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# Active & Reactive Power Control Of A Doubly Fed Induction Generator Driven By A Wind Turbine

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**Abstract** - Wind Energy is gaining interest now-a – days as one of the most important renewable sources of energy due to its ecofriendly nature. But the major disadvantage lies in variable speed wind generation and this paper gives a study on control of Wind driven doubly fed Induction Generators. The speeds above and below Synchronous speeds are obtained using a bidirectional power flow converter. By using this reactive power is controlled and hence the overall Power factor of system can be kept at unity under varying load conditions. . This paper presents simulation results of a Grid-connected DFIG. A switch-by-switch representation of the PWM converters with a carrier-based Sinusoidal PWM modulation for both rotor- and stator-side converter has been proposed. Stator-Flux Oriented vector control approach is deployed for both stator- and rotor-side converters to provide independent control of active and reactive power and keep the DC-link voltage constant. A 7.5 KW generator is designed and its effectiveness in controlling is verified in different operating conditions i.e. above and below synchronous speeds.

**Key words** - DFIG; Grid side Converter(GSC); Rotor Side Converter(RSC); Active and Reactive Powers; Stator Flux Oriented control.

## I. INTRODUCTION

Industrial drive applications are generally classified into constant speed and variable speed operations. For constant speed applications generally ac machines are used where as for variable speed applications dc machines are used. But due to the disadvantages of dc machines lies mainly with commutators and brushes which limit the machine speed and peak current. As a result for variable speed applications ac machines are gaining more importance than the dc machines recently. In order to meet power needs, taking into account economical and environmental factors, wind energy conversion is gradually gaining interest as a suitable source of renewable energy. With increased penetration of wind power into electrical grids, wind turbines are largely deployed due to their variable speed feature and hence influencing system dynamics. But unbalances in wind energy are highly impacting the energy conversion and this problem can be overcome by using a Doubly Fed Induction Generator (DFIG).

Doubly fed wound rotor induction machine with vector control is very attractive to the high performance variable speed drive and generating applications. In variable speed drive application, the so called slip power recovery scheme is a common practice here the power due to the rotor slip below or above synchronous speed is recovered to or supplied from the power source resulting in a highly efficient variable speed system. Slip

power control can be obtained by using popular Static Scherbius drive for bi directional power flow. The major advantage of the DFIG is that the power electronic equipment used i.e. a back to back converter that handles a fraction of (20-30%) total system power. The back to back converter consists of two converters i.e. Grid Side Converter (GSC) and Rotor Side Converter (RSC) connected back to back through a dc link capacitor for energy storage purpose.

In this paper a control strategy is presented for DFIG. Stator Active and Reactive power control principle is also presented. In order to decouple the active and reactive powers Stator Flux Oriented control is used and hence the induction machine model is developed, PI Controllers design is applied for stator flux oriented reference frame. The simulation model is developed and implemented in MATLAB/SIMULINK software.

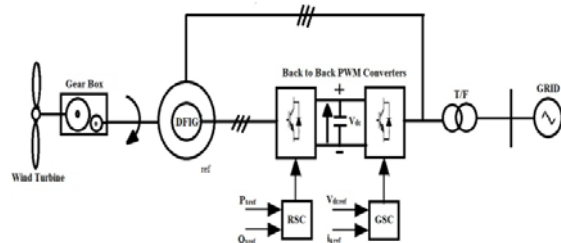


Fig. 1 : Doubly Fed Induction Generator Driven by a Wind Turbine.

## II. PRINCIPLE OF OPERATION

Figure.2 shows the basic scheme adopted in the majority of systems. The stator is directly connected to the AC mains, whilst the wound rotor is fed from the Power Electronics Converter via slip rings to allow DFIG to operate at a variety of speeds in response to changing wind speed. Indeed, the basic concept is to interpose a frequency converter between the variable frequency induction generator and fixed frequency grid. The DC capacitor linking stator- and rotor-side converters allows the storage of power from induction generator for further generation. To achieve full control of grid current, the DC-link.

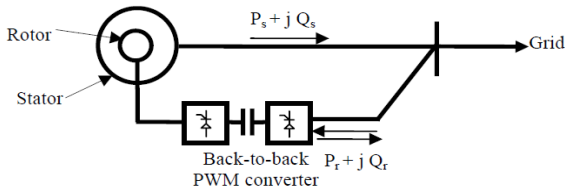


Fig. 2 : Schematic Diagram of a Doubly Fed Induction Generator.

The slip power can flow in both directions, i.e. to the rotor from the supply and from supply to the rotor and hence the speed of the machine can be controlled from either rotor- or stator-side converter in both super and sub-synchronous speed ranges. As a result, the machine can be controlled as a generator or a motor in both super and sub-synchronous operating modes realizing four operating modes. Below the synchronous speed in the motoring mode and above the synchronous speed in the generating mode, rotor-side converter operates as a rectifier and stator-side converter as an inverter, where slip power is returned to the stator. Below the synchronous speed in the generating mode and above the synchronous speed in the motoring mode, rotor-side converter operates as an inverter and stator-side converter as a rectifier, where slip power is supplied to the rotor. At the synchronous speed, slip power is taken from supply to excite the rotor windings and in this case machine behaves as a synchronous machine.

## III. WIND TURBINE MODEL

Several models for power production capability of wind turbines have been developed. The mechanical power, captured  $P_{mech}$  by a wind turbine, depends on its power coefficient  $C_p$  given for a wind velocity and can be represented by

$$P_{mech} = \frac{1}{2} C_p \rho \pi R^2 v^3. \quad (1)$$

Where  $\rho$  and  $R$  correspond to the air density and the radius of the turbine propeller, respectively. The power coefficient can be described as the portion of mechanical power extracted from the total power available from the wind, and it is unique for each turbine. This power coefficient  $C_p$  is generally defined as a function of the tip-speed-ratio which, in turn, is given by  $\lambda$

$$\lambda = \frac{\omega R}{v} \quad (2)$$

where  $\omega$  represents the rotational speed of the wind turbine. Figure3. shows a typical relationship between the power coefficient  $C_p$  and the tip-speed-ratio. It should be noted that there is a value of  $\lambda$  to ensure a maximum of  $C_p$ . Thus, it can be stated that, for a specified wind velocity, there is a turbine rotational speed value that allows capturing the maximum mechanical power attainable from the wind, and this is, precisely, the turbine speed to be followed.

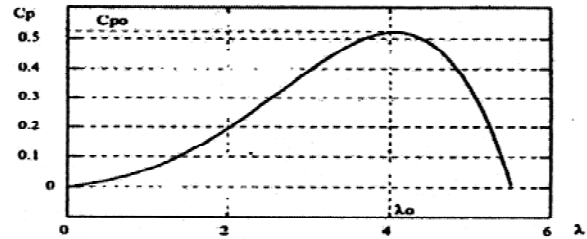


Fig. 3 : Typical Power Coefficient Versus Tip-Speed-Ratio Curve.

The method followed in this paper in order to reach the optimum tip-speed-ratio at each wind velocity consists in, based on the generator rotor speed, estimating and, therefore, trying to achieve the optimum active power to be generated by means of the rotor current stator-flux-oriented vector control.

Specifically, assuming that the optimum power coefficient  $C_p$  and, as a result, the optimum  $\lambda$  tip-speed-ratio values for the particular wind turbine employed are properly identified, the stator side active power reference  $P_{s\_ref}$  value which is made equal to  $P_{mech}$  is established starting from the turbine  $\omega$  angular speed through equations (1) and (2).

## IV. DYNAMIC SIMULATION OF DFIG IN TERMS OF DQ - WINDINGS

The dynamic performance of ac machine is somewhat complex because the three phase rotor windings move with respect to three phase stator windings. Hence a three phase machine can be represented with an equivalent two phase machine replacing the variables associated with the stator windings of a machine with variables associated with

fictitious windings rotating with the rotor at synchronous speed. The analysis can be simplified greatly by transforming the three phase stator and rotor windings (with angular displacement) to a fictitious two phase stator and rotor (with no displacement). These fictitious two phase windings are called d-q windings. The stator and rotor a-, b- and c-phase voltage equations can be transformed to the d-q axis. Then the generator electrical model is derived from the following equations.

$$v_{sD} = R_s i_{sD} - \omega_s \psi_{sQ} + \frac{d\psi_{sD}}{dt}. \quad (3)$$

$$v_{sQ} = R_s i_{sQ} - \omega_s \psi_{sD} + \frac{d\psi_{sQ}}{dt}. \quad (4)$$

$$v_{rD} = R_r i_{rD} - \omega_r \psi_{rQ} + \frac{d\psi_{rD}}{dt}. \quad (5)$$

$$v_{rQ} = R_r i_{rQ} + \omega_r \psi_{rD} + \frac{d\psi_{rQ}}{dt}. \quad (6)$$

$$T_e = \frac{3}{2} P L_m (i_{sQ} i_{rD} - i_{sD} i_{rQ}). \quad (7)$$

$$\psi_{sD} = L_s i_{sD} + L_m i_{rD}. \quad (8)$$

$$\psi_{qS} = L_s i_{dS} + L_m i_{qR}. \quad (9)$$

$$\psi_{dr} = L_m i_{dS} + L_r i_{dr}. \quad (10)$$

$$\psi_{qr} = L_m i_{qS} + L_r i_{qr}. \quad (11)$$

$$L_s = L_{ls} + L_m. \quad (12)$$

$$L_r = L_{lr} + L_m. \quad (13)$$

## V. ACTIVE AND REACTIVE POWER CONTROL OF DFIG

The per phase equivalent for a DFIG is shown in the figure 4. Variables with the ' notation denote rotor quantities as seen from stator side.

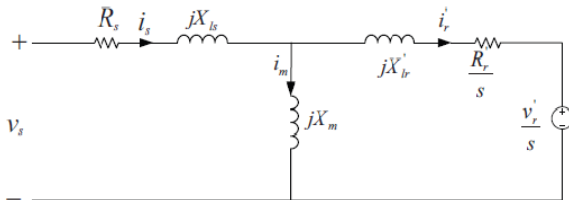


Fig. 4 : Per Phase Equivalent Circuit of a DFIG.

By neglecting the effects of  $R_s$ ,  $jX_{ls}$  and  $jX_{lr}$  the per phase stator power  $S_s$  and rotor power  $S_r$  can be expressed as

$$\therefore S_s = P_s + jQ_s = V_s I_s^*. \quad (14)$$

$$S_r = P_r + jQ_r = V_r I_r^*. \quad (15)$$

The active and reactive powers are found by using the Equations as below.

$$P_s \approx \frac{3}{2} (\overline{v_s}) i_{sy} = -\frac{3}{2} (\overline{v_s}) \frac{L_m}{L_s} i_{ry}. \quad (16)$$

$$Q_s \approx \frac{3}{2} (\overline{v_s}) i_{s\alpha} = -\frac{3}{2} (\overline{v_s}) \frac{L_m}{L_s} (|\overline{i_{ms}} - i_{rx}|)$$

$$\approx \frac{3}{2} (\overline{v_s}) \frac{L_m}{L_s} \left( \frac{|\overline{v_s}|}{2\pi f_s L_m} - i_{rx} \right) \quad (17)$$

## VI. CONTROL SCHEME OF DFIG

### A. Stator Flux Oriented Vector Control Principle

Vector control can also be possible with air gap flux or stator flux orientation, but at the cost of a coupling effect that demands decoupling compensation. Stator flux oriented direct vector control has the advantage that flux vector estimation accuracy is estimated by the stator resistance  $R_s$  variation only. In this control we developed a strategy for stator flux oriented vector control by using the equations derived from d-q equivalent circuits. If the stator flux is oriented on the d-axis, then the flux q-axis component  $\Psi_{qs} = 0$ . Figure 4. Shows the stator flux phasor diagram represented in d-q frames rotating at synchronous speed  $\omega_s$ .

The following steps are used to implement the stator flux oriented principle and shown in Figure 5.

a) By using Clarke's transformation both the stator and rotor side three phase currents are converted into two phase currents.

$$X_{\alpha\beta} = P(\theta) X_{abc}. \quad (18)$$

$$P(\theta) = \frac{2}{3} \begin{bmatrix} \cos \theta & \cos \left( \theta - \frac{2\pi}{3} \right) & \cos \left( \theta - \frac{4\pi}{3} \right) \\ -\sin \theta & -\sin \left( \theta - \frac{2\pi}{3} \right) & -\sin \left( \theta - \frac{4\pi}{3} \right) \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{bmatrix} \quad (19)$$

b) The stator flux linkage space phasor  $\rho_s$  angular position with respect to the stationary direct axis is estimated by using the following equations.

$$i_{rd} = i_{r\alpha} \cos \theta_r - i_{r\beta} \sin \theta_r. \quad (20)$$

$$i_{rq} = i_{r\alpha} \sin \theta_r + i_{r\beta} \cos \theta_r. \quad (21)$$

$$i_{msD} = \frac{L_s}{L_m} i_{sD} + i_{rd} \quad (22)$$

$$i_{msQ} = \frac{L_s}{L_m} i_{sQ} + i_{rq} \quad (23)$$

$$\rho_s = \arctan \frac{i_{msQ}}{i_{msD}} \quad (24)$$

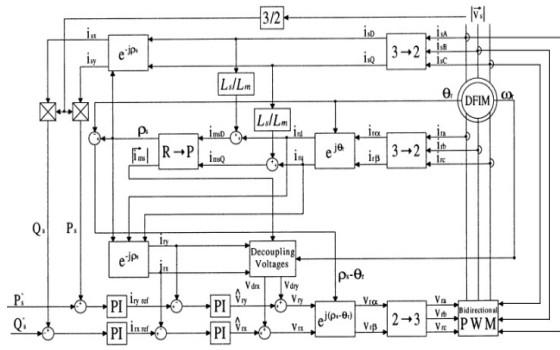


Fig. 5 : Overall Control Structure of a DFIG.

c) The voltage components to be applied to the rotor side are generated by means of two identical PI controllers as shown below.

$$i_{rx} = i_{rd} \cos \rho_s + i_{rq} \sin \rho_s \quad (25)$$

$$i_{ry} = -i_{rd} \sin \rho_s + i_{rq} \cos \rho_s \quad (26)$$

$$\hat{i}_{rx} = K_p (b i_{rxref} - i_{rx}) + K_i \int_0^t (i_{rxref} - i_{rx}) dt \quad (27)$$

$$\hat{i}_{ry} = K_p (b i_{ryref} - i_{ry}) + K_i \int_0^t (i_{ryref} - i_{ry}) dt \quad (28)$$

d) In order to improve the decoupling between x & y axes, the  $v_{drx}$  and  $v_{dry}$  decoupling voltage components given below are added to  $\hat{i}_{rx}$  and  $\hat{i}_{ry}$  respectively.

$$v_{drx} = -\omega_{sl} L'_r i_{ry} \quad (29)$$

$$v_{dry} = \omega_{sl} (L_r - L'_r) |\vec{i}_{ms}| + \omega_{sl} L'_r i_{rx} \quad (30)$$

$$L'_r = L_r - \left( \frac{L_m^2}{L_s} \right) \quad (31)$$

$$\omega_{sl} = 2\pi f_s - \omega_r \quad (32)$$

$$|\vec{i}_{ms}| = \sqrt{i_{msD}^2 + i_{msQ}^2} \quad (33)$$

The resultant voltages in both axes will be referred to as  $v_{rx}$  and  $v_{ry}$ .

e) Expression for  $v_{rx}$  and  $v_{ry}$  according to the rotor natural reference frame as follows.

$$v_{r\alpha} = v_{rx} \cos(\rho_s - \theta_r) - v_{ry} \sin(\rho_s - \theta_r) \quad (34)$$

$$v_{r\beta} = v_{ry} \sin(\rho_s - \theta_r) + v_{rx} \cos(\rho_s - \theta_r) \quad (35)$$

f) By using Inverse Clarke's transformation the rotor three phase voltages are obtained from two phase to three phase.

$$P(\theta)^{-1} X_{\alpha\beta} = X_{abc} \quad (36)$$

$$P(\theta)^{-1} = \begin{bmatrix} \cos \theta & \sin \theta & 1 \\ \cos \left( \theta - \frac{2\pi}{3} \right) & \sin \left( \theta - \frac{2\pi}{3} \right) & 1 \\ \cos \left( \theta - \frac{4\pi}{3} \right) & \sin \left( \theta - \frac{4\pi}{3} \right) & 1 \end{bmatrix} \quad (37)$$

## B. Controllers Design

The DFIG control structure consists of two cascaded control loops. The outer one governs the stator active and reactive powers, so that the power factor value determined by the electric energy distribution company is complied with as accurately as possible. Simultaneously, it would be convenient to employ profitably provided by the wind at each moment from the income yield capacity point of view.

Then the rotor circuit can be represented in d-q frames by the transfer function given in equation

$$\frac{i_r(s)}{v_r(s)} = \frac{1}{s\sigma L_r + R_r} \quad (38)$$

Where  $\sigma$  is the leakage factor

$$\sigma = 1 - \frac{L_0^2}{L_s L'_r} \quad (39)$$

$$L_0 = \sqrt{L_m L_s} \quad (40)$$

The PI controllers transfer function is given as

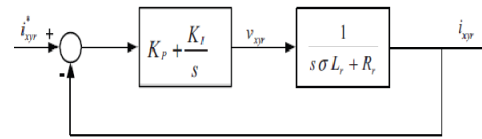


Fig. 6 : Rotor Current Inner Control Loop Design.

Where  $K_p$  and  $K_i$  are inner control loop PI controller parameters.

On the other hand, the inner control loop task consists in controlling independently the rotor current direct  $i_{xr}$  and quadrature  $i_{yr}$  components expressed according to the reference frame fixed to the stator flux linkages space phasor. In order to implement this inner control loop, the stator flux oriented vector controls based on two identical PI controllers are used.

The active and reactive powers control can be derived similarly as shown in Figure 7.

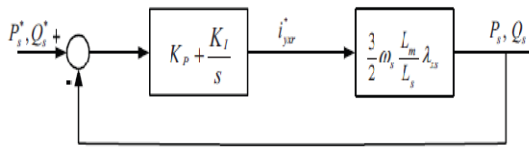


Fig. 7 : Active and Reactive Power Outer Control Loop Design.

**C. Modeling of DFIG in MATLAB/SIMULINK**

*(a) Closed Loop diagram of DFIG by using Back to Back PWM Converters*

In the area of wind energy production, machines of medium and high power which are mainly used. Thus, the stator resistance was neglected. By using the stator flux oriented principle the stator flux is oriented on the d-axis, then the flux q-axis component.

$$\psi_{sQ} = 0. \tag{41}$$

$$\dot{\psi}_{sD} = \psi_s. \tag{42}$$

Hence the stator voltage can be written as

$$v_{sD} = \dot{\psi}_{sD}$$

$$v_{sQ} = V_s = \omega_s \psi_s$$

By using the above equation expression for electromagnetic torque becomes as

$$T_e = \frac{3}{2} P L_m \psi_{sD} i_{rQ}. \tag{45}$$

According to Torque equation (45), the electromagnetic torque of the DFIG can be controlled by controlling the q-axis rotor current  $i_{qr}$ . Using the vector control, the active and reactive powers of the DFIG can be expressed as follows.

$$P_s = -V_s \frac{L_m}{L_s} i_{rQ}. \quad P_r = S V_s \frac{L_m}{L_s} i_{rQ}.$$

$$Q_s = \frac{V_s \psi_s}{L_s} - \frac{V_s L_m}{L_s} i_{rD}.$$

$$Q_r = S V_s \frac{L_m}{L_s} i_{rD}.$$

Hence the total active and reactive output powers of the wind generator are obtained as

$$P_g = P_s + P_r = (S - 1) V_s \frac{L_m}{L_s} i_{rQ}.$$

$$Q_g = Q_s + Q_r = \frac{V_s \psi_s}{L_s} + (S - 1) V_s \frac{L_m}{L_s} i_{rD}.$$

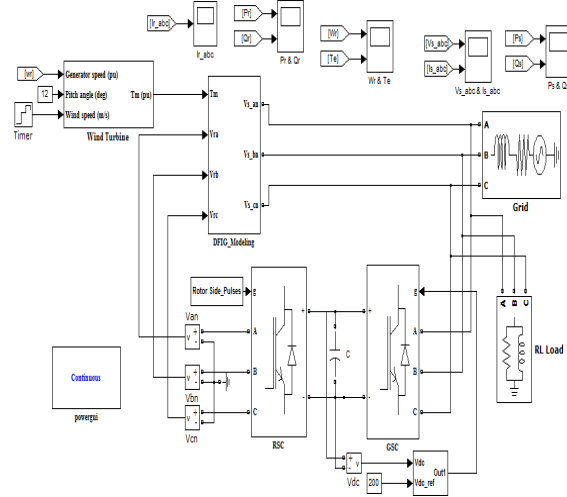


Fig. 8 : Closed Loop Diagram of a DFIG in Simulink Model.

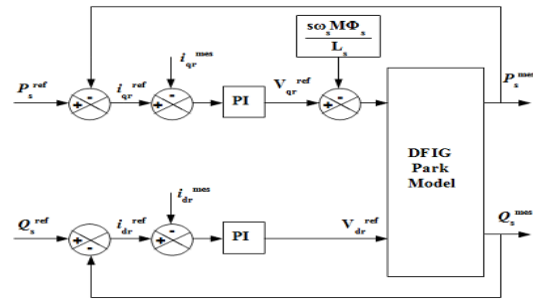


Fig. 9 : Power Control of DFIG.

*(b) Rotor Side Converter Control*

The control principle of the rotor side converter (RSC) allows the control of active and reactive power and the extraction of maximum wind power as shown in Figure 10.

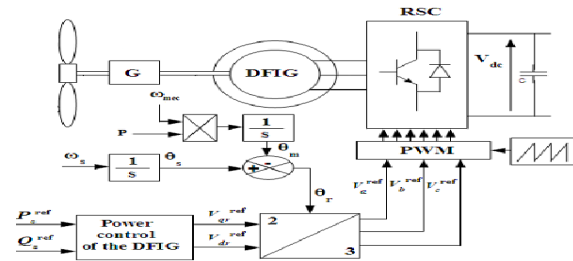


Fig. 10 : Control Structure of Rotor Side Converter.

*(c) Grid Side Converter Control*

The Grid Side Converter (GSC) ensures the regulation of the DC bus voltage and adjusts the power factor on the grid side. The GSC is a bidirectional converter which operates as a rectifier when the slip (S)



is positive (sub synchronous mode) and as an inverter when the slip is negative (super synchronous mode).Figure 11. shows the schematic control of a Grid Side Converter Control.

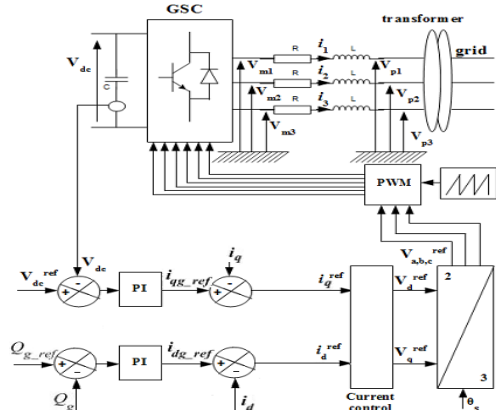


Fig. 11 : Control Structure of Grid Side Converter Control.

**VII.SIMULATION RESULTS**

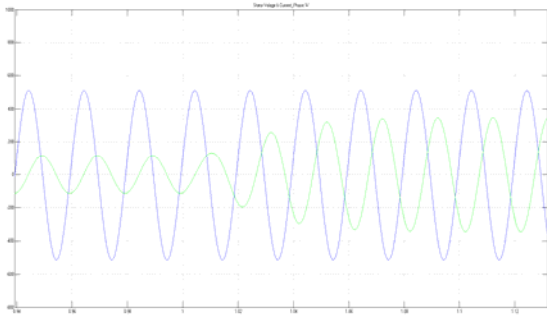


Fig. 12 : Stator Voltage & Current in Phase 'A'.

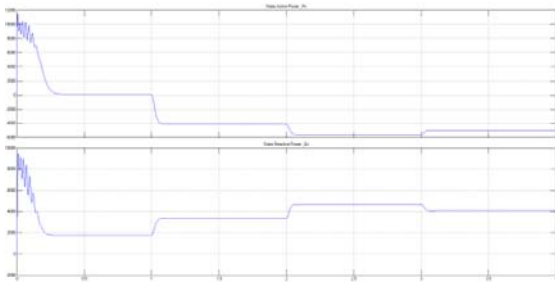


Fig. 13 : Stator Active ( $P_s$ ) & Reactive ( $Q_s$ ) Powers.

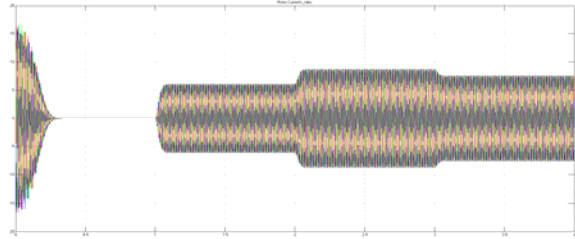


Fig. 14 : Rotor Three Phase Currents ( $I_r$  abc).

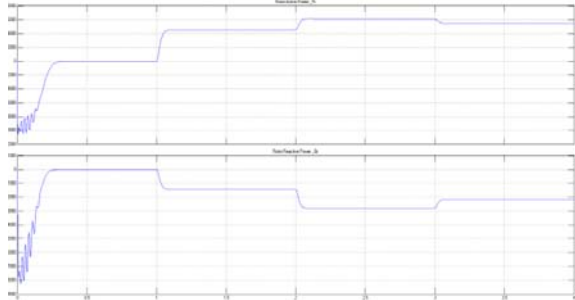


Fig. 15 : Rotor Active ( $P_r$ ) & Reactive ( $Q_r$ ) Powers.

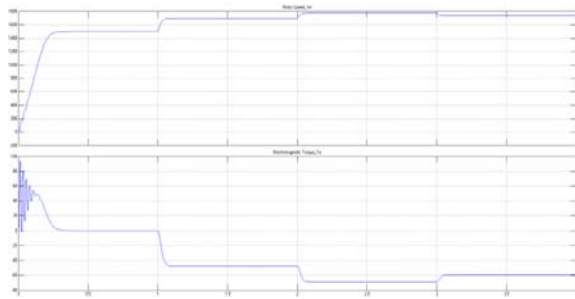


Fig. 16 : Rotor Angular Speed ( $\omega_r$ ) & Electromagnetic Torque ( $T_e$ ).

**VIII.ANNEXURE**

Wound Rotor Induction Machine Parameters:-

Nominal Power	$P_n = 7.5 \text{ Kw}$
Stator Voltage	$V_s = 415 \text{ V}$
Stator Frequency	$f_s = 50 \text{ Hz}$
Stator Resistance	$R_s = 7.83 \Omega$
Stator Inductance	$L_s = 0.4751 \text{ H}$
Rotor Resistance	$R_r = 7.55 \Omega$
Rotor Inductance	$L_r = 0.4751 \text{ H}$
Mutual Inductance	$L_m = 0.4535 \text{ H}$
Inertia Constant	$J = 0.06 \text{ Kg-m}^2$

Number of Pair of Poles  $P = 2$   
 Rating Speed  $N_r = 1440\text{rpm}$ .

**IX. CONCLUSION**

The simulation results obtained when running the wind generator and its overall control system model presented in this paper, correspond strictly to those that of a real doubly fed induction generator working in a wind farm. The results are obtained for different operating conditions such as sub synchronous and super synchronous speeds when the speed of the wind turbine changes periodically for the given input. Hence from these results we can determine that for super synchronous speeds the torque is negative (generating) and for sub synchronous speeds it is positive (motoring). As a result the active & reactive powers are controlled by using the stator flux oriented principle which yields the better results. The machine side provides good decoupling between active and reactive powers.

**A. NOMENCLATURE**

$v_s, v_r$  Stator and rotor voltages  
 $i_s, i_r$  Stator and rotor currents  
 $\psi_s, \psi_r$  Stator and rotor flux linkages  
 $L_m, X_m$  Machine magnetizing inductance, Reactance  
 $L_s, L_r$  Stator and rotor per phase winding inductances  
 $L_{ls}, L_{lr}$  Stator and rotor per phase leakage inductances  
 $R_s, R_r$  Stator and rotor per phase winding resistances  
 $\sigma$  Leakage factor  
 $S_s, S_r$  Stator and rotor apparent power  
 $P_s, P_r$  Stator and rotor active power  
 $Q_s, Q_r$  Stator and rotor reactive power  
 $P_n, Q_n$  Wind Turbine net active & reactive powers  
 $f_s$  Grid frequency  
 $\vec{i}_{ms}$  Stator magnetizing current space phasor modulus  
 $|\vec{i}_r|$  Rotor current space phasor modulus  
 $P_{sref}$  Stator side active power reference value  
 $Q_{sref}$  Stator side reactive power reference value  
 $i_{rx}, i_{ry}$  Direct-and quadrature-axis rotor current components respectively expressed in the stator-flux-oriented reference frame  
 $i_{rxref}, i_{ryref}$  Reference values of the rotor current  $i_{rx}, i_{ry}$  components, respectively

$i_{ra}, i_{rb}$  Direct- and Quadrature – axis rotor current components respectively expressed in the rotor natural reference frame  
 $i_{sD}, i_{sQ}$  Direct – and quadrature- axis stator current components respectively, expressed in the stationary reference frame  
 $i_{sx}, i_{sy}$  Direct – and quadrature – axis stator current components respectively, expressed in the stator- flux- oriented reference frame  
 $K_p, K_i$  Inner loop vector controller PI compensator parameters  
 $K_{p1}, K_{i1}$  Outer loop vector controller PI compensator parameters  
 $i_{msD}, i_{msQ}$  Direct- quadrature-axis stator magnetizing current components respectively, expressed in the stationary reference frame  
 $v_{drx}, v_{dry}$  Direct- and quadrature- axis rotor decoupling voltage components, respectively, expressed in the stator- flux- oriented reference frame  
 $v_{rx}, v_{ry}$  Direct- and quadrature- axis rotor voltage components, respectively, expressed in the stator- flux- oriented reference frame  
 $v_{ra}, v_{rb}$  Direct- and quadrature- axis rotor voltage components, respectively, expressed in the rotor natural reference frame  
 $|\vec{v}_s|$  Stator voltage space phasor modulus  
 $v_{sD}, v_{sQ}$  Direct- and quadrature- axis stator voltage components, respectively, expressed in the stationary reference frame  
 $\rho_s$  Phase angle of stator flux- linkage space phasor with respect to the direct – axis of the stationary reference frame  
 $\omega_{sl}$  Angular slip frequency  
 $v_{rD}, v_{rQ}$  Direct- and quadrature- axis rotor voltage components, respectively, expressed in the stationary reference frame  
 $v_{dcref}$  DC Link Voltage Reference Value  
 $i_{qref}$  Quadrature axis reference current  
 $v_{as}$  Stator voltage at Phase A  
 $v_{bs}$  Stator voltage at Phase B  
 $v_{cs}$  Stator voltage at Phase C  
**B. SUFFICES, SUPERSCRIPTS**  
 s, r Stator, rotor



$\alpha, \beta$	$\alpha, \beta$ Stationary reference frame
d, q	d-q reference frame
x, y	x, y stator-flux-oriented reference frame
a,b,c	Three-phase reference

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