Novel Active Power Control Strategy for Fully fed Wind Turbine with Stator Controlled Cage Induction Generator (SCCIG)

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Abstract: The variable speed wind turbine with stator controlled cage induction generator (SCCIG) is today widely used technology in wind energy scenario. This paper presents a control system of the SCCIG wind turbine with the focus on the control strategies and on active power command value achievement. The proposed control method is designed for super-synchronous, sub-synchronous and synchronous working modes. In order to investigate the dynamic responses during step load of SCCIG 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 modules.

Key-Words: SCCIG, wind turbine, dynamic simulation and command value of active power.

1 Introduction

In a few last years, variable speed wind turbines with SCCIG 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 SCCIG connected to the electric grid include automatic control of active and reactive power control. By these wind turbines, dynamic of electric system is being faster than dynamic of mechanical system (drive train).

The control system of SCCIG consists of two control subsystems: control system of power converter connected to the stator side and control system of power converter connected to the electric grid side. These two control systems must be interfaced with the pitch controller (Control system of wind turbine).

2 Fundamental structure of the SCCIG wind turbine control system

Typical configuration of the wind turbine with SCCIG consists of a squirrel cage induction generator with stator winding connected to the three phase grid by the use of 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 stator 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 vector control for induction machine. In this theory, two-axis control strategy has been described in three different reference frames.

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

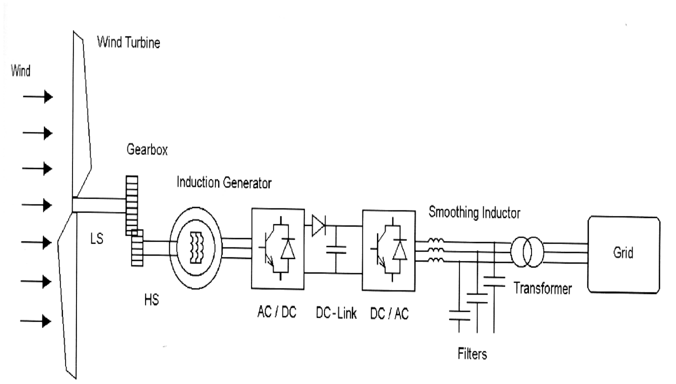

Fig. 1(a). Wind turbine control system with SCCIG

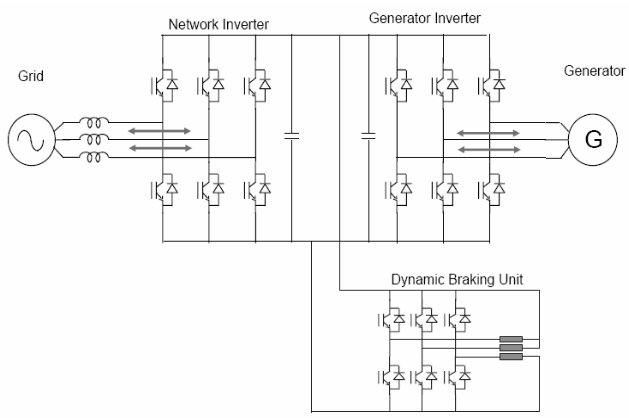

Fig. 1(b). Power converter circuit for SCCIG

The main rule of SCCIG is conversion of power captured from the wind and subsequent mechanical power p_t into the electric power p_{sa} and electric power delivery from SCCIG stator to the electric grid. The wind power is extremely variable value depending about the wind speed, hence SCCIG 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 electric grid has a practically constant voltage value v_{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. There are many variables namely active stator power p_{sa}, 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, stator active power p_{sa} is the consequence of reference value p_a^* for defined wind turbine power. Induction generator can work in super-synchronous mode ($p_{sa}<0$), sub-synchronous mode ($p_{sa}>0$) and in synchronous mode ($p_{sa}=0$). This paper describes dependence of the stator 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 SCCIG 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.

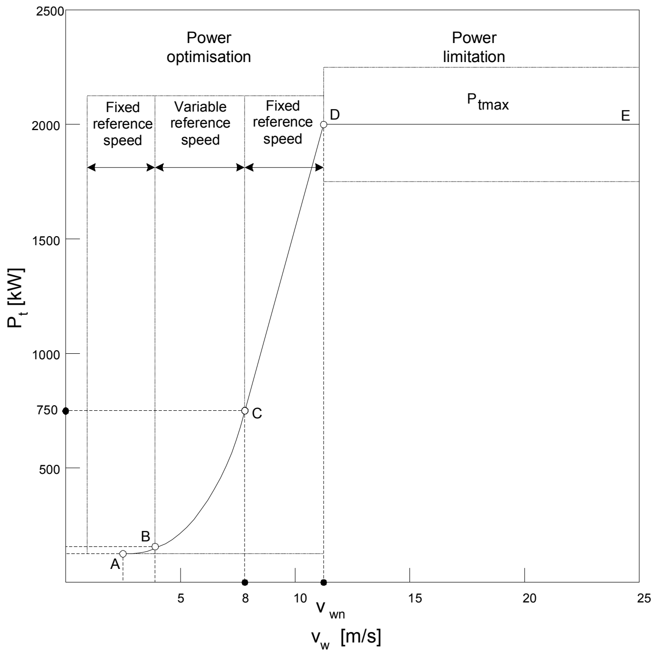

Fig. 2. Static characteristic of wind turbine mechanical power P_t as a function of mean wind speed

3 Modeling of the active and reactive power control system of the SCCIG 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 which acts as an interaction system between the wind turbine and electric power system. For modeling of the drive train system, it is required to 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, well-known two-mass model of the wind turbine and generator drive train have been chosen for simulation. The 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:

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

where:

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

Time constants of the wind turbine T_t and induction generator T_g, damping coefficient D_{vtt} and shaft stiffness K_{vtt} in equations (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],
$D_{vtt} = (D_{vt}\omega_b^2)/(P_b i_{mk}^2 p^2)$ [pu] and
$K_{vtt} = (K_{vt}\omega_b)/(P_b i_{mk}^2 p^2)$ [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 SCCIG.
The state variable of wind turbine dynamic model, with the output values, as 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 SCCIG

In the grid side power converter, vector control is used to achieve active and reactive power control of SCCIG. In this control, the machine model uses the transformation of current, voltage and flux 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 windings and by the equation of rotor motion. The solutions of these equations define dynamic characteristics of the machine.

The differential equations of the stator windings described in vector mode and in d-q reference frame rotating in angular speed ω_k are [4]:

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

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

where: ω – electric angular rotor speed.

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

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

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:

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

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

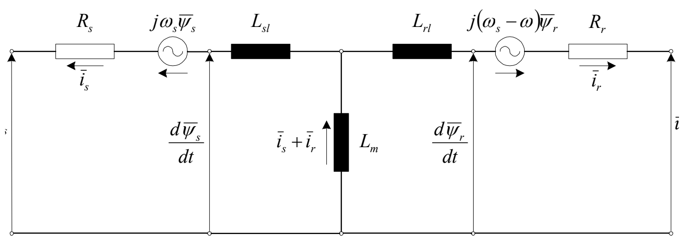

Fig. 3. Equivalent diagram of the induction machine for dynamic states

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:

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

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

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

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

Choice of the reference frame angular speed depends on selected structure of SCCIG control system connected to the Grid. Since, for control system realization of the converter connected to the stator side and converter connected to the grid side, it is required to apply different reference frames which is selected as α-β reference frame (ω_k=0) and 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 of mathematical models of the SCCIG wind turbine drive train are given in equations ((1) and (2)) and electromagnetic torque of induction generator given in dynamic model of SCCIG ((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 SCCIG.

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

- induction generator is modeled in α-β reference frame that, by comparison with original abc reference frame, is at rest.
- Power converter which is connected to the stator side is modeled in d-q reference frame; vector of stator magnetic flux is aligned to d-axis,
- Power converter which is connected to the electric grid side is modeled in d-q reference frame; vector of grid voltage is aligned to d-axis.

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

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

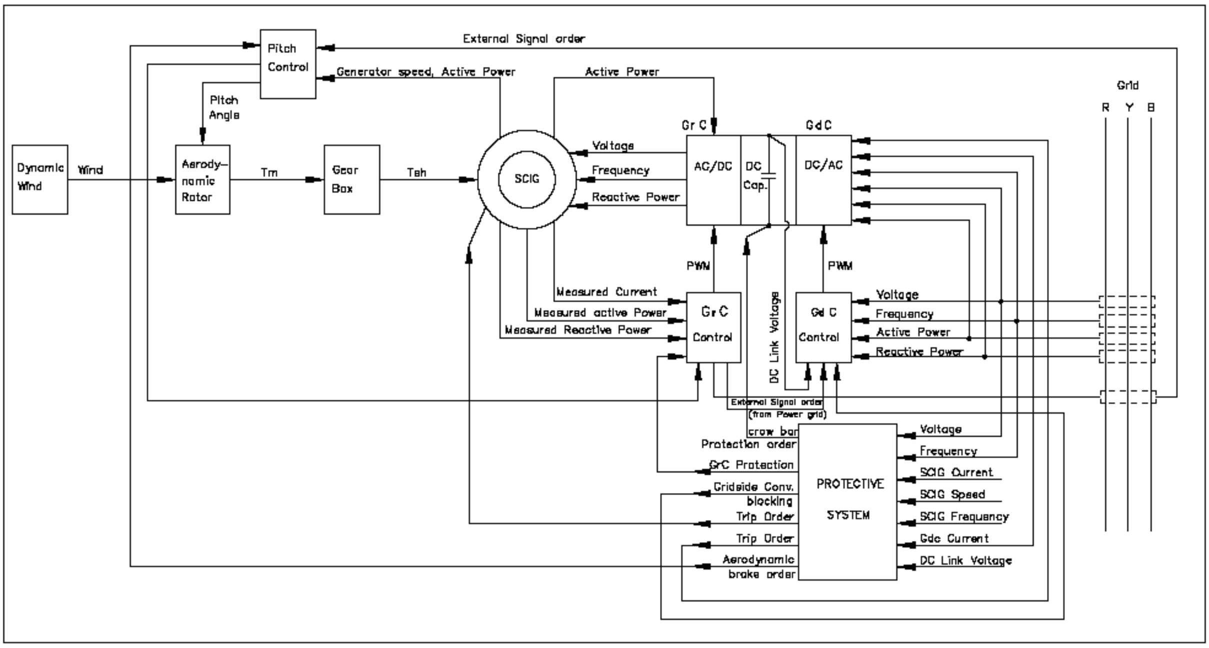

Fig. 4. Active and reactive power vector control system of SCCIG

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

The rule of converter connected to the stator 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 stator side work in d-q 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 d-q reference frame that is aligned to stator magnetic flux vector too. As induction generator model is in α-β reference frame, outputs of controllers assigned to the rotor side have to be transformed from α-β reference frame in d-q reference frame.

Mathematical model of control system connected to the stator side can be derived from voltage equation of stator (4) that described in scalar mode as:

$$u_{sd} = i_{sd} R_s + \frac{d\psi_{sd}}{dt} - \omega_s \psi_{sq}, \tag{10}$$

$$u_{sq} = i_{sq} R_s + \frac{d\psi_{sq}}{dt} - \omega_s \psi_{sd}. \tag{11}$$

From equations (10) and (11),

$$u'_{sd} = -\omega_s \psi_{sq}, \tag{12}$$

$$u'_{sq} = -\omega_s \psi_{sd}, \tag{13}$$

which are shown in Fig. 4.

The parameters of active and reactive power for PI controllers are as shown in Fig. 4. They 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 stator current $\bar{i}_{sdq}$, vector of stator magnetic flux $\overline{\psi}_{sdq}$ and angular speed ω_g. Output is vector of stator voltage $\overline{u}_{sdq}$.

5 Simulation results

By simulation, the aim of this paper is to show the distribution of power (power on the axis of SCCIG) into stator. Stator active power p_{sa} and p_{ra} depending on reference active power p_{sa}^*. Stator active power decides power from the back-to-back converter located in the stator circuit. Losses caused by the SCCIG and power converter depending on the active power reference value.

Responses of the stator and stator active power p_{sa} and p_{ra}, copper losses p_{Cu} and rotor speed of generator ω_g by step load of SCCIG are shown in Fig. 5. to Fig. 9. Results shown are as per reactive power reference value $q_{sr}^* = 0{,}0[pu]$. Figures 5,6 and 7 are performed by wind speed $v_w = 14[m/s]$ and by wind turbine power $p_t = 1{,}0[pu]$, and figures 8. and 9. are performed by wind speed $v_W = 9[m/s]$ and by wind turbine power $p_t = 0{,}577[pu]$. By analysis of simulation results it is observed that active stator power p_{sa} is responding well with reference value in the steady state mode. Power in the axis of SCCIG p_t is divided, in steady state modes, in active power of stator p_{sa} and active power of rotor p_{ra} and rest in copper losses p_{Cu} of generator.

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 SCCIG deliver in electric grid.

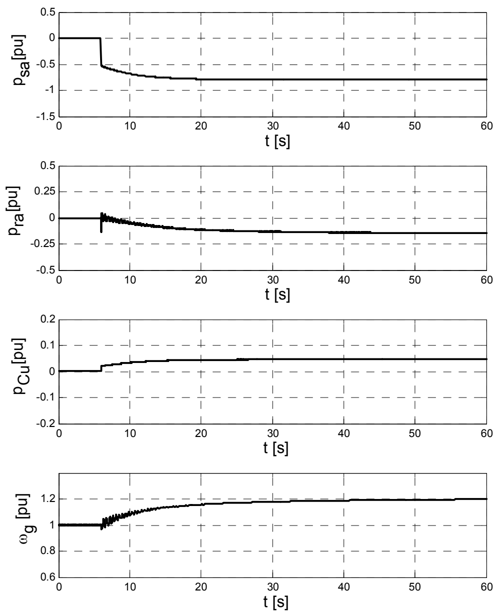

Fig.5. Time responses of p_{sa}, p_{ra}, p_{Cu} and ω_g SCCIG to step load; $v_w = 14[m/s]$, $p_{sa}^* = -0{,}8[pu]$

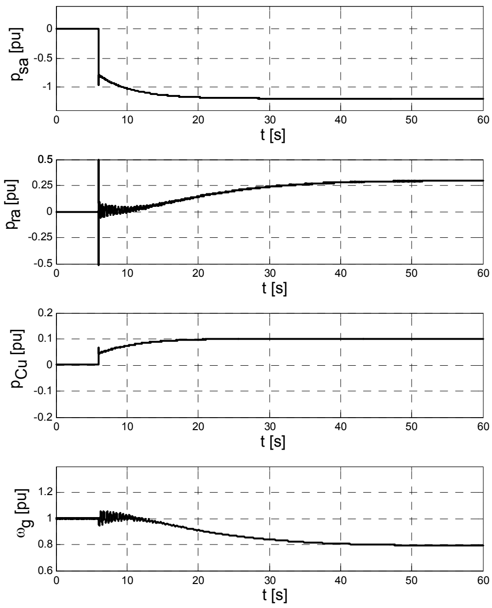

Fig.6. Time responses of p_{sa}, p_{ra}, p_{Cu} and ω_g SCCIG to step load; $v_w = 14[m/s]$, $p_{sa}^* = -1{,}2[pu]$

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 stator active power p_{sa} from electric grid.

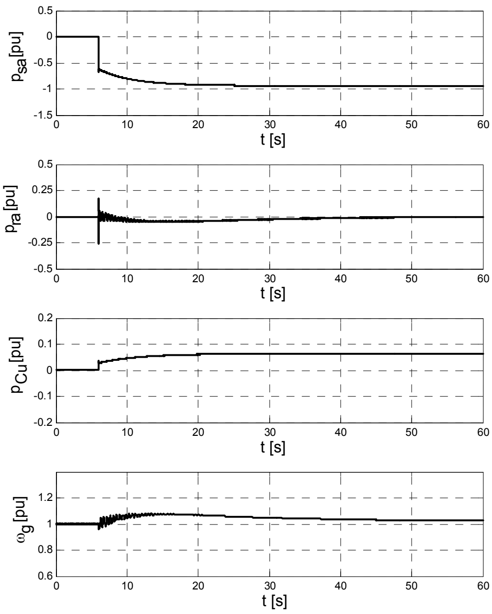

Fig.7. Time responses of p_{sa}, p_{ra}, p_{Cu} and ω_g SCCIG to step load; $v_w = 14[m/s]$, $p_{sa}^* = -0{,}94[pu]$

In the case of reference power value $p_{sa}^* = -0,94[pu]$ for $v_w = 14[m/s]$ in Fig. 7. and $p_{sa}^* = -0,55[pu]$ for $v_w = 9[m/s]$ in Fig. 9. the active power of stator, 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 stator side are unloaded.

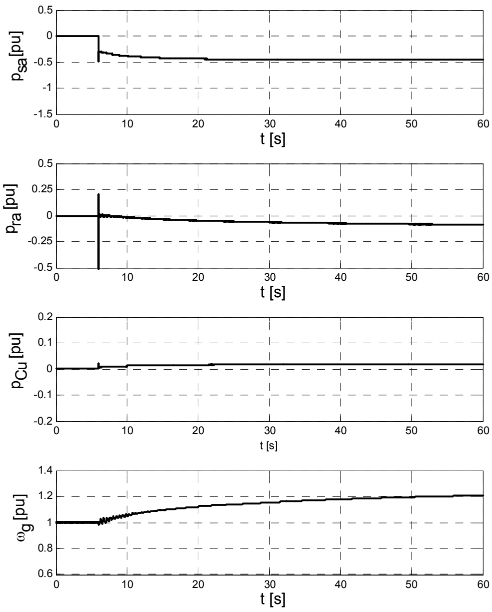

Fig.8. Time responses of p_{sa}, p_{ra}, p_{Cu} and ω_g SCCIG to step load; $v_w = 9[m/s]$, $p_{sa}^* = -0,45[pu]$

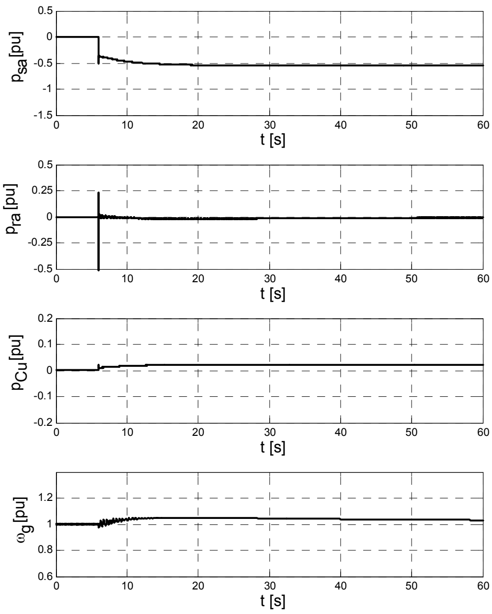

Fig.9. Time responses of p_{sa}, p_{ra}, p_{Cu} and ω_g SCCIG to step load; $v_w = 9[m/s]$, $p_{sa}^* = -0,55[pu]$

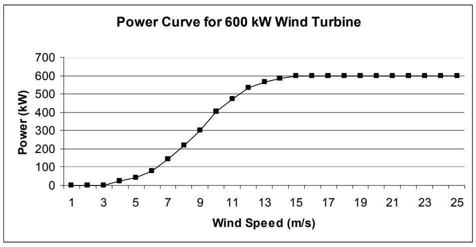

Figure 10. Power Curve

By using the proposed technique, power curve of 600 kW wind turbine has been obtained by the simulation and the same is shown in Figure 10.

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

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

6 Conclusion

In this paper, dynamic model of the wind turbine connected to electric grid which consists of dynamic model of wind turbine drive train, model of SCCIG and model of the active and reactive power vector control system has been presented. Active and reactive power control system is based on well-known vector control modeled in different reference frames.
In this paper, active power reference value choice has been presented. By MATLAB-SIMULINK simulation program, it is shown that it is possible to ensure active power reference value by the control system located in stator circuit of SCCIG. From simulation results, it can be concluded that the best choice of active power reference value is in working mode with p_{sa} = 0,0[pu]. In that case, copper losses are satisfactory, and load of converter in stator circuit is just equal to zero.

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

V_b= 690 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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