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Sensorless Synergetic Control Approach for Decoupled Power Control of Doubly-Fed Induction Generator

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***Abstract*: A new method of sensorless synergetic control of active and reactive power flowing between the stator of the doubly-fed induction generator (DFIG) and the power grid is proposed in this paper. For converting wind energy to electrical energy, doubly-fed induction generator with rotor side and supply side power converters are using. Rotor side converter is controlled by synergetic control technique to control output power. DFIG is modelled in synchronous reference frame and vector control method is used on stator-side to decouple the coupling effect of d-q currents of stator and rotor. This gives the good ability for regulating the active power of output and reactive power of output independently by controlling the currents of rotor q-axis and d-axis respectively. Sensorless control of active power and reactive power is obtained by calculating the rotor d-axis and q-axis currents. This paper presents the characteristics of synergetic control of power for a grid-connected, wind turbine DFIG for a change in input wind power, output active power, reactive power and grid voltage and also presents the characteristics which depicts the effectiveness of this controller.**

***Keywords*: Synergetic control, DFIG, vector control, Sensorless control, Active and reactive power control.**

Nomenclature

L_s , L_r , L_m = Stator, rotor, mutual inductances
$\varphi_{ds}, \varphi_{qs}$ = Stator d-axis, q-axis fluxes
$\varphi_{dr}, \varphi_{qr}$ = Rotor d-axis, q-axis fluxes
i_{ds} , i_{qs} = Stator d-axis, q-axis currents
i_{dr} , i_{qr} = Rotor d-axis, q-axis currents
v_{ds} , v_{qs} = Stator d-axis, q-axis voltages
v_{dr} , v_{qr} = Rotor d-axis, q-axis voltages
T_{em} = Electromagnetic Torque
ω_r = Rotor speed
P_s, Q_s = stator output active , reactive power
P = Number of poles
J = Moment of Inertia

1. Introduction

The wind power, which is one of the vital renewable green power sources is also a permanent source with no need of transporting and exploring. To solve the problem of energy's shortage and improve the environmental quality, wind power is used to produce the electrical energy by many countries. Large wind farms have been planned and installed in various locations around the world. Mostly DFIGs are being used with AC-DC-AC converter system. DFIGs have many advantages when compared to synchronous generators while they are used in wind farms, such as reliability, robustness, variable speed operation, low price, active power and reactive power control, lower converter cost and relatively high efficiency.

In wind turbine connected DFIG, the input mechanical speed is depends on wind speed, it varies and depends on atmospheric conditions. In order to get output power at grid frequency, the air gap flux must rotate at synchronous speed [1]. Generally, the speed of air gap flux depends on input mechanical speed, which is not constant. Rotor side converter is used to adjust the frequency of alternating currents fed into the rotor windings because rotating air gap flux passing through the generator stator windings not only rotates due to rotation of generator rotor; but also due to the rotational effect which is caused by the alternating currents fed into the windings of the rotor. Therefore, in DFIG-based wind turbine the resultant flux in air gap is always rotates at synchronous speed independent of wind speed and thus, the frequency of the power generated matches to the grid frequency. The basic configuration of DFIG wind turbine is shown in Fig.1.

In this paper, DFIG is modelled in d-q reference frame rotating at synchronous speed. Rotor-side vector control method is used by fixing the d-axis of the synchronous frame on the stator flux vector to de-couple the active and reactive power generated by DFIG [2]. So, that independent controlling of active and reactive power fed to the power grid by DFIG is obtained by controlling the currents to be injected into rotor circuit by rotor-side converter. In this paper, sensorless synergetic control technique is used to control the active and reactive power [6]. In this method control variables are chosen in such way that they control ultimately the active and reactive power. This control technique will force the chosen control variables to the desired values within the setting time and will improve the overall system dynamic performances [7]. In this paper, after modelling the DFIG in d-q reference frame, active and reactive powers are controlled using sensorless synergetic control method and its dynamic performances are studied by changing the reference values of grid voltage, input mechanical power, active and reactive power.

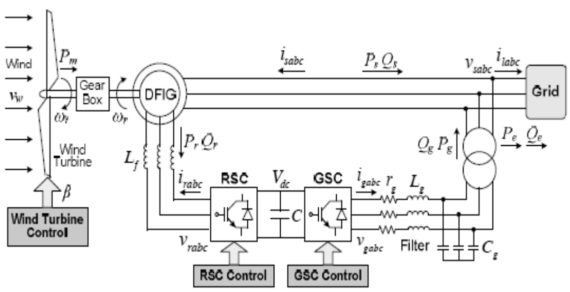


Fig. 1. Basic configuration of the DFIG wind turbine

2. DFIG Modelling and Power Control

A. DFIG Model

The model, which is used in this paper is presented here using the d-q synchronous reference frame. By applying Park model of the DFIG [3], the dynamic voltages and fluxes in d-q reference frame rotating at synchronous speed can be written as follows

$$\begin{cases} v_{ds} = i_{ds} R_s + \frac{d}{dt}\varphi_{ds} - \omega_s \varphi_{qs} \\ v_{qs} = i_{qs} R_s + \frac{d}{dt}\varphi_{qs} + \omega_s \varphi_{ds} \\ v_{dr} = i_{dr} R_r + \frac{d}{dt}\varphi_{dr} - (\omega_s - \omega_r)\varphi_{qr} \\ v_{qr} = i_{qr} R_r + \frac{d}{dt}\varphi_{qr} + (\omega_s - \omega_r)\varphi_{dr} \end{cases} \quad (1)$$

The d-q synchronous reference frame equations of stator and rotor flux linkages are given by

$$\begin{cases} \varphi_{ds} = L_s i_{ds} + L_m i_{dr} \\ \varphi_{qs} = L_s i_{qs} + L_m i_{qr} \\ \varphi_{dr} = L_r i_{dr} + L_m i_{ds} \\ \varphi_{qr} = L_r i_{qr} + L_m i_{qs} \end{cases} \quad (2)$$

The electromagnetic torque is expressed as

$$T_{em} = \frac{3}{2}\left(\frac{P}{2}\right) L_m (i_{dr} i_{qs} - i_{qr} i_{ds}) \quad (3)$$

And it's associated motion equation is

$$T_{pm} = T_{em} + \frac{J}{P}\frac{d\omega_r}{dt} + B\omega_r$$

The stator active and reactive powers can be expressed as

$$P_s = \frac{3}{2}(v_{ds} i_{ds} + v_{qs} i_{qs}) \quad (4)$$

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

B. De-Coupled control of active and reactive power

In this section, we proposed a vector control law for DFIG machine based on the orientation of the stator flux for decoupled control of active and reactive power. We use a Park reference frame linked to the stator flux. By supposing that the d-axis is oriented along the stator flux position and based on equations (1) and (2), by neglecting Rs we can write

$$\varphi_{ds} = \varphi_s \quad \text{and} \quad \varphi_{qs} = 0 \quad (5)$$

From equations (2) φ_{ds} and φ_{qs} becomes

$$\begin{cases} \varphi_s = L_s i_{ds} + L_m i_{dr} \\ 0 = L_s i_{qs} + L_m i_{qr} \end{cases} \quad (6)$$

if we are assuming that the grid is stable and stator flux is constant.

Then, from equations (1), v_{ds} and v_{qs} becomes

$$\begin{cases} v_{ds} = 0 \\ v_{qs} = \omega_s \varphi_{ds} \end{cases} \quad (7)$$

By using equations (5), (6), (7), equation (4) can be written as

$$\begin{cases} P_s = \frac{3}{2}(\omega_s \varphi_s i_{qs}) = -\frac{3}{2}\left(\omega_s \varphi_s \left(\frac{L_m}{L_s}\right) i_{qr}\right) \\ Q_s = \frac{3}{2}(\omega_s \varphi_s i_{ds}) = -\frac{3}{2}\left(\omega_s \varphi_s \left(\frac{\varphi_s - L_m i_{dr}}{L_s}\right)\right) \end{cases} \quad (8)$$

Equation (8) shows the decoupled control of active and reactive power of DFIG. It can be observed that active power depends on only i_{qr} and reactive power depends on only i_{dr}. So, independent control of active and reactive power is possible, which gives effective controlling of DFIG output power.

3. Design of the Non-Linear Synergetic Controller

The synergetic control technique is one of the modern approach for controlling the non-linear dynamic system. In this paper, synergetic control method is used to control the rotor-side converter of DFIG in order to control the output power. This approach is derived from the concept of Analytical Design of Aggregated Regulators method (ADAR).

Synergetic control algorithm mainly consists of two steps. First, select the macro variable which are in the function of system variables. Then, this macro variable will be used to determine a control equation, which is capable of forcing the selected macro variables to zero and achieving the desired controlling operation of system.

A non-linear dynamic system is represented as follows [4].

$$\frac{dx}{dt} = f(x, g, t) \quad (9)$$

where x is the dynamic system state variable vector, g is the input control vector to be designed and t represents the time.

Start this control algorithm by defining a macro-variable μ, as a function system state variables which is defined by μ(x, t). The main aim of this method is to force the macro variables to zero which is represented as

$$\mu(x, t) = 0 \quad (9)$$

According to this synergetic control theory, a control equation is to be developed and will be given as input controlling equations to the DFIG model to make the machine to operate in a desired manner.

Now, a control equation is obtained as a function of macro variable by using the following equation

$$T\frac{d\mu}{dt}+\mu=0\,;T>0 \qquad (10)$$

This is the equation of desired dynamic evolution of the macro variables, where T is a design parameter that specifies the time for convergence of macro variables to zero. By the chain rule of differentiation

$$\frac{d\mu}{dt}=\frac{d\mu}{dx}\cdot\frac{dx}{dt} \qquad (11)$$

Substitute (11), (9) in (10), we get

$$T\frac{d\mu}{dx}f(x,g,t)+\mu=0 \qquad (12)$$

So, equation (12) is used to derive the control equation as represented below,

$$g = h(x, t, \mu(x, t), T) \qquad (13)$$

This is the desired controller expression. So, a synergetic controller can be designed by selecting the macro variables and the time parameter.

In this paper, the macro variables should be selected in such a way that they can control the output active and reactive power effectively. From equation (8) , we knows that the active and active power decoupled and they are independently controlled by controlling i_{qr} and i_{dr} separately.

Therefore, two macro variables are selected as shown below

$$\begin{cases}\mu_{dr}=(i_{dr}-i_{drref})+k_d\int(i_{dr}-i_{drref})dt \\ \mu_{qr}=(i_{qr}-i_{qrref})+k_q\int(i_{qr}-i_{qrref})dt\end{cases} \qquad (14)$$

where k_d , k_q are positive coefficients , i_{drref} , i_{qrref} are the reference currents of rotor in d-q synchronous reference frame. So, to design the desired controller, the main objective is to force the macro variables to zero.

Therefore, from equation (10), the desired dynamic evolution of macro variable is

$$\begin{cases}T_d\frac{d\mu_{dr}}{dt}+\mu_{dr}=0 \\ T_q\frac{d\mu_{qr}}{dt}+\mu_{qr}=0\end{cases} \qquad (15)$$

By using equations (1), (2), (5), we obtain the following equations

$$\begin{cases}v_{dr}=\frac{di_{dr}}{dt}(\lambda L_r)+R_ri_{dr}-(\omega_s-\omega_r)\lambda L_ri_{qr} \\ v_{qr}=\frac{di_{qr}}{dt}(\lambda L_r)+R_ri_{qr}+(\omega_s-\omega_r)(\lambda L_ri_{dr}-\frac{L_mV_{qs}}{L_s\omega_s})\end{cases} \qquad (16)$$

Where $\lambda=1-\frac{L_m{}^2}{L_sL_r}$

By using equations (14), (15), (16) , we obtain the control equations as a function of macro variables given by the equations as follows

$$v_{dr}=R_r\,i_{dr}-\frac{\lambda L_r}{T_d}\Big((k_dT_d+1)(i_{dr}-i_{drref})\Big)-\frac{\lambda L_r k_d}{T_d}\int(i_{dr}-i_{drref})dt-(\omega_s-\omega_r)\lambda L_ri_{qr}$$

$$v_{qr}=R_r\,i_{qr}-\frac{\lambda L_r}{T_d}\Big((k_qT_q+1)(i_{qr}-i_{qrref})\Big)-\frac{\lambda L_r k_q}{T_d}\int(i_{qr}-i_{qrref})dt-(\omega_s-\omega_r)\lambda L_ri_{dr}+(\omega_s-\omega_r)(\lambda L_ri_{dr}+\frac{L_mV_{qs}}{L_s\omega_s}) \qquad (17)$$

Equation (17) is the output control equation of the synergetic controller feeding into the DFIG model. It is observed that these expressions are in the functions of i_{dr}, i_{qr} . By using this control strategy, the dynamic response of the non-linear system will be improved. The synergetic control scheme is shown in Fig. 2.

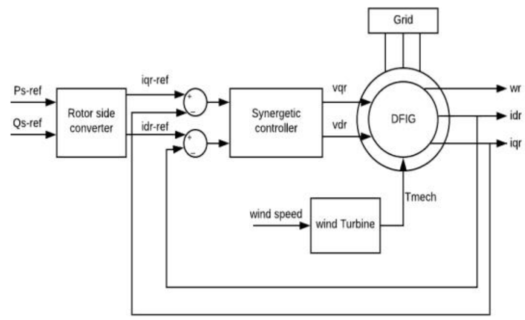


Fig. 2. Block diagram of the synergetic control system connected to DFIG-wind turbine

4. Simulation Results

We can understand the sensorless synergetic control approach for grid-connected wind turbine DFIG by using the simulation results [5]. For complete understanding the performance of synergetic controller, we introduced some disturbances to test the system. In this paper, we studied about four types of disturbances for understanding the complete dynamic behaviour of the system. They are as follows

1.a step change in

a. the active power reference point,

b. the reactive power reference point,

c. the mechanical input power,

at different instants of time and observing the controller accuracy

2. a step change in the grid voltage.

a) A step change in the active power reference value

The simulation is carried out with a step change in stator output active power reference point of DFIG. Initially, the reference value of active power is 10 KW and we introducing a step change to 30 KW at time 3 sec shown in fig 3(a). While there is no change in reactive power reference value, by keeping it at zero, wind mechanical input power given to the rotor shaft is 20KW and kept it as constant are shown in fig 3(b) and 3(c) respectively

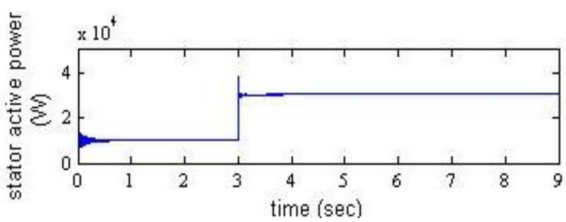
The simulation results, fig. 3 shows how the DFIG's rotor speed, electromagnetic torque, output active and reactive power, rotor currents changes to step change in active power reference value. From equation (8), it can be observed that active power depends on only iqr and reactive power depends on only idr fig 3(d) and 3(e) shows the same observation very well. The step change in output active power reference make changes in iqr and no changes in output reactive power reference causes no change in idr. The stator active power reference value changes from 10KW to 30KW, means initially the input mechanical power 20KW is more than stator active power reference and after step change ,the input mechanical power is less than the stator active power reference. So, the speed decreases after the step change and consequently electromagnetic torque will increases which is shown in the fig. 3(f) and 3(g) respectively.

b) A step change in the Reactive Power Reference value

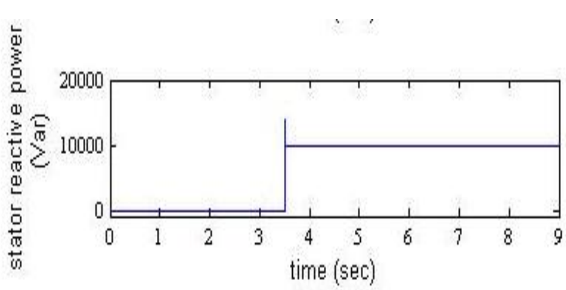
The simulation is carried out with a step change in stator output reactive power reference point of DFIG. Intially the reference value of reactive power is 0 Kvar and we introducing a step change to 10 Kvar at 3.5 sec and maintaining the output active power reference at 30 KW shown in fig 3(a) and fig 3(b) respectively. idr and iqr which are related to Qs, Ps respectively shown in fig 3(d), 3(e). Due to increment in idr makes electromagnetic torque (Te) to increase and consequently rotor speed will decrease shown in fig 3(g) and 3(f) respectively.

c) A step change in the Mechanical Input Power

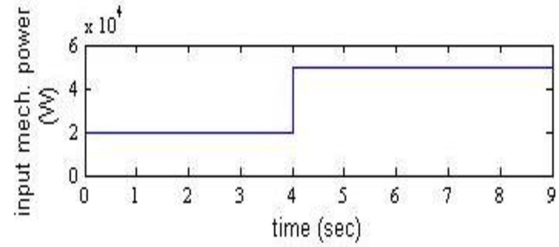
The simulation is carried out with a step change in the input wind mechanical power from 10 KW to 30KW at 4 sec showin in fig 3(c) with maintaining stator output active power reference value at 30 KW and reactive power reference value at 10 Kvar. As there is no change in active power and reactive power, there would be no changes in idr and iqr respectively, this is observed from fig 3(d), 3(e). Due to the increment in input mechanical power, rotor speed of the DFIG increases as the input power is more than the output power So, speed increases at 4 sec shown in fig 3(f) and consequently electromagnetic torque (Te) will decreases shown in fig. 3(g).



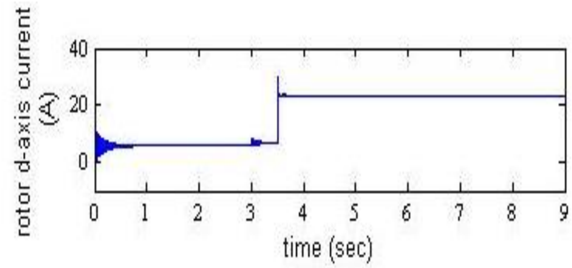
(a) Stator active power



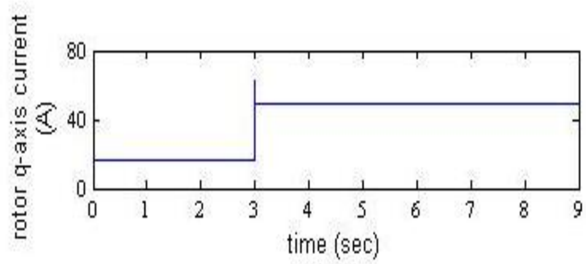
(b) Stator reactive power



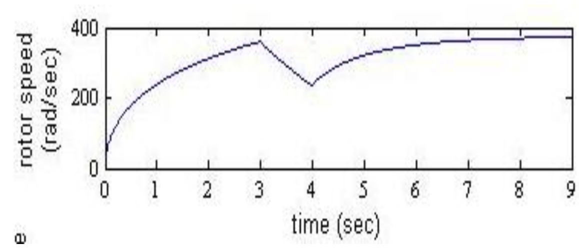
(c) Mechanical input power



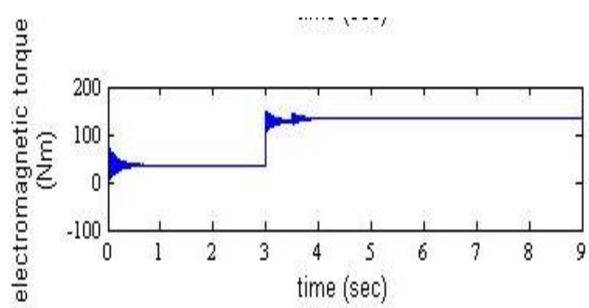
(d) rotor d-axis current



(e) rotor q-axis current



(f) rotor speed

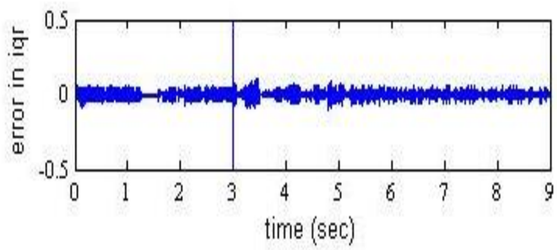


(g) electromagnetic torque

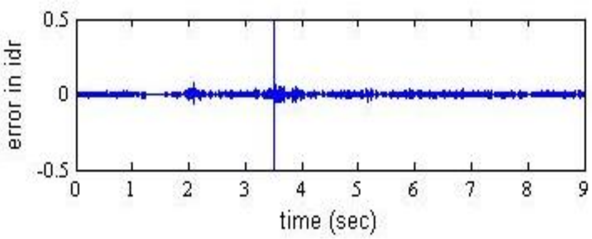
Fig. 3. Simulation results of step change in the stator output active power, reactive power and rotor input mechanical power.

Observing the controller accuracy:

Further investigation is made to understand the effectiveness of this controller. From de-coupled control of active and reactive power, already known that active power depends on only iqr and reactive power depends on only idr makes independent control of active and reactive power. Fig. 4(a), 4(b) shows error graphs between idrref and idr and between iqrref and iqr repectively. It is observed that Psref and Psact, Qsref and Qsact are almost same, it shows that the controller is reliable and working accurately while controlling the output active and reactive power of DFIG.



(a) Error in iqr



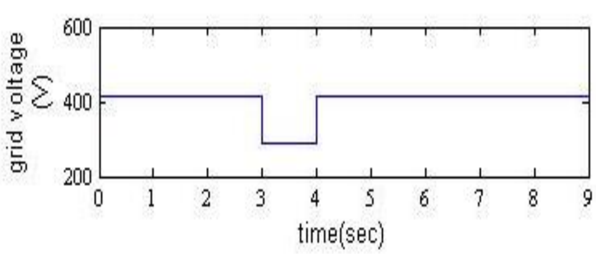
(b) Error in idr

Fig 4. Simulation results of error in rotor d-axis and q-axis currents

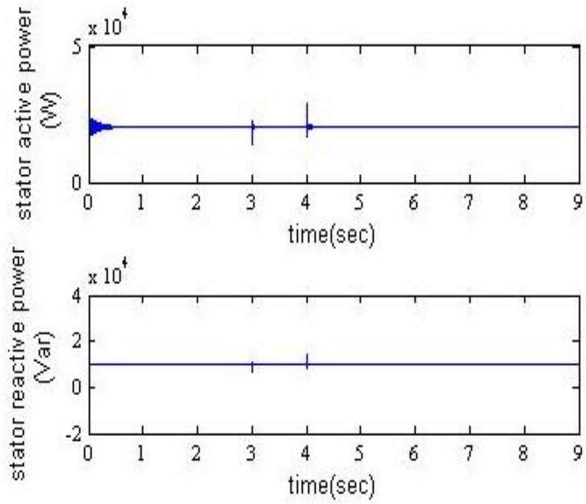
2) A step change in the Grid Voltage

The simulation is carried out with a step change in grid voltage drops to 70% of original grid voltage from 3 sec to 4 sec as shown in fig 5(a), which indicates the voltage dip in transmission line or DFIG connected grid. By keeping active power reference point at 20 KW and reactive power reference at 10 Kvar. A constant input mechanical power 30 KW is given to DFIG. Due to dip in the grid voltage causes a small disturbance in stator output active power and reactive power. As the iqr controls the stator ouput active power to maintain at reference point by increasing from 3 sec to 4 sec shown in fig 5(b), 5(e). In same way, idr controls the stator ouput reactive power by increasing during disturbance because decrease in the magnitude of grid voltage shown in fig 5(c), 5(d).

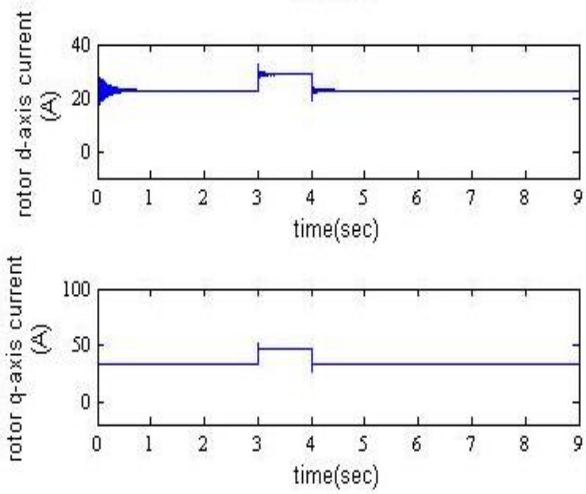
As dip in voltage causes decreament in the speed and consequently, electromagnetic torque (Te) increases during disturbance shown in fig 5(f), 5(g). But, after clearing the disturbance at 4 sec the system regains its original state.



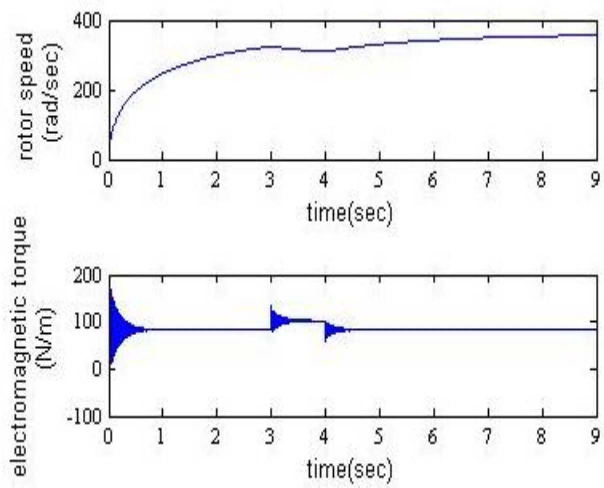
(a) grid voltage



(b) Stator active power, and (c) stator reactive power



(d) rotor d-axis current, and (e) rotor q-axis current



(f) rotor speed, and (g) electromagnetic torque

Fig. 5. Simulation results for a step change in the grid voltage

5. Conclusion

This paper presents a new method of sensorless synergetic control of active and reactive power of DFIG connected to grid.

The converter in the rotor side is controlled by synergetic control technique to control the output power. DFIG is modelled in stator-side vector control method to decouple the output active and reactive power. The response of DFIG with synergetic controller is shown by creating disturbances of four different modes and observed from simulation results that the system regaining its stability and steady state fast, effectively and accurately.

Appendix

The parameters of the DFIG and the synergetic controller under study are shown as follows:
R_s = 2.9 Ω, R_r = 2.6 Ω, L_s= 0.26 mH , L_r = 0.26 mH, L_m = 0.25 mH, J = 0.25 Kg-m², f = *50* Hz , P = 2, k_d=9, k_q=9, T_d =10^{-4}, T_q = 10^{-4}

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