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Reference Value Choice of the Wind Turbine Active Power with Doubly-Fed Induction Generator

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Abstract: The variable speed wind turbine with doubly-fed induction generator (DFIG) is today widely used concept. This paper presents a control system of the DFIG wind turbine with focus on the control strategies and on active power reference value choice. The present control method is designed for super-synchronous, sub-synchronous and synchronous working modes. In order to investigate the dynamic responses during step load of DFIG connected to the electric grid, a model has been developed. This model includes the mechanical drive train, the induction generator as well as the control parts.

Key-Words: DFIG, wind turbine, dynamic simulation, reference value of active power

1 Introduction

In a few last years variable speed wind turbines with DFIG are the most applied wind turbine. The great interest for variable speed wind turbine is because of very good characteristics with modern semiconductor converters and digital control systems.
The variable speed wind turbines with DFIG connected to the electric grid include automatic control of active and reactive power control. By these wind turbines dynamic of electric system is faster than dynamic of mechanical system (drive train).
The control system of DFIG consists of two control subsystems: control system of power converter in rotor circuit and control system of power converter connected to the electric grid side.

2 Fundamental structure of the DFIG wind turbine control system

Typical configuration of the wind turbine with DFIG consists of an induction wound rotor generator with stator winding connected directly to the three phase grid by the use back-to-back power semiconductor converter. Back-to-back is bi-directional semiconductor power converter consists of two pulse-width voltage converter (converter connected to the rotor and converter connected to the grid side with voltage PWM inverter) and common DC link.
The active and reactive power control system of the wind turbine is based on the theory of the induction machine vector control. That theory mean two-axis control described in three different reference frames.

The active and reactive power control system of the wind turbine with DFIG and back-to back converter connected to the electric grid is shown in Fig. 1.

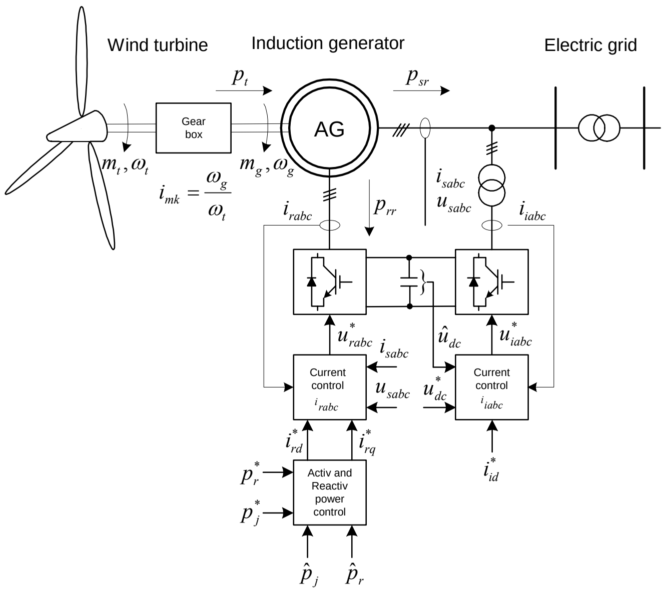

Fig. 1. Wind turbine control system with DFIG

The main rule of DFIG is conversion of power given from the wind turbine p_t to the electric power p_{sr} and electric power delivery from DFIG stator to the electric grid. The wind power is extremely variable value depending about the wind speed, so DFIG from the wind turbine side has variable turbine torque m_t and turbine angular speed ω_t, i. e. generator torque m_g and generator angular speed ω_g. Simplified observed, electric grid has practically constant voltage u_{mabc} and constant angular frequency ω_s. Working conditions of the wind turbine based on fundamental equation that describes relationship of the angular frequencies of the stator and rotor speed $\omega_s=\omega_g+\omega_r$, provide control system of the generator. Thereat, there are variable active rotor power p_{ra}, stator losses p_{Cus} and rotor losses p_{Cur}.

Stator active power p_{sa} determines set value of the reference active power p_a^*. So, rotor active power p_{ra} is the consequence of reference value p_a^* for defined wind turbine power. Induction generator can work in super-synchronous mode (p_{ra}<0), sub-synchronous mode (p_{ra}>0) and in synchronous mode (p_{ra}=0). This paper describes dependence of the rotor power about wind turbine reference value power for constant wind speeds, i. e. constant wind turbine power.

Static characteristic of the mechanical wind turbine power as a function of mean value of wind speed, used in wind turbine control system is shown in Fig. 2.

For wind turbine powers P_t>750 [kW] and for wind speeds v_w>8 [m/s] (the point C in Fig. 2.) it is possible ensure active power reference value by the DFIG control system, instead by rotor speed reference value [1]. For minimum wind speeds between points A and B in Fig. 2. reference value of active power is adapted as a function of minimum rotor speed of generator ω_{gmin}. In the case of rotor speed higher than ω_{gmin} and less than nominal rotor speed ω_{gn} (interval between points B and C in Fig. 2.) the goal is to reach maximum speed of wind turbine.

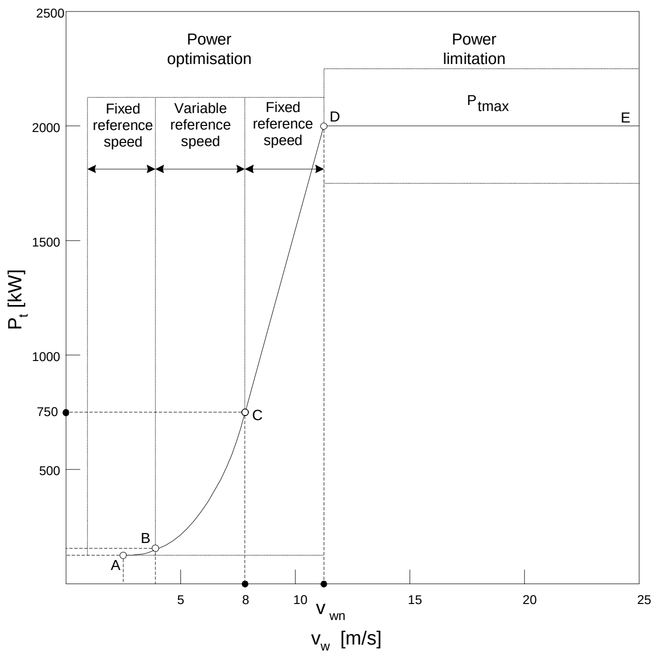

Fig. 2. Static characteristic of wind turbine mechanical power P_t as a function of mean wind speed

3 Modeling of the active and reactive power control system of the DFIG wind turbine

3.1 Modeling of the wind turbine drive train

Dynamical model of the wind turbine describes the main parts of the wind turbine drive train system and induction generator that participate in interaction of the wind turbine with electric power system. By modeling of the drive train system it is need apply two-mass model. Accordingly, low frequency torsion fluctuations that dominate in dynamic behavior of the wind turbine can be recognized. Model of the drive train include inertias of the wind turbine, generator and gearbox which connect two rotating masses.

In this paper is chosen well-known two-mass model of the wind turbine and generator drive train. The grate mass of the wind turbine is represented by inertia J_t, and the small mass of the induction generator is represented by inertia J_g.

The system of equations for simulation of the wind turbine drive train described in base quantities is:

$$\begin{aligned} d\vartheta_t / dt &= \omega_t , \\ d\vartheta_g / dt &= \omega_g , \\ d\omega_t / dt &= \left(D_{vtt}\omega_g + K_{vtt}\vartheta_g - D_{vtt}\omega_t - K_{vtt}\vartheta_t - m_t \right) / T_t , \\ d\omega_g / dt &= \left(- D_{vtt}\omega_g - K_{vtt}\vartheta_g + D_{vtt}\omega_t + K_{vtt}\vartheta_t + m_g \right) / T_g , \end{aligned} \qquad (1)$$

where:

$$m_t = P_t / \omega_t . \qquad (2)$$

Time constants of the wind turbine T_t and induction generator T_g, damping coefficient D_{vt} and shaft stiffness K_{vt} in equations system (1) are:

$T_t = (J_t \omega_b^2)/(P_b i_{mk}^2 p^2)\,[s]$, $T_g = (J_g \omega_b^2)/(P_b p^2)\,[s]$,

$D_{vt} = (D_{vt}\omega_b^2)/(P_b i_{mk}^2 p^2)\,[pu]$ and

$K_{vt} = (K_{vt}\omega_b)/(P_b i_{mk}^2 p^2)\,[pu]$, where i_{mk} is gearbox ratio.

Model input values are: v_w – wind speed that defines wind turbine electric power upon Fig. 1., m_t – wind turbine torque and m_g – electromagnetic torque of induction generator obtained from dynamic model of DFIG.

The state variable of wind turbine dynamic model, whose at the same time output values, are: ϑ_t – angle of the wind turbine axis, ϑ_g – angle of rotor of induction generator and ω_g – angular speed of induction generator.

Dynamic model of the wind turbine is composed of simplified quasi-stationary aerodynamic power of the wind turbine for constant wind speed and dynamic two-mass model of wind turbine drive train.

3.2 Dynamic model of the DFIG

In the wind turbine system connected to the grid side with vector control of active and reactive power of DFIG, usually is used transformation of current, voltage and magnetic fluxes vectors of stator and rotor from original abc reference frame into two-phase rotating dq reference frame.

Dynamic working modes of induction generator can be described by the differential equations system for stator and rotor windings and by the equation of rotor motion. The solutions of these equations define dynamic characteristics of the machine.

The differential equations of the induction machine stator and rotor windings described in vector mode and in dq reference frame rotating by angular speed ω_k are [4]:

$$\bar{u}_{sdq} = \bar{i}_{sdq} R_s + \frac{d\bar{\psi}_{sdq}}{dt} + j\omega_k \bar{\psi}_{sdq} , \qquad (3)$$

$$\bar{u}_{rdq} = \bar{i}_{rdq} R_r + \frac{d\bar{\psi}_{rdq}}{dt} + j(\omega_k - \omega)\bar{\psi}_{rdq} , \qquad (4)$$

where: ω – electric angular rotor speed.

Relationships between vectors of magnetic fluxes and vectors of stator and rotor currents are:

$$\begin{aligned} \bar{\psi}_{sdq} &= L_s \bar{i}_{sdq} + L_m \bar{i}_{rdq} , \\ \bar{\psi}_{rdq} &= L_m \bar{i}_{sdq} + L_r \bar{i}_{rdq} . \end{aligned} \qquad (5)$$

By substituting vector of stator current $\bar{i}_{sdq}$ and vector of rotor current $\bar{i}_{rdq}$ in equations (3) and (4) with vectors of magnetic fluxes of stator $\bar{\psi}_{sdq}$ and rotor $\bar{\psi}_{rdq}$ become:

$$\begin{aligned} \bar{u}_{sdq} &= \frac{d\bar{\psi}_{sdq}}{dt} + \left(\frac{1}{T_s'} + j\omega_k \right) \bar{\psi}_{sdq} - \frac{k_r}{T_s'} \bar{\psi}_{rdq} , \\ \bar{u}_{rdq} &= \frac{d\bar{\psi}_{rdq}}{dt} - \frac{k_s}{T_r'} \bar{\psi}_{sdq} + \left(\frac{1}{T_r'} + j(\omega_k - \omega) \right) \bar{\psi}_{rdq} . \end{aligned} \qquad (6)$$

The equivalent diagram of the three-phase induction machine for dynamic states, given from equations (3) to (6), is shown in Fig. 3.

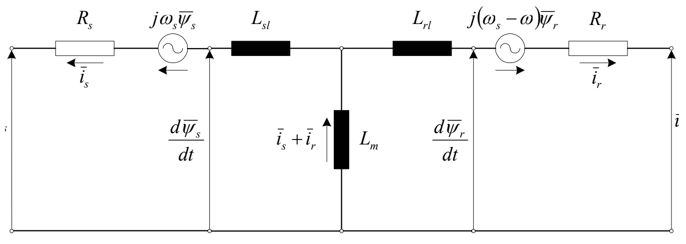

Fig. 3. Equivalent diagram of the induction machine for dynamic states

The parameters presented in equations (3) to (6) are:

$L_s' = \sigma L_s$, $L_r' = \sigma L_r$, $\sigma = 1 - L_m^2 / L_s L_r$, $k_s = L_m / L_s$, $k_r = L_m / L_r$, $T_s' = L_s' / R_s$ and $T_r' = L_r' / R_r$.

Equation of electromagnetic generator expressed in base quantities is:

$$m_g = \frac{k_r}{L_s'} (\psi_{sq}\psi_{rd} - \psi_{sd}\psi_{rq}) . \qquad (7)$$

Current active and reactive power of induction generator is given from product of stator voltage vector and complex conjugate vector of stator current:

$$p_a = u_{sd} i_{sd} + u_{sq} i_{sq} , \qquad (8)$$

$$p_r = u_{sq} i_{sd} - u_{sd} i_{sq} . \qquad (9)$$

Choice of the reference frame angular speed depends about selected structure of DFIG control system connected to the electric grid. Since, for control system realization of the converter connected to the rotor side and converter connected to the grid side required apply different reference frames it is selected αβ reference frame (ω_k=0) as a basic frame for mathematical model of the electric components in power circuits of the wind turbine.

The input values of vector equations (6) are vector of stator supply $\bar{u}_{sdq}$ and vector of rotor supply $\bar{u}_{rdq}$. The state variables, at the same time output values, are vectors of magnetic fluxes of stator $\bar{\psi}_{sdq}$ and rotor $\bar{\psi}_{rdq}$.

Other output values are electromagnetic torque of generator and vectors of stator and rotor currents.

Dynamic model of the doubly-fed induction generator is expressed in αβ reference frame, and all inputs and outputs of the model are expressed in that reference frame. The parameters of induction generator and base quantities are shown in appendix.

The state variables and input/output values connecting mathematical models of the wind turbine drive train and DFIG are angular speed of generator given from dynamic model of the drive train (eq. (1) and (2)) and electromagnetic torque of induction generator given from dynamic model of DFIG (eq. (3) - (6)).

4 Active and reactive power control system of the wind turbine

Vector control of active and reactive power control of wind turbine is decoupled power control of DFIG.

In vector control of active and reactive power control of wind turbine is applied next reference frames:

- induction generator is modeled in αβ reference frame that, by comparison with original abc reference frame, is at rest.
- semiconductor power converter connected to the rotor side is modeled in dq reference frame; vector of stator magnetic flux is aligned to d-axis,

- semiconductor power converter connected to the electric grid side is modeled in dq reference frame; vector of grid voltage is aligned to d-axis.

Simulations in this paper have performed by constant DC link voltage, so mathematical model of the semiconductor power converter connected to the grid side have not token into consideration.

Vector control system of active and reactive power of wind turbine is shown in Fig. 4.

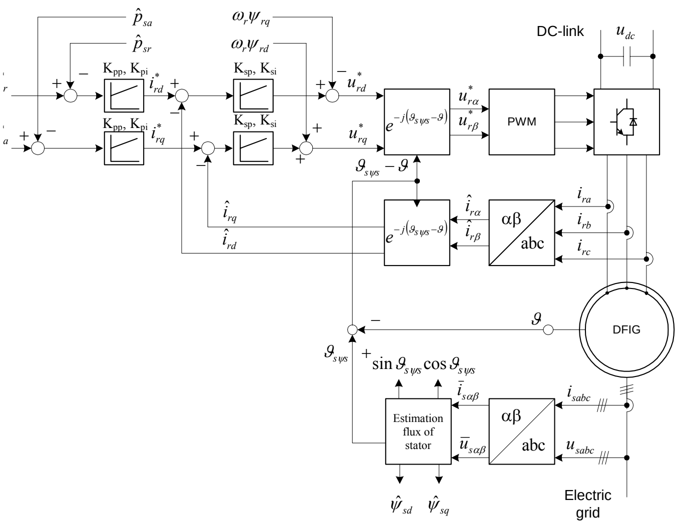

Fig. 4. Active and reactive power vector control system of DFIG

In the vector control system shown in Fig. 4. standard PI controllers with anti wind-up effect have applied.

The rule of converter connected to the rotor side is independently control of active and reactive power control of induction generator. Active and reactive power control is not achieved directly, but power control is achieved through stator current vector. Control system connected to the rotor side work in dq reference frame aligned to stator magnetic flux vector $\overline{\psi}_{sdq} = \psi_{sd}$. Rotor current vector in that reference frame is separated in i_{rd} component that is in parallel with $\overline{\psi}_{sdq}$ and i_{rq} component that is orthogonal with $\overline{\psi}_{sdq}$. So, active power is controlled by i_{rq} component, and reactive power is controlled by i_{rd} component of vector $\bar{i}_{rdq}$ [5].

Outputs of the current controllers u_{rd}^* and u_{rq}^* (Fig. 4.) are expressed in dq reference frame that is aligned to stator magnetic flux vector too. As induction generator model is in αβ reference frame, outputs of controllers assigned to the rotor side have to be transformed from αβ reference frame in dq reference frame.

Mathematical model of control system connected to the rotor side can be derived by voltage equation of rotor (4) that described in scalar mode is:

$$u_{rd} = i_{rd} R_r + \frac{d\psi_{rd}}{dt} - \omega_r \psi_{rq}, \qquad (10)$$

$$u_{rq} = i_{rq} R_r + \frac{d\psi_{rq}}{dt} + \omega_r \psi_{rd}. \qquad (11)$$

In equations (10) and (11) there are the parts:

$$u_{rd}^{'} = -\omega_r \psi_{rq}, \qquad (12)$$

$$u_{rq}^{'} = \omega_r \psi_{rd}, \qquad (13)$$

which are shown in Fig. 4. [6].

The parameters of active and reactive power PI controllers shown in Fig. 4. are: K_{pi}, K_{pp} gain constants and K_{ii}, K_{pi} integral constant.

Input values are reference (sign *) and estimated (sign ˆ) active and reactive power of the wind turbine, vector of rotor current $\bar{i}_{rdq}$, vector of rotor magnetic flux $\overline{\psi}_{rdq}$ and angular speed of rotor ω_g. Output is vector of rotor voltage $\bar{u}_{rdq}$.

5 Simulation results

By the simulation is the goal to show distribution of wind turbine power (power on the axis of DFIG) into stator and rotor active power p_{sa} and p_{ra} depending about reference active power p_{sa}^*. Rotor active power decides power of the back-to-back converter located in the rotor circuit. By conversion of mechanical power of the wind turbine into grid electric power it is occurred the losses in DFIG cooper and losses of the converter in rotor circuit, which depend about active power reference value of the wind turbine.

Responses of the stator and rotor active power p_{sa} and p_{ra}, losses in cooper p_{Cu} and rotor speed of generator ω_g by step load of DFIG are shown in Fig. 5. to Fig. 9. The all shown results are given for reactive power reference value $q_{sr}^* = 0{,}0[pu]$. Figures 5. to 7. are performed by wind speed $v_w = 14[m/s]$ and by wind turbine power $p_t = 0{,}577[pu]$.

By analysis of simulation results it is shown that active stator power p_{sa} good corresponding with reference value in the steady state mode. Power in the axis of DFIG p_t is divided, in steady state modes, in active powers of stator p_{sa} and rotor p_{ra} and in cooper losses p_{Cu} of generator.

In sub-synchronous working mode (for $v_w = 14[m/s]$ in Fig. 6.) generator deliver active power p_{sa} that is higher than wind turbine power p_t. Because of that, generator takes rotor active power p_{ra} from electric grid. In the case of reference power value $p_{sa}^{*} = -0{,}94[pu]$ for $v_w = 14[m/s]$ in Fig. 7. and $p_{sa}^{*} = -0{,}577[pu]$ for $v_w = 9[m/s]$ in Fig. 9. the active power of rotor, in steady state working mode, is just equal to zero. Therefore, in these steady state working modes, overall wind turbine power is distributed in electric grid over stator, and converters in rotor side are unloaded.

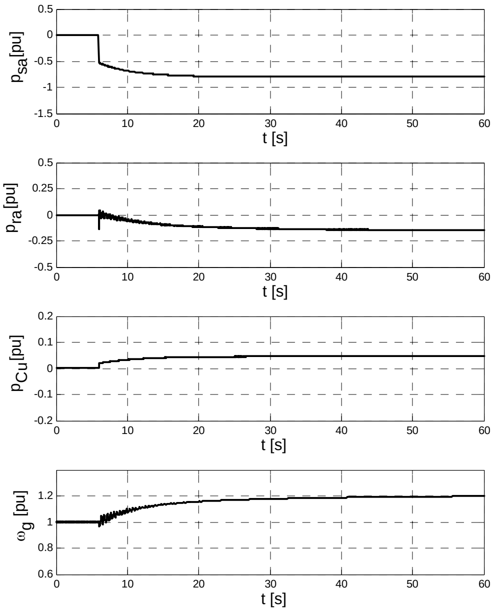

Fig.5. Time responses of p_{sa}, p_{ra}, p_{Cu} and ω_g DFIG to step load; $v_w = 14[m/s]$, $p_{sa}^{*} = -0{,}8[pu]$

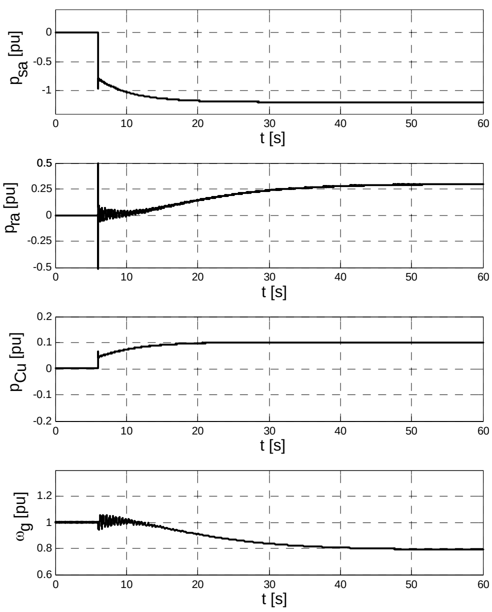

Fig.6. Time responses of p_{sa}, p_{ra}, p_{Cu} and ω_g DFIG to step load; $v_w = 14[m/s]$, $p_{sa}^{*} = -1{,}2[pu]$

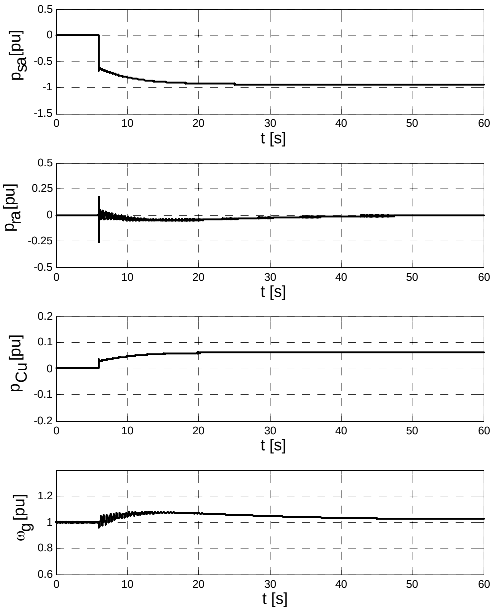

Fig.7. Time responses of p_{sa}, p_{ra}, p_{Cu} and ω_g DFIG to step load; $v_w = 14[m/s]$, $p_{sa}^{*} = -0{,}94[pu]$

In super-synchronous working mode (for $v_w = 14[m/s]$ in Fig. 5. and for $v_w = 9[m/s]$ in Fig. 8.) the wind turbine power is divided in stator active power p_{sa} and rotor active power p_{ra} that DFIG deliver in electric grid.

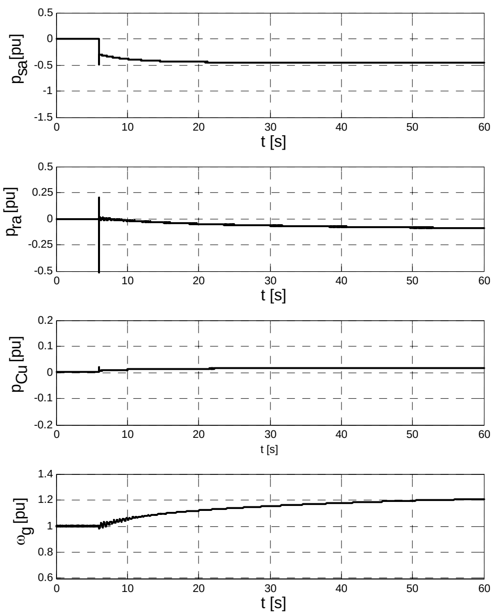

Fig.8. Time responses of p_{sa}, p_{ra}, p_{Cu} and ω_g DFIG to step load; $v_w = 9[m/s]$, $p_{sa}^{*} = -0{,}45[pu]$

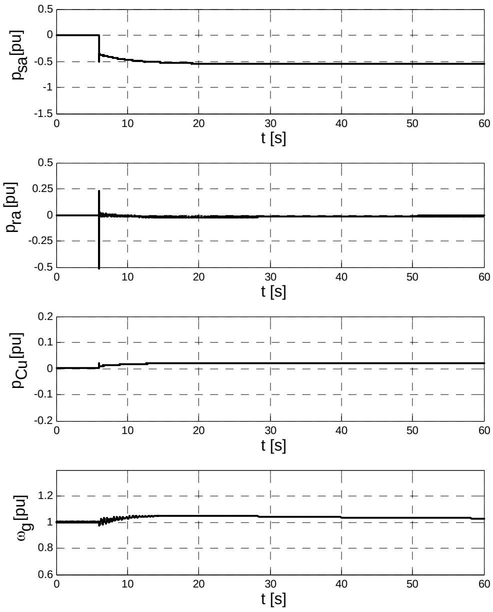

Fig.9. Time responses of p_{sa}, p_{ra}, p_{Cu} and ω_g DFIG to step load; $v_w = 9[m/s]$, $p_{sa}^* = -0{,}55[pu]$

By carefully analyses of cooper losses in stator and rotor for observed working modes it is shown that losses become higher for higher active power reference values. So, in sub-synchronous working modes (Fig. 6.), cooper losses of DFIG are much magnified.

Active power of DFIG rotor p_{ra} takes from electric grid, and it is unfavourable working mode. In super-synchronous working mode (Fig. 5. and 8.) cooper losses are minimal, but converter in rotor circuit is loaded. Cooper losses at working modes with $p_{ra} = 0{,}0[pu]$ (Fig. 7. and Fig. 9.) are satisfactory, and load of power converter in rotor circuit is just equal to zero.

6 Conclusion

Shown dynamic model of the wind turbine connected to electric grid consist of dynamic model wind turbine drive train, model of DFIG and model of the active and reactive power vector control system. Active and reactive power control system is based on well-known vector control modeled in different reference frames.

In this paper is presented issues of active power reference value choice. By simulation in program MATLAB-SIMULINK is shown that it is possible to ensure active power reference value by the control system located in rotor circuit of DFIG. From simulation results can be concluded that the best choice of active power reference value is in working mode with $p_{ra} = 0{,}0[pu]$. In that case, cooper losses are satisfactory, and load of converter in rotor circuit is just equal to zero. In future papers it would research options for application of rotor active power feedback instead of manual choice of reference value power in wind turbine.

Appendix

A. Wind Turbine Data

Rated power	P_{tn}=2 [MW]
Gearbox ratio	i_{mk}=89
Shaft stiffness	K_{vt}=12*10^7 [Nm/rad]
Damping coefficient	D_{vt}=3.5*10^5[Nms/rad]
Induction generator inertia	J_g=90 [kgm^2]
Wind turbine inertia	J_t=9*10^6 [kgm^2]

B. Generator Data

Rated power	P_{gn}=2 [MW]
Nominal voltage	U_n=690 [V]
Rated frequency	f_n=50 [Hz]
Number of pole-pairs	p=2
Stator resistance	R_s=0,048 [pu]
Rotor resistance	R_r=0,018 [pu]
Stator inductance	L_s=3,875 [pu]
Rotor inductance	L_r=3,912 [pu]
Magnetizing inductance	L_m=3,8 [pu]

C. Base quantities

$U_b = 563[V]$, $I_b = 2366{,}66[A]$, $\omega_b = 314[rad/s]$,
$P_b = 2000[kVA]$, $Z_b = 0{,}237[\Omega]$, $\psi_b = 1{,}793[Vs]$,
$T_b = 0{,}003185[s]$, $M_b = 12739[Nm]$

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