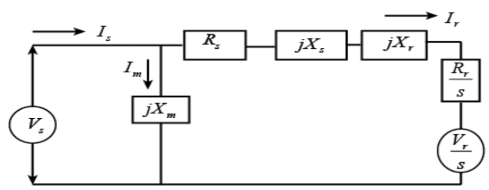


Figure 8(b) Equivalent approximated equivalent circuit of DFIAM with magnetizing branch transferred to stator.

The electromagnetic torque in an induction machine is the sum of air gap power and rotor fed power given by

$$T_e = (I_r^2\left(\frac{R_r}{S_{slip}}\right) + P_R) \qquad (21)$$

Where, T_e is the electromechanical torque from stator side, PR is the rotor fed active power.

Alternatively, the electromagnetic torque is given as

$$T_s = \frac{3}{2}\frac{P\ R_r I_r^2}{S_{slip}\omega_{syn}} \qquad (22)$$

B. DYNAMIC MODEL

The per unit dynamic model of the three phase doubly fed induction asynchronous machine is derived by the transformation of three variable phase quantities to a set of two stationary vectors. Then these stationary vectors are transformed to rotating frame with d-axis and q-axis coordinates.

a) abc to αβo (stationary)

$$\begin{bmatrix} v_\alpha \\ v_\beta \\ v_0 \end{bmatrix} = \begin{bmatrix} \frac{2}{3} & -\frac{1}{3} & -\frac{1}{3} \\ 0 & \frac{1}{\sqrt{3}} & -\frac{1}{\sqrt{3}} \\ \frac{1}{3} & \frac{1}{3} & \frac{1}{3} \end{bmatrix} \begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} \qquad (23)$$

stationary reference frame as follows

b) αβo(stationary) to dqo reference

$$\begin{bmatrix} v_d \\ v_q \\ v_0 \end{bmatrix} = \begin{bmatrix} cos\omega t & sin\omega t & 0 \\ -sin\omega t & cos\omega t & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} v_\alpha \\ v_\beta \\ v_0 \end{bmatrix}$$

c) dqo to abc reference

$$\begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} = \begin{bmatrix} cos\omega t & -sin\omega t & 1 \\ \cos(\omega t - \frac{2\pi}{3}) & -sin(\omega t - \frac{2\pi}{3}) & 1 \\ \cos(\omega t - \frac{2\pi}{3}) & -sin(\omega t - \frac{2\pi}{3}) & 1 \end{bmatrix} \begin{bmatrix} v_d \\ v_d \\ v_q \end{bmatrix} \qquad (24)$$

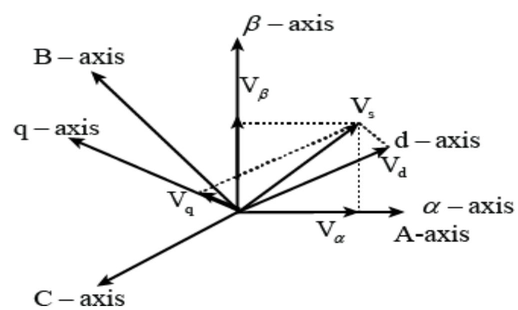


Figure 9. Stator phase voltages along *dq*and *αβ*-axis[11].

As per park's transformation the three-phase stator and rotor voltages transformed to a dqo rotating frame is given the following equations,

$$\begin{bmatrix} V_{qs} \\ V_{ds} \\ V_{os} \end{bmatrix} = \begin{bmatrix} -sin\theta_s & cos\theta_s & 1 \\ -sin(\theta_s - \frac{2\pi}{3}) & \cos(\theta_s - \frac{2\pi}{3}) & 1 \\ -sin(\theta_s - \frac{2\pi}{3}) & \cos(\theta_s + \frac{2\pi}{3}) & 1 \end{bmatrix} \begin{bmatrix} V_{as} \\ V_{bs} \\ V_{cs} \end{bmatrix}$$

(25)

dq–axis components of stator voltages in terms of stator line voltages are given as:

$$\begin{bmatrix} V_{ds} \\ V_{qs} \end{bmatrix} = \left(\frac{1}{3}\right) \begin{bmatrix} \sqrt{3}\, sin\theta_s + cos\theta_s & 2cos\theta_s\, V_{bcs} \\ -\sqrt{3} cos\theta_s + sin\theta_s & 2sin\theta_s V_{bcs} \end{bmatrix}$$

(26)

dq–axis components of rotor voltages in terms of rotor line voltages are given as:

$$\begin{bmatrix} V_{dr} \\ V_{qr} \end{bmatrix} = \left(\frac{1}{3}\right) \begin{bmatrix} (\sqrt{3}\sin(\theta_s - \theta_r) + cos(\theta_s - \theta_r))V_{abr} & 2cos(\theta_s - \theta_r)V_{bcr} \\ (-\sqrt{3}\cos((\theta_s - \theta_r) + sin(\theta_s - \theta_r))V_{abr} & 2sin(\theta_s - \theta_r)V_{bcr} \end{bmatrix} \quad (27)$$

θ_s= angle of reference frame

$\theta_s - \theta_r$= angle between reference frame and position of rotor.

ω_s= speed of stator flux

$\omega_s - \omega_r$= relative speed between stator's flux and rotor's actual angular speed.

C. DYNAMIC MODEL OF DFIG UNDER ROTOR REFERENCE FRAME

In this reference frame θ_s=θ_r=0 stator and rotor dqcomponent corresponds to line voltage given by Equations (26) and (27). θ_r = the position of phase 'a' of rotor 'abc' frame in electrical degree with respect to phase 'a' of stator 'abc'reference frame as shown in Figure (4.3).

Stator voltage equations in *dq*-frame with respect to stator line voltages as:

$$\begin{bmatrix} V_{ds} \\ V_{qs} \end{bmatrix} = \left(\frac{1}{3}\right) \begin{bmatrix} (\sqrt{3}\sin(\theta_r) + cos(\theta_r))V_{abs} & 2cos(\theta_r)V_{bcs} \\ (-\sqrt{3}\cos((\theta_r) + sin(\theta_r))V_{abs} & 2sin(\theta_r)V_{bcs} \end{bmatrix} \quad (28)$$

Rotor voltage equations in *dq*-frame with respect to the rotor line voltages as:

$$\begin{bmatrix} V_{dr} \\ V_{qr} \end{bmatrix} = \begin{bmatrix} V_{abr} + 2V_{bcr} \\ -\sqrt{3}V_{abr} \end{bmatrix} \quad (29)$$

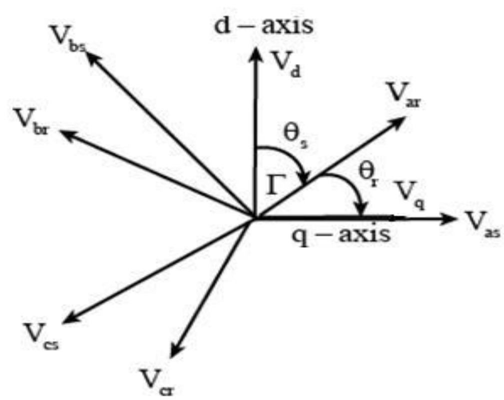


Figure 10. Stator and rotor phase voltages along dq-axis for rotor reference frame[11].

D. DYNAMIC MODEL OF DFIG UNDER STATOR OR STATIONARY REFERENCE FRAME

For stationary reference frame phase 'a' of the stator voltage is in phase with the d-axis, thus θ_s=0, and stator and rotor voltages to dqcomponent are given by Equation (28) and Equation (29) respectively.

$$\begin{bmatrix} V_{ds} \\ V_{qs} \end{bmatrix} = \begin{bmatrix} V_{abs} + 2V_{bcs} \\ -\sqrt{3}V_{abs} \end{bmatrix} \qquad (28)$$

$$\begin{bmatrix} V_{dr} \\ V_{qr} \end{bmatrix} = \left(\frac{1}{3}\right) \begin{bmatrix} (-\sqrt{3}\sin(\theta_r) + cos(\theta_r))V_{abr} & 2cos(\theta_r)V_{bcr} \\ (-\sqrt{3}\cos(\theta_r) - sin(\theta_r))V_{abr} & -2sin(\theta_r)V_{bcr} \end{bmatrix} \qquad (29)$$

Where,

ω_s is the speed of stator flux and $\omega_s - \omega_r$ is the relative speed between stator's flux and rotor's actual speed.

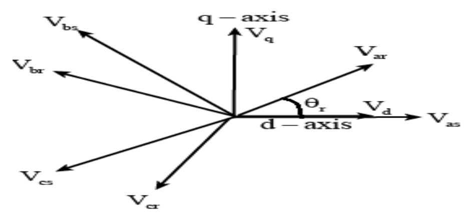


Figure 11. Stator and rotor phase voltages along dq-axis for a stationary reference frame

V SIMULINK MODEL OF DFIG WITH PITCH CONTROL ARRANGEMENTS

The wind energy conversion system introduced in this work begins with a DFIG. It is followed by a passive rectification system. The inverter chosen for this is a PWM controlled set of IGBTs with incorporated controls system. Following that is a harmonic. Figure 12. is shows the simulink model of DFIG generator with pitch control system.

filter and a step-up transformer connected to the AC supply grid

The current simulation model is a 9 MW wind farm consisting of six 1.5 MW wind turbines connected to a 25 kV distribution system exports power to a 120 kV grid through a 30 km, 25 kV feeder. In this simulation model the wind speed is maintained constant at 15 m/s. The control system uses a torque controller in order to maintain the speed at 1.2 pu. The reactive power produced by the wind turbine is regulated at 0 Mvar.

VI RESULTS & ANALYSIS

A. RESULTS USING WITH PI CONTROLLERS

The stator voltage for the d-q axis is shown in Figure13.

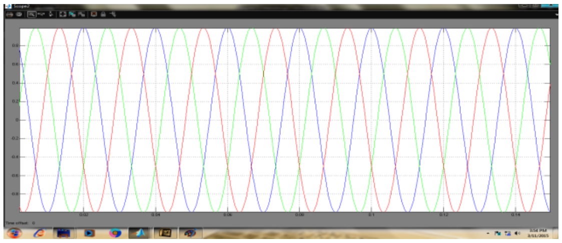


Figure: 13 Stator Voltage for d-q axis

The active and reactive power controlled by DFIG with PI controller shown in Figure 14.

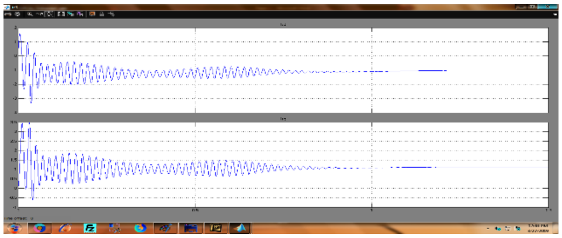


Figure 14 Active and reactive power

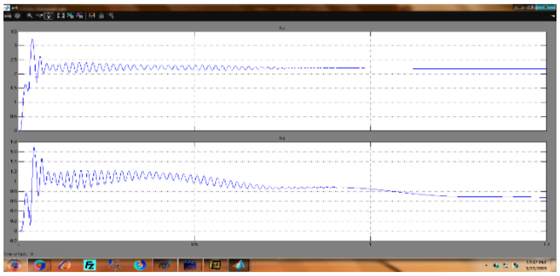


Fig. 15 Rotor currents for d-q axis

The torque characteristic of the DFIG system is shown in the fig.5.23. This characteristic represents the mechanical operation of the generator rotor.

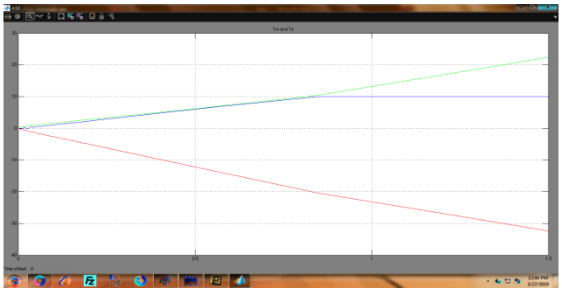


Figure 16 Torque characteristic

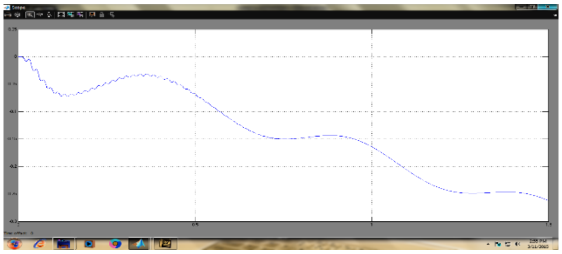


Figure 17 Mechanical characteristic of wind generator

Mechanical characteristic of wind generator is shown in figure 18

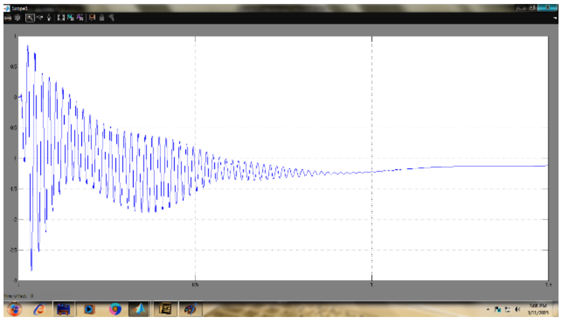


Figure 18 DFIG torque characteristic

The wind characteristic is shown in figure19, its show the constant and stable with time.

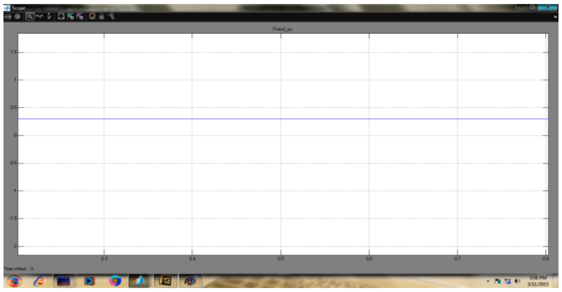


Figure19 Wind power characteristic

B. RESULTS WITH PITCH CONTROL SYSTEM

With the aim to examine the performance of the system under the variable wind speeds condition, the Matlab Simulink software and Sim power system toolbox has been used to model the DFIG cascaded to wind turbine with pitch angle control scheme. Characteristic of Rotor voltage of wind generator is shown in figure 20 and figure21.

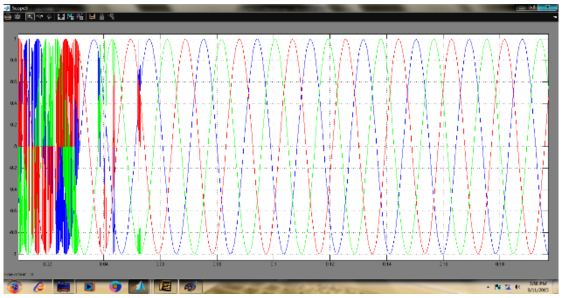
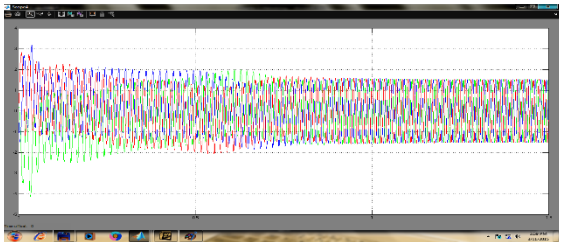
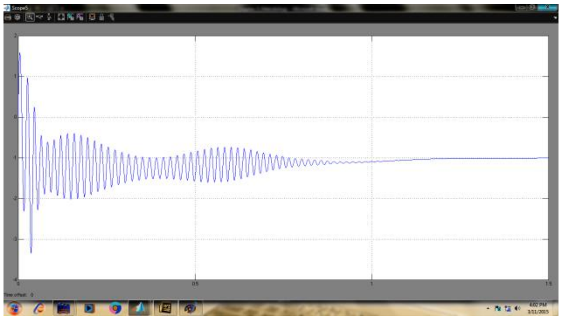


Fig 20 Rotor voltage of wind generator

Fig 21 Phase Rotor current



Stator active power characteristic is shown in figure 22 and figure 23 shows the characteristic of reactive power.



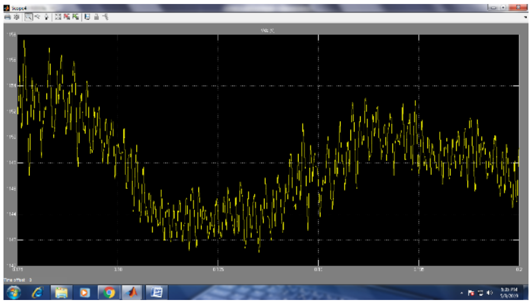
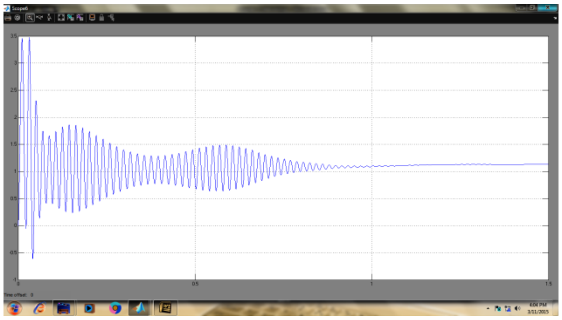
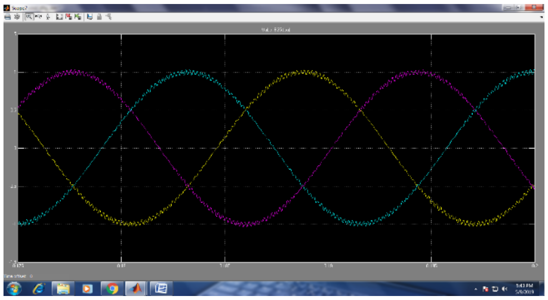


Fig 22. Active power of stator **Fig 23. Reactive power of stator**





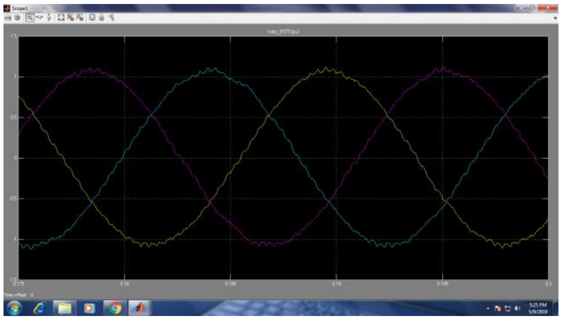
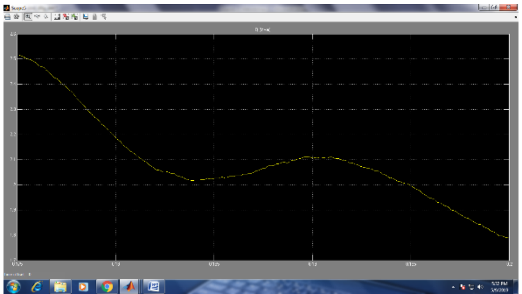


Fig 24. Characteristic of 3 stator voltage pahse system



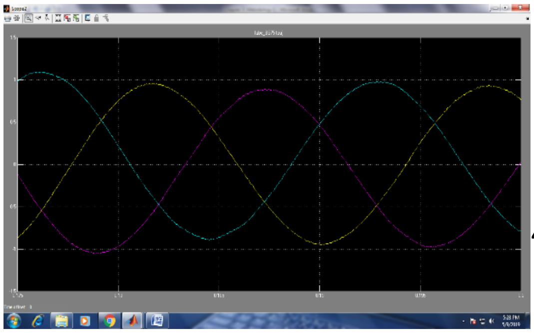


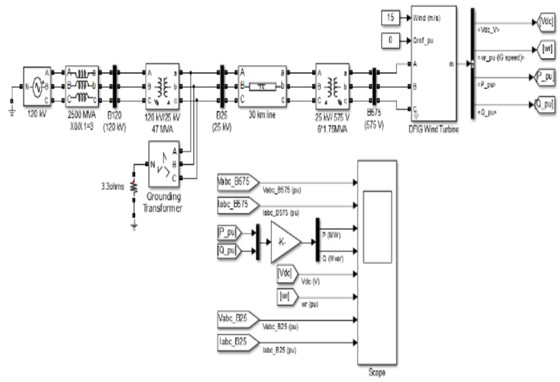
Fig 25. Characteristic of 3 phase stator voltage system

Fig 26. Characteristic of reactive power

Fig 27. Characteristic of active power

Fig 28. Characteristic of DC voltage

Fig 29. Characteristic of rotor speed



CONCLUSIONS

In this work carried out the main objective is power quality improvement and it can be obtained when we generate constant output power from the wind power plant. Using DFIG model with PI controller simulated.

Same as the results of rotor current also clearly indicate the stable operation of DFIG model with PI controller.

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