American Journal of Engineering Research (AJER)
e-ISSN : 2320-0847 p-ISSN : 2320-0936
Volume-03, Issue-04, pp-76-83
www.ajer.org

Research Paper Open Access

"Simulation of Active and Reactive Power Control of DFIG"

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***Abstract*: -** The penetration of wind energy generation units into existing electrical power system network is In creasing rapidly during recent years. The number of Doubly-Fed Induction Generator (DFIG) has grown over the last few years in several countries as a result of the tremendous increase in wind power generation. They use electronic converters in order to operate at different speeds. This converter system decouples the electrical and mechanical behavior of the generator from the grid voltage and frequency. The generator is fully decoupled from the grid by the power converter; therefore the power factor of the generator does not affect the reactive power factor at the grid connection. The behaviour of the DFIG has been modelled in the dedicated power electronics and system simulation tool PSCAD/EMTDC. This paper presents a model through which steady-state behaviours of a Doubly-Fed Induction Generator (DFIG) can be simulated for analytical studies. It presents the complete picture of the independent control of active power and reactive power using the decoupled control.

***Keywords*: -** *DFIG, PSCAD, Vector control, FOC, back-to- back connected converters.*

I. INTRODUCTION

Advances in technology have changed the world into a place with better living standards and higher consumer expectations than ever before. For sustaining this trend, worldwide, the need is for maintaining an increased and continual supply of energy amidst the depletion of finite fossil fuel reserves at an alarming rate. Amongst the available types of wind turbine generators, Doubly-Fed Induction Generator (DFIG) is gaining more attention and application in wind energy systems due to its ability to extract maximum power. This is because of its unique ability of varying its rotor speed to match the wind velocity.

The main advantages of DFIG are as follows [1]:

1. Independent control of stator side active and reactive power is possible; hence power factor can be controlled.
2. Ability to supply power at constant voltage and frequency while the rotor speed varies.
3. Lower power rating of power electronic converters is required because the converters handle a fraction (20% to 30%) of total power i.e. the slip power.
4. Rotor speed may vary according to wind speed in order to improve wind generator efficiency.
5. Mechanical stress is reduced as well as torque oscillations are not transmitted to the grid; gusts of wind can be absorbed as energy is stored in the mechanical inertia of the turbine.

The main disadvantages of DFIG are [1]:

1. Control is more complicated.
2. Cost is more as more electronic components are used.
3. Use of slip rings induction machine may result into increase of maintenance.

II. MACHINE DESCRIPTION

The DFIG would generate the electrical energy if driven at a speed greater than its synchronous speed. But the rotor would absorb the electrical power from the system at lesser speed than its synchronous speed. The generated voltage frequency is directly proportional to the difference in two frequencies, known as slip frequency. The slip frequency is transformed to grid frequency before the generated power is taken to the grid. The stator is normally connected directly with the supply grid. The rotor is then supplied using a frequency converter. A part of the developed model in PSCAD is shown in Figure 1.

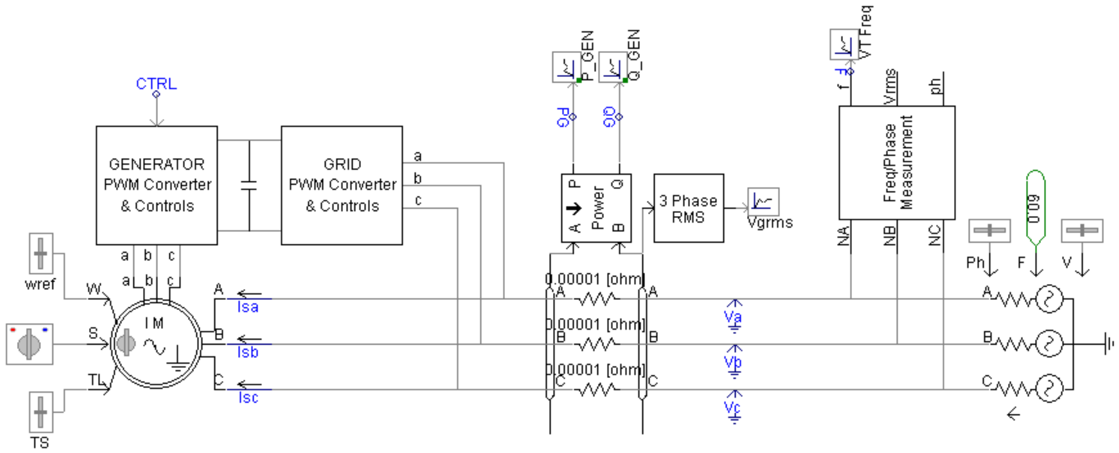

Figure 1 Model of DFIG in PSCAD

The back-to-back connected converters are able to transfer energy in both directions enabling them to work as a rectifier or as an inverter [2]. The net power output is a combination of the power of the machine's stator and the rotor through the converter. Using a proper field orientation, the stator and rotor currents can be decomposed into a flux producing component and torque producing component and these two components are then controlled independently. The rotor-side converter is used to optimize the power generation and improve the stability and stator-side converter maintains a constants voltage on the DC link with a desired power factor, regardless of the magnitude and direction of the power [2]. Generally field orientation can be classified into stator air-gap flux and rotor flux orientation. In order to achieve the independent control of the active and reactive power flowing between the grid and converter, stator flux vector is aligned with d-axis.

III. MATHEMATICAL MODEL

It is well known that a DC drive has excellent dynamic performance, as it is possible to decouple the stator magnetic flux and electromagnetic torque of the drive. The vector control, also known as Field Orientation Control (FOC), of induction machines emulates the DC drive control. In this section a dynamic model of DFIG and its control have been presented using the generator convention. The DFIG modelling and control have been carried out in the well known coordinate systems using Park's transformation for both three-phase to two-phase and two-phase to three-phase axes transformation. The stator and rotor windings of a three-phase induction machine are represented by two sets of orthogonal fictitious coils [4, 5]. The model is based on the commonly known as 'Park model'.

The equivalent circuit of a DFIG in an arbitrary reference frame rotating at synchronous speed is shown in Figure 2.

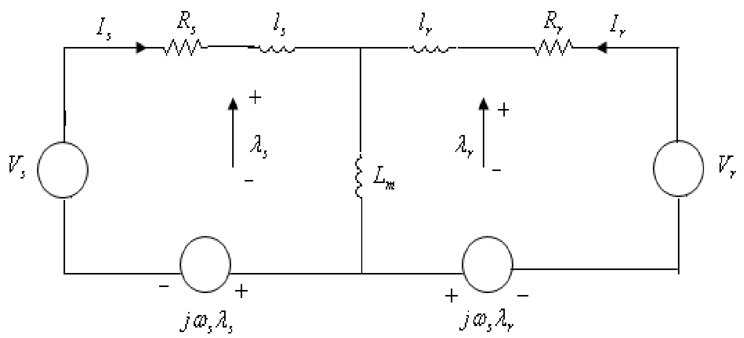

Figure 2 Equivalent circuit of DFIG in an arbitrary reference frame rotating at synchronous speed

According to the Figure 2, the stator and rotor fluxes λ_s and λ_r are represented by equation (1) [3].

$$\left.\begin{aligned} \lambda_s &= (l_s + L_m)i_s + L_m i_r = L_s i_s + L_m i_r \\ \lambda_r &= (l_r + L_m)i_r + L_m i_s = L_m i_s + L_r i_r \end{aligned}\right\} \quad (1)$$

The stator and rotor voltage in reference frame are expressed by equation (2).

$$\left.\begin{aligned} V_s &= R_s i_s + j\omega_s \lambda_s + \frac{d\lambda_s}{dt} \\ V_r &= R_r i_r + j(\omega_s - \omega_r)\lambda_r + \frac{d\lambda_r}{dt} \end{aligned}\right\} \quad (2)$$

The above set of equations for stator and rotor voltages in d-q coordinates can be written as shown in equation (3).

$$\left.\begin{aligned} V_{ds} &= R_s i_{ds} - \omega_s \lambda_{qs} + \frac{d\lambda_{ds}}{dt} \\ V_{qs} &= R_s i_{qs} + \omega_s \lambda_{ds} + \frac{d\lambda_{qs}}{dt} \\ V_{dr} &= R_r i_{dr} - s\omega_s \lambda_{qr} + \frac{d\lambda_{dr}}{dt} \\ V_{qr} &= R_r i_{qr} + s\omega_s \lambda_{dr} + \frac{d\lambda_{qr}}{dt} \end{aligned}\right\} \quad (3)$$

The subscripts d and q indicate the direct and quadrature axis components of the reference frame, where s and r represent stator and rotor quantities, respectively. The decomposition into d-q coordinate systems is required for the control.

The equations for active and reactive power in d-q axes are expressed by equation (4).

$$\left.\begin{aligned} P_s &= V_{ds} i_{ds} + V_{qs} i_{qs} \\ Q_s &= V_{qs} i_{ds} - V_{ds} i_{qs} \end{aligned}\right\} \quad (4)$$

Normally a medium to high power generator is used in wind farms; therefore the stator resistances can be neglected. The stator voltage along d-q axis from equations (3) will reduce to equation (5).

$$\left.\begin{aligned} V_{ds} &= -\omega_s \lambda_{qs} + \frac{d\lambda_{ds}}{dt} \\ V_{qs} &= \omega_s \lambda_{ds} + \frac{d\lambda_{qs}}{dt} \end{aligned}\right\} \quad (5)$$

In vector control method, which is used to achieve independent control of active and reactive power, the stator flux vector is aligned with d- axis which gives the following equation (6).

$$\left.\begin{aligned} \lambda_{ds} &= \lambda_s = L_s i_{ds} + L_m i_{dr} \\ \lambda_{qs} &= L_s i_{qs} + L_m i_{qr} = 0 \end{aligned}\right\} \quad (6)$$

The stator voltage in DFIG, which is a variable-speed constant-frequency generator, remains constant. Moreover the three-phase sinusoidal voltage is transformed into d-q synchronous reference frame. This gives the relation as shown in equation (7).

$$\left.\begin{aligned} V_{ds} &= 0 \\ V_{qs} &= V_s \end{aligned}\right\} \qquad (7)$$

From equations (4), (6) & (7), the stator active and reactive power can be obtained as shown in equations (8) & (9) respectively.

$$P_s = V_s \frac{L_m}{L_s} i_{qr} \qquad (8)$$

$$Q_s = \frac{V_s \lambda_s}{L_s} - \frac{V_s L_m}{L_s} i_{dr} \qquad (9)$$

From equations (8) & (9), it can be concluded that the delivered power depends directly on the d-q components of rotor currents except that for the reactive power there is second term, which represents power needed to magnetize the machine.

Using transformed axes, the rotor currents (i_{ra}, i_{rb}, i_{rc}) of the machine are resolved into direct and quadrature components idr and i_{qr}. The component i_{dr} produces a flux in the air gap, which is aligned with the rotating flux vector linking the stator; whereas the component i_{qr} produces flux at a right angle to this vector. Once the stator flux vector is aligned with d-axis, the component i_{dr} then controls the reactive power entering the machine. In order to calculate the stator flux linkage vector in the rotor reference frame, its value in the stationary frame is estimated first. It is then transformed into the rotor α-β frame using the rotor position. In the stationary reference frame, the stator flux linkage λ_s is estimated as shown in equation (10) [2]

$$\lambda_s = \int (V_s - I_s R_s) dt \qquad (10)$$

Since the stator voltage V_s is relatively free of harmonics and its frequency is fixed, the above equation will provide an accurate estimation of the stator flux. The correct values of i_{dr} and i_{qr} in the rotor are achieved by generating the corresponding phase currents references $i_{ra\text{-}ref}$, $i_{rb\text{-}ref}$, $i_{rc\text{-}ref}$ and then using a Voltage Source Converter (VSC) based current source to force these currents into the rotor. The latter action is achieved using Current-Reference Pulse Width Modulation (CRPWM). The crucial step is to obtain the instantaneous position of the rotating flux ($Ø_s$) in space in order to obtain the rotating reference frame. This is achieved by realizing that on account of Lenz's law of electromagnetism, the stator voltage (after subtracting resistive drop) is simply the derivative of the stator flux linkage λ_s as in equation (10).

The location of the rotating flux vector ($Ø_s$) is found using the control structure in Figure 3. The three phase stator voltages (after removal of resistive voltage drop) are converted into the Clarke (α-β) components V_α and V_β which are orthogonal in the balanced steady state. This transformation is explained in the previous chapter. Integrating V_α and V_β, we obtainλ_α and λ_β, the Clarke components of stator flux. Converting to polar form gives equation (11).

$$|\lambda| = \sqrt{\lambda_\alpha^2 + \lambda_\beta^2} \quad \text{and} \quad \phi_s = \tan^{-1}\left(\lambda_\beta / \lambda_\alpha \right) \qquad (11)$$

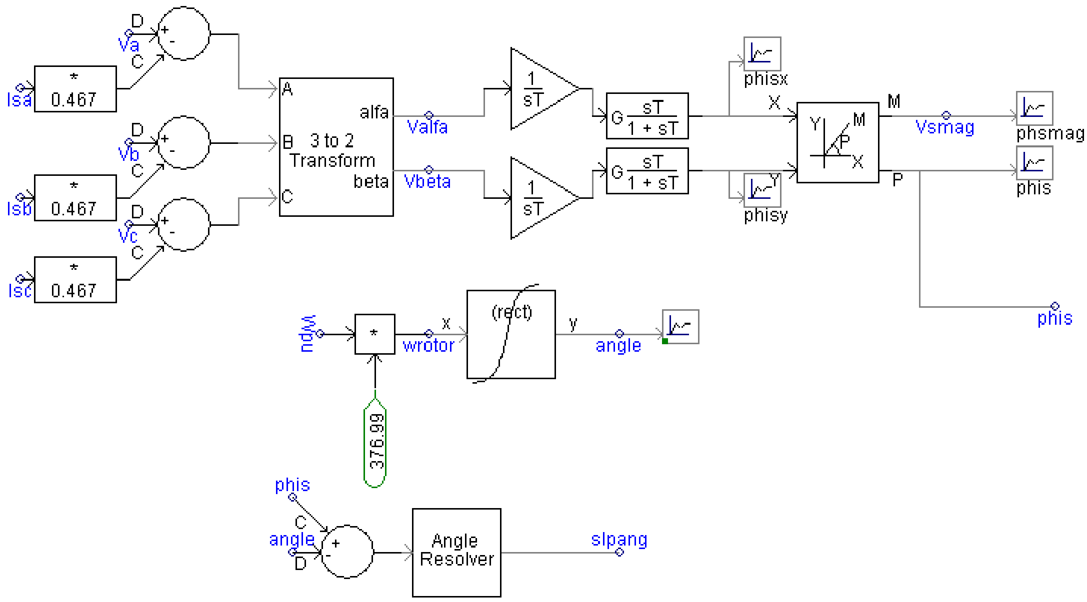

Figure 3 Determination of rotating magnetic flux vector location

The angle $Ø_s$ gives the instantaneous location of the stator's rotating magnetic field. The rotor itself rotates and is instantaneously located at angle $Ø_r$ (rotor angle). Thus, with a reference frame attached to the rotor, the stator's magnetic field vector is at location $Ø_s$- $Ø_r$ which is referred to the 'slip angle'. This slip angle is used to determine the difference between stator flux and the rotor position for resolving rotor currents. The instantaneous values for the desired rotor currents are then readily calculated using the inverse d-q transformation, with respect to slip angle, as shown in Figure 4 [6, 7].

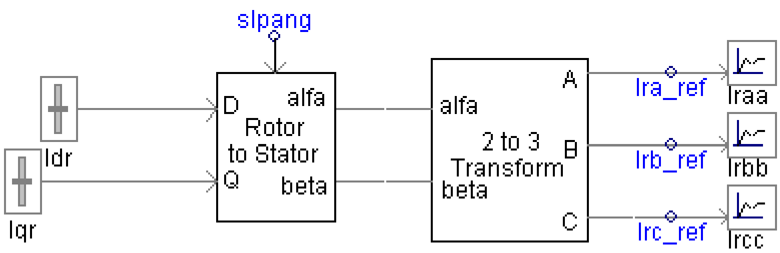

Figure 4 Generation of rotor phase reference currents

IV. SIMULATION RESULTS

The PSCAD is a powerful tool for solving and representing mathematical differential equations and therefore provides an opportunity to combine a wide range of different modelling issues. It is a highly developed graphical interface that is instrumental in PWM control [6]. Therefore, the proposed system model is developed in the dedicated power electronics and system simulation tool, PSCAD/EMTDC. The three-phase sinusoidal voltage and currents can be depicted as vectors and resolved into orthogonal components in phase and in quadrature with the stator magnetic field. Vector control method transforms rotor currents into two parallel controllers, one for the q-component and other d-component. The stator flux rotating synchronously with grid voltage is aligned with the d- axis and equations (8) and (9) indicate that q - component of the rotor current is used to control the active power, while the d component is used to control the reactive power.

To investigate the control of active power under steady-state conditions, initially the active and reactive power references are adjusted approximately to 2.2 MW and zero respectively, by adjusting the i_{qr} and i_{dr}. The machine is simulated at super-synchronous condition (1.2 pu). A step increment in i_{qr} is applied at 2 sec and is held constant for the remaining period of simulation. The simulation in Figure 5 shows that the active power (P-Gen) is increased showing that the active power can be directly controlled by i_{qr}, but there is no appreciable change in reactive power (Q- Gen).

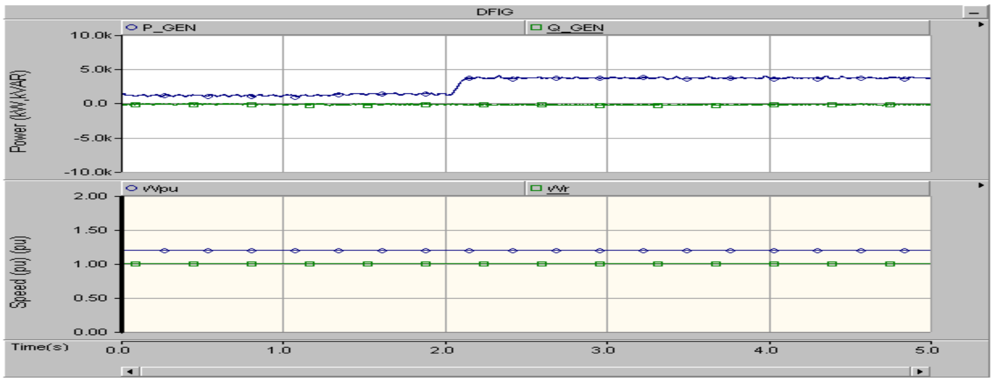

Figure 5 Effect of change in i_{qr}

The reactive power exchanged with the grid at stator terminals is dependent on the direct component of the rotor currents. It also depends on the control of the grid-side converter feeding the rotor-side. Normally the reactive power is adjusted to zero, which means that the grid-side converter operates at unity factor. The generator is fully decoupled from the grid by the power converter; therefore the power factor of the generator does not affect the reactive power factor at the grid connection. It is mentioned in equation (9) that reactive power can be controlled by decoupled component i_{dr} of the rotor currents. The model is simulated to investigate the control of reactive power by applying a step change in i_{dr} at 2 sec and is held constant for the remaining part of simulation. The simulation result confirms Figure 6 that a change in i_{dr} controls the reactive power while the active power remains unchanged.

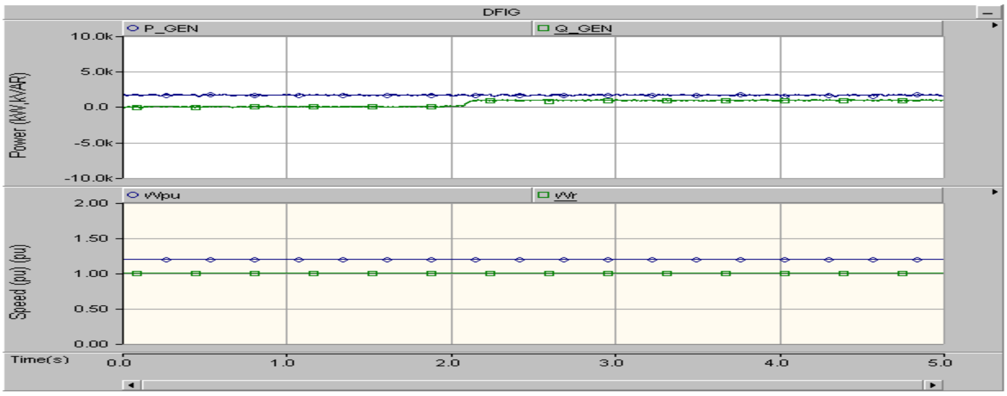

Figure 6 Effect of change in i_{dr}

The model is also simulated for sub-synchronous and super-synchronous speeds. The responses of the various parameters can be observed in Figures 7 and 8 for sub-synchronous speed. It is observed in the Figure 6 that the active power (P-Gen) is supplied from the stator to the grid. At this point the reactive power (Q-Gen) supplied by the stator is very less. However, the rotor power flow is negative at sub-synchronous speed showing that the power is drawn into the generator from the source as observed in Figure 7. It means that the converter is feeding power in to the rotor circuit.

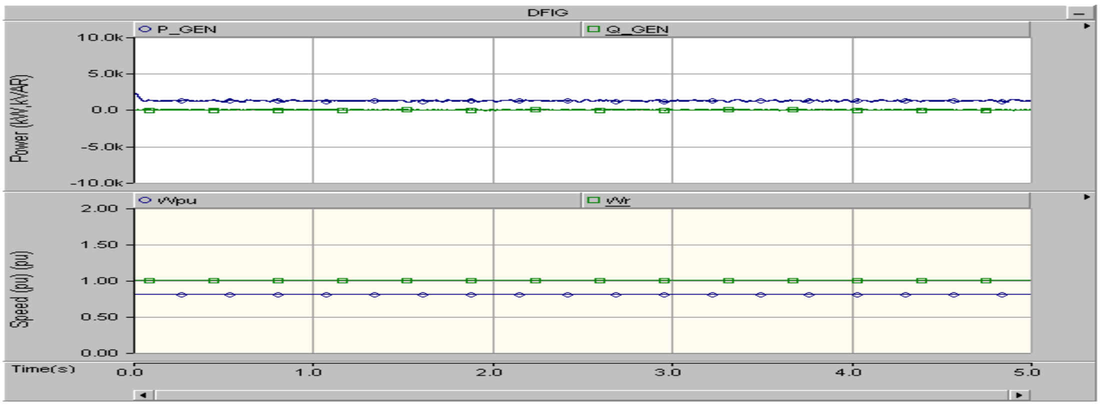

Figure 7 Stator power flow at sub-synchronous speed

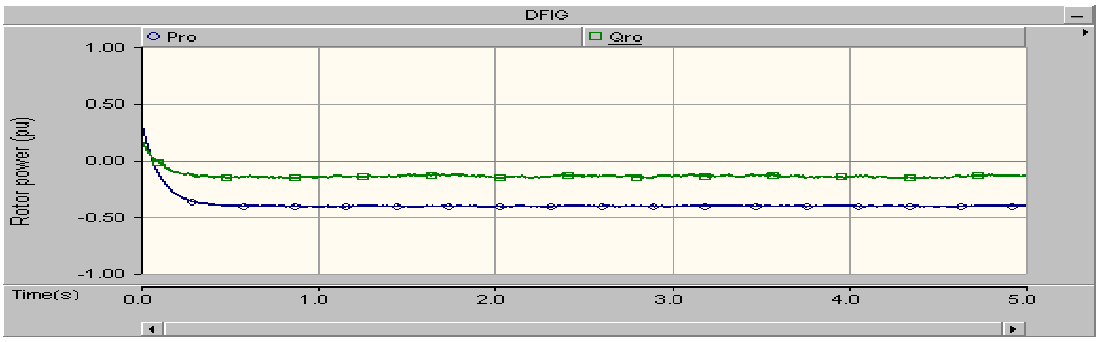

Figure 8 Rotor power flow at sub-synchronous speed

Further, the system is simulated for a change in speed from sub-synchronous speed (0.8 pu) to super-synchronous speed (1.2 pu) at 2s. (Figure 9). This causes in the phase sequence of rotor currents as shown in Figure 10 as slip is changed from sub-synchronous to super-synchronous speed,

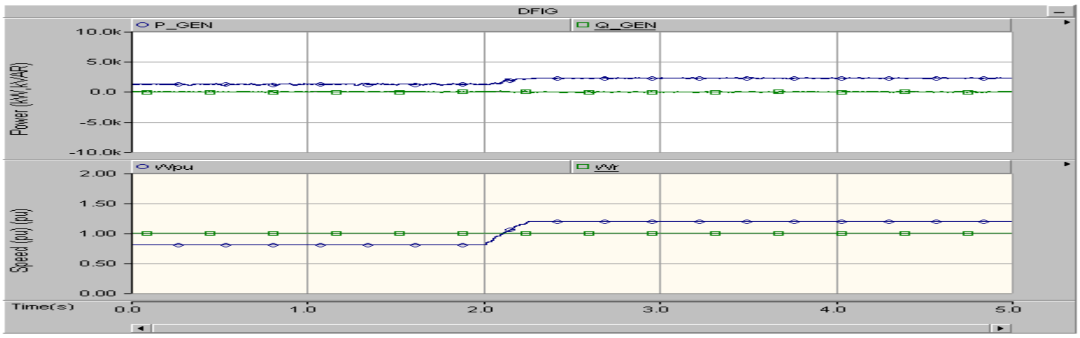

Figure 9 Change in speed from sub-synchronous to super-synchronous speed

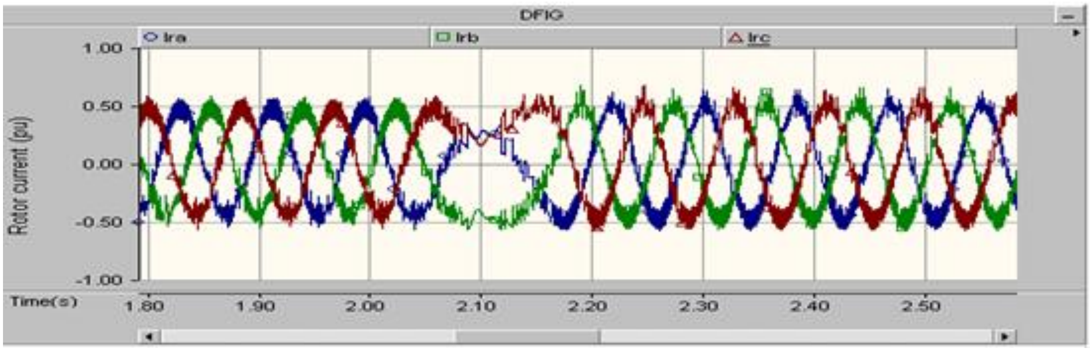

Figure 10 Rotor and stator currents for change in speed from sub-synchronous to super-synchronous

In DFIG, the electrical rotor power output P_r is positive for negative slip (super-synchronous speed) and is negative for positive slip (sub-synchronous speed). This means that, below the synchronous-speed, the rotor-side power P_r flows from the grid to the rotor of the DFIG, whereas at super-synchronous speed, it flows in the opposite direction. Therefore when the speed was changed from sub-synchronous to super-synchronous speed, it resulted in reversal of rotor output power. The change in the active power P_{ro} and reactive power Q_{ro} in rotor circuit are verified in Figure11.

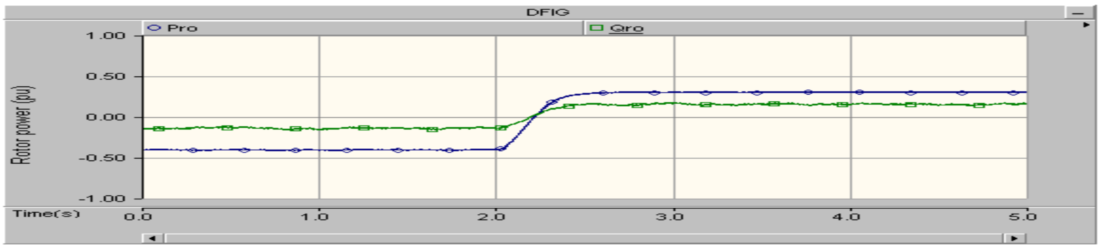

Figure 11 Rotor power flow from sub-synchronous to super-synchronous speed

V. CONCLUSION

The nature of real & reactive powers in stator and rotor circuits of doubly-fed induction generator has been investigated under decoupled control. The system was developed in PSCAD/EMTDC software. These findings suggest that vector control can optimize the output of DFIG. The real and reactive powers generated are also controlled independently to obtain proper operational stability.

Machine Data: 2.2 MW, 13.8 kV, Wound rotor Induction Machine [6].

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BIOGRAPHY

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