Rotor Power Feedback Control of Wind Turbine System with Doubly-Fed Induction Generator

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Abstract: The paper deals with a new system of wind turbine active power vector control. The already familiar cascade regulation with internal vector component feedback of rotor current and external active and reactive power feedbacks control of wind turbine has been applied. A new supraordinated rotor active power feedback control at the same determining the stator active power reference of the doubly-fed induction generator (DFIG) power, has been introduced. By introducing a rotor active power feedback control into the wind turbine active power vector control, the power in the rotor circuit, as well as losses in the generator coils, are considerably reduced, both in the stationary and dynamic operation modes. Wind turbine active power dynamic features with and without rotor active power feedback control in DFIG vector control system have also been explored and discussed.

Key-Words: Doubly-Fed Induction Generator, vector control, DFIG rotor power regulator, simulation

1 Introduction

Variable speed wind turbines fitted with a DFIG connected to the electric grid are nowadays increasingly gaining in importance due to their total automatic control of both active and reactive power output. Active and reactive DFIG control system consists of two control sub-systems [1,5]: two semiconductor power converters, one on the rotor side and one on the grid side. Both converter systems employ the DFIG active and reactive power vector control. The rotor current vector is divided into two components: one controlling the magnetic flux and the other controlling the generator electromagnetic moment.

Mechanical power obtained from the wind turbine is converted into electric power by the DFIG and imparted to the grid through the generator stator and rotor. In this it is necessary to make up for the losses in stator and rotor copper coils (iron losses, as well as the ones caused by friction and ventilation have not been considered in this paper). The wind turbine power distribution between the DFIG stator and rotor depends on the wind turbine control system active power reference [3]. The DFIG can operate in both the super-synchronous and the sub-synchronous operation modes, and the DFIG can impart power to the grid or take power from it with increased losses in the generator copper coils.

The wind turbine power control system should ensure a conversion of wind turbine mechanical power into the wind turbine electric power imparted to the grid with a minimum rotor power in both stationary and dynamic variable speed wind turbine operation modes. By introducing a rotor active power feedback control into the structure of the DFIG wind turbine active power vector control system a minimum active power in the rotor circuit and the back-to-back converter is ensured.

The supraordinated rotor active power feedback control at the same time acts as the DFIG stator active power reference in all stationary and dynamic wind turbine operation modes. The wind turbine vector control structure as presented in this paper provides a reliable conversion of the wind turbine mechanical power into the DFIG electric power with a minimum active power in the rotor circuit, as well as minimum losses in the generator coils. This configuration of the DFIG vector control is particularly suited to a wind turbine exposed to pronounced wind speed changes.

2 DFIG Wind Turbine Control System Basic Configuration

A typical DFIG wind turbine configuration consists of an induction wound generator with the stator coil connected to the three-phase grid and the rotor coil connected to the grid by means of a back-to-back semi conductor power converter [1,6]. A functional block diagram of an active and reactive power wind turbine control system fitted with the DFIG and a back-to back converter connected to the electric grid is shown in Fig.1.

The structure of the wind turbine active and reactive power control system has been resolved by applying a known induction machine vector control based on a double-axis theory of electric motors. The rotor-side converter vector control system makes use of the aligned to stator magnetic flux vector coordinate system, while the grid-side converter regulation system employs the grid voltage vector.

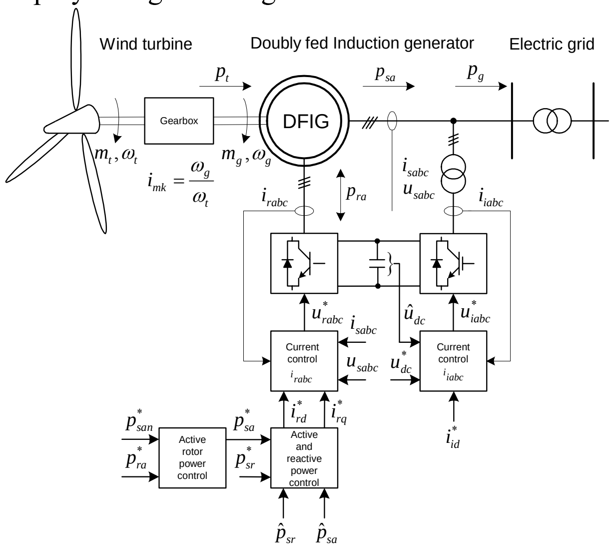

Fig.1. Wind turbine control system with DFIG

The role of the DFIG is to convert the wind turbine mechanical power p_t into the electric power p_g imparted to the grid. The rotor active power can be imparted to the grid ($p_{ra} > 0$) or taken from it by the generator ($p_{ra} < 0$), or the DFIG rotor power may be equal to zero ($p_{ra} = 0$). The stator active power reference p_{sa}^* determines the distribution of the wind turbine power p_t to stator p_{sa} and rotor active power p_{ra} respectively [3].

By introducing a rotor active power feedback into the DFIG vector control structure an automatic generation of the required reference is obtained p_{sa}^*, thereby ensuring a minimum rotor active power in both stationary and dynamic generator operation modes. In stationary operation modes the rotor power equals zero ($p_{ra} = 0$), and the electric power imparted to the grid equals the stator power $(p_g = p_{sa})$.

3 Wind Turbine Dynamic Model

A wind turbine mathematical model usually contains the following elements representing its basic functional components (Fig.2): the wind turbine aero-dynamic model, the wind turbine drive train model, the model of the DFIG induction generator fitted with a back-to-back converter in the rotor circuit, eletric grid model and the wind turbine control system model.

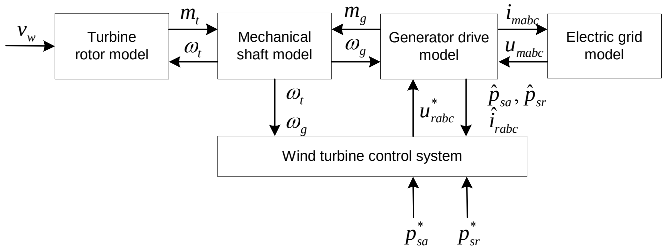

Fig.2. Block diagram of the dynamic model of a wind turbine connected to the electric grid

This paper is primarily concerned with exploring the effects of rotor power regulation within the DFIG wind turbine vector control system. Simulations have been run for the fixed electric grid and the known mean value of wind speed. The complexity of the wind turbine dynamic model has been designed in accordance with the aims of this research.

Wind turbine dynamics simulations have been run for wind step changes. The characteristic feature of the dependence of the wind turbine power upon the wind speed has been illustarted in Fig. 3 (the nominal power being 2 MW) [2].

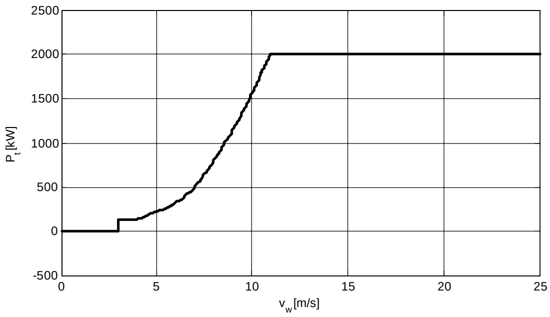

Fig. 3. Static characteristic of wind turbine mechanical power P_t as a function of mean wind speed

For a given wind speed v_w the wind turbine power p_t and the moment $m_t = p_t / \omega_t$ are obtained, the latter representing an input value into the mathematical two-mass model drive train (Fig.2).

Two-mass shaft system model

In this paper a known dynamic wind turbine and generator two-mass drive train model have been chosen [2,3]. The differential equation dynamic model system coefficients are as follows: J_t – wind turbine inertia;

J_g – induction generator inertia; D_{vt} – wind turbine shaft damping coefficient; K_{vt} – wind turbine shaft stiffness coefficient; and i_{mk} – gearbox transmission ratio.

Model input values are as follows: v_w – wind speed by means of which, based on the static characteristic as shown in Fig. 3, the wind turbine power is obtained; m_t – wind turbine torque, and m_g – induction generator electromagnetic moment obtained from the DFIG dynamic model.

Wind turbine dynamic model status variables, at the same time representing the model output values, are as follows: ϑ_t – wind turbine rotor angle; ϑ_g – generator rotor angle: ω_t – wind turbine rotational speed; ω_g – generator rotor rotational speed.

The wind turbine drive train model includes the inertia of the wind turbine, generator and gearbox connecting the two rotating shafts. The common equation of the turbine and generator shaft mechanical motion connects the drive train system dynamic model to that of the DFIG.

Doubly-fed induction generator dynamic model

Induction machine dynamic operation modes have been described by means of a system of voltage differential equations for the stator and rotor coils respectively. The DFIG mathematical model expressed in unit values and $\alpha\beta$ coordinate system are as follows [3,4]:

$$\begin{aligned}
\frac{d\psi_{s\alpha}}{dt} &= -\frac{1}{T_s'}\psi_{s\alpha} + \frac{k_r}{T_s'}\psi_{r\alpha} + u_{s\alpha}, \\
\frac{d\psi_{s\beta}}{dt} &= -\frac{1}{T_s'}\psi_{s\beta} + \frac{k_r}{T_s'}\psi_{r\beta} + u_{s\beta}, \\
\frac{d\psi_{r\alpha}}{dt} &= \frac{k_s}{T_r'}\psi_{s\alpha} - \frac{1}{T_r'}\psi_{r\alpha} - \omega\psi_{r\beta} + u_{r\alpha} \\
\frac{d\psi_{r\beta}}{dt} &= \frac{k_s}{T_r'}\psi_{s\beta} + \omega\psi_{r\alpha} - \frac{1}{T_r'}\psi_{r\beta} + u_{r\beta},
\end{aligned} \qquad (1)$$

Rotor and stator feed voltage vector components are:

$$\begin{aligned}
u_{s\alpha} &= u_{sa}, \\
u_{s\beta} &= \frac{1}{\sqrt{3}}\left(u_{sb} - u_{sc}\right), \\
u_{r\alpha} &= u_{ra}, \\
u_{r\beta} &= \frac{1}{\sqrt{3}}\left(u_{rb} - u_{rc}\right).
\end{aligned} \qquad (2)$$

The stator and rotor current vector components, expressed by means of the known magnetic flux components, are as follows:

$$\begin{aligned}
i_{s\alpha} &= \frac{1}{L_s'}\psi_{s\alpha} - \frac{k_s}{L_r'}\psi_{r\alpha}, \\
i_{s\beta} &= \frac{1}{L_s'}\psi_{s\beta} - \frac{k_s}{L_r'}\psi_{r\beta}, \\
i_{r\alpha} &= -\frac{k_r}{L_s'}\psi_{s\alpha} + \frac{1}{L_r'}\psi_{r\alpha}, \\
i_{r\beta} &= -\frac{k_r}{L_s'}\psi_{s\beta} + \frac{1}{L_r'}\psi_{r\beta}.
\end{aligned} \qquad (3)$$

The generator electromagnetic moment, at the same time representing the input value of the wind turbine two-mass model, is:

$$m_e = \psi_{s\alpha} i_{s\beta} - \psi_{s\beta} i_{s\alpha}. \qquad (4)$$

The following are the parametres as occurring in the equations from (1) to (3) :

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

$$k_r = \frac{L_m}{L_r},\ T_s' = \frac{L_s'}{R_s} \text{ and } T_r' = \frac{L_r'}{R_r}.$$

The induction generator stator active and reactive power momentary value is obtained by multiplying the stator voltage vector by conjugated-complex value of the stator current vector, as illustrated below:

$$p_{sa} = u_{s\alpha} i_{s\alpha} + u_{s\beta} i_{s\beta}, \qquad (5)$$

$$p_{sr} = u_{s\beta} i_{s\alpha} - u_{s\alpha} i_{s\beta}. \qquad (6)$$

The DFIG rotor active power momentary value may be calculated in a similar way:

$$p_{ra} = u_{r\alpha} i_{r\alpha} + u_{r\beta} i_{r\beta}. \qquad (7)$$

The momentary value of the rotor reactive power equals zero.

The momentary values of the induction generator stator and rotor current may be obtained from the αβ coordinate system components by means of the following equations:

$$\begin{aligned}
i_s &= \sqrt{i_{s\alpha}^2 + i_{s\beta}^2}, \\
i_r &= \sqrt{i_{r\alpha}^2 + i_{r\beta}^2}.
\end{aligned} \qquad (8)$$

Input values of voltage equation system (1) reperesent the components of the stator feed voltage vector $\overline{u}_{s\alpha\beta}$ and rotor feed vector $\overline{u}_{r\alpha\beta}$, whereas the status variables, being at the same time the system output values, act as stator and rotor flux vectors. The output values are represented by the generator electromagnetic flux, stator and rotor power, as well as stator and rotor current vector components.

4 Wind Turbine Active and Reactive Power Control System

The vector regulation of the wind turbine active and reactive power is ensured by the regulation of the DFIG active and reactive power. The DFIG active and reactive power vector control system (Fig.1) employs the following coordinate systems:

- induction generator is modelled in the αβ coordinate system which, in relation to the abc coordinate system, stands still;
- the rotor-side converter is modelled in the dq coordinate system linked to the stator magnetic flux vector.

The simulations as run in this paper refer to the DC-link fixed voltage source, therefore the mathematical model of the grid-side converter has not been presented.

The structural block diagram of the DFIG active and reactive power vector control system fitted with the rotor power feedback control has been illustrated in Fig. 4.

By introducing a rotor active power feedback control into the structure of wind turbine active power DFIG vector contol, the power in the rotor circuit is considerably reduced, and also the losses in the generator coils in both stationary and dynamic operation modes at different wind speeds. By choosing the zero reference of the rotor active power regulation ($p_{ra}^* = 0$), this vector control system enables the turbine active power to be converted into the DFIG stator active power with a minimum active power in the back-to-back converter rotor circuit.

5. Simulation Results

Simulations for wind step changes $v_w = 9[m/s]$ at the moment $t = 6[s]$ and $v_w = 14[m/s]$ at the moment $t = 50[s]$ have been run within the research as presented in this paper (Fig.5). Figures 6., 7. and 8. illustrate time responses of the generator rotor rotational speed ω_g, stator active power p_{sa}, rotor active power p_{ra}, losses in the stator and rotor coils p_{Cu}, stator current vector value i_s, rotor current vector value i_r, as well as the DFIG stator reactive power p_{sr}. Time responses simulations have been run with respect to the stator active power reference $p_{sa}^* = 1.0[pu]$, stator reactive power reference $p_{sr}^* = 0.0[pu]$ and the rotor active power reference $p_{ra}^* = 0.0[pu]$. The calculations have been done by means of the parameters pertaining to the wind turbine and induction generator of 2MW power as qouted in the references [2,3].

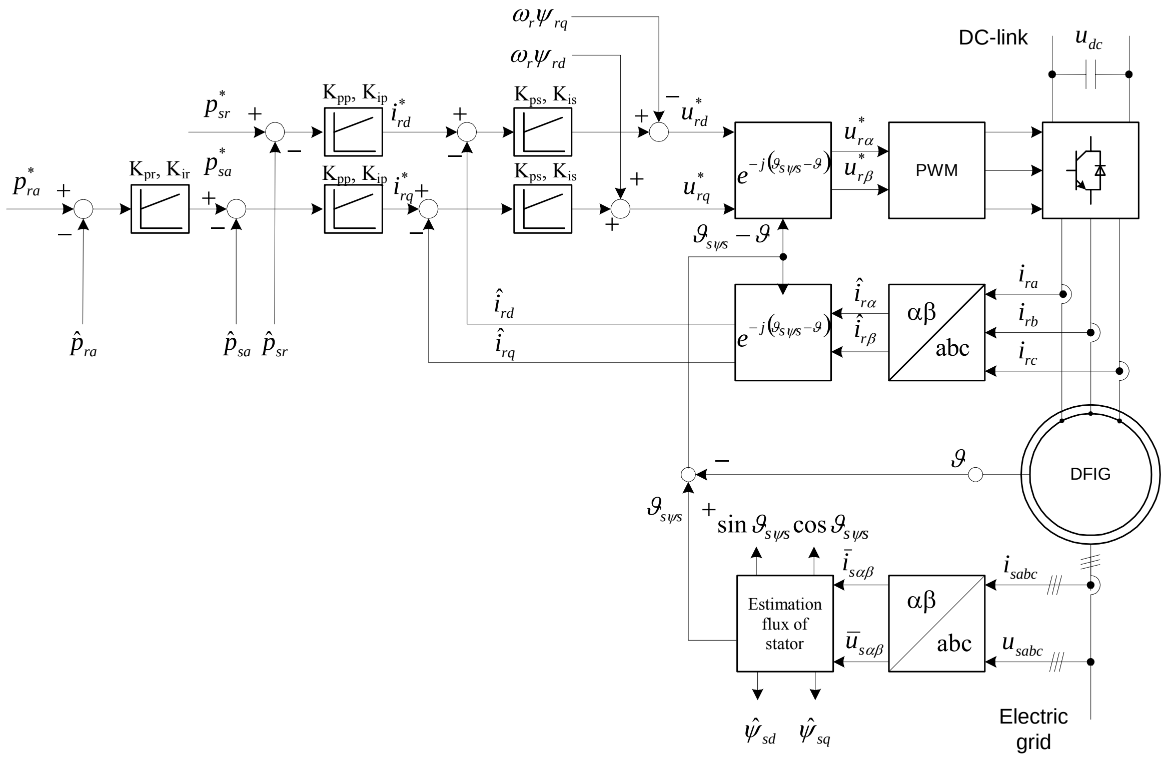

Fig. 4. Active and reactive power vector control system of DFIG with rotor power feedback control

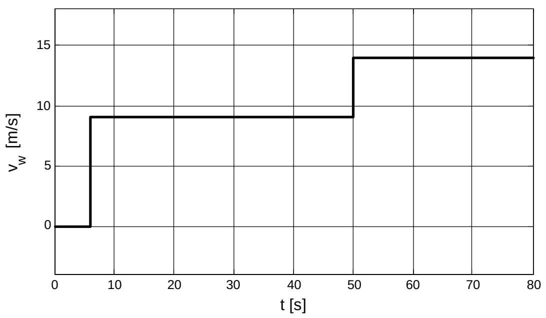

Fig.5. Wind speed time dependence

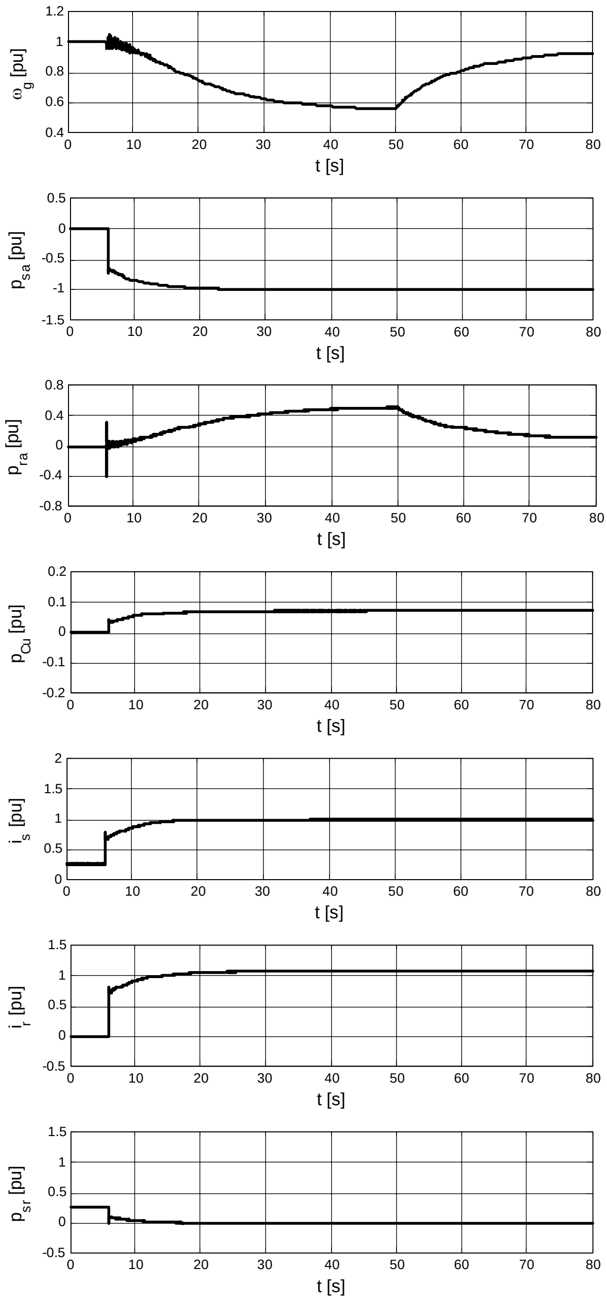

Fig.6. Time responses without the rotor active power regulation

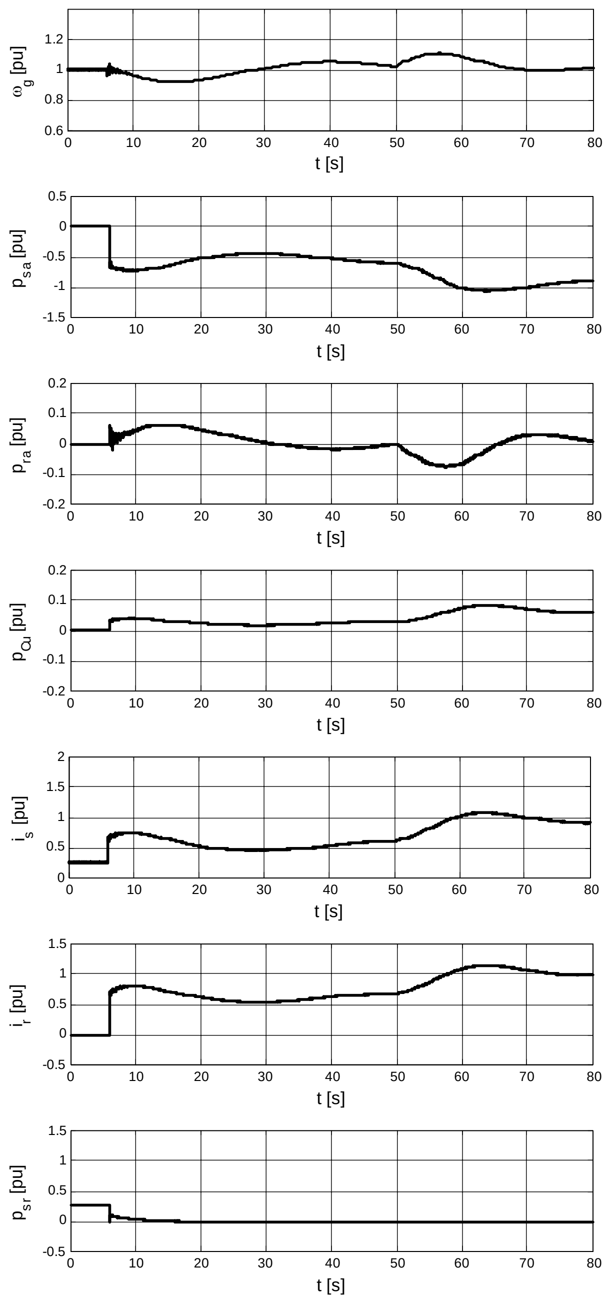

Fig.7. Time responses with the rotor active power regulation; $K_{pr} = 2.0$, $K_{ir} = 0.002$.

Simulation of the vector control time responses without the rotor active power regulation has been shown in Fig. 6, whereas Figures 7. and 8. illustrate the time responses with the rotor active power regulation. The rotor active power regulation parameters as shown in Fig.7. are equal to the stator power regulation in the DFIG cascade regulation mode ($K_{pr} = 2, K_{ir} = 0.002$). All the physical values presented in this figure display a pronounced transitional phenomenon.

By choosing the rotor active power regulation $K_{pr} = 100$ and $K_{ir} = 0.05$ time responses with considerably better indicators of regulation quality are obtained, as shown in Fig.8. Transitional phenomena of electric values are considerably shorter, thereby rendering the entire DFIG wind turbine system more adjustable to sudden wind step changes. The DFIG vector control system fitted with rotor active power regulation follows the power obtained from the wind turbine regardless of the given stator active power reference.

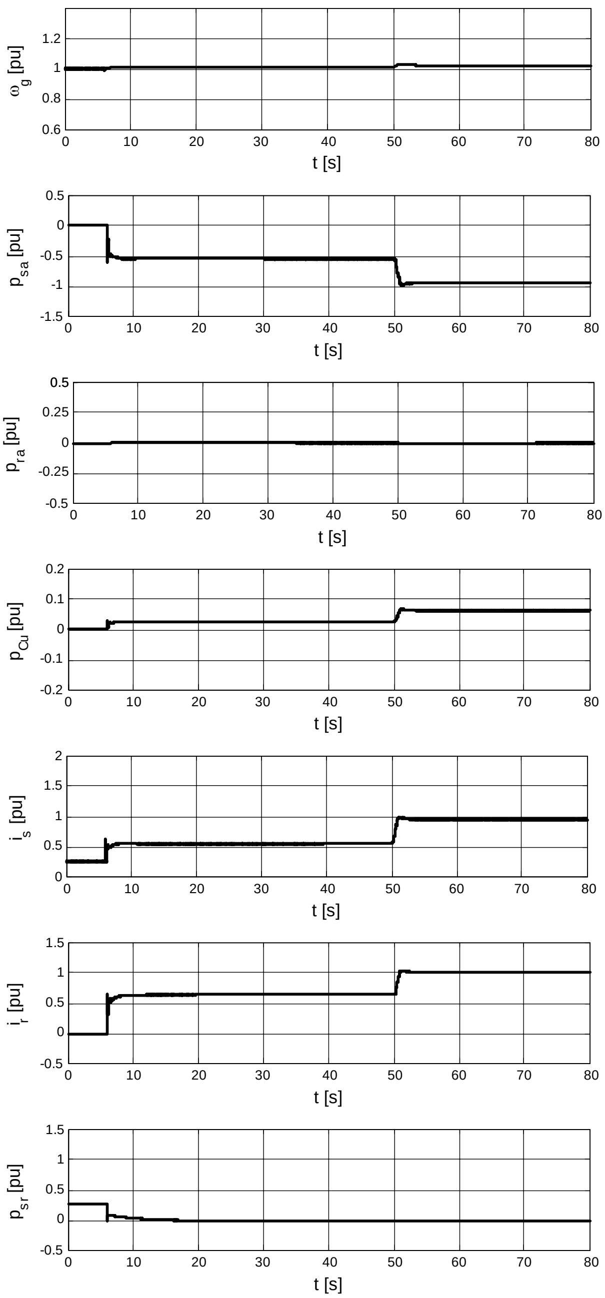

Fig.8. Time responses with the rotor active power regulation; $K_{pr} = 100.0$, $K_{ir} = 0.05$.

6 Conclusion

A new configuration of wind turbine active power vector controlled system has been presented and discussed in this paper. A rotor active power feedback control has been incorporated into the DFIG wind turbine vector control system, thereby ensuring a minimum power in the rotor circuit for both the stationary and dynamic wind turbine operation modes. The DFIG vector control system fitted with rotor power regulation follows the wind turbine mechanical power regardless of the given stator active power reference and variable wind speed. This configuration of DFIG vector control has proved to be particularly suitable while operating in conditions of wind step changes. The rotor active power feedback control provides an option of considerably reduced power of back-to back converter in the rotor circuit.

Results of simulation of DFIG vector control system with and without rotor active power feedback control have been compared, clearly indicating that, by choosing the rotor active power regulation parameters, time responses with a considerably shorter transitional phenomenon are obtained. Furthermore, the DFIG wind turbine power vector control system has proved to be more adjustable to modes of operation involving wind step changes.

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