

MODELING AND CONTROL OF DOUBLY FED INDUCTION GENERATOR FOR WIND POWER

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Abstract- With increased penetration of wind power into the electrical grid, Doubly Fed Induction Generator (DFIG) for wind turbines are largely deployed due to their variable speed feature and hence influencing system dynamics. This paper presents the modeling and control of DFIG in details, where the stator is connected directly to a stiff grid and the rotor is connected to the grid through bidirectional back-to-back AC-DC-AC converter. The proposed model is the only complete detailed Simulink model which does not use the Semi-Power System toolbox and will be suitable to be operated in both sub-synchronous and super-synchronous mode of operation. A new vector control strategy based on the rotor flux oriented vector control has been proposed in this paper. The new vector control strategy is compared with the stator flux oriented vector control which is commonly used to control the DFIG. The two indirect vector control strategies based on the stator flux estimation, and rotor flux estimation have been applied to the rotor side converter (RSC) to control the stator active power produced by the generator. 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.

Index Terms- Doubly Fed Induction Generator (DFIG), Vector Control, Wind Energy, Power Control.

I. INTRODUCTION

DUE to the increasing concern about CO₂ emissions, renewable energy systems and especially wind energy generation have attracted great interests in recent years. Large wind farms have been installed or planned around the world and the power ratings of the wind turbines (individually and farm) are increasing. Typically for any wind farms, wind turbines based on the doubly fed induction generator (DFIG) technology with converters rated at about 25%–30% of the generator rating are used. Compared to wind turbines using fixed speed induction generators, DFIG-based wind turbines offer several advantages including variable speed operation, and four-quadrant active and reactive power capabilities. Such system also results in lower converter costs and lower power losses compared to a system based on a fully fed synchronous

generator with full-rated converter. DFIG is basically a standard rotor-wound induction machine in which stator is directly connected to the grid, and the connection of the rotor to the grid is via a back-to-back pulse width modulation (PWM) converter. A simplified schematic diagram of a DFIG based wind energy generation system is shown in Fig. 1. This paper first explains the model of DFIG in the “d-q reference frame” and the second part is explaining vector control strategy of DFIG. Indirect vector control approach with linear proportional-integral PI controllers has been adopted in this paper in order to control the active and reactive power of DFIG independently. The control strategy performance is evaluated in terms of reference tracking of active and reactive power. Two different indirect vector control strategies are applied in this paper depending on the flux oriented frame. First control strategy is based on stator flux oriented frame [4], and the second strategy is based on the rotor flux oriented frame [1].

The paper is organized as follows. Section II presents the set of equations of the d-q model of DFIG. The concept of the low vector control strategies is presented in section III while in section IV simulation results are presented and discussed. The conclusion is drawn in section V.

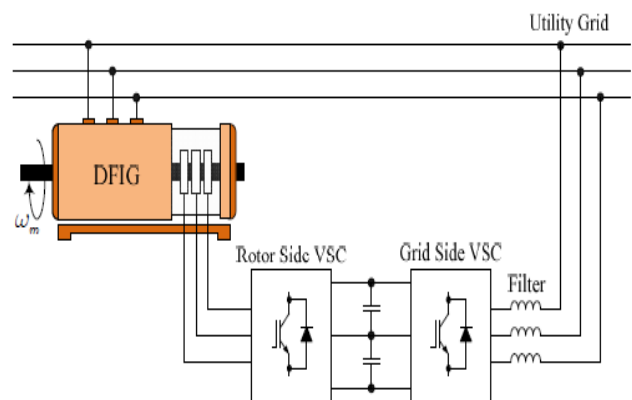


Fig. 1. Configuration of DFIG wind Energy conversion system using back-to-back converter [6].

II. DOUBLY-FED INDUCTION GENERATOR (DFIG) MODEL

The induction machine d-q or dynamic equivalent circuit is shown in Fig.2 [3]. Based on the equivalent circuit, the main equations of modeling doubly fed induction generator in flux linkage form can be derived as follows.

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$$\frac{dF_{qs}}{dt} = \omega_b [v_{qs} - \frac{\omega_e}{\omega_b} F_{ds} + \frac{R_s}{X_{ls}} (F_{mq} + F_{qs})] \quad (1)$$

$$\frac{dF_{ds}}{dt} = \omega_b [v_{ds} + \frac{\omega_e}{\omega_b} F_{qs} + \frac{R_s}{x_{ls}} (F_{md} + F_{ds})] \quad (2)$$

$$\frac{dF_{qr}}{dt} = \omega_b [v_{qr} - \frac{(\omega_e - \omega_r)}{\omega_b} F_{dr} + \frac{R_r}{x_{lr}} (F_{mq} - F_{qr})] \quad (3)$$

$$\frac{dF_{dr}}{dt} = \omega_b [v_{dr} + \frac{(\omega_e - \omega_r)}{\omega_b} F_{qr} + \frac{R_r}{x_{lr}} (F_{md} - F_{dr})] \quad (4)$$

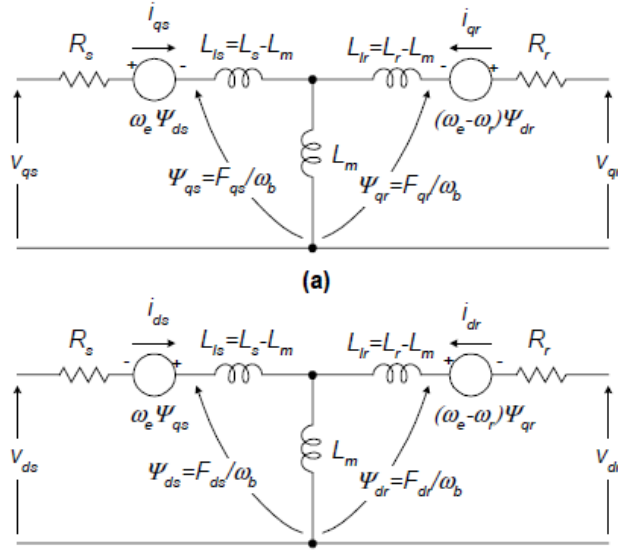


Fig. 2. d-q equivalent circuit of an induction machine [3]

$$F_{mq} = x_{ml} * (\frac{F_{qs}}{x_{ls}} + \frac{F_{qr}}{x_{lr}}) \quad (5)$$

$$F_{md} = x_{ml} * (\frac{F_{ds}}{x_{ls}} + \frac{F_{dr}}{x_{lr}}) \quad (6)$$

The stator and rotor currents can be calculated as following.

$$i_{qs} = \frac{1}{x_{ls}} (F_{qs} - F_{mq}) \quad (7)$$

$$i_{ds} = \frac{1}{x_{ls}} (F_{ds} - F_{md}) \quad (8)$$

$$i_{qr} = \frac{1}{x_{lr}} (F_{qr} - F_{mq}) \quad (9)$$

$$i_{dr} = \frac{1}{x_{lr}} (F_{dr} - F_{md}) \quad (10)$$

The electromagnetic torque can be calculated as following.

$$T_e = \frac{3}{2} (\frac{P}{2}) \frac{1}{\omega_b} (F_{ds} i_{qs} - F_{qs} i_{ds}) \quad (11)$$

$$T_e - T_L = J \frac{2}{P} \frac{d\omega_r}{dt} \quad (12)$$

$$P_s = \frac{3}{2} (v_{ds} i_{ds} + v_{qs} i_{qs}) \quad (13)$$

$$Q_s = \frac{3}{2} (v_{qs} i_{ds} - v_{ds} i_{qs}) \quad (14)$$

Where:

F_{ij} is the flux linkage ($i = d$ or q , and $j = s$ or r)

v_{qs}, v_{ds}, v_{qr} , and v_{dr} are the stator and rotor voltages on d-q axis.

i_{qs}, i_{ds}, i_{qr} and i_{dr} are the stator and rotor currents on d-q axis.

F_{mq}, F_{md} are q and d axis magnetizing flux linkage.

R_s and R_r are the stator and rotor resistances.

X_{ls} and X_{lr} are the stator and rotor reactance's.

P is number of poles, J is moment of inertia.

T_e is the electromagnetic torque.

T_L is the load torque (mechanical torque).

P_s and Q_s are the stator active and reactive power.

ω_e and ω_r are the stator angular electrical frequency and the rotor angular electrical speed respectively.

ω_b is angular electrical base frequency where $F_{ij} = \psi_{ij} * \omega_b$.

ψ_{ij} is the flux.

The set of equations from (1) to (12) have been implemented in Matlab/Simulink to model the DFIG. The mechanical torque, the stator and rotor input voltages and the synchronous speed are the inputs and the electromagnetic torque, the stator and rotor currents and the rotor speed are the outputs. The complete Simulink model of DFIG in is shown in Fig 3. The model can be run in both sub-synchronous and super-synchronous mode. Using a positive load torque will operate the model as a motor (sub-synchronous mode $\omega_e > \omega_r$), while applying a negative load torque will operate the model as a generator (super-synchronous mode $\omega_r > \omega_e$). The power flow scheme of both operating modes is shown in Fig5 [6].

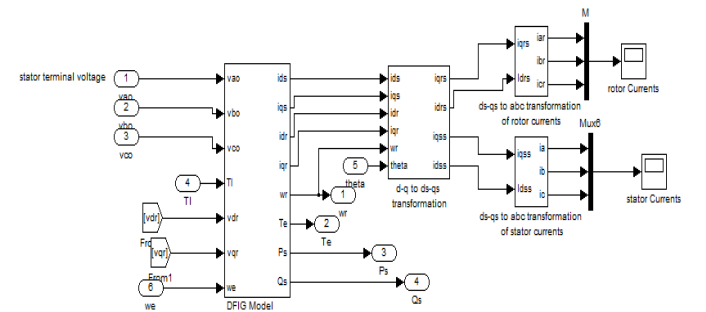


Fig. 3. Implementation of DFIG in Matlab/Simulink

The model also included back-to back AC-DC-AC PWM converter which connected the rotor circuit to the grid (Fig 4) which include both rotor side converter (RSC) and the grid side converter (GSC).

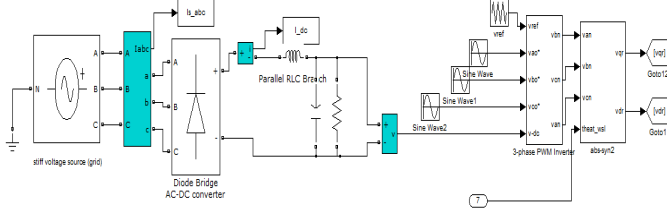


Fig. 4. Implementation of AC-DC-AC converter in Matlab/Simulink

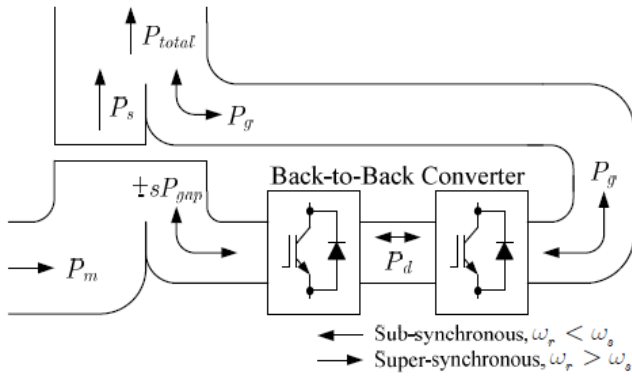


Fig. 5. Power flow of a DFIG system [6].

III. PROPOSED VECTOR CONTROL SCHEME OF DFIG

When the DFIG is connected to an existing grid, power regulation between the stator and the grid is an important step that must be done [8]. Vector control is one of the most commonly methods applied to DFIG to control the flow of active and reactive power between the stator and the grid.

The vector control technique can be applied on both rotor side converter (RSC) and grid side converter (GSC). The objective of the RSC is to govern both the stator-side active and reactive powers independently; while the objective of the GSC is to keep the dc-link voltage constant regardless of the magnitude and direction of the rotor power. The GSC control scheme can also be designed to regulate the reactive power. The reactive power control by the RSC and GSC is necessary to keep the voltage within the desired range, when the DFIG feeds into a weak power system with insufficient local reactive compensation. The design of the RSC controller will be the main focus of this paper.

Design of the RSC Controller

The RSC control scheme consists of two cascaded control loops. The inner current control loops regulate independently the d -axis and q -axis rotor current components, i_{dr} and i_{qr} , according to some synchronously rotating reference frame [4]. Stator flux oriented reference frame is the most popularly used one, but in this paper rotor flux oriented reference frame is

used and compared with stator flux oriented reference frame. The outer control loops regulate both the stator active power (or the generator torque) and reactive power independently.

A. RSC Controller Based on Stator Flux Oriented Vector Control

In the stator flux oriented reference frame, the d -axis is aligned with the stator flux linkage vector ψ_s , namely,

$$\psi_{ds} = \psi_s \text{ and } \psi_{qs} = 0 \text{ as shown in Fig 6 [1].}$$

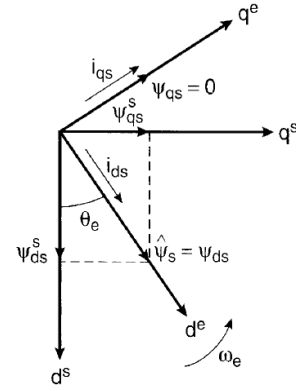


Fig. 6. Phasor diagram with stator flux-oriented vector control [1].

The stator flux is estimated using the stator machine equation in stationary reference frame ($d^s - q^s$), as shown below.

$$\psi_{ds}^s = \int v_{ds}^s - R_s i_{ds}^s \quad (15)$$

$$\psi_{qs}^s = \int v_{qs}^s - R_s i_{qs}^s \quad (16)$$

From the $d^s - q^s$ components of the stator flux the stator flux angle θ_s used of orientation of the control, is obtained:

$$\theta_s = \tan^{-1} \left(\frac{\psi_{qs}^s}{\psi_{ds}^s} \right) \quad (17)$$

From the above dynamic machine equations (1) – (4), the equations can be rewritten it terms of flux by multiplying in ω_b and rearrange we obtained.

$$v_{ds} = R_s i_{ds} - \omega_e \psi_{qs} + \frac{d\psi_{ds}}{dt} \quad (18)$$

$$v_{qs} = R_s i_{qs} + \omega_e \psi_{ds} + \frac{d\psi_{qs}}{dt} \quad (19)$$

$$v_{dr} = R_r i_{dr} - (\omega_e - \omega_r) \psi_{qr} + \frac{d\psi_{dr}}{dt} \quad (20)$$

$$v_{qr} = R_r i_{qr} + (\omega_e - \omega_r) \psi_{dr} + \frac{d\psi_{qr}}{dt} \quad (21)$$

Where

$$F_{ij} = \psi_{ij} * \omega_b$$

$$\begin{cases} \psi_{ds} = L_s i_{ds} + L_m i_{dr} \\ \psi_{qs} = L_s i_{qs} + L_m i_{qr} \\ \psi_{dr} = L_r i_{dr} + L_m i_{ds} \\ \psi_{qr} = L_r i_{qr} + L_m i_{qs} \end{cases} \quad (22)$$

As stated before the reference frame attached to the stator flux at steady conditions, gives the following conditions:

$$\psi_{ds} = \psi_s \text{ and } \psi_{qs} = 0 \quad (23)$$

Substituting (23) in (18) to (22) and we obtain.

$$\begin{cases} v_{ds} = R_s i_{ds} \\ v_{qs} = R_s i_{qs} + \omega_e \psi_{ds} \end{cases} \quad (24)$$

$$i_{qs} = \frac{-L_m}{L_s} i_{qr} \quad (25)$$

$$i_{ds} = \frac{L_m}{L_s} (i_{ms} - i_{dr}) \quad (26)$$

where

$$i_{ms} = \frac{v_{qs} - R_s i_{qs}}{\omega_e L_m} \quad (27)$$

By substituting (25), (26) and (27) in (13) and (14), the stator active and reactive power can be obtained by the following equations.

$$P_s = \frac{-3 L_m^2}{2 L_s} \omega_e i_{ms} i_{qr} \quad (28)$$

$$Q_s = \frac{3 L_m^2}{2 L_s} \omega_e i_{ms} (i_{ms} - i_{dr}) \quad (29)$$

By substituting (22), (26) and (27) in (20) and (21), we obtain.

$$v_{dr} = R_r i_{dr} + \sigma L_r \frac{di_{dr}}{dt} - (\omega_e - \omega_r) \sigma L_r i_{qr} \quad (30)$$

$$v_{qr} = R_r i_{qr} + \sigma L_r \frac{di_{qr}}{dt} + (\omega_e - \omega_r) \left(\frac{\sigma L_r i_{dr} + L_m^2 i_{ms}}{L_s} \right) \quad (31)$$

where

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

Equations (28) and (29) indicate that P_s and Q_s can be controlled independently by regulating the rotor current

components, i_{qr} and i_{dr} , respectively. Consequently, the reference values of i_{dr} and i_{qr} can be determined from the outer power control loops.

If R_s is ignored, which is perfectly acceptable to high power electrical machines, the final expression of stator active power is given by:

$$P_s = \frac{-3 L_m}{2 L_s} i_{qr} \quad (32)$$

$$Q_s = \frac{3 L_m}{2 L_s} \left(\frac{v_{qs}}{\omega_e L_m} - i_{dr} \right) \quad (33)$$

Where v_{qs} is constant and equal to the stator voltage.

From equations (30) and (31) the inner current control loop can be designed using PI controllers, all the details of the design of the inner control loop can be found in [4]. The final form the inner current control loop is shown below.

$$v_{dr} = \left(k_p + \frac{k_i}{s} \right) (i_{dr}^* - i_{dr}) - s \omega_e \sigma L_r i_{qr} \quad (34)$$

$$v_{qr} = \left(k_p + \frac{k_i}{s} \right) (i_{qr}^* - i_{qr}) + s \omega_e (\sigma L_r i_{dr} + \frac{L_m^2}{L_s} i_{ms}) \quad (35)$$

k_i and k_p are the integral and proportional gains of the PI controller. Fig. 7 shows the overall vector control scheme of the RSC [4]. The compensated outputs of the two current controllers, v_{dr} and v_{qr} , are used by the PWM module to generate the IGBT gate control signals to drive the IGBT converter.

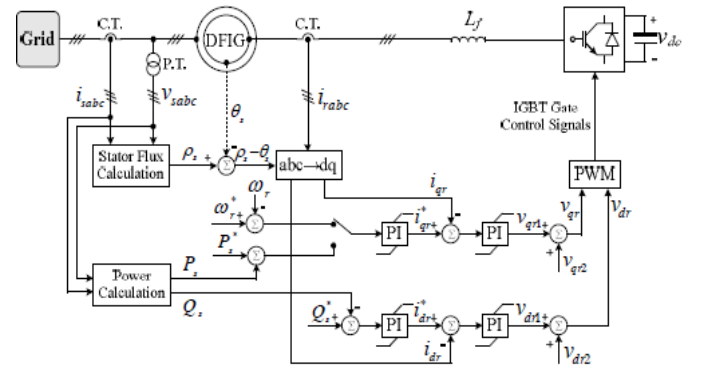


Fig. 7. Vector control scheme of RSC [4].

The terms v_{dr2} and v_{qr2} in Figure 7 are the third terms in equations (30) and (31).

$$v_{dr2} = -s \omega_e \sigma L_r i_{qr}$$

$$v_{qr2} = s \omega_e (\sigma L_r i_{dr} + L_m^2 i_{ms} / L_s)$$

where

$$s \omega_e = (\omega_e - \omega_r)$$

B. RSC Controller Based on Rotor Flux Oriented Vector Control

In the rotor-flux oriented reference frame, the d -axis is aligned with the rotor flux linkage vector ψ_r , namely, $\psi_{dr} = \psi_r$ and $\psi_{qr} = 0$ as shown in Fig 8 [1].

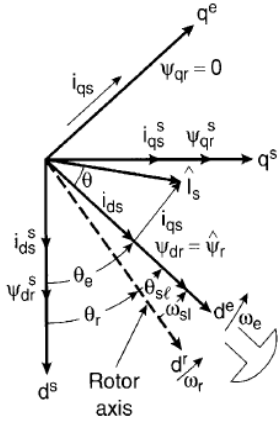


Fig. 8. Phasor diagram with rotor flux-oriented vector control [1].

Based on the above orientation equation (21) can be re-written as following.

$$v_{qr} = R_r i_{qr} + (\omega_e - \omega_r) \psi_r \quad (36)$$

By re-arrange we obtain

$$\omega_{sl} = (\omega_e - \omega_r) = \frac{v_{qr} - R_r i_{qr}}{\psi_r} \quad (37)$$

Where

$$\psi_r = \psi_{dr}$$

Since the rotor is connected to a stiff grid with a constant voltage, its **worth** to assume the stator flux constant [1].

The stator flux the stator flux angle θ_s used of orientation of the control, is obtained:

$$\omega_e = \omega_r + \omega_{sl} \quad (38)$$

$$\theta_e = \int \omega_e dt \quad (39)$$

In the super-synchronous mode, ω_{sl} will be negative, to verify that the rotor angular speed higher the electrical synchronous speed, and ensure the validation of equation (38).

v_{qr} and i_{qr} in equation (37) has to be calculated directly from the inner control loop by using the PI controllers. The Simulink implementation of inner control loop which derives equation (37) is shown in Fig.9. The inner control loop calculates from the desired active and reactive power signals the rotor voltage command v_d and v_{qr} .

The output of the inner control loop will be applied as a gate commands to the rotor side converter (PWM inverter) to control the rotor currents which control independently the stator active and reactive power [4].

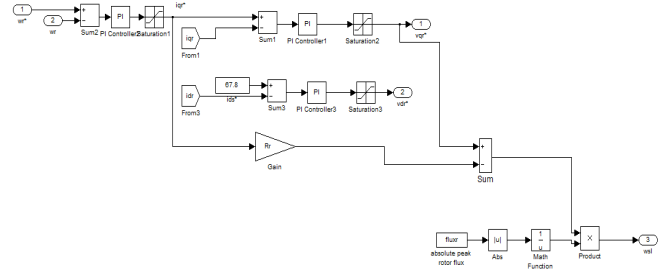


Fig. 9. Simulink implementation of inner control loop of rotor flux oriented vector control

IV. SIMULATION RESULTS AND DISCUSSION

To ensure the validity of the proposed DFIG model, the model has been run using Matlab/Simulink under steady state condition. The machine parameters are shown in the appendix below. Fig10a –Fig10f, and Fig11a –Fig11f show the output of the DFIG model in both super-synchronous and sub-synchronous modes respectively. These plots are self explanatory. By applying a positive load torque the machine is operating as a motor (sub-synchronous mode), while applying a negative load torque makes the machine operates in generating mode. In the generating mode the machine reaches steady state conditions after 0.3s, while in the motoring mode takes 0.5s.

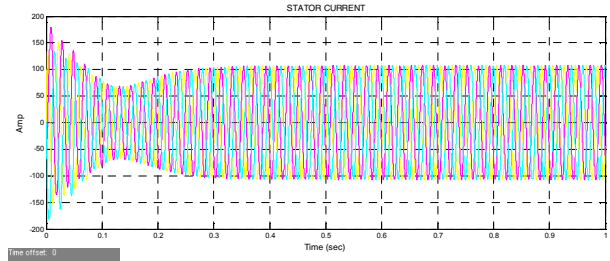


Fig. 10a . Stator currents of DFIG in super-synchronous mode

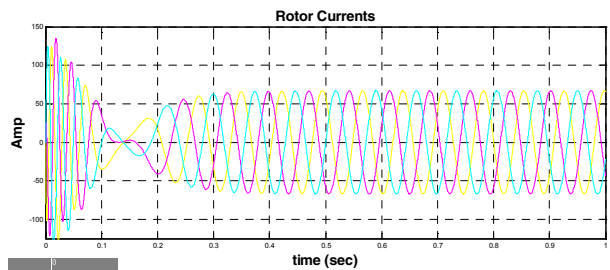


Fig. 10b. Rotor Currents of DFIG in super-synchronous mode

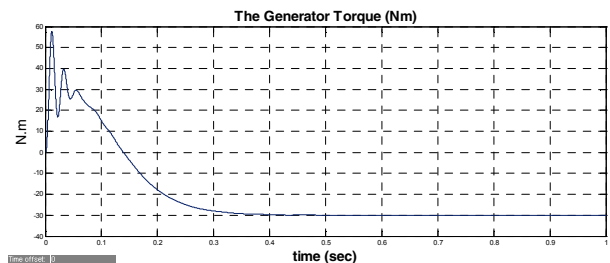


Fig. 10c. Electrical Torque of DFIG in super-synchronous mode

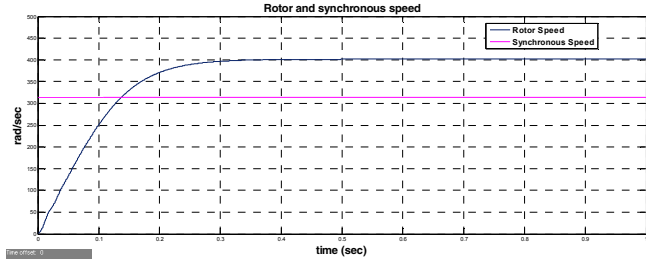


Fig. 10d. The rotor and the synchronous speed of DFIG in super-synchronous mode

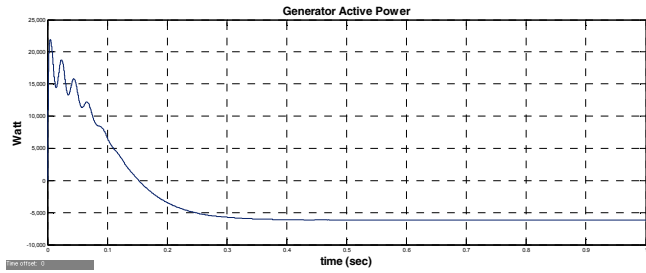


Fig. 10e. The stator active power of DFIG in super-synchronous mode

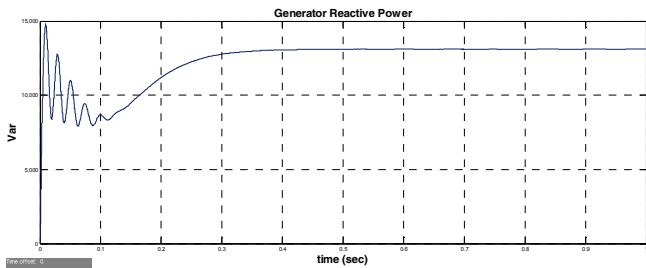


Fig. 10f. The reactive power of DFIG in super-synchronous mode

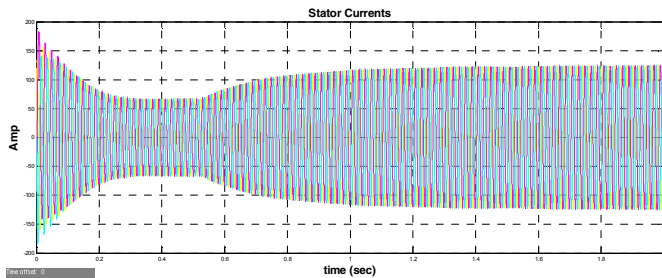


Fig. 11a. The stator currents of DFIG in sub-synchronous mode

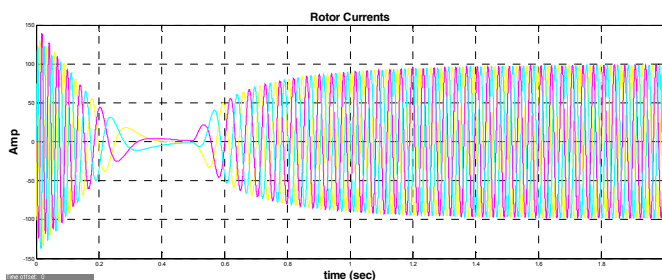


Fig. 11b. The rotor currents of DFIG in sub-synchronous mode

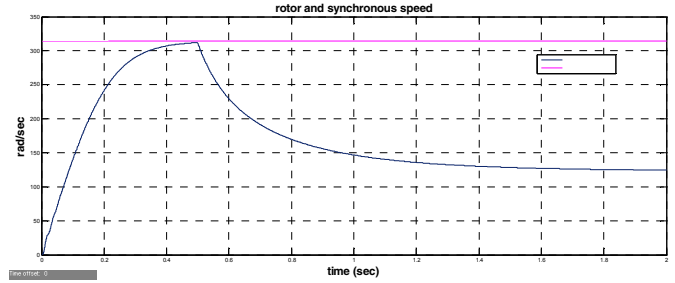


Fig. 11c. The rotor and synchronous speed of DFIG in sub-synchronous mode

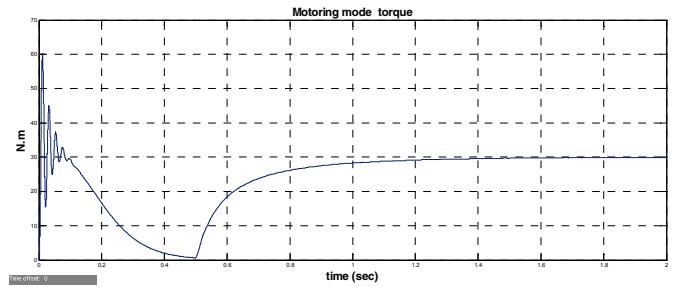


Fig. 11d. the electromagnetic torque of DFIG in sub-synchronous mode

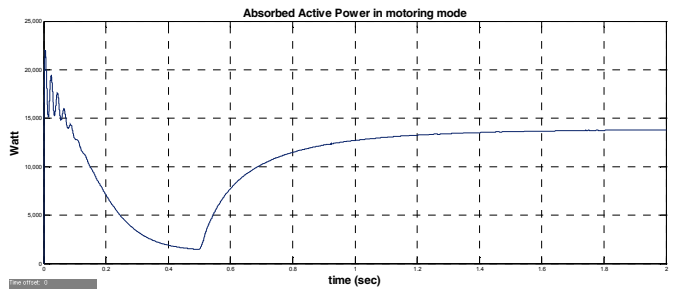


Fig. 11e. the absorbed active power of DFIG in sub-synchronous mode

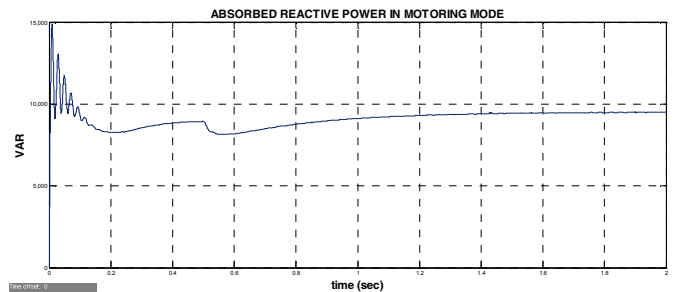


Fig. 11f. the absorbed reactive power of DFIG in sub-synchronous mode

The negative sign of the active power means generated active power (super-synchronous mode), while the positive sign mean the absorbed active power (sub-synchronous mode). It's also clear from the above result that at super-synchronous mode the rotor speed is higher than the synchronous speed Fig 10d, and in the sub-synchronous speed the rotor speed is less than the synchronous speed Fig11c which confirms the validity of the model.

The vector control system based on the stator flux oriented reference frame has been run in Matlab/Simulink, and a reference stator active power (or electrical torque) was applied to the outer control loop, while a constant rotor current in d axis i_{dr} was applied for the reactive power loop instead of a

reference value of reactive power. The stator active power was able to track the applied reference value which confirms the validity of the control system as shown in Fig 12. The reactive power control is beyond the scope of this paper.

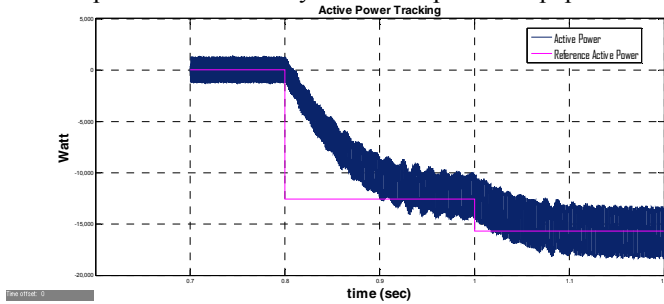


Fig. 12a. The stator active power tracking the reference power using stator flux oriented vector control

The results have also confirmed that the active power was controlled by the rotor current component on q axis i_{qr} , Fig 12b shows the variation in i_{qr} which corresponds the variation in the active power. The change in i_{qr} follows exactly the change in the step reference power at 0.8s, and 1s which results the same step change in the stator active power.

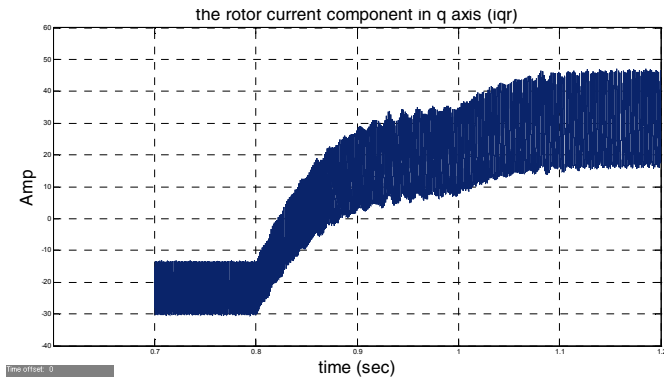


Fig. 12b. the control of i_{qr} component in the stator flux oriented vector control

The same response was given when the vector control was run using the rotor flux oriented vector control, the active power tracking is shown in Fig 12c.

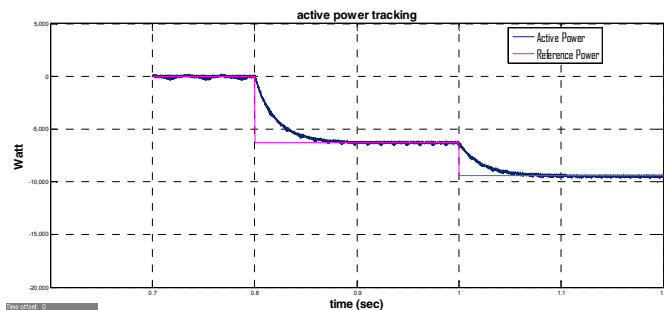


Fig. 12c. The stator active power tracking the reference power using rotor flux oriented vector control

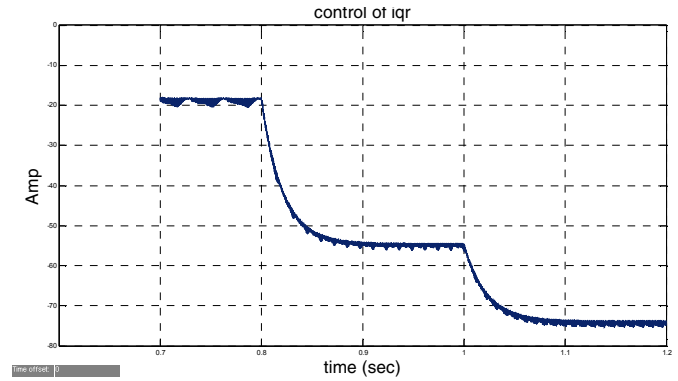


Fig. 12d. the control of i_{qr} component in the rotor flux oriented vector control

Fig 12d shows the variation in i_{qr} which corresponds the variation in the active power when rotor flux oriented vector control is applied. The change in i_{qr} follows exactly the change in the step reference power at 0.8s, and 1s which results the same step change in the stator active power. According to the simulation results, figures (12a) to (12d), the rotor flux oriented vector control strategy proposed in this paper provides a much better active power tracking accuracy compare with the stator flux oriented vector control strategy.

V. CONCLUSION

The Simulink model of DFIG has been used in many studies regarding doubly fed induction generator. Semi-Power System toolbox was the most popularly tool to model DFIG, a detailed complete DFIG model including the AC-DC-AC converter using Matlab/Simulink has not been addressed yet, only a detailed induction motor model has been introduced in [3]. Modeling and control of DFIG is addressed in this paper. a detailed DFIG model in Matlab/Simulink is proposed and the simulation results have been discussed and confirmed the validity of the model. Vector control strategy based in stator flux oriented reference frames is presented and the simulation results show satisfaction of the new strategy. A new vector control strategy based on the rotor flux oriented reference frame is presented in this paper, and compared with the stator flux oriented vector control. The results have confirmed the satisfaction of the new vector control strategy. The vector control strategies were applied on the rotor side converter (RSC) of the DFIG in order to control the active power independently by controlling the rotor current component in q axis i_{qr} . The control of the grid side converter can be a future work in order to control the reactive power and control the DC voltage of AC-DC-AC converter.

VI. APPENDIX

Specifications of the Machine [3]:

10HP, 3-phase, 4 poles, 50Hz, 220/380 volt.

$$R_s = 0.19 \Omega \quad R_r = 0.39 \Omega \quad L_{lr} = 0.0006 \text{ H}$$

$$L_{ls} = 0.00021 \text{ H} \quad L_m = 0.004 \text{ H}$$

VII. REFERENCES

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