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Doubly-Fed Induction Generator for Variable Speed Wind Energy Conversion Systems-Modeling & Simulation

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Abstract: The aim of this paper is to present the complete modeling and simulation of wind turbine driven doubly-fed induction generator which feeds ac power to the utility grid. For that, two pulse width modulated voltage source converters are connected back to back between the rotor terminals and utility grid via common dc link. The grid side converter controls the power flow between the DC bus and the AC side and allows the system to be operated in sub-synchronous and super synchronous mode of operation. The proper rotor excitation is provided by the machine side converter, wind power, as an important and promising renewable resource, is widely studied. Recently, doubly fed induction generator (DFIG) becomes more popular in wind power due to its various advantages over other types of wind turbines, such as variable speed, lower power electronic cost and so on. In this paper, first of all, a dynamic model of DFIG-based wind power system is derived in complex form. Based on the dynamic model, a complete control strategy is presented to control the rotor-side converter and grid-side converter, respectively. A decoupled control method, which is capable of separating d-axis and q-axis components of rotor current, is applied to harness wind power. The concept of instantaneous power is introduced to regulate DC-link voltage. The complete system is modeled and simulated in the MATLAB Simulink environment in such a way that it can be suited for modeling of all types of induction generator configurations.

Keywords: doubly-fed induction generator (DFIG), pulse width modulation (PWM), dynamic vector approach, utility grid, wind energy conversion systems, decoupled control, active and reactive power.

I. INTRODUCTION

The conventional energy sources are limited and have pollution to the environment. So more attention and interest have been paid to the utilization of renewable energy sources such as wind energy, fuel cell and solar energy etc. Wind energy is the fastest growing and most promising renewable energy source among them due to economically viable Wind energy is being actively pursued worldwide as a clean and renewable resource to solve today's energy crisis. Prospects for 2020 in the United States aim at a total 100,000 MW installed capacity of wind power [1]. The development of the wind turbine system has experienced three stages [2]:

- fixed speed, stall controlled induction generator;
- variable speed, pitch controlled synchronous generator;
- variable speed, pitch controlled doubly fed induction generator (DFIG).

DFIGs are getting preferred for wind application due to their excellent performances. DFIG can be suitable for the variable nature of wind. Also, DFIG can be operated in any desired power factor through power electronic converter control. Moreover, the special connection of rotor windings results in a lower converter cost and also a lower power loss [1], [3]. A schematic diagram of DFIG system is shown in Fig.1. The stator of DFIGs is directly connected to the grid while the rotor is indirectly connected to the grid through back-to-back converters grid-side converter and rotor-side converter, which are capable of providing 10-40% of the generator's rated power.

The back-to-back converters are controlled by pulse width modulation. Several strategies have been proposed to control DFIG's behavior [1]-[8]. A general mathematical method of decoupling rotor current is presented in [2]. This method stands on the electrical point of view and is suitable for any type of DFIG model regardless the manufacturer. In [3], a direct active and reactive power control strategy of DFIG is designed in the rotor reference frame. An improved method is presented in [4] for mitigating DC-link voltage fluctuation in DFIG using instantaneous rotor power feedback scheme.

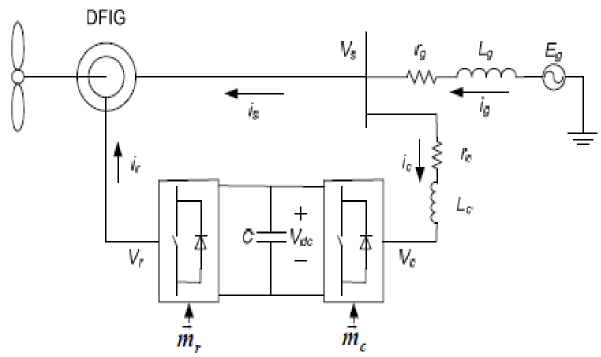

Fig1. DFIG-based wind power system.

II; DFIG WIND POWER SYSTEM MODEL

The wind generation system studied in this paper consists of two components: the Doubly-Fed Induction Generator (DFIG) and the variable speed wind turbine. A detailed description of these two components is given below. The DFIG may be regarded as a slip-ring induction machine, whose stator winding is directly connected to the grid, and whose rotor winding is connected to the grid through a bidirectional frequency converter using back-to-back PWM voltage-source converters [9]. The electrical part of the DFIG is represented by a fourth-order state space model, which is constructed using the synchronously rotating reference frame (dq-frame), where the d-axis is oriented along the stator-flux vector position. The relation between the three phase quantities and the dq components is defined by Park's transformation. The voltage equations of the DFIG are

$$V_{ds} = R_s i_{ds} - \omega_s \psi_{qs} + \frac{d\psi_{ds}}{dt} \quad (1)$$

$$V_{qs} = R_s i_{qs} - \omega_s \psi_{ds} + \frac{d\psi_{qs}}{dt} \quad (2)$$

$$V_{dr} = R_r i_{dr} - (\omega_s - \omega_r)\psi_{qr} + \frac{d\psi_{dr}}{dt} \quad (3)$$

$$V_{qr} = R_r i_{qr} - (\omega_s - \omega_r)\psi_{dr} + \frac{d\psi_{qr}}{dt} \quad (4)$$

where Vds, Vqs, Vdr, Vqr are the d- and q-axis of the stator and rotor voltages; Ids, Iqs,Idr,Iqr are the d- and q-axis of the stator and rotor currents; $\Psi_{ds}, \Psi_{qs}, \Psi_{dr}, \Psi_{qr}$ are the d- and q-axis of the stator and rotor fluxes ω_s is the angular velocity of the synchronously rotating reference frame; the rotor angular velocity; and Rs,Rr are the stator and rotor resistances[9]. The flux equations of the DFIG are

$$\psi_{ds} = L_s I_{ds} + L_m I_{dr} \quad (5)$$

$$\psi_{dr} = L_m I_{ds} + L_r I_{dr} \quad (6)$$

$$\psi_{qr} = L_m I_{qs} + L_r I_{qr} \quad (7)$$

Where Ls, Lr, and Lm are the stator, rotor, and mutual inductances, respectively. From the flux equations (5)–(7), the current equations can be written as

$$I_{ds} = \frac{1}{\sigma L_s}\psi_{ds} - \frac{L_m}{\sigma L_s L_r}\psi_{dr} \quad (8)$$

$$I_{qs} = \frac{1}{\sigma L_s}\psi_{qs} - \frac{L_m}{\sigma L_s L_r}\psi_{qr} \quad (9)$$

$$I_{dr} = \frac{-L_m}{\sigma L_s L_r}\psi_{ds} + \frac{1}{\sigma L_r}\psi_{dr} \quad (10)$$

$$I_{qr} = \frac{-L_m}{\sigma L_s L_r}\psi_{qs} + \frac{1}{\sigma L_r}\psi_{qr} \quad (11)$$

Where $\sigma = 1 - \frac{L_m^2}{L_s L_r}$ is the leakage coefficient. Neglecting the power losses associated with the stator and rotor resistances, the active and reactive stator and rotor powers are given by

$$P_s = -V_{ds} I_{ds} - V_{qs} I_{qs} \quad (12)$$

$$Q_s = -V_{qs} I_{ds} + V_{ds} \quad (13)$$

$$P_r = -V_{dr} I_{dr} - V_{qr} I_{qr} \quad (14)$$

$$Q_r = -V_{qr} I_{dr} + V_{dr} I_{qr} \quad (15)$$

And the total active and reactive powers of the DFIG are

$$P = P_s + P_r \quad (16)$$

$$Q = Q_s + Q_r \quad (17)$$

Where positive (negative) values of *P* and *Q* mean that the DFIG injects power into (draws power from) the grid[9]. The mechanical part of the DFIG is represented by a first-order model

$$J\frac{d\omega_r}{dt} = T_m - T_e - C_f \omega_r \quad (18)$$

where *Cf* is the friction coefficient, *Tm* is the mechanical torque generated by the wind turbine, and *Te* is the electromagnetic torque given by

$$T_e = \psi_{ds} I_{ds} - \psi_{qs} I_{qs} \qquad (19)$$

Where positive (negative) values mean the DFIG acts as a generator (motor) [9].

The Direct Torque Control (DTC) method is basically a performance enhanced scalar control method. The main features of DTC are direct control of flux and torque by the selection of optimum inverter switching vector, indirect control of stator current and voltages, approximately sinusoidal stator flux and stator currents and high dynamic performance even at standstill. The advantages of DTC are minimal torque response time, absence of coordinate transformations which are required in most of vector controlled drive implementation and absence of separate voltage modulation block which is required in vector controlled drives. The disadvantages of DTC are inherent torque and stator flux ripple and requirement for flux and torque estimators implying the consequent parameters identification. The overall DFIG-based wind power system, as shown in Fig. 1, consists of three blocks: wind power model, DFIG model and wind power system model. The following section will describe the three blocks using mathematical dynamic equations.

A. Wind power model equations

Decoupled Control of Doubly Fed Induction Generator for Wind Power System, The wind power can be expressed as a function of wind speed, as shown in Fig. 2

$$P_w = \frac{\rho}{2} c_p(\lambda, \theta) A_R v_w^3 \qquad (20)$$

where ρ is the air density [kg/m3]; A_R is the area swept by the rotor; v_w is the upstream wind speed; c_p is the performance coefficient with respect to the tip speed ratio λ and the pitch angle θ, as shown in Fig. 3 [7]:

$$c_p(\lambda, \theta) = 0.22\left(\frac{116}{\lambda_i} - 0.4\theta - 5\right) e^{\frac{-12.5}{\lambda_i}} \qquad (21)$$

where λ_i can be approximated by a function of the tip speed m ratio λ and the pitch angle θ, which is given by:

$$\frac{1}{\lambda_i} = \frac{1}{\lambda + 0.08\theta} - \frac{0.035}{\theta^3 + 1} \qquad (22)$$

The mechanical torque is given by:

$$T_{mech} = P_w / \omega_r \qquad (23)$$

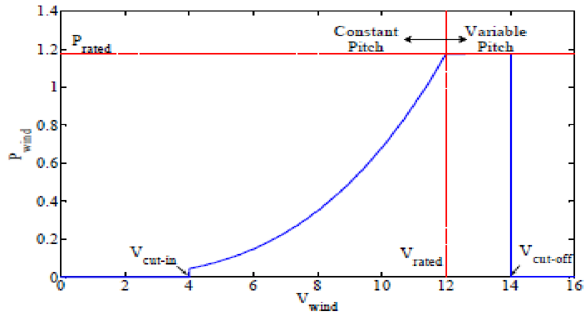

Fig. 2. Characteristics of *Pw* versus *Vw*.

The characteristics of *Pw* versus *Vw* is illustrated in Fig. 2. When *Vw* is higher than 12m/s, the wind turbine reaches its rated power. A variable pitch control can be applied to limit the wind power at rated level.

B. DFIG model equations

DFIG and the wind power system are modeled in synchronous *dq* reference frame, where all the variables are expressed as $\vec{f} = f_d + jf_q$. DFIG equations are given by:

$$\vec{v}_s = -L_s \frac{d}{dt}\vec{i}_s - j\omega_s L_s \vec{i}_s - L_m \frac{d}{dt}\vec{i}'_r - j\omega_s L_m \vec{i}'_r - r_s \vec{i}_s \qquad (24)$$

$$\vec{v}'_r = -L'_r \frac{d}{dt}\vec{i}'_r - j\omega_{sl} L'_r \vec{i}'_r - L_m \frac{d}{dt}\vec{i}_s - j\omega_{sl} L_m \vec{i}_s - r'_r \vec{i}'_r \qquad (25)$$

$$T_{em} = \frac{3P}{4} L_m \operatorname{Im}(\vec{i}_r \vec{i}_s^*) \qquad (26)$$

$$\frac{d\omega_r}{dt} = \frac{P}{2J}(T_{mech} + T_e) \qquad (27)$$

$$P_s = \frac{3}{2}\operatorname{Re}(\vec{v}_s \vec{i}_s^*) \qquad (28)$$

$$Q_s = \frac{3}{2}\operatorname{Im}(\vec{v}_s \vec{i}_s^*) \qquad (29)$$

$$P_r = \frac{3}{2}\operatorname{Re}(\vec{v}_r \vec{i}_r^*) \qquad (30)$$

$$Q_r = \frac{3}{2}\operatorname{Im}(\vec{v}_r \vec{i}_r^*) \qquad (31)$$

where the rotor side parameters including voltage, current, resistance and inductance, have been referred onto stator side; subscripts ‘d’, ‘q’, ‘s’ and ‘*r*’ represent d-axis component, qaxis component, stator and rotor, respectively; ωs is the synchronous speed; ωr is the rotor angular frequency; *P* is the number of poles; ‘*’ represents the complex conjugate; ω_{sl} is the slip frequency, which is given by:

$$\omega_{sl} = \omega_s - P\omega_r / 2 \qquad (32)$$

C. Wind power system model equations

The wind power system equations contain power grid equations, grid-side converter equations, DC-link equation and rotor-side converter equations. Based on KCL and KVL, the wind power system equations are derived as follows:

(a) power grid equations:

$$\vec{E}_g = r_g\vec{i}_g + L_g\frac{d}{dt}\vec{i}_g + j\omega_e L_g\vec{i}_g + \vec{v}_s \quad (33)$$

$$\vec{i}_g = \vec{i}_s + \vec{i}_c \quad (34)$$

(b) grid-side converter equations:

$$\vec{v}_s = r_c\vec{i}_c + L_c\frac{d}{dt}\vec{i}_c + j\omega_e L_c\vec{i}_c + \vec{v}_c \quad (35)$$

$$\vec{v}_c = \vec{m}_c V_{dc}/2 \quad (36)$$

(c) DC-link equation:

$$C\frac{d}{dt}V_{dc} = \frac{3}{2}\mathrm{Re}\left(\vec{m}_c\vec{i}_c^* - \vec{m}_r\vec{i}_r'^*\right) \quad (37)$$

(d) rotor-side converter equations:

$$\vec{v}_r = \vec{m}_r V_{dc}/2 \quad (38)$$

$$\vec{v}_r = r_r\vec{i}_r' + L_r\frac{d}{dt}\vec{i}_r' + j\omega_e L_r\vec{i}_r' \quad (39)$$

where subscripts 'g' and 'c' represent grid variables and gridside converter variables, respectively; $\vec{m}_c$ and $\vec{m}_r$ are the modulation signals of the grid-side converter and rotor-side converter, respectively.

III. CONTROL STRATEGY

In this paper, the control system is divided into two parts: rotor-side converter control and grid-side converter control, each of which consists of two levels. The first level is used to obtain the reference value while the second is used to generate pulse width modulation (PWM) signal. The overall structure of the control system is shown in Fig. 4.

The objective of the decoupled method is to decouple the rotor current such that the active and reactive power of DFIG can be independently controlled. The motivation comes up from the stationary reference frame transformation.

$$-L_m\frac{d}{dt}\vec{i}_s - j\omega_{sl}L_m\vec{i}_s \quad (40)$$

is required to be eliminated in order to decouple the stator and rotor currents. Referring to the following equation [2]

$$\frac{d\vec{\psi}_{\alpha\beta s}}{dt} = \frac{d\vec{\psi}_s}{dt} - j\omega_{sl}\vec{\psi}_s \quad (41)$$

$$-L_m\frac{d}{dt}\vec{i}_s - j\omega_{sl}L_m\vec{i}_s = \frac{L_m}{L_s}\left(\frac{d}{dt}\vec{\psi}_s - j\omega_{sl}\vec{\psi}_s\right) + \frac{L_m^2}{L_s}\left(\frac{d}{dt}\vec{i}_r' - j\omega_{sl}\vec{i}_r'\right) \quad (42)$$

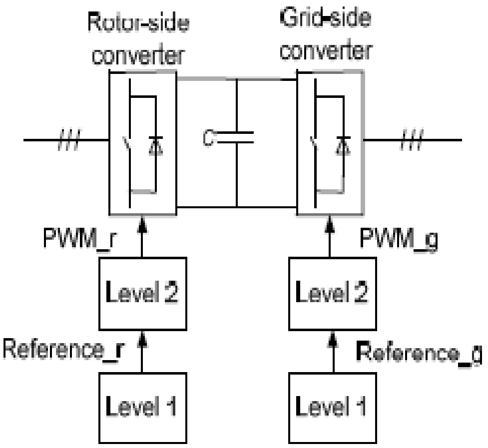

Fig. 3. The overall structure of control system.

A. Decoupled Method and machine control

Referring to the following equation

$$\frac{d\vec{\psi}_{\alpha\beta s}}{dt} = \frac{d\vec{\psi}_s}{dt} - j\omega_{sl}\vec{\psi}_s \quad (43)$$

the following expression is obtained:

$$-L_m\frac{d}{dt}\vec{i}_s - j\omega_{sl}L_m\vec{i}_s = \frac{L_m}{L_s}\left(\frac{d}{dt}\vec{\psi}_s - j\omega_{sl}\vec{\psi}_s\right) + \frac{L_m^2}{L_s}\left(\frac{d}{dt}\vec{i}_r' - j\omega_{sl}\vec{i}_r'\right) \quad (44)$$

The above equations can be simplified by aligning d-axis with the stator flux field vector. Hence, the stator flux component along q-axis becomes zero. Considering the stator flux is constant, the decoupled rotor voltage equations are obtained:

$$\vec{v}_r' = \frac{L_m}{L_s}\vec{\psi}_s + L_\sigma\left(\frac{d}{dt}\vec{i}_r' - j\omega_{sl}\vec{i}_r'\right) - r_r'\vec{i}_r' \quad (45)$$

where

$$L_\sigma = \frac{L_m^2}{L_s} - L_r' \quad (46)$$

In such a way, the rotor voltage does not rely on the stator current any more. Considering all the terms in the above equations but the derivative of rotor current as feed-forward variables, a decoupled rotor current controller can be designed as shown in Fig. 4.

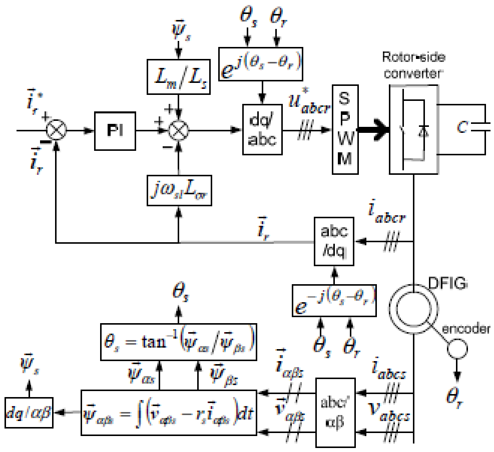

Fig. 4. Control block of rotor-side level.

To control the active and reactive power of the machine, the equations (8) and (9) are need to be simplified using stator flux orientation. As analyzed above, after stator flux orientation, d-axis component of stator flux is constant while q-axis component of stator flux becomes zero. Furthermore, neglecting stator copper loss, equations (8) and (9) can be rearranged as follows:

$$P_s = \frac{3}{2}\omega_s \frac{L_m}{L_s}\psi_{ds} i'_{qr} \qquad (47)$$

$$Q_s = \frac{3}{2}\left(\frac{\omega_s \psi_{ds}^2}{L_s} - \frac{\omega_s L_m}{L_s}\psi_{ds} i'_{dr}\right) \qquad (48)$$

where i'_{dr} and i'_{qr} are the d-axis and q-axis components of rotor m current, respectively.

Equations (47) and (48) indicate the linear correlation between the active and reactive power of the machine and rotor current. Combining the rotor current decoupled method, the active power and reactive power of the machine can be controlled independently. In other words, as shown in Fig. 6, the reference value of rotor current can be calculated when the scheduled active and reactive power of the machine are known.

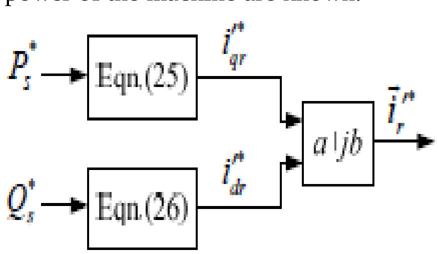

Fig 5. Reference calculation block for rotor-side level 1.

B. Reactive power compensation and DC-link voltage regulation

These objectives are achieved by controlling grid-side converter. To simplify the case, a stator voltage orientation is required [5]. After *dq* reference frame is aligned with stator voltage vector, d-axis component of stator voltage is constant while q-axis component of stator voltage becomes zero. Therefore, the active and reactive power delivered from gridside converter is given by:

$$P_c = v_{ds} i_{dc} \qquad (49)$$

$$Q_c = -v_{ds} i_{qc} \qquad (50)$$

where *idc* and *iqc* are the d-axis and q-axis components of ACside current of grid-side converter, respectively.
By adjusting *iqc*, the required reactive power can be compensated since the stator voltage is constant. Eq. (49) can be used to regulate DC-link voltage. Substituting equations (39) and (40) into (49) to eliminate $\vec{m}_c$ and $\vec{m}_r$, we obtain,

$$\frac{C}{3}V_{dc}\frac{d}{dt}V_{dc} = \frac{C}{6}\frac{d}{dt}V_{dc}^2 = P_c - P_r \qquad (51)$$

$$\Rightarrow i_{dc} = \frac{1}{v_{ds}}\left(\frac{C}{6}\frac{d}{dt}V_{dc}^2 + P_r\right)$$

where $P_c = \mathrm{Re}[\vec{v}_c \vec{i}_c^{\,*}]$ and $P_r = \mathrm{Re}[\vec{v}_r \vec{i}_r^{\,*}]$ are the instantaneous active power of grid-side converter and that of rotor-side converter, respectively. Based on equation (28) and (29), when the desired compensating reactive power and DC-link voltage are given, the reference value of AC-side current of grid-side converter is obtained as:

$$\vec{i}_c^{\,*} = i_{dc}^* + j \cdot i_{qc}^* \qquad (52)$$

The reference calculation block is illustrated in Fig. 7. The control block can be designed according to the grid-side converter equations as shown in Fig. 8.

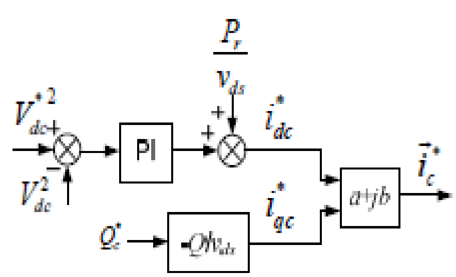

Fig.6. Reference calculation block for grid-side level 1.

A commonly used model for induction generator converting power from the wind to serve the electric grid is shown in figure 3.The stator of the wound rotor induction machine is connected to the low voltage balanced three-phase grid and the rotor side is fed via the back-to-back PWM voltage-source inverters with a common DC link. Grid side converter controls the power flow between the DC bus and the AC side and allows the system to be operated in sub-synchronous and super synchronous speed. The proper rotor excitation is provided by the machine side power converter and also it provides active and reactive power control on stator and rotor sides respectively by employing vector control.

DFIG can be operated as a generator as well as a motor in both sub-Synchronous and super synchronous speeds, thus giving four possible operating modes. Only the two generating modes at sub-synchronous and super synchronous speeds are of interest for wind power generation. So, an approach of using active power set point from the instantaneous value of rotor speed and controlling the rotor current in stator flux-oriented reference frame to get the desired active power will result in obtaining the desired values of speed and torque according to the optimum torque speed curve. The reactive power set point can also be calculated from active power set point using a desired power factor.

IV. MATLAB SIMULATION AND RESULTS

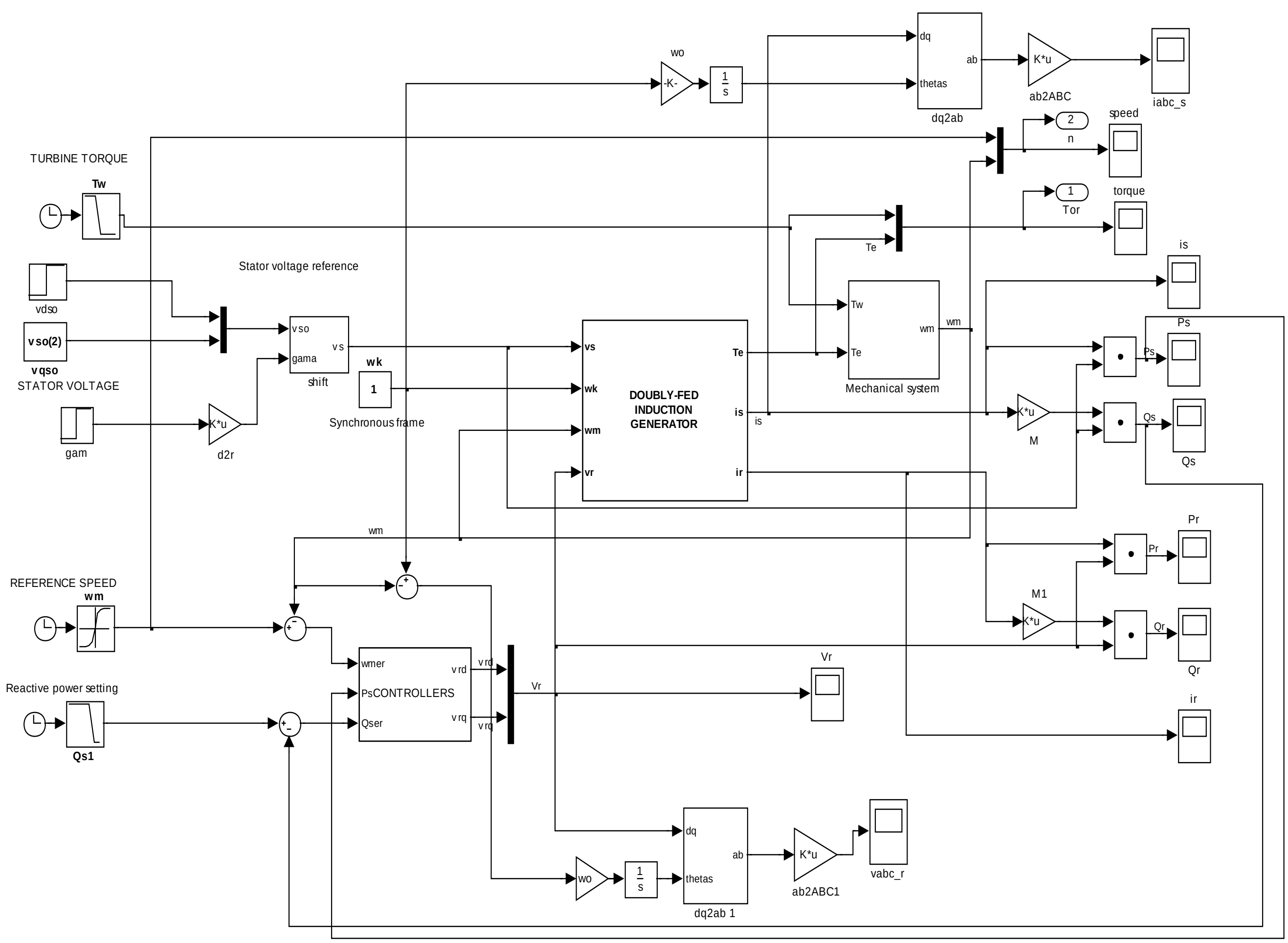

Fig7. final.mdl:

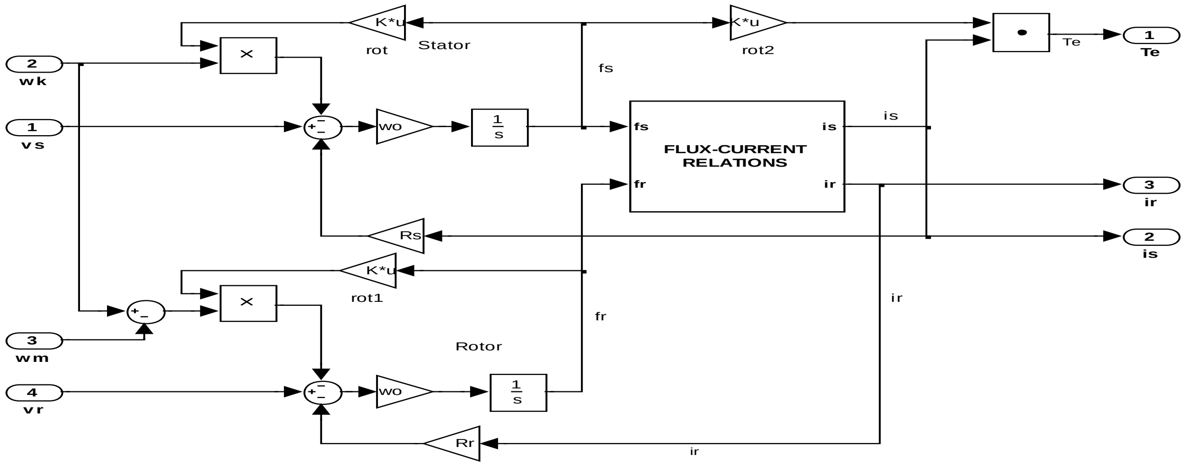

Fig8. Final/Doubly-Fed Induction Generator.mdl:

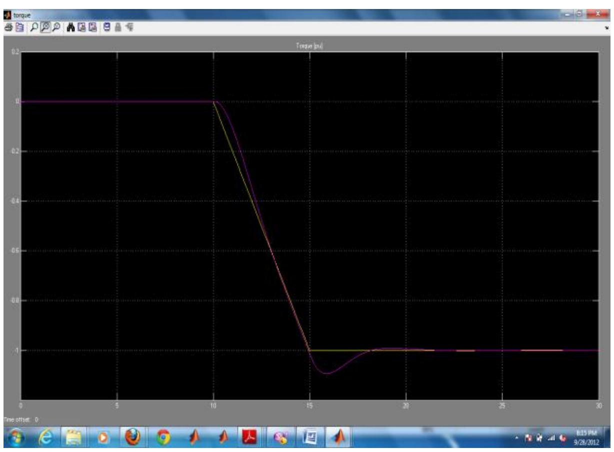

Fig9. Torque Response

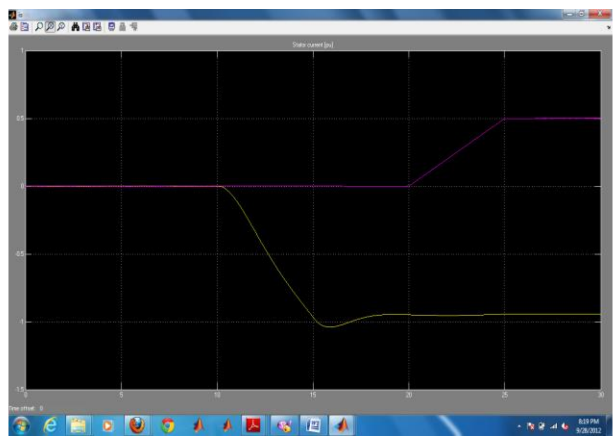

Fig11. Active and Reactive power for Stator Current:

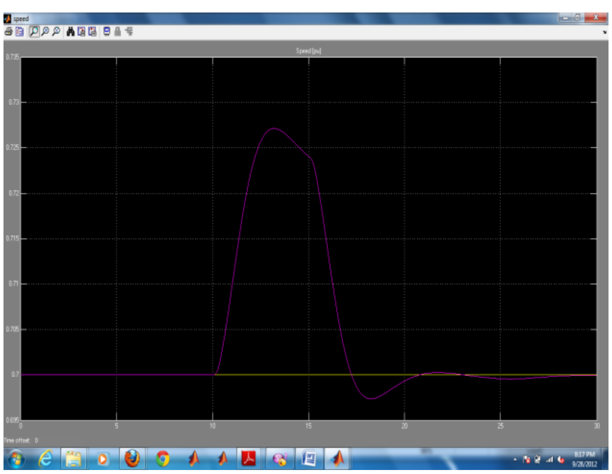

Fig10. Speed Response

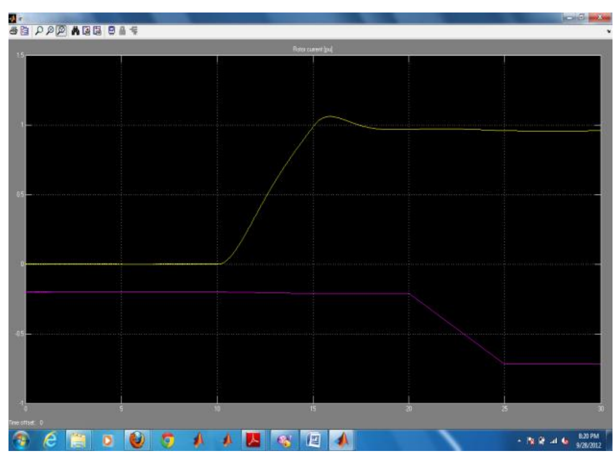

Fig12. Active and Reactive power for Rotor Current:

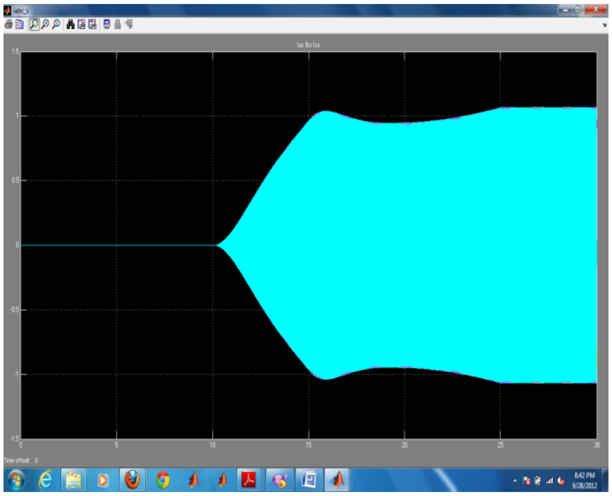

Fig13. Simulation Result of 3 phase fault with connecting inverter all time

V. CONCLUSION

This paper has presented the modeling and simulation of wind turbine driven doubly-fed induction generator which feeds power to the utility grid. Wind turbine modeling has been described in order to extract maximum possible mechanical power from the wind according to the wind velocity and tip-speed ratio. DFIG model has been described based on the vectorized dynamic approach and this model can be applicable for all types of induction generator configurations for steady state and transient analysis. However the choice of the reference frame will affect the waveforms of all d-q variables. It will also affect the simulation speed and in certain cases the accuracy of the results. Generally the conditions of operation will determine the most convenient reference frame for analysis. The power flow control in the DFIG can be obtained by connecting two back to back PWM converters between rotor and utility grid.

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