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A REVIEW OF CONTROL METHODS OF WIND TURBINE SYSTEMS WITH PERMANENT MAGNET SYNCHRONOUS GENERATOR

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Abstract. *The paper presents a review of control methods of the wind energy conversion systems with permanent magnet synchronous generator. The modern vector control methods for converter system of variable-speed wind energy conversion have been described. In order to improve the energy efficiency of wind turbine, the maximum power point tracking algorithm has been applied. To verify the effectiveness of the considered configuration and its control strategy, the selected simulation studies have been performed. The obtained study results showed the high effectiveness of the considered configuration and its control methods.*

Keywords: wind energy, permanent magnet synchronous generator, power converter, simulation

PRZEGLĄD METOD STEROWANIA SYSTEMÓW ELEKTROWNI WIATROWYCH Z GENERATOREM SYNCHRONICZNYM O MAGNESACH TRWAŁYCH

Streszczenie. *W artykule przedstawiono przegląd metod sterowania elektrowni wiatrowej z generatorem synchronicznym o magnesach trwałych. Opisano nowoczesne metody sterowania wektorowego dla przekształtnikowych układów elektrowni wiatrowych. W celu zwiększenia skuteczności przetwarzania energii wiatrowej zastosowano algorytm śledzenia mocy maksymalnej. W celu sprawdzenia skuteczności rozpatrywanej topologii i metody sterowania, wybrane badania symulacyjne zostały przedstawione i omówione. Przeprowadzone badania potwierdziły prawidłowość i dużą dokładność sterowania rozpatrywanej topologii i ich metod sterowania.*

Słowa kluczowe: energia wiatrowa, generator synchroniczny PMSG, przekształtnikowe układy, badania symulacyjne

1. Introduction

The application of wind energy conversion systems (WECS) have been increased over the last decades [1, 2, 8, 17]. In WECS the mechanical energy of wind turbine is converted into electrical energy with the help of appropriate electrical generator. Recently the direct-driven permanent magnet synchronous generators (PMSG) are predominant in wind turbine systems due to the possibility of multi-pole design. Among all wind energy generators, the PMSG features with high efficiency and low maintenance cost [2, 13, 15].

In order to convert the electrical energy produced by the generator, the full-rating power converter to interface the generator with the grid must be applied. The applications of converter systems allow to control the speed and electromagnetic torque of the generator and adjust the power flow to the AC grid. Different types of power converter topologies for direct-driven PMSG were presented in the literature [2, 15].

Among the many different wind energy conversion systems, one of the most promising is the direct drive back-to-back converter system. The scheme of back-to-back converter system is presented in figure 1. In this scheme the PMSG is connected to the AC grid through a full-scale back-to-back voltage source converter. This converter system is composed of the machine side converter (MSC) and grid side converter (GSC). The application of back-to-back converter system allows to enhance the performance of the wind energy conversion system.

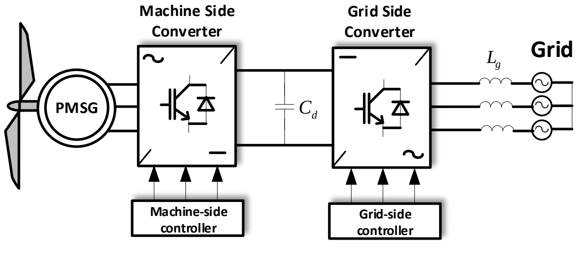

Fig. 1. Configuration of back-to-back variable speed wind energy system with direct driven PMSG

With the use of these types of power converter system, the PMSG is completely decoupled from the grid and can be operated in the wide range of wind speed changes. In this topology the both converters are separately controlled.

As alternative solution for back-to-back converter system is the application of uncontrolled diode bridge with DC/DC boost converter [13, 15]. In the scheme presented in figure 2 the machine side converter is composed of uncontrolled bridge and DC/DC boost converter. This converter system is named as Switch Mode Rectifier. In both topologies the machine side converter is controlled with using the Maximum Power Point Tracking (MPPT) algorithm. The main objective of MPPT algorithm is to maximize the power that the turbine extracts from the wind.

The control technique for the MSC is designated for decoupled control of the electromagnetic torque and stator flux of PMSG. Besides, the control technique for GSC is designated for control of instantaneous active and reactive power. The control strategy for MSC is the Rotor Field Oriented Control (RFOC) and Direct Torque Control (DTC).

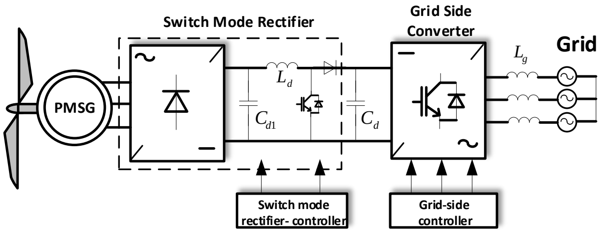

Fig. 2. Configuration of variable speed wind energy system with switch mode rectifier and direct driven PMSG

The main task of the GSC is to control the voltage in the DC-link and the active and reactive power delivered to the AC grid, respectively. The control strategies for the GSC are the Voltage Oriented Control (VOC) and Direct Power Control (DPC).

The aim of the paper is to review of the control methods of wind energy conversion system with PMSG. The paper is divided into 9 sections as follows: section 1 presents the operation of development of wind energy conversion system. Section 2 and 3 are dedicated to the description of the mathematical model of wind turbine and PMSG. The MPPT algorithm and pitch angle controller has been presented in section 4. Section 5 presents the description of the vector control system of the MSC, including RFOC and DTC. The control of SMC has been studied in section 6. The principle of vector control method for GSC has been investigated in section 7, together with VOC and DPC. The simulation results of selected control strategies are presented in section 8. Finally, the section 9 presents the research conclusions.

2. Wind turbine model

The total mechanical power captured by the wind turbine can be expressed through the following relation [1, 3, 5, 12].

$$P_t = 0.5\rho A C_p(\lambda,\beta) v_w^3 \tag{1}$$

where: ρ – air density; $A = \pi R^2$ – area swept by the rotor blades; R –radius of the turbine blade; C_p – power coefficient of the wind turbine; λ – tip speed ratio; β – blade pitch angle; v_w – wind speed.

While the pitch angle β is constant, the C_p is only a function of λ. The tip speed ratio is defined as a ratio of the speed of the blade tip (V_{tip}) to the wind speed v_w.

$$\lambda = \frac{V_{tip}}{v_w} = \frac{\omega_m R}{v_w} \tag{2}$$

where: ω_m – angular speed of turbine rotor.

The turbine power coefficient C_p describes the power extraction efficiency of the wind turbine. The power coefficient can be approximated by the following equation [9, 12]:

$$C_p(\lambda,\beta) = 0{,}5176\left(\frac{116}{\lambda_i} - 0{,}4\beta - 5\right)\cdot \exp^{\left(-\frac{21}{\lambda_i}\right)} + 0{,}0068\lambda \tag{3}$$

$$\lambda_i = \left(\frac{1}{\lambda + 0{,}08\beta} - \frac{0{,}035}{\beta^3 + 1}\right)^{-1} \tag{4}$$

Figure 3 shows the curve of power coefficient C_p as function of tip speed ratio λ and blade pitch angle β. As it can be seen, for each value of angle β the optimal tip speed ratio λ_{opt} exists at which the power coefficient C_p has the maximum value C_{pmax}.

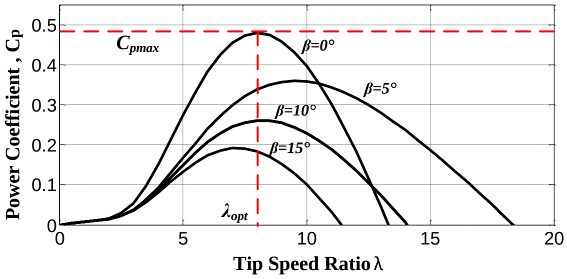

Fig. 3. Power coefficient curves of C_p for different tip speed ratio λ and pitch blade angle β

The typical power characteristics of wind turbine operating at different wind speeds have been shown in figure 4.

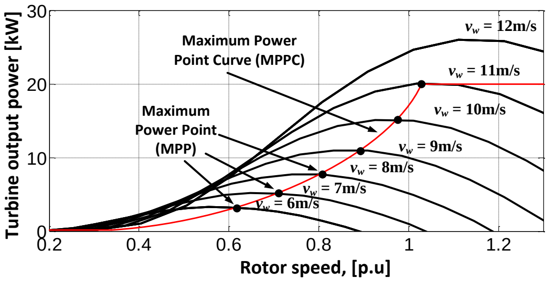

Fig. 4. Characteristics of the *wind turbine power curves as function of rotor angular speed at various wind speeds*

These characteristics represent the wind turbine power curves as function of rotor angular speed ω_m at various wind speeds v_w. From this figure it can be stated, that for each wind speed, there is a maximum power point, that the turbine would extract the maximum power.

3. Model of permanent magnet synchronous generator

The dynamic equations of permanent magnet synchronous generator (PMSG) can be expressed in synchronously rotating *dq* reference frame [4, 13, 15]. The electrical equations of the PMSG are shown in (5) and (6), the electromagnetic torque equation in (7) and the mechanical motion of the wind turbine system equation (8). Electrical and torque equations are expressed in the rotating *dq* frame, where the *d*-axis is aligning with the direction of the rotor flux vector and the *q*-axis is 90^0 ahead.

$$v_{sd} = R_s i_{sd} + L_d \frac{d}{dt} i_{sd} - \omega_e L_q i_{sq} \tag{5}$$

$$v_{sq} = R_s i_{sq} + L_q \frac{d}{dt} i_{sq} + \omega_e L_d i_{sd} - \omega_e \psi_{PM} \tag{6}$$

$$T_e = \frac{3}{2} n_p [\psi_{PM} i_{sq} - (L_d - L_q) i_{sd} i_{sq}] \tag{7}$$

$$T_m + T_e = J\frac{d\omega_m}{dt} + K_f \omega_m \tag{8}$$

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; $L_s = L_d = L_q$ – direct and quadrature stator inductances; ψ_{PM} – flux linkage established by the permanent magnets; n_p – number of pole pairs of PMSG; ω_e, ω_m – electrical and mechanical angular speed of the PMSG, T_e – electromagnetic torque, T_t – mechanical torque of wind turbine, J – moment of inertia of the system turbine and generator, K_f – friction coefficient.

A simplified cross section of PMSG have been presented in figure 5.

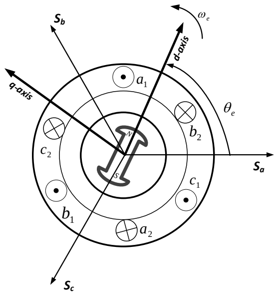

Fig. 5. Simplified cross section of PMSG

4. Maximum power point tracking algorithm and pitch angle control

The total output power from wind energy conversion system depends upon the accuracy at which the peak power point are tracked by MPPT algorithm. The main objective of MPPT algorithm is to maximize the power, that the turbine extracts at different wind speeds. Many MPPT strategies have been proposed in literature [5, 6, 10, 14, 15, 17]. The MPPT algorithm can be classified into three control methods including optimal torque, optimal tip speed ratio and power signal feedback control.

The first method of MPPT is related to the control of the optimal torque of wind turbine [1, 14, 17]. The block scheme of optimal torque control for wind energy conversion system is presented in figure 6.

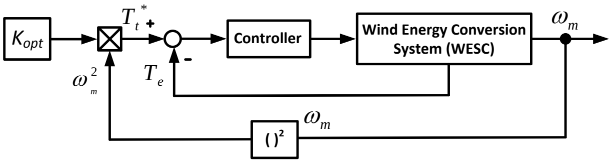

Fig. 6. The block scheme of optimal torque control MPPT method

It can be noticed, that the concept of this methods is based of adjusting the PMSG electromagnetic torque according to the optimal reference torque of wind turbine. The reference mechanical torque T_t^* can be calculated according to curve of optimal torque of wind turbine [17]:

$$T_t^* = \frac{P_{t\max}}{\omega_m} = K_{opt}\omega_{opt}^2 \tag{9}$$

where: K_{opt} – coefficient of wind turbine, which can be calculated as:

$$K_{opt} = 0.5\frac{C_{p\max}}{\lambda_{opt}^3}\cdot\rho\pi R^5 \tag{10}$$

According to the equation (9), it can be stated that the maximum torque of turbine is the function of the second power of the rotational turbine speed.

The second method of MPPT is related to the control of the optimal tip speed ratio. This algorithm allows to regulate the rotational speed of the generator in order to maintain the optimal tip speed ratio at reference value [5, 6, 10, 14]. For implementation of this algorithm the wind speed sensor is required. The block scheme of tip speed ratio control for wind energy conversion system is presented in figure 7.

The maximum power of wind turbine is achieved by maintaining the tip speed ratio to the optimal reference value. This condition is achieved by controlling the rotational speed of wind turbine. At optimal wind speed, the maximum power of wind turbine is produced.

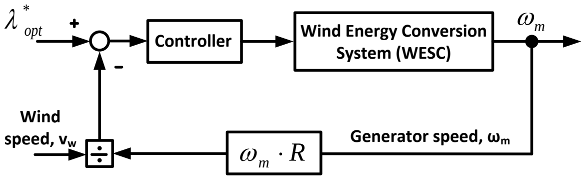

Fig. 7. The block scheme of the tip speed ratio control

The optimal tip speed ratio is constant for a given blade. The optimal speed of the turbine that produces that maximum power is related to λ_{opt} and wind speed v_w can be calculated as:

$$\omega_{opt} = \frac{\lambda_{opt}}{R}v_w \tag{11}$$

From above equation, it can be noticed, that in order to obtain the maximum power from wind, the turbine speed must be adjustable according to the wind speed. In this control method, anemometers are typically required to measure the wind speed.

The third method of MPPT is related to the characteristic of turbine power versus wind speed. This MPPT control technique is based on the knowledge of the wind turbine maximum power curve presented in figure 4 [14, 15, 17]. According to equation (1), the curve of the maximum wind turbine power versus shaft speed can be described as:

$$P_{opt} = K_{opt}\omega_{opt}^3 \tag{12}$$

Figure 8. Shows the block diagram of power signal feedback control of wind energy conversion system.

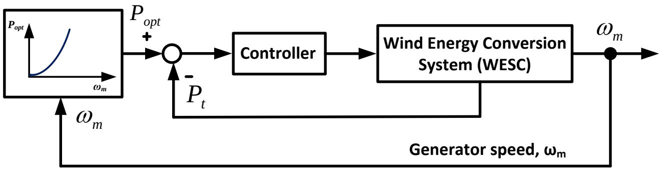

Fig. 8. The block scheme of power signal feedback control

As the wind speed increases above the rated speed the aerodynamic power control of blades is required to keep the power at the rated value. This task is performed by using the pitch angle control.

The pitch angle control is designed to limit either the active power generation or the rotor speed, when it is extremely high [8, 9, 12, 16]. When the wind speed exceeds the rated value the pitch controller will reduce the angle of blades. When the wind speed is below the rated speed, the angle of blade is kept at it optimal value. The schematic diagram of the turbine blade pitch angle controller is shown in figure 9.

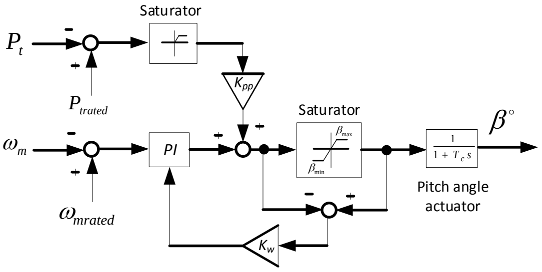

Fig. 9. Wind turbine pitch angle controller

In the pitch angle controller, the reference speed of wind turbine is compared with the measured rotor speed. The PI controller with anti-windup circuits sets the output value of the pitch angle *β*.

The pitch actuator is considered as first-order dynamic system with amplitude and rate limitation.

5. Control system of machine side converter

The control strategy of the machine side converter (MSC) ensures the decoupled control of the electromagnetic torque and stator flux.

The block scheme of the RFOC strategy with Space Vector Modulation (SVM) for the MSC is shown in figure 10.

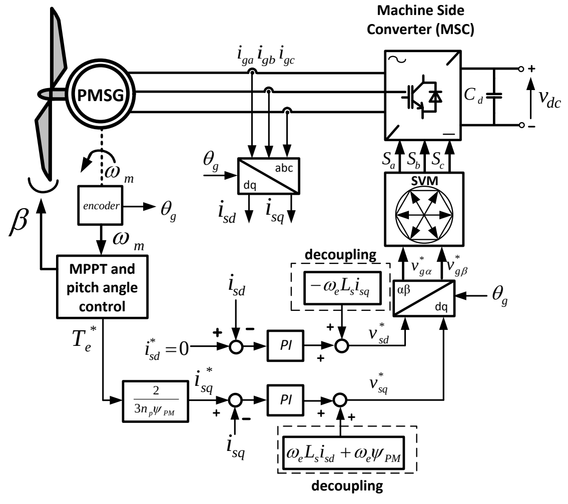

Fig. 10. Control diagram of RFOC for Machine Side Converter

The control scheme of RFOC for MSC consists of two control loops with PI controllers. Consequently, the PI controllers operate independently from each other.

The two control loops regulate the stator current vector components to follow the reference values i_{sq}^*, i_{sd}^*. The reference stator current i_{sq}^* components can be calculated as [15]:

$$i_{sq}^* = \frac{2T_e^*}{3(n_p\psi_{PM})} \tag{13}$$

where: T_e^* is reference electromagnetic torque designated from MPPT algorithm.

In order to obtain the maximum value of generator electromagnetic torque at minimum stator current, the *d-axis* component of the stator current i_{sd} is set to zero [1, 15]. From this dependency it is apparent, that the electromagnetic torque is controlled directly by *q-axis* component of the stator current i_{sq}. The resultant control signals from PI controllers are the required *dq* components of stator voltages v_{sd}^* and v_{sq}^* established for MSC control. The required switching signals for machine side converter are generated through SVM. In order to improve the dynamic performance of RFOC, the decoupling circuits should be added to the control system.

Recently the Direct Torque Control (DTC) is an alternative to the RFOC method in high performance applications due to the advantages of fast response of the electromagnetic torque [4, 11]. The block scheme of the DTC strategy with Space Vector Modulation (SVM) for the machine side converter is shown in figure 11.

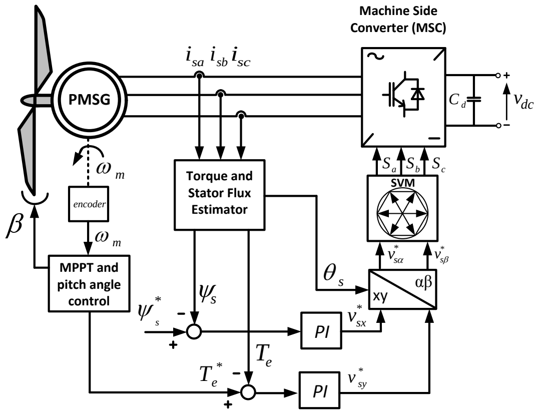

Fig. 11. Control diagram of DTC for Machine Side Converter

The DTC-SVM ensures the lower harmonic of the stator currents and allows reducing the electromagnetic torque ripples. The application of SVM allows maintaining the constant switching frequency in comparison to DTC with switching table [11].

In the DTC strategy, stator flux vector and electromagnetic torque are controlled directly and independently.

The control scheme of DTC-SVM consists of two control loops. The two control loops with PI controllers regulate the magnitude of stator flux vector ψ_s and the electromagnetic torque T_e of the PMSG. The stator flux magnitudes and the values of electromagnetic torque can be estimated according to the mathematical model of PMSG. The magnitude of the stator flux vector can be calculated as [4, 11]:

$$\psi_s = \sqrt{\psi_{s\alpha}^2 + \psi_{s\beta}^2} \tag{14}$$

where: $\psi_{s\alpha}$, $\psi_{s\beta}$ – stator flux vector components in $\alpha\beta$ system.

The stator flux linkages $\psi_{s\alpha}$, $\psi_{s\beta}$ are estimated by the following equations:

$$\psi_{s\alpha} = \int (v_{s\alpha} - R_s i_{s\alpha}) dt \tag{15}$$

$$\psi_{s\beta} = \int (v_{s\beta} - R_s i_{s\beta}) dt \tag{16}$$

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

The magnitude of the stator flux vector ψ_s and the electromagnetic torque T_e are compared with their reference values. The both error signals are sent to two PI controllers. The resultant control signals from PI controllers determine the reference stator voltages v_{sx}^* and v_{sy}^* for the MSC. The required switching signals for machine side converter are generated through SVM.

6. Control of switch mode rectifier

To reduce the costs of wind energy conversion systems, the configuration of back-to-back voltage source converter can be replaced by uncontrolled diode bridge and DC/DC boost converter [15]. This topology is known as Switch Mode Rectifier (SMR). The diode bridge converts the generator AC voltage to DC voltage and this voltage is then boosted by DC/DC boost converter.

The SMR configuration in comparison to the back-to-back converter system is more cost-effective [6, 13]. However, the stator current is more distorted due to the diode bridge causing the torque ripple [15]. The application of DC/DC boost converter allows to the control of electromagnetic torque of PMSG with using the Maximum Power Point Tracking (MPPT) algorithm [5, 6, 13]. The block scheme of optimal torque control of DC/DC has been presented in figure 12.

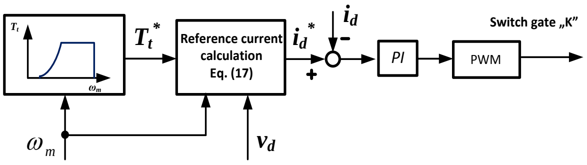

Fig. 12. The principle of Switch Mode Rectifier control strategy with optimal torque control

The reference torque of wind turbine is calculated according to equation (9). The condition of optimal torque control is fulfilled by the proper control strategy of the switch mode rectifier. The DC current of boost converter can be calculated as:

$$i_d^* = \frac{T_t^* \omega_m}{v_d} \tag{17}$$

The control deviation between the reference and measured DC current is sent to PI regulator, which is used to designate the duty cycle *D* of the switch *K*.

The another control method for DC/DC boost converter with optimal speed has been presented in figure 13 [5].

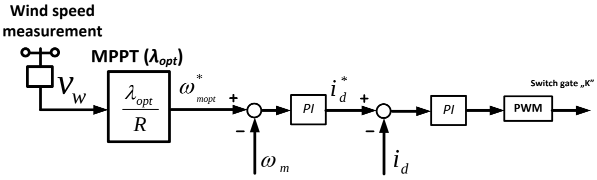

Fig. 13. The principle of Switch Mode Rectifier control strategy with optimal tip speed ratio

The control strategy consists of two control loops with PI controllers. The outer control loop regulates the speed of generator to follow the optimal speed obtained from MPPT algorithm. The output signal from PI controller is the reference value of DC current of boost converter. The inner control loop regulates the DC current. The required control signal from PI controller determines the reference duty cycle of boost converter.

7. Control system of grid side converter

The control objective for the Grid Side Converter (GSC) is to stabilize the DC-link voltage and to send the maximum power generated from wind turbine to the AC grid. One of the most often applied strategies is a Voltage Oriented Control [1, 3, 6, 15].

In the VOC system the *d-axis* is aligned with the grid voltage vector. The proper orientation of the reference frame according to angle position of the grid voltage vector is obtained from the PLL (Phase-Locked-Loop) block [7]. The PLL estimates the grid voltage vector, for coordinates transformation. The block scheme of PLL is presented in figure 14.

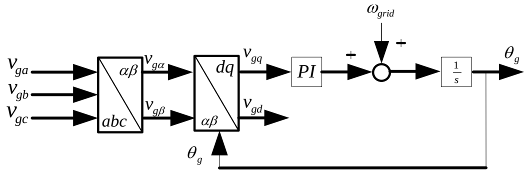

Fig. 14. Block scheme of Phase Locked Loop id dq-frame

The inputs of PLL block are the 3-phase grid voltages and the output is the angle θ_g of grid voltage vector.

The block scheme of VOC for GSC control system has been presented in figure 15. The GSC control system is based on grid voltage orientation control. The control of VOC for grid side converter consists of three control loops with PI controllers.

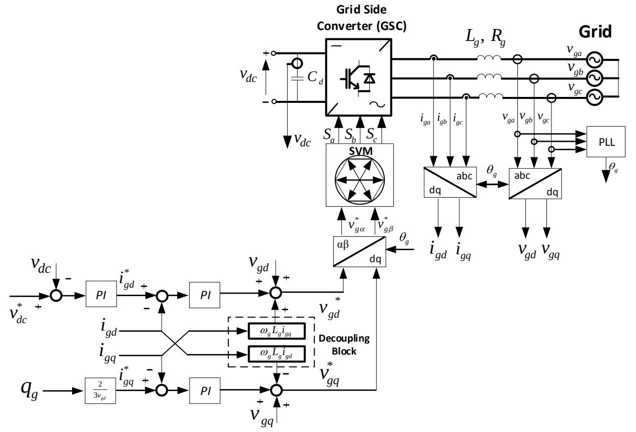

Fig. 15. Control diagram of VOC for Grid Side Converter

The outer control loop regulates the DC link voltage of GSC. The output value from this PI controller determines the reference value of grid current vector component i_{gd}^*. Two inner control loops regulate the components i_{gd} and i_{gq} of grid current vector. The reference components v_{gd}^* and v_{gq}^* of grid voltage are then transformed to system α-β and are sent to the block of SVM. The condition of unit power factor operation is achieved when i_{ga}^* is set to zero. In order to improve the dynamic performance of VOC, the decoupling circuits should be added.

However, nowadays the Direct Power Control method has gained much attention, due to its simplicity, fast response and high efficiency [6, 7].

Figure 16 shows the block scheme of Direct Power Control for GSC. The principle of Direct Power Control is controlling directly the instantaneous active and instantaneous reactive power. In order to obtain the constant switching frequency, the application of Space Vector Modulation is applied.

The control algorithm of DPC-SVM is based on the instantaneous active and instantaneous reactive power estimation as:

$$p_g = \frac{3}{2}\left(v_{g\alpha} i_{g\alpha} + v_{g\beta} i_{g\beta}\right) \tag{18}$$

$$q_g = \frac{3}{2}\left(v_{g\alpha} i_{g\beta} - v_{g\beta} i_{g\alpha}\right) \tag{19}$$

where: $v_{g\alpha}$, $v_{g\beta}$ – components of the grid voltage vector, $i_{g\alpha}$, $i_{g\beta}$, – components of the grid current vector in the stationary $\alpha\beta$ frame.

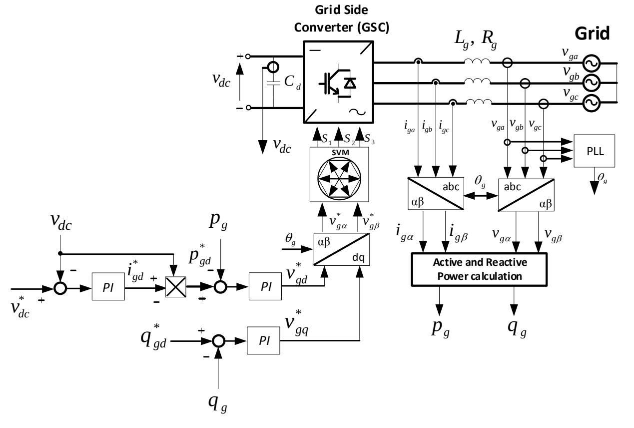

Fig. 16. Control diagram of DPC for Grid Side Converter

In the control of DPC-SVM three control loops with PI controllers have been applied. The outer control is responsible for control of DC link voltage. The active grid power reference is calculated on the base of multiplication of the measured DC voltage of the converter and the reference value of i_{gd}*.

The two inner control loops regulate the instantaneous active and reactive grid power. The estimated values of active and reactive power are compared with the reference values. In the same way, as strategy of VOC the reactive power is set to zero to achieve the operation at unit power factor.

The output value 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 SVM.

8. Simulation results

In order to evaluate of the behavior of the wind energy conversion system with PMSG, the digital simulations have been performed. The conducted simulation studies were carried out using the MATLAB/Simulink environment. The data and parameters of wind turbine and PMSG have been presented in Table 1 and Table 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 Permanent Magnet Synchronous Generator

PMSG parameter	Value
Rated power; P_N	20 kW
Stator resistance; R_s	0.1764 Ω
Stator *dq-axis* inductance; L_d, 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

For the purposes of this article in the control of MSC the Rotor Field Oriented Control has been chosen, which control structure has been presented in figure 10. In the control of GSC the Voltage Oriented Control presented in figure 15 has been studied.

The waveforms of simulation results have been presented in figures 17 and 18. The considered wind speed variation has been presented in figure 17a. Figure 17b shows the responses of generator angular speed ω_m caused by wind speed changes. The generator speed increases gradually to the established values due to rotor inertia.

Figure 17c presents the responses of the stator current vector components i_{sd}, i_{sq} caused by the variations of wind speed. The component i_{sd} of the stator current vector is kept at zero value in order to obtain the maximum electromagnetic torque of generator with minimum current. The responses of component i_{sq} of the stator current vector have similar waveforms as the variations of the wind speed. The waveforms of tip speed ratio and the pitch angle response for step changes for wind speed is shown in figure 17d. The tip speed ratio is maintained its maximum value equal to $\lambda_{opt}=8.1$. However, when the wind speed is higher than the rated wind, the proper operation of pitch angle controller can be observed. For this reason, the angle of blade is increasing causing the decrease of tip speed ratio and power coefficient.

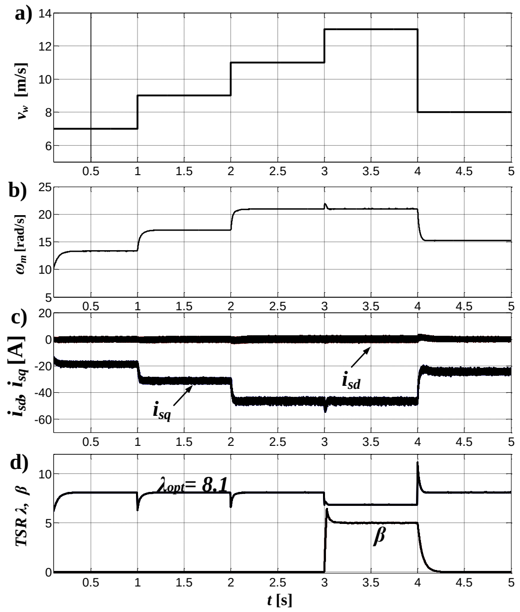

Fig. 17. Waveforms of: a) wind speed v_w; b) measured speed ω_m of PMSG; c) stator current vector components i_{sd}, i_{sd}; d) tip speed ratio λ and blade pitch angle β

The waveform of DC link voltage has been presented in figure 18a. The average value of DC link voltage is quite constant. Figure 18b shows the waveforms of the phase grid voltage and phase grid current. It can be stated, that the phase grid voltage and phase grid current are in phase, respectively. The waveforms of instantaneous active power p_g and reactive power q_g have been presented in figure 18c. It can be noticed, that the instantaneous reactive power is maintaining at zero values. So, only the instantaneous active power is fully delivered to the AC grid.

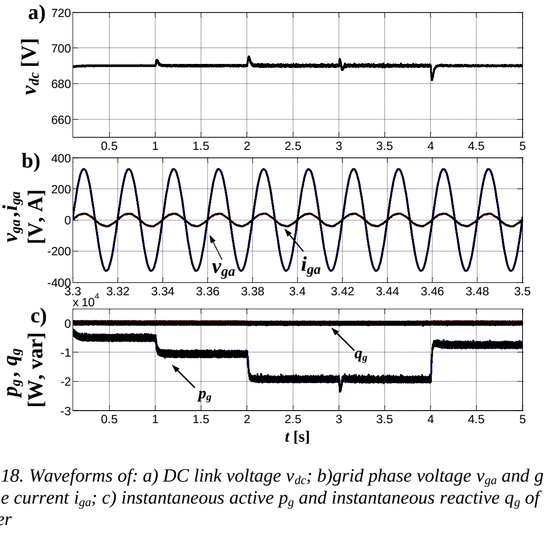

Fig. 18. Waveforms of: a) DC link voltage v_{dc}; b)grid phase voltage v_{ga} and grid phase current i_{ga}; c) instantaneous active p_g and instantaneous reactive q_g of grid power

9. Conclusions

This paper has presented the review of control methods of wind turbine systems with direct driven PMSG. The back-to-back converter system with machine side converter and grid side converter has been described. The uncontrolled diode bridge and DC/DC boost converter has been considered as machine side converter. The efficiency of proposed control strategy including Rotor Field Oriented Control for machine side converter and Voltage Oriented Control for grid side converter have been tested by digital simulation. The simulation results demonstrate the high accuracy of considered control strategy. The application of MPPT algorithm allows to achieve the maximum power from the wind despite to wind speed variation. The simulation results present the tip speed ratio is kept at reference and maximum value. In order to achieve limitation of the aerodynamic power produced by the wind turbine, the pitch angle controller has been used. The application of VOC control for GSC enables to keep the DC link voltage at desired values and allows to adjust the instantaneous active and reactive power. In summary, it can be stated that the described vector methods of WECS provided the high performance of control. However, the suitable selection of control methods are descended from specific the requirements of particular applications which are needed.

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