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Complex Power Control of Double Fed Induction Generator in a Wind Power System

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Abstract: ***The combined operation of wind energy power into present electrical network is increasing very fast during current scenario. Ethiopia is one of these countries that use wind power as its renewable and complement power source of the country. The DFIG (Doubly-fed Induction Generator) is among the most commonly used generator in conversion of wind energy in present scenario. This paper emphasizes on complex power control. Simulation models have been developed using a versatile simulation tool Matlab-Simulink for a 1 MW Dual Fed Induction machine. The work presented in this paper uses a field flux control method or vector control methodology which moves synchronously frame of reference.***

Keywords **:** ***Complex power, Double fed induction Generator, Matlab-Simulink, Proportional Integral, Pulse Width Modulation, Vector control.***

I. INTRODUCTION

In developing country, there is rapid economic growth and this rapid economic growth needs higher consumption of electric energy. Electrical energy is vital energy source in our homes, workplaces and industries, fulfilling its demand are critical. Ethiopia is developing country that needs higher electric consumption for many purposes. for this rapid economy growth, Ethiopia must have state of art energy (smart) systems which is dependent on the non-conventional sources i.e. sun, ocean, magneto hydro dynamic and geothermal energy but since contribution to feed existing load is not so much appreciable. The harnessing energy from renewable sources is very dearer and very complex as compared to traditional methods of energy transformation. Wind turbines may run on constant and adjustable speed. For a constant speed wind turbine, the generator can be clutched to the grid directly. For the change in speed of wind turbine, the speed is adjusted by means of solid-state converters.

The merits of using adjustable-speed of wind turbines is to reduce mechanical stresses on the structure, reduction of acoustic noise and to control complex power [1].DFIG are the most used along with adjustable-speed wind turbines because of highly efficient systems and good degree of controllability [2]. In conventional format stator side of DFIG is attached to grid but rotor part is attached to grid via solid state power converter [3]. Focus on this energy is due to its implications in term of quality of energy and its environmental impact.

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II. RESEARCH METHODOLOGY

The methodology adopted ins this study i.e Data collection and Survey, as well as Data analysis. The detail methodology is resented below.

- Step 1: Modeling DFIG[4]
- Step 2: PI design for determining a proportional gain (Kp) and integral gain (Ki) parameters.
- Step 3: Overall control system of Active (P) and Reactive (Q) power of DFIG.
- Step 4: Modeling the system using MATLAB simulation software. [5]

simulation results analysis was based on the output data obtained with relation to input and following power system guidelines For the purposes of better understanding a model of DFIG is adequate for designing the control system of complex power control of wind power system. Lastly ,control system related to P and Q power of DFIG is design and simulation result is obtained. [6]

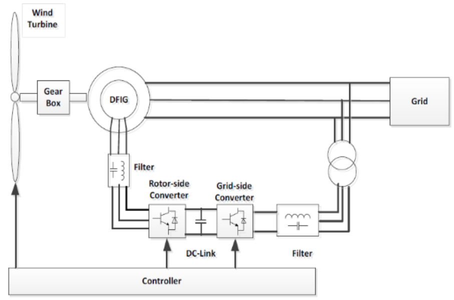

Figure 1: DFIG wind turbine scheme

2.1 Modeling of A Wind Turbine Generation System

Modeling of Variable Speed Wind Turbine[7]

The wind turbine model comprises of the following key components: Aerodynamic model evaluated by following relation $T_t = f(Vv)$ where Vv is wind velocity.

Angular speed of turbine Ω_t and Pitch system calculates the dynamics of pitch angle which is a function of βref (pitch reference).
The proposed Mechanical system calculates the generator and turbine angular speed (Ω_t and ω_m)

$$(\Omega_t \text{ and } \omega_m) = f\,(Tem)[8]$$

i.e turbine torque and generator torque. The Electrical system and power Electronics converters system converts the generator torque into a grid current which is further a function of grid voltage grid. Tem, β_{ref} and Q are serving as a reference function for wind velocity and grid voltage.[9]

2.2. Aerodynamic Model[10]

This model tells about rotor power extraction, thus evaluating mechanical torque as a function of the wind velocity on rotor blades. We consider average incident wind speed on the swept area covered and main objective is is to find T_{av} on axle
The torque developed by the rotor is shown by expression[11]

$$T_t = \frac{1}{2} P\pi R^3 V_v^3 C_t(\beta\lambda)$$

where, T_t , is the power harnessed by wind turbine, p , is the density of air, R is radius of the turbine rotor blade, and V_v is the wind velocity, C_t is the wind power coefficient of the turbine, function of the pitch angle β, and tip speed ratio λ.
A fundamental concept in understanding wind technology is wind energy capture. Since wind speed varies at every point of time, wind turbines should have high operating range in terms of wind speed. In this system, the wind kinetic energy is transformed to electrical energy by the use of double fed induction generator and then feedback into the smart grid.[12]
The wind turbines are classified as a constant speed windy turbine and adjustable speed windy turbine. The constant speed windy turbine are designed to be used for many electrical and mechanical applications.
In wind turbines the DFIG is located inside the nacelle. By means of control system the complex power is controlled and regulated by amount of current passing in rotor winding in order to harness efficient value of wind power. [13]

2.3. Double-excited Induction Generator (DEIG) Models[14]

This model used by Simulink was the asynchronous generator from the power system library of MATLAB/Simulink. It usually consists of two winding (stator and rotor). The rotor is accessible through, slip rings. The stator side is clutched to the system grid by means of transformer. The rotor side consists of three phase windings and is connected through, the converters. So the converter could insert or absorb current into/from the rotor. The rotor and stator winding should be coupled very tightly, such a way that magnetic coupling between them is maximized.[15]
In the wind turbines the DFIG is located inside the nacelle. While designing the model of control system of electrical machine , must include dynamic system during steady state and transient conditions.The design response should be prompt and respond quickly to any time variations parameters of converters which acts as a source of power for the machine.[16]Such a model must validate its feasible operation under both dynamic conditions under both reference frames(abc,dqo).[17]
The performance of the DEIG at the natural frequency is decided by the performance of power electronics converter. In DEIG System generator-converter set behaves like current regulated VSI converter represented like a regulated current source[18]. To control complex power by vector control method it becomes mandatory to study the performance of phase wound type induction machine. Using Parks transformation abc frame of reference is transformed into dqo axis frame of reference to make inductance time invariant.[19]

2.4.DEIG Model Using ABC Frame of Reference[20]

As in comparison DFIG model of SCIM is similar except rotor voltage is not zero.

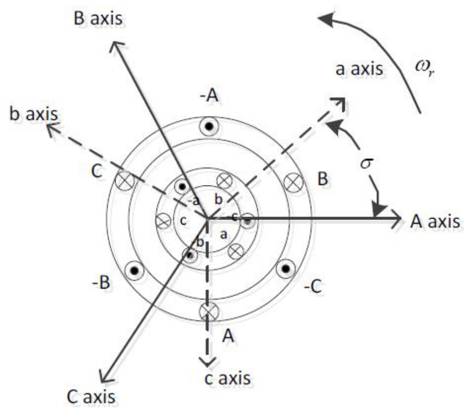

Figure:2.Cross Sectional View Of DEIG (21)

Assumptions used are as follows for creating model :

- Symmetrically distribution of supply phases to DEIG are i.e the resistances per phase, magnetizing reactance per phase and leakage inductances per phase should be equal for three phases.
- Generated MMF has sinusoidal distribution at the circumference of stator of DEIG, which results in zero harmonic component present in system.
- constant air-gap with constant air-gap reluctance at the mid circumference of the air-gap sphere.
- Neglecting Core losses and power losses considered for phase resistances of both stator and rotor.
- The saturation effect due to the coupling of magnetic field of d and q axis are neglected. [6].

Terminal voltage of phase A, V_A can be expressed by Faraday's law

$$V_A = r_A i_A + \frac{d}{dt}(\Psi_A)$$

$$r_A i_A + \frac{d}{dt}(L_{BA} i_A + L_{AB} i_B + L_{AC} i_C + L_{Aa} i_a + L_{Ab} i_b + L_{Ac} i_c) - - - 1)$$

$$r_B i_B + \frac{d}{dt}(L_{BA} i_A + L_{BB} i_B + L_{BC} i_C + L_{Ba} i_a + L_{Bb} i_b + L_{Bc} i_c) - - -(2)$$

$$r_C i_C + \frac{d}{dt}(L_{CA} i_A + L_{CB} i_B + L_{CC} i_C + L_{Ca} i_a + L_{Cb} i_b + L_{Cc} i_c) - - -(3)$$

For asymmetrical case, the resistance of stator can be written as

$$r_a = r_b = r_c = r_s$$

Where r_s is stator resistance of phase winding.

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for the coil representing 3 phases (ABC) on the rotor expressions may be written as follows.

$$V_a = r_a i_a + \frac{d}{dt}(L_{Aa} i_A + L_{Ba} i_B + L_{Ca} i_C + L_{aa} i_a + L_{ab} i_b + L_{ac} i_c) ----(4)$$

$$V_b = r_b i_b + \frac{d}{dt}(L_{Ab} i_A + L_{Bb} i_B + L_{Cb} i_C + L_{ab} i_a + L_{bb} i_b + L_{bc} i_c) ----(5)$$

$$V_c = r_c i_c + \frac{d}{dt}(L_{Ac} i_A + L_{Bc} i_B + L_{Cc} i_C + L_{ac} i_a + L_{bc} i_b + L_{cc} i_c) ----(6)$$

The DFIG is fed from 3phase AC supply, stator windings is attached grid utility without power converters while rotor windings are fed by solid state power converter. There are different types of control strategies for this type of machine but vector control is mostly used .[22]

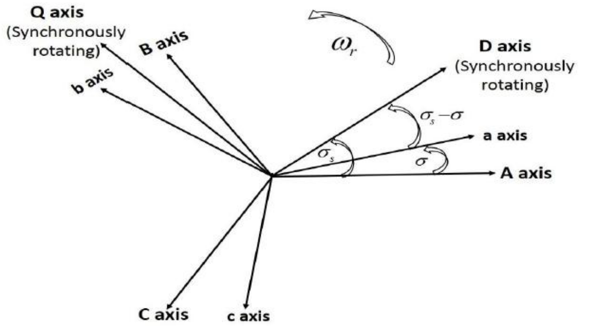

Figure 3: Schematic diagram of the ABC to DQ [23]

2.5. Vector Control of DFIG Connected with the Grid (abc Model)[24]

The complex powers are needed to be controlled in DFIG and described in per unit as:

$$P_s = (v_{ds} i_{ds} + v_{qs} i_{qs} ------(7)$$

$$Q_s = (v_{qs} i_{ds} - v_{ds} i_{qs} ------(8)$$

$$P_r = (v_{dr} i_{dr} + v_{qr} i_{qr} ------(9)$$

$$Q_r = (v_{qr} i_{dr} - v_{dr} i_{qr} ------(10)$$

2.6. Vector Control strategy for Converter facing grid side[25]

The application of grid facing converter system is to maintain constant DC-link voltage which is unaffected by grid side voltages magnitude. and in order to have cosφ=1 while viewing from the grid end.

To have better control activity of system, a fed forward controlling method is used to decouple the d and q axes components values for the grid facing converter.[26] The expressions for output complex power for a DFIG are expressed in dqo reference frame roating synchronously are as

$$P_g = \frac{3}{2}(e_d i_{dg} + e_q i_{qg}) ------(11)$$

$$Q_g = \frac{3}{2}(e_q i_{dg} - e_d i_{qg}) ------(12)$$ 27]

The reference frame should be aligned with the d-axis direction and the q-axis direction of the grid voltage ,$e_q$will be zero, while, the d-axis grid voltage,e_d, is constant and may as follows:

$$e_d = e_q = \sqrt{e_{\dot{\alpha}}^2} + \sqrt{e_{\dot{\alpha}}^2} --- (13)$$

Table.1 Grid-Side Converter Simulation Data

Parameter	Value	Unit
Grid voltage	690	V
Inductance	5.474	Mh
Rated current	660	A
Load resistance	2.631	Ohm
Rated continuous DC voltage	975	V

In DEIG variable speed operation is achieved by controlling external circuitry attached to the rotor circuit [28],while stator of the DEIG is clutched via grid by a transformer where as the rotor is clutched via grid through solid state power converters, harmonic filters. The rating for the DFIG is normally from few Kw to Mw. The stator supplies power from the wind turbine to grid and the power flow is unidirectional. However flow of power is bidirectional in the rotor circuit and it basically depends upon the operating systems.[29]

2.7. Design of PI Controller for Grid Side Voltage Source Converter [30]

A Proportional-Integral controller was designed for DFIG rotor circuit for the purpose of output power to follow the reference input. In Matlab/Simulink steady-state and transient simulation models was designed to analyze DFIG performance and also power controller by using two different orientation frames[31]. The V_q will be zero, while, the d-axis grid voltage V_d will be a fixed. The complex power of a grid Facing converter under a reference frame will be directly proportional to the currents, i_{dg} and i_{qg} , respectively.[32]

$$P_g = \frac{3}{2} v_d i_{dg} ------- (14)$$

$$Q_g = -\frac{3}{2} v_d i_{qg} ------- (15)$$

Hence, though, controlling the i_{dg} and i_{qg} , the complex power flow between the grid and the grid-side converter can be stabilized.[33]

From the d and q axes equations have coupling $wl_g i_{qg}$ *and* $wl_g i_{dg}$ a decoupled control signals are

$$V_{d1} = -R_g i_{dg} + \omega L_g i_{qg} + v_d + \Delta v_d --- (16)$$

$$V_{q1} = R_g i_{qg} - \omega L_g i_{dg} + v_q + \Delta v_q ---- (17)$$

Decoupled state equations are written as under[34]

$$\begin{pmatrix} L_g \frac{d}{dt} i_{dg} + \Delta v_d = & 0 \\ L_g \frac{d}{dt} i_{qg} + \Delta v_q = & 0 \end{pmatrix} --- (18)$$

The Δv_d and Δv_q are produced by comparing the actual Vdc with the Vref. The Δv_d and Δv_q signal is processed by a PI controller to keep dc voltage constant. In PI controller, i_{gd} is produced and q-axis current part i_{gq} is set to zero, to keep unit power factor at the grid.

$$i_{gd} = \left(Kp_1 + \frac{Ki_1}{s}\right)(V_{DC} - v_{dc}) - - - -(19)$$

The for grid converter control signals are generated by comparing the i_{gd} with i_{gq} as

$$\Delta V_d = \left(Kp_2 + \frac{Ki_2}{s}\right)(I_{DG} - i_{dg}) - - - -(20)$$

$$\Delta V_q = \left(Kp_3 + \frac{Ki_3}{s}\right)(I_{QG} - i_{qg}) - - - -(21)$$

2.8. Control and Simulation of DEIG (35)

Using MATLAB/Simulink software model of wind turbine generator system is designed which is to be simulated for various wind velocity conditions. For model, the defined wind velocity is 10 m/s.During low wind velocity conditions i.e below rated value, the point of maximum power can be tracked by the converter control of generator-side. The aim of the vector-control method for the grid facing VSC is to keep the DC link voltage fixed under various wind velocity conditions.

Table.2 Wind turbine-generator system parameters

Parameters	Value	Unit
Wind turbine rotor radius	38.7	m
No. of pole pairs	2	unitless
Rated power	1.5	MW
Rated voltage	690	V
Stator resistance	2.65	mΩ
Rotor resistance	2.63	mΩ
Stator inductance	0.1687	mH
Rotor inductance	0.1337	mH
Magnetizing inductance	5.4749	mH

2.9. Complex Power Control of DEIG

In control of complex power of DFIG in wind power generation, displaying the result of complex power separately without changing the value of each other, by using i_{dr} and i_{qr} for Q and P. For design of DEIG flux control method for stator side is used. In this iq component handles control of active power and id component handles control of reactive power. In stator voltage control method, the id component is used for active power control and iq component is used for reactive power control.

There is infinity of different controllers that is meant for the control loop. The proportional-integral (PI) controller is mostly used due to its simplicity. To calculate the PI regulator parameters, the rotor voltage and the rotor currentselationship must be known.[36] The Masked Matlab-Simulink model done using the Math Function tool box. In this tool box of the Matlab, all the DFIG and related equations described in previous sections are entered with input-output values. Many things, mainly related to the operation of the machine under different conditions can be analyzed from the block diagram.

This design shows the DFIG vector control method of the DEIG modeled in Matlab. This blocks consists of a DEIG model presented in abc to dq frame OF reference and control system part. The Clarke and park transformation rules are applied during the conversion process from one reference frame to another. [37]

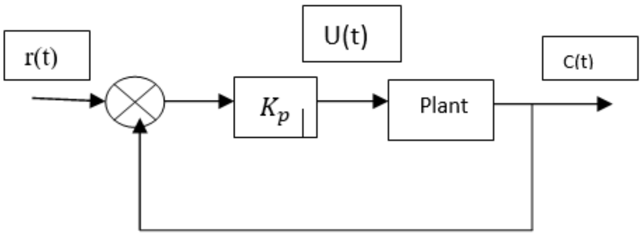

Figure.4 PI controller for plant system

The PI control in mathematical expression is given as

$$u(t) = ke(t) + k_i \int_0^t e(t)\, dt\text{-------}(22)$$

Where u(t) is an input to the plant or output of PI controller.

Taking Laplace transformation

$$U(S) = k_p E(s) + k_i \frac{E(s)}{s} = \left[k_p + k_i \frac{1}{s}\right] E(s) - \ (23)$$

Where K_p and K_i are proportional and integral gain constant respectively. Taking

$$k_i = \frac{k_p}{T_i}$$

Where Ti is integral time constant.

$$U(s) = k_p\left[1 + \frac{1}{T_i s}\right] - - - -(24)$$

In another ways, in this block diagram, the sample frequency (f_s) is used as twice of switching frequency (f_{sw}). The sampling and switching period are $f_s = 2f_{sw}$ and $T_s = 1/f_s$, where T_s is sampling time. Since the f_{sw} used in this thesis is 5 KHz as recommended in different literatures, a delay time is required to ensure the performance of the loop. [38]

$$T_e = 1.5T_s$$

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III. RESULTS AND DISCUSSION

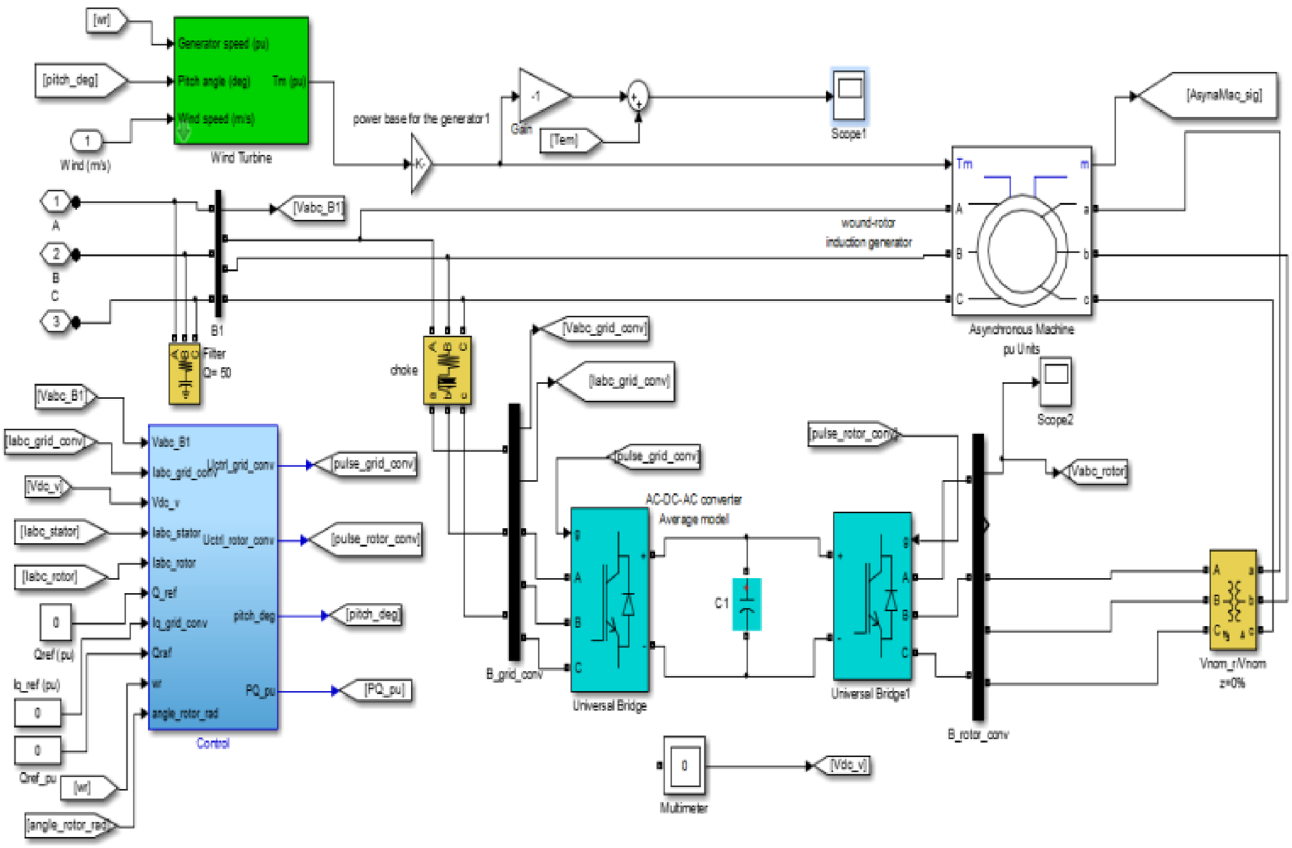

Figure. 5 Design of 1.5 MW DFIG wind power generation system

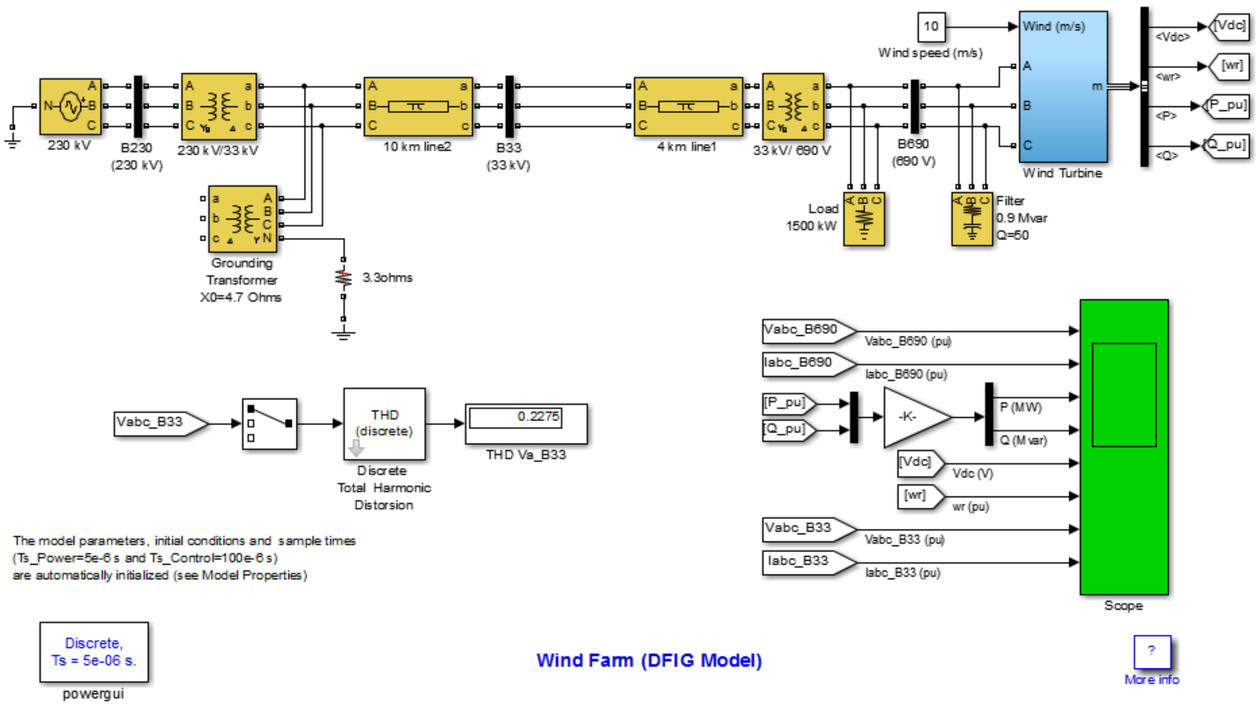

Figure 6: Over all control system and simulation of 1.5 MW wind power generation system

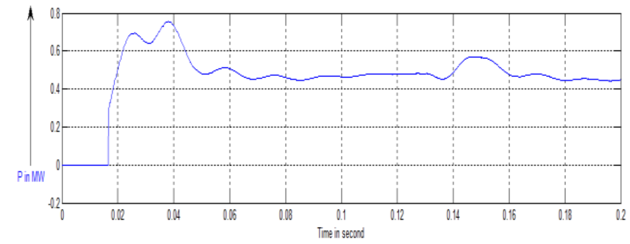

Figure.7 Simulation result of grid side Active power

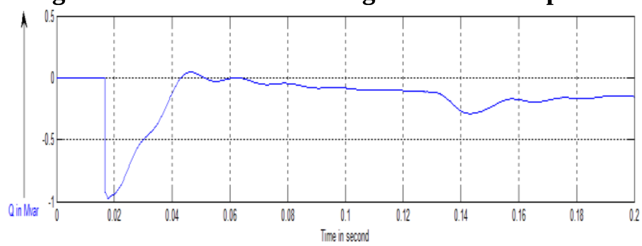

Figure.8 Simulation result of grid side Reactive power

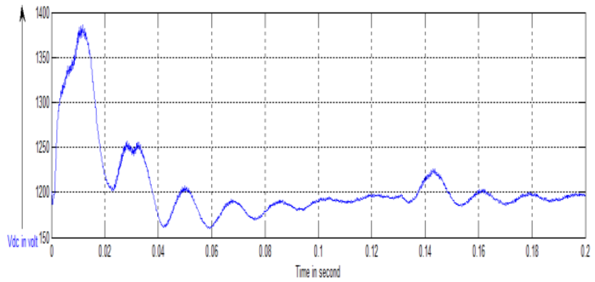

Figure.9 Simulation result of grid side V_{dc} voltage

The results shows , the grid facing converter tries to maintain the DC-link voltage constant at 1200v which is the set point value under various wind speed conditions. Figure a and figure b shows the voltage and current in per unit and time in 0.2second grid-side current and voltage in ABC reference frame respectively.[39]

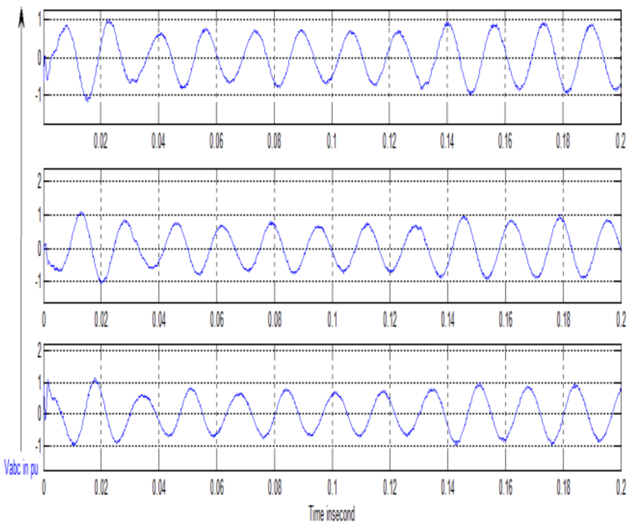

Figure.10 Simulation result of grid side three phase voltages as V_{abc}.

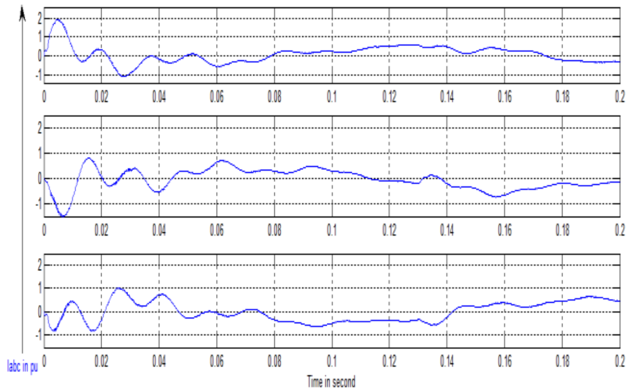

Figure. 11 Simulation result of grid side three phase current as I_{abc}.

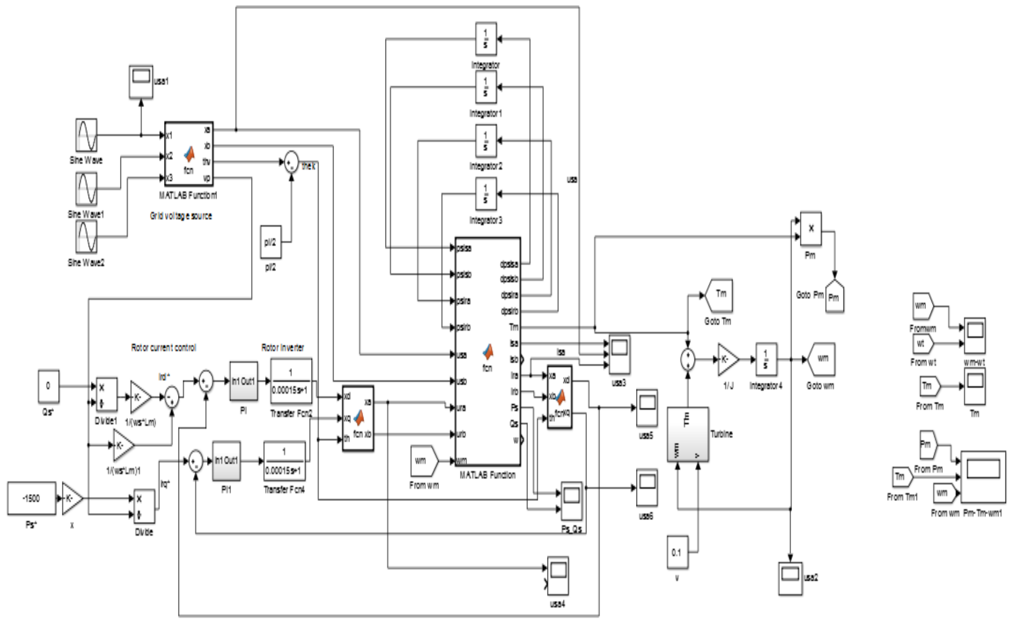

Figure.12. Control systems of active and reactive power of wind energy

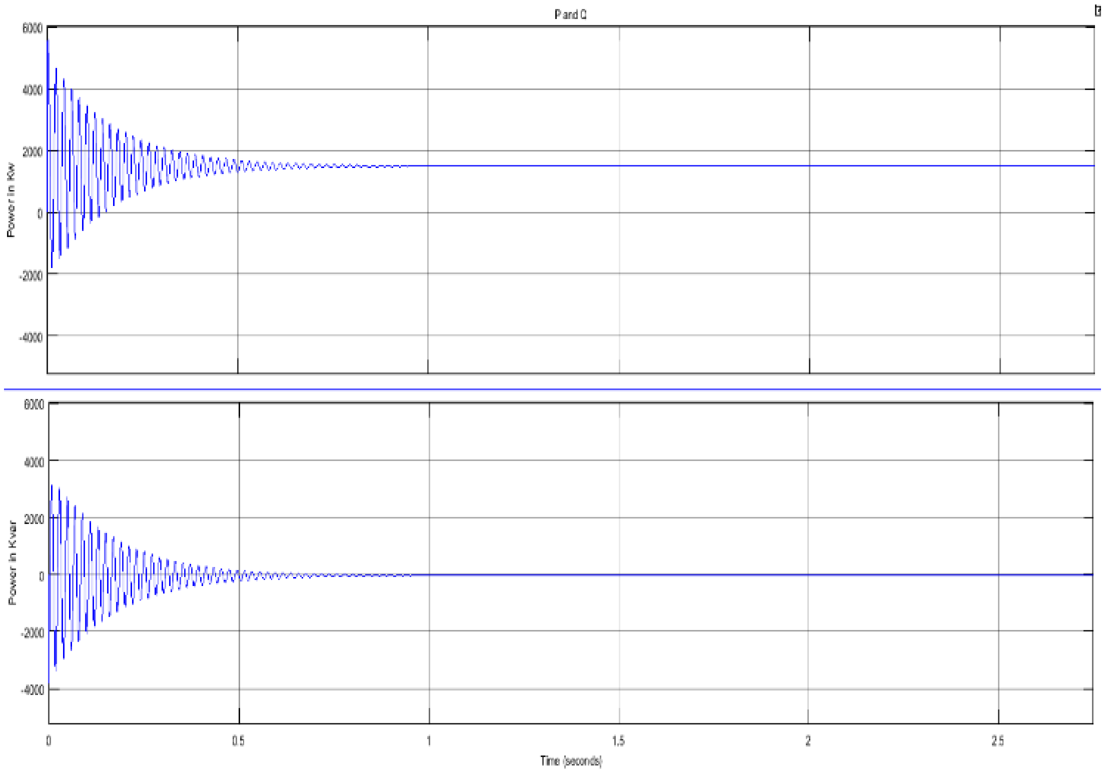

Figure.13. Simulation result of complex power using PI controller (34)

IV. CONCLUSION

The Simulation result showed the control of complex power at any reference points as per the demand of power utility, depending on the wind conditions and other related issues. The simulation results obtained, model presented in this thesis corresponds mainly to real DFIG working in wind farm as its parameters are obtained from nameplate Date, factory test reports and numerical analysis. The above said results are obtained for various operating conditions, when the wind turbine velocity changes periodically for the given input. The PI controller controls the complex power by closely track and follows the input reference.

The control of Complex power in power generation system is an important and mandatory procedure for power quality. The electrical characteristics of the generators and aerodynamic characteristics of the wind turbine generator are studied jointly to analyze DFIG speed control and maximum power extraction technique. A linear and precise mathematical model is required for the PI controller which is very tedious to find out and may not give good results under parameter variations of the system. The advantage of fuzzy controllers over conventional one are that they do require accurate mathematical models and can work with non accurate inputs can handle non –linearity, and are more robust than conventional controllers.

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