

PERFORMANCE OF SENSORLESS CONTROL OF PERMANENT MAGNET SYNCHRONOUS GENERATOR IN WIND TURBINE SYSTEM*

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Abstract: The paper presents a sensorless control of permanent magnet synchronous generator (PMSG) in a variable-speed wind energy conversion system. The system of wind turbine consists of PMSG and back-to-back power converter. The back-to-back converter system is composed of machine side converter (MSC) and grid side converter (GSC). In the control of MSC and GSC the methods of vector control have been applied. For operation of MSC the method of Rotor Field Oriented Control (RFOC) with MPPT algorithm has been used. For estimation of angular rotor position and angular speed the flux linkage estimator with synchronous frame phase locked loop (SF-PLL) has been used. In the control of GSC the method of Voltage Oriented Control (VOC) has been considered. Simulation studies have been carried out in order to evaluate the system of sensorless strategy. The results of simulation studies demonstrate the high efficiency and high accuracy of the sensorless control system considered.

Keywords: *wind turbine, PMSG, power converters, sensorless algorithm, simulation studies*

1. INTRODUCTION

The number of application of wind energy conversion systems with permanent magnet synchronous generators (PMSGs) has increased rapidly in recent years [2], [10]. The wind turbine is one of the most important elements in wind energy conversion system. The wind turbine is responsible for conversion of the wind energy into mechanical rotational energy. Nowadays the total average power rating of installed wind turbines and generators has grown rapidly. To reduce the high maintenance cost of gearbox, a direct driven wind turbine system with low speed, multipole PMSG is a profitable technology [6], [9]. Reduction of cost and increasing reliability are the results of application of wind turbine systems without gearbox.

* Manuscript received: March 30, 2016; accepted: May 18, 2016.

In order to convert electrical energy produced by the PMSG generator the power converters should be applied. The converter systems enable the control of speed and electromagnetic torque of the generator and allow the power flow to the AC grid to be adjusted. Different designs and combinations of power converters lead to a wide variety of wind energy conversion systems (WECS) [3]–[5]. The application of full capacity power converter system allows the performance of the wind energy conversion system to be enhanced. With the use of this type of power converter systems, the generator is completely decoupled from the grid and can be operated in full speed range.

For conventional vector control of PMSG, the sensors of rotor position and angular speed are required. The information of generator rotor position makes it possible to orient correctly the stator current vector to the flux vector of permanent magnets. However, these sensors are undesirable due to the cost, big size, maintenance and poor reliability [4]. For these reasons there are different ways to manage of this problem. In this paper, a sensorless control method based on stator and rotor flux linkage estimators is presented. Additionally, for design of angular rotor position and speed of PMSG the application of synchronous frame phase locked loop (SF-PLL) is considered. In the literature, usually the sensorless methods of control have been mainly restricted to the control of motors, but not for generators with power electronic converters, applied in wind energy systems. The application of sensorless control methods and systems should significantly improve the reliability and the cost of wind turbine systems [10].

2. MODEL OF PERMANENT MAGNET SYNCHRONOUS GENERATOR

The dynamic equations of three-phase PMSG can be expressed in synchronously rotating dq reference frame. The d -axis is aligned with the direction of the rotor flux vector and the q -axis is 90° ahead. The mathematical equations of the PMSG in dq frame can be described as follows [2], [3], [5], [10]

$$\begin{bmatrix} v_{sd} \\ v_{sq} \end{bmatrix} = R_s \begin{bmatrix} i_{sd} \\ i_{sq} \end{bmatrix} + p \begin{bmatrix} \psi_{sd} \\ \psi_{sq} \end{bmatrix} + \omega_e \begin{bmatrix} -\psi_{sq} \\ \psi_{sd} \end{bmatrix}, \quad (1)$$

$$\psi_{sd} = L_d i_{sd} + \psi_{PM}, \quad (2)$$

$$\psi_{sq} = L_q i_{sq}, \quad (3)$$

$$\omega_e = n_p \cdot \omega_m, \quad (4)$$

where v_{sd} , v_{sq} – components of the stator voltage vector in d and q axis; i_{sd} , i_{sq} – components of the stator current vector in d and q axis, R_s – stator resistance; ψ_{sd} , ψ_{sq} – direct

and quadrature vector components of the stator flux linkages; L_d, L_q – direct and quadrature stator inductances; ψ_{PM} – flux linkage established by the permanent magnets; n_p – number of pole pairs of PMSG; $p = d/dt$ – differential operator; ω_e, ω_m – electrical and mechanical angular speed of the PMSG.

The electromagnetic torque of generator can be expressed as follows

$$T_e = \frac{3}{2} n_p \cdot [\psi_{PM} i_{sq} - (L_d - L_q) i_{sd} i_{sq}]. \quad (5)$$

For a non-salient pole machine the stator direct and quadrature inductances L_d and L_q are approximately equal and $L_s = L_d = L_q$. In this case, the equation of electromagnetic torque can be described in the following form

$$T_e = \frac{3}{2} n_p \psi_{PM} i_{sq}. \quad (6)$$

Equation (6) shows that the generator torque can be controlled by the quadrature component i_{sq} of stator current vector.

The equation of mechanical motion of the wind turbine system is given as

$$T_t + T_e = J \cdot \frac{d}{dt} \omega_m + B_f \omega_m \quad (7)$$

where T_t – mechanical torque of wind turbine, J – the total inertia of the system, B_f – coefficient of viscous friction.

3. CONTROL OF BACK-TO-BACK CONVERTER SYSTEM

The developed configuration and control circuits of direct driven WECS with PMSG are presented in Fig. 1. This configuration consists of a wind turbine, a PMSG generator, a back-to-back converter system and a grid filter. The converter system is composed of the Machine Side Converter (MSC) and Grid Side Converter (GSC). The PMSG is directly coupled to the wind turbine and connected to the MSC. The GSC is connected to the AC grid through the grid filter.

In the control systems of both converters, a vector control method has been applied. In the control system of the MSC the Rotor Field Oriented Control (RFOC) with sensorless method has been used. Additionally, in order to obtain the maximum power from the wind turbine, the optimal tip speed ratio MPPT algorithm has been included. In the control system of the GSC the Voltage Oriented Control (VOC) with control of instantaneous reactive and active power has been applied.

The control scheme of MSC consists of three control loops. The outer control loop regulates the angular generator speed ω_m to follow the reference value ω_{opt} , which is

obtained by MPPT algorithm. In the control system the estimated value of angular generator speed ω_{mest} is used by application of sensorless control method.

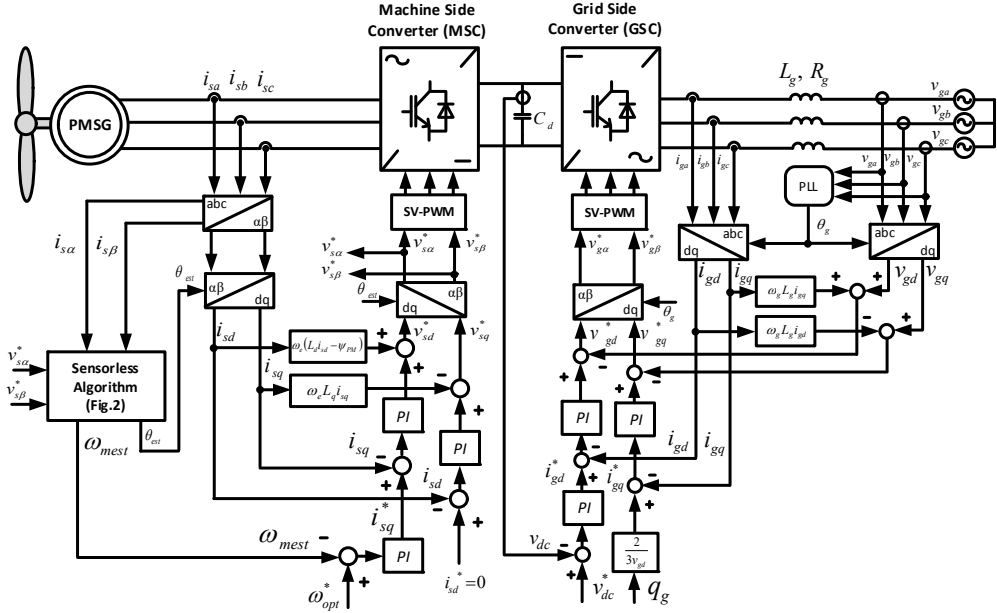


Fig. 1. The scheme of variable speed wind turbine control system with direct-driven PMSG generator and back-to-back converter system

In order to obtain the MPPT condition at any wind speed the rotational speed of the wind turbine rotor should be regulated to the their optimal value ω_{opt} . The reference speed ω_{ref} should be equal to ω_{opt} and can be determined from the general equation of the mechanical output power of the wind turbine

$$P_t = 0.5 \rho \pi R^2 v_w^3 C_p(\lambda, \beta) \quad (8)$$

where ρ – air density; R – radius of the turbine blade; v_w – wind speed; C_p – power coefficient of the wind turbine; λ – tip speed ratio; β – blade pitch angle.

This equation of wind turbine power (8) can be expressed as a function of the rotational speed ω_m of wind turbine

$$P_t = 0.5 \rho \pi R^5 \frac{C_p(\lambda, \beta)}{\lambda^3} \omega_m^3. \quad (9)$$

In order to fulfil the MPPT algorithm λ should be replaced by λ_{opt} , and $C_p(\lambda, \beta) = C_{pmax}(\lambda_{opt}, \beta)$. After this operation the following expression is obtained

$$\omega_{opt} = \sqrt[3]{P_t \lambda_{opt}^3 / (0,5 \rho \pi R^5 \cdot C_{p \max}(\lambda_{opt}, \beta))} = \sqrt[3]{P_{MPPT} / K_{opt}} \quad (10)$$

where K_{opt} – coefficient of wind turbine, P_{MPPT} – maximum wind turbine mechanical power at the wind speed considered.

The MPPT algorithm can be achieved by keeping the optimal value of tip speed ratio λ_{opt} and the maximum value of power coefficient $C_{p \max}$. This condition allows the maximum mechanical power to be produced by wind turbine at wide range of wind speeds.

To regulate the stator current vector components i_{sq} , i_{sd} the two inner control loops have been used. In the RFOC strategy the reference value of stator current vector component i_{sd}^* is set to zero. This condition allows the torque per ampere ratio of PMSG to be maximized [9], [10]. The reference value of stator current vector components i_{sd}^* and i_{sq}^* are compared with the measured stator current vector components i_{sd} , i_{sq} . The error signals are sent to two PI controllers. The required reference components of voltage vector of MSC v_{sd}^* and v_{sq}^* obtained from PI controllers are then transformed to the α - β -system. The required switching signals for MSC are generated through Space Vector PWM modulation block (SV-PWM). Additionally, the decoupled circuits have been applied to obtain high performance of the RFOC method considered.

The control system of GSC is based on grid voltage vector orientation control (VOC). The angle position θ_g of the grid voltage vector is obtained from the PLL (Phase Locked Loop) block. In the control system of GSC the three control loops with PI controllers have been used. The outer control loop is responsible for keeping the constant value of the dc-link voltage between MSC and GSC converter. The output value from this PI controller determines the reference value of grid current vector component i_{gd}^* . In order to obtain the operation of the unity power factor, the instantaneous reactive power is controlled directly by i_{gq} and is set to zero value. Then, the reference values of grid current vector components i_{gd}^* and i_{gq}^* are compared with the measured and transformed grid phase currents i_{gd} and i_{gq} . The decoupled terms have been applied in order to obtain high performances of VOC control system. The output values from both PI controllers determine the reference values of voltages v_{gd}^* and v_{gq}^* for the GSC. These reference voltages are then transformed to the α - β -system and are sent to the block of SV-PWM.

4. SENSORLESS SPEED CONTROL OF PMSG SYSTEM

The elimination of speed sensor or encoder makes it possible to reduce the costs and possibility of failure of the wind turbine system. The information of rotor position of PMSG generator is required to perform the control with rotor flux orientation [1], [2], [4], [7], [9].

The use of sensorless vector control is attractive for wind turbine applications with PMSG generators. The application of sensorless algorithm for estimation of rotor position and angular rotor speed allows reliability to be increased and maintenance requirements to be reduced. In this paper, the synchronous frame phase locked loop (SF-PLL) control technique has been used to obtain the rotor position and rotor speed. This technique is based on calculation of the components of the stator and rotor flux vectors.

The voltage equations of PMSG obtained in dq -axis system can be rewritten in stationary α - β reference frame

$$v_{s\alpha} = R_s i_{s\alpha} + \frac{d}{dt} \psi_{s\alpha}, \quad (11)$$

$$v_{s\beta} = R_s i_{s\beta} + \frac{d}{dt} \psi_{s\beta}, \quad (12)$$

where $v_{s\alpha}$, $v_{s\beta}$ – components of stator voltage vector in α - β system, $\psi_{s\alpha}$, $\psi_{s\beta}$ – components of stator flux vector in α - β system, $i_{s\alpha}$, $i_{s\beta}$ – components of stator current vector in α - β system.

Based on the mathematical model of PMSG the components of stator and rotor flux vector can be calculated as

$$\psi_{s\alpha} = \int (v_{s\alpha}^* - R_s i_{s\alpha}) dt, \quad (13)$$

$$\psi_{s\beta} = \int (v_{s\beta}^* - R_s i_{s\beta}) dt, \quad (14)$$

$$\psi_{r\alpha} = \psi_{s\alpha} - L_s i_{s\alpha}, \quad (15)$$

$$\psi_{r\beta} = \psi_{s\beta} - L_s i_{s\beta}, \quad (16)$$

where $\psi_{r\alpha}$, $\psi_{r\beta}$ – rotor flux linkages in α and β axes.

According to the practice the components of stator voltage vector $v_{s\alpha}$, $v_{s\beta}$ have been replaced in equations (13), (14) by their reference values $v_{s\alpha}^*$, $v_{s\beta}^*$. The angle of the rotor flux vector θ_e is also an electrical angle of rotor position of PMSG, which is required by the Rotor Field Oriented Control.

The applied block scheme of flux linkage estimation (SF-PLL) of angular rotor position θ_{est} and angular rotor speed ω_{est} is presented in Fig. 2 [1], [2], [4], [8].

The presented block consists of voltage model for stator and rotor flux vector estimation and the SF-PLL block for estimation of angular rotor speed and position [2], [6], [8]. The basic scheme of the SF-PLL system is a feedback system with PI-controller tracking the angle position of rotor flux vector. The inputs of SF-PLL block are the rotor flux vector components in α - β system. The outputs of SF-PLL block are

the estimated angular position θ_{est} of rotor flux vector and estimated angular rotor speed ω_{est} of the rotor flux vector. The component of rotor flux vector ψ_{rq} is forced to zero, so the SF-PLL system is synchronized with ψ_{rd} component of rotor flux vector.

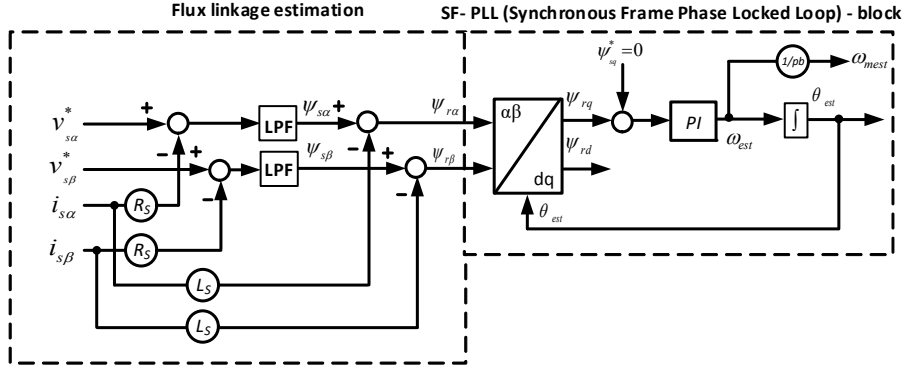


Fig. 2. The scheme of block estimation of angular rotor position θ_e and angular rotor speed ω_{est}

The application of the integrators usually causes the limits of the effectiveness of the voltage model and contributes to inaccuracy of estimation. For this reason, in the control system the integrator blocks have been replaced by equivalent low-pass filter blocks (LPF) of first order [3]. The integrator blocks in the voltage model may also cause problems due to unknown initial rotor position and sensitivity to influence of drifts [2], [6].

5. SIMULATIONS RESULTS

The control strategy of proposed wind energy conversion system has been tested by digital simulation in MATLAB/Simulink in order to evaluate the behavior of the proposed sensorless vector control. Digital simulation studies were made for the system with wind energy conversion system data and parameters which are presented in Tables 1 and 2.

Table 1. Data and parameters of wind turbine

| Parameter | Value |
|------------------------------|-------------------------|
| Rated power P_t | 20 kW |
| Rotor radius R | 4.4 m |
| Power coefficient C_{pmax} | 0.48 |
| Air density ρ | 1.225 kg/m ³ |

Table 2. Data and parameters of PMSG

| PMSG parameter | Value |
|--|---------------------|
| Rated power; P_N | 20 kW |
| Stator resistance; R_s | 0.1764Ω |
| Stator dq -axis inductance; $L_{ds} L_q$ | 4.48 mH |
| Number of pole pairs; n_p | 18 |
| Rated speed; n_N | 211 rpm |
| Stator rated phase current; I_{sN} | 35.1 A |
| Total moment of inertia; J | 1.8 kgm^2 |
| Permanent magnet flux; Ψ_{PM} | 0.92 Wb |

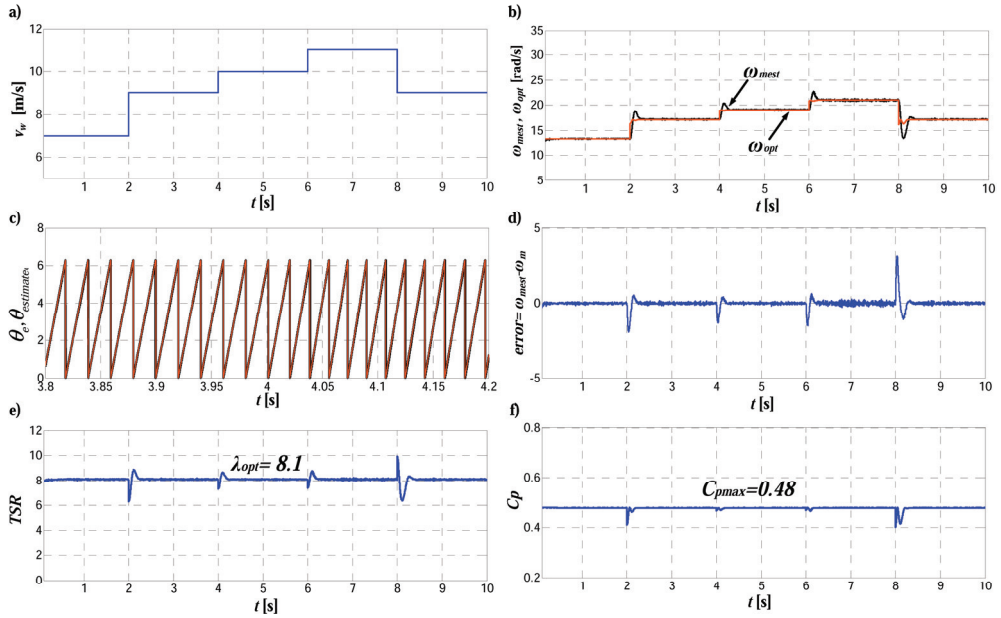


Fig. 3. Waveforms of: (a) wind speed v_w ; (b) reference speed ω_{opt} and estimated speed ω_{mest} of PMSG; (c) measured θ_e and estimated θ_{est} rotor angle position; (d) error of measured speed ω_m and estimated speed ω_{mest} ; (e) tip speed ratio λ ; (f) power coefficient C_p of wind turbine

The waveforms of simulation results are presented in Figs. 3 and 4. Figure 3a shows the wind speed variation for the period of a 10 s simulation. Figure 3b contains the estimated ω_{mest} and reference ω_{opt} value of angular speed of PMSG. The estimated speed is obtained by the SR-PLL block. From this figure, it can be stated that control strategy based on the sensorless algorithm ensures high control accuracy and fast responses at wide ranges of speeds. Figure 3c shows the measured θ_e and estimated rotor position θ_{est} of PMSG. This figure confirms the high accuracy of the control strategy considered. The waveform errors of the measured and estimated angular speed of

PMSG are presented in Fig. 3d. It can be noticed that the errors between reference and estimated speed are close to zero. The waveforms of tip speed ratio and power coefficient are presented in Fig. 3e, f. From these waveforms, it can be noticed that the values of tip speed ratio and power coefficient are kept at reference and maximum values according to the operation of the MPPT algorithm.

Figure 4a presents the waveforms of the stator current vector components i_{sd} , i_{sq} caused by the variation of wind speed. The component i_{sd} of the stator current vector is kept at zero values in order to maximize the torque per ampere ratio [8]. The responses of the component i_{sq} of the stator current vector have similar waveforms as the variations of the wind speeds. The waveforms of electromagnetic torque T_e of PMSG and mechanical torque T_t of wind turbine are shown in Fig. 4b. The responses of PMSG electromagnetic torque T_e have similar behavior as mechanical torque T_t of wind turbine. This is caused by high accuracy and fast responses of control strategy. Figure 4c presents the waveform of the voltage v_{dc} in dc link. The instantaneous values of voltage v_{dc} are quite constant across the wide range of variations of wind speeds. The waveforms of instantaneous active and reactive power p_g , q_g delivered to the AC grid are presented in Fig. 4d. From this figure it is clear that the reactive power is set to zero in order to perform the condition of unity power factor. The changes of instantaneous active power delivered to the AC grid are in accordance with changes of the wind speeds.

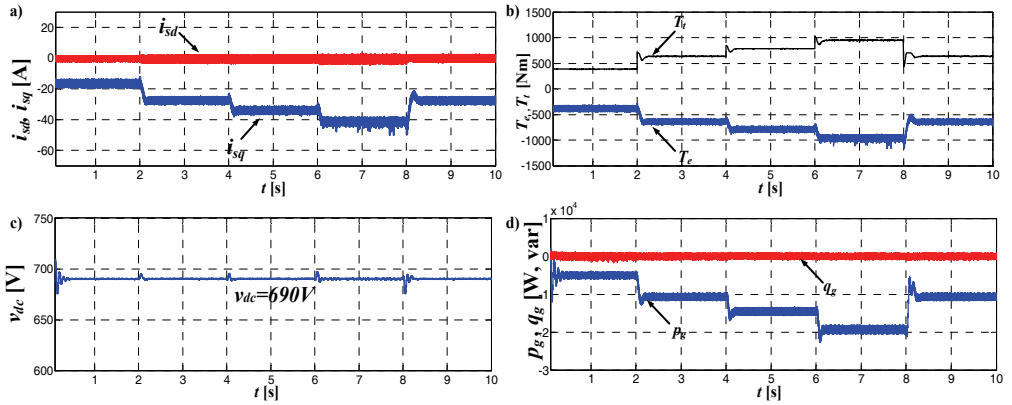


Fig. 4. Waveforms of: (a) stator current vector components i_{sd} , i_{sq} ; (b) electromagnetic torque T_e of PMSG and mechanical torque T_t of wind turbine; (c) dc link voltage v_{dc} ; (d) instantaneous active and reactive grid power p_g , q_g

6. CONCLUSIONS

This paper has presented a wind energy conversion system with direct-driven PMSG. For estimation of angular rotor speed and rotor position the sensorless vector

control of PMSG using a flux linkage with SR-PLL has been used. The simulation results demonstrate the high accuracy of proposed sensorless control strategy. The application of sensorless control based on vector control has many advantages including higher reliability, simplicity and ease of implementation. Additionally, the application of vector control with MPPT algorithm allows conversion of the maximum power obtained from the wind turbine. The simulation results demonstrate that the tip speed ratio and power coefficient of wind turbine are kept at reference and maximum values. The use of VOC for GSC makes it possible to perform the unity power factor. So, the instantaneous reactive power is kept at zero value and the instantaneous active power is only delivered to AC grid. The presented simulation results of the back-to-back wind energy conversion system with PMSG demonstrate high accuracy and fast responses of the vector control method considered.

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