

THE PERFORMANCE OF DIRECT-DRIVEN VARIABLE SPEED WIND TURBINE WITH PMSG AND CONVERTER SYSTEMS*

PIOTR GAJEWSKI, KRZYSZTOF PIEŃKOWSKI

Wrocław University of Science and Technology, Department of Electrical Machines, Drives and Measurements, Wybrzeże Wyspiańskiego 27, 50-370, Wrocław, Poland,
e-mail: piotr.gajewski@pwr.edu.pl, krzysztof.pienkowski@pwr.edu.pl

Abstract: The article presents control strategy for the operation of a variable-speed wind energy conversion system with permanent magnet synchronous generator (PMSG). The electrical system of wind turbine consists of PMSG, Switch Mode Rectifier (SMR) and Grid Side Converter (GSC). The SMR converter is composed of an uncontrolled diode bridge and a DC/DC boost converter. In the control of the DC/DC boost converter the algorithm of Maximum Power Point Tracking (MPPT) has been applied. The MPPT algorithm allows the wind turbine to operate at maximum value of power coefficient in a wide range of wind speed. In the control of Grid Side Converter a method of Voltage Oriented Control (VOC) has been applied. High efficiency and accuracy of this control system were confirmed by simulation studies.

Keywords: *wind turbine, PMSG, machine and grid side converter, MPPT*

1. INTRODUCTION

The number of wind energy systems has grown rapidly over the last decade [1]–[4]. According to the construction of the wind turbine system, the turbines are classified as the geared and the direct-driven types [5], [11]. Currently, the direct-driven wind turbine systems with permanent magnet synchronous generator (PMSG) are most often applied [5]. The PMSG generators are widely used because of their high reliability and simple control structure. The PMSG generator can be constructed with a large number of poles and can be operated as the direct-driven system without gearbox. Nowadays the direct-driven PMSG is suitable for the wind turbine system application due to its high power, high efficiency, high torque, no gear and simple control methods. This results in a reduction of installation and maintenance costs and provides an advantage over the other types of generators [11].

* Manuscript received: March 10, 2016; accepted June 20, 2016.

In wind power systems with PMSGs the power converters should be applied in order to convert and control the electrical energy produced. Converter systems of wind energy conversion can be divided into two common topologies: the high and low cost systems [1], [5], [7], [11].

The first topology is designed as a full size back-to-back configuration with two voltage source converters: Machine Side Converter (MSC) attached to the stator winding of the PMSG and Grid Side Converter (GSC) attached to the grid [2], [3], [5]. A dc-link capacitor is connected between two converters (MSC and GSC). This capacitor provides decoupling between the Machine Side Converter and Grid Side Converter.

The second widely used topology is presented in Fig. 1. This configuration is much cheaper than the conventional back-to-back system. The system consists of two basic converters: Switch Mode Rectifier (SMR) and Grid Side Converter (GSC). The Switch Mode Rectifier contains two converters: diode bridge rectifier and DC/DC boost converter. In this topology, the uncontrolled rectifier is connected to the PMSG terminals. The dc output voltage of the rectifier is converted by DC/DC boost converter. The additional capacitor C_{d1} is connected between the rectifier and DC/DC converter. The DC/DC boost converter provides the step-up of dc voltage obtained from the diode rectifier. Grid Side Converter is connected to the grid through a 3-phase inductance filter. The dc link capacitor C_d is connected between the DC/DC converter and GSC. The principle of control of the boost converter has been based on the application of the Maximum Power Point Tracking (MPPT) algorithm [1], [2], [7], [9]. This algorithm ensures the extracting of maximum power from the wind turbine.

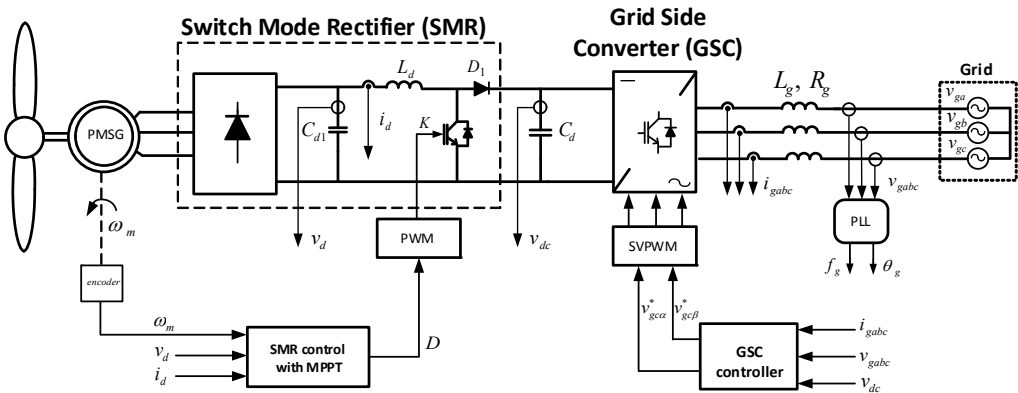


Fig. 1. Scheme of wind turbine system with direct-driven PMSG generator and converter systems

The aim of the paper is to analyze the converter system with PMSG presented in Fig. 1 in order to investigate the effectiveness of the wind energy conversion systems.

The mechanical system of wind turbine and direct driven PMSG is considered as reduced one-mass system. The studies considered in this paper are the continuation of studies presented in [2], [3]. In comparison with the previous papers, in this article, the other topology of MSC converter, which consists of SMR converter has been described and investigated.

2. ANALYSIS OF MPPT ALGORITHM

In the wind turbine system considered the MPPT algorithm has been applied, which ensures the possibility to obtain the maximum mechanical power of converted wind energy. The output mechanical power of wind turbine can be calculated as [5]–[9], [12]

$$P_t = 0.5 \rho \pi R^2 v_w^3 C_p(\lambda, \beta) \quad (1)$$

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.

Considering the relationship between the wind speed and tip speed ratio [7], [11], the wind turbine power can be expressed as a function of the rotational speed ω_m of wind turbine

$$P_t = 0.5 \rho \pi R^5 \frac{C_p(\lambda, \beta)}{\lambda^3} \omega_m^3. \quad (2)$$

The maximum value of wind turbine power $P_{t \max}$ is specified at maximum value of $C_{p \max}$, which is obtained at optimal value of tip speed ratio λ_{opt} . Replacing λ by λ_{opt} and inserting $C_p(\lambda, \beta) = C_{p \max}(\lambda_{opt}, \beta)$ the maximum power of the wind turbine can be expressed as [4]

$$P_{t \max} = K_{opt} \omega_m^3 \quad (3)$$

where K_{opt} – coefficient of wind turbine

$$K_{opt} = 0.5 \rho \pi R^5 \frac{C_{p \max}(\lambda_{opt}, \beta)}{\lambda_{opt}^3}. \quad (4)$$

According to equations (3) and (4) it can be stated that the maximum torque of turbine is the function of the second power of the rotational turbine speed and can be expressed as follows

$$T_{t \max} = \frac{P_{t \max}}{\omega_m} = K_{opt} \omega_m^2. \quad (5)$$

In order to obtain the maximum power from the wind, the turbine should operate at optimum tip speed ratio λ_{opt} by using the method of optimal torque control. The optimal torque control means that the wind turbine is operated at maximum power in the wide range of turbine rotational speeds. The condition of optimal torque control is fulfilled by the proper control strategy of the switch mode rectifier. The control strategy of this converter is shown in Fig. 2.

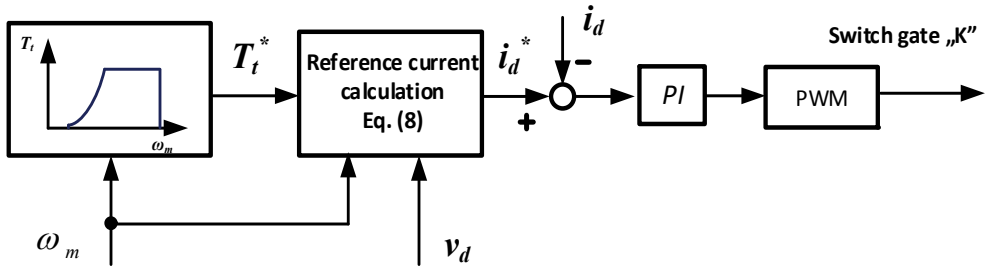


Fig. 2. The principle of Switch Mode Rectifier control strategy

The control of the DC/DC converter is based on control of dc current i_d by using PI current regulator and pulse width modulator (PWM), which generates the control signals to the transistor switch K . The optimal torque control strategy of switch mode rectifier (SMR) includes the following steps:

- determination of the reference coefficient K_{opt} of wind turbine in accordance with the parameters of the turbine

$$K_{opt} = 0.5 \rho \pi R^5 C_{p \max} / \lambda_{opt}^3, \quad (6)$$

- determination of the reference torque T_t^* of wind turbine on the basis of measured signal of angular speed of PMSG

$$T_t^* = K_{opt} \omega_m^2, \quad (7)$$

- determination the reference dc current i_d^* of DC/DC boost converter

$$i_d^* = T_t^* \omega_m / v_d. \quad (8)$$

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 of the DC/DC boost converter. It is assumed that the PWM switching frequency of DC/DC boost converter is equal to 10 kHz. The low frequency of PWM of boost converter can cause the problems with tracking of the maximum power curve. For the purpose of this study the values of capacity in the DC/DC boost converter C_{d1} and Grid Side Converter C_d were assumed as equal to $C_{d1} = C_d = 2000 \mu\text{F}$.

3. CONTROL SYSTEM OF GRID SIDE CONVERTER

The Grid Side Converter controls the active and reactive power delivered to the AC grid and the dc-link voltage v_{dc} [7], [10], [11]. The principle of GSC control is based on grid voltage Vector Orientation Control (VOC). In the implementation of VOC strategy the d -axis of the synchronous reference frame is aligned with the grid voltage vector \underline{V}_g . The angle position θ_g of the grid voltage vector is determined by the Phase-Locked Loop (PLL) block. The basic scheme of the PLL system is a feedback system with PI-regulator tracking the phase angle of grid voltages. The inputs of PLL block are the 3-phase grid voltages and the output is the angle θ_g of grid voltage vector.

The equations of grid side circuits of GSC for VOC control have the following form [2], [11]

$$v_{gd} = V_g = R_g i_{gd} + L_g \frac{d}{dt} i_{gd} - \omega_g L_g i_{gq} + v_{gcd}, \tag{9}$$

$$v_{gq} = 0 = R_g i_{gq} + L_g \frac{d}{dt} i_{gq} + \omega_g L_g i_{gd} + v_{gcq}, \tag{10}$$

where v_{gd} , v_{gq} , V_g – the dq -axis components and the magnitude of the grid voltage vector; i_{gd} , i_{gq} – the dq -axis components of the grid current vector; v_{gcd} , v_{gcq} – the dq -axis components of the voltage vector of Grid Side Converter; L_g , R_g – inductance and resistance of the grid filter; ω_g – angular frequency of the grid phase voltages.

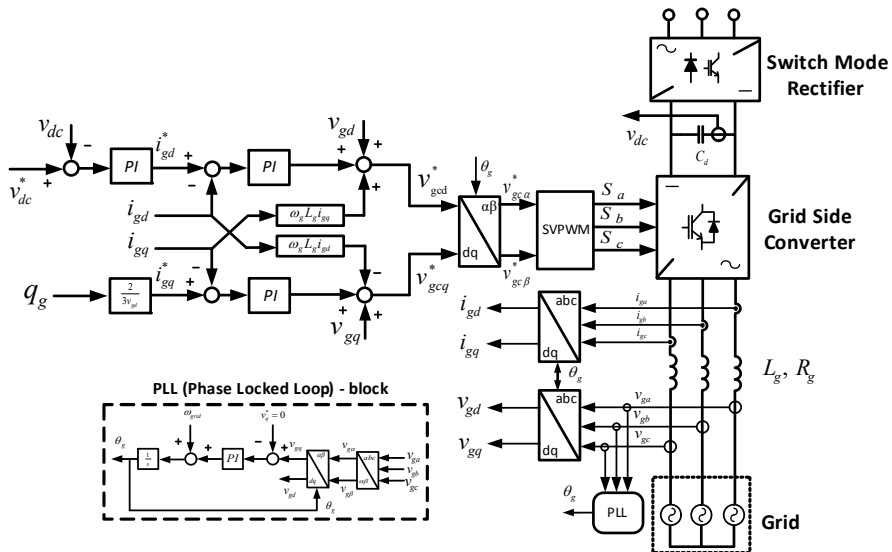


Fig. 3. Scheme of control system of Grid Side Converter

The block control scheme of GSC system is presented in Fig. 3. In the VOC control system of GSC three control loops with PI controllers have been applied. The control of active and reactive grid power can be achieved by controlling the d -axis and q -axis of grid current vector components, respectively. For unit power factor the q -axis component of grid current vector is controlled to be zero. The d -axis component of grid current vector is controlled to deliver the active power flowing from the GSC to the grid. The outer loop of voltage control is responsible for the control of DC link voltage of GSC. The reference components i_{gd}^* , i_{gq}^* of grid current vector are compared with the components i_{gd} , i_{gq} of grid current vector obtained from measure and transformation of grid phase currents.

The error signals are sent to two PI controllers. In order to obtain good properties of control system the applications of additional decoupled circuits are necessary and have been applied in the control system. Thus the active and reactive power can be controlled directly only by i_{gd} and i_{gq} , respectively. In the common control systems applied the reactive power reference is set to zero to perform the operation at unity power factor. The reference components v_{gcd}^* and v_{gcq}^* of output voltage vector of GSC are then transformed to α - β system and sent to the block of SVPWM.

4. SIMULATION RESULTS

The proposed control strategy for wind energy conversion system with PMSG has been simulated in MATLAB/SIMULINK. The data and parameters of the wind turbine and PMSG system under study are given in Table 1 and Table 2.

Table 1. Wind turbine parameters

Parameter	Value
Rated power P_t	5 kW
Rotor radius R	2.8 m
Power coefficient C_{pmax}	0.47
Air density ρ	1.225 kg/m ³

Table 2. Data and parameters of PMSG

PMSG Parameter	Value
Rated power P_N	5 kW
Rated frequency f_N	36 Hz
Rated torque T_N	200 Nm
Stator resistance R_s	1.5 Ω
Stator dq -axis inductance L_d, L_q	14.04 mH
Stator rated phase current I_{sN}	15 A
Total moment of inertia J	0.4 kgm ²
Number of pole pairs p_b	8

The simulation results are presented in Figs. 4–12. Figure 4 shows the established wind speed variation for the period of a 10 s simulation, that has been used for simulations.

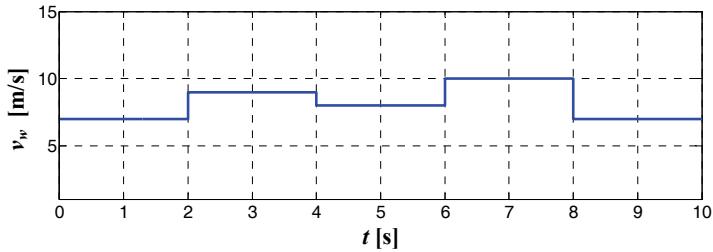


Fig. 4. Waveform of wind speed v_w

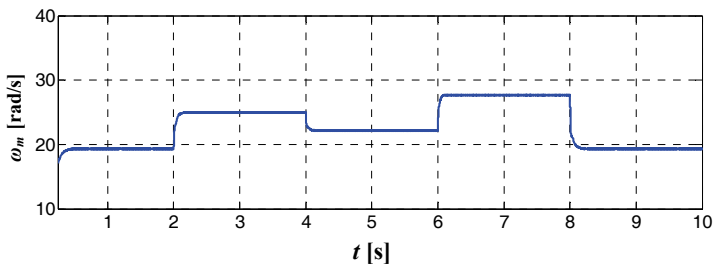


Fig. 5. Waveform of measured speed ω_m of PMSG

For the wind speed variation considered the simulation studies of wind energy conversion system with control circuits have been developed. The chosen simulation results are presented below.

Figure 5 shows the waveform of the measured angular speed ω_m of PMSG. It can be stated that according to the waveform of wind speed variation the angular speed of the PMSG changes approximately in the same way as the real change of the wind.

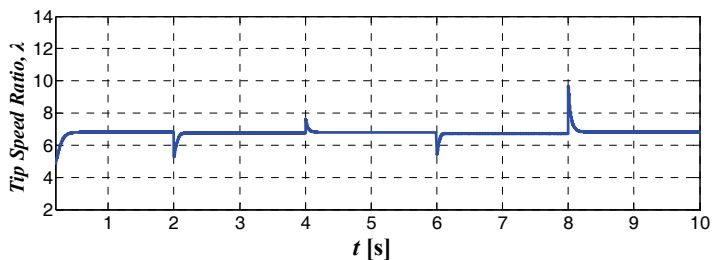


Fig. 6. Waveform of tip speed ratio λ

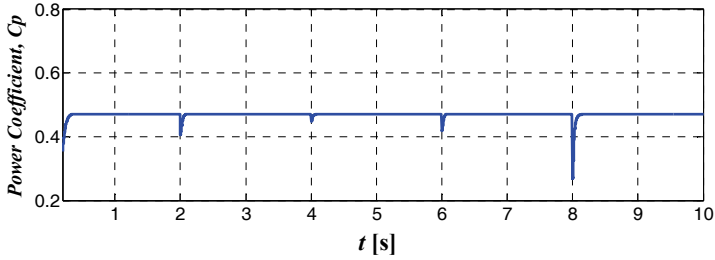


Fig. 7. Waveform of power coefficient C_p of wind turbine

The waveforms of tip speed ratio λ and power coefficient C_p at various wind speeds are presented in Figs. 6 and 7. It can be noticed that the tip speed ratio and power coefficient are kept by the control systems at their optimum values despite the wind speed variations.

The time variations of the mechanical torque T_t of the wind turbine and the electromagnetic torque T_e of PMSG generator are presented in Fig. 8. In this case, the waveforms of PMSG electromagnetic torque are approximately similar to the waveforms of the mechanical torque of wind turbine.

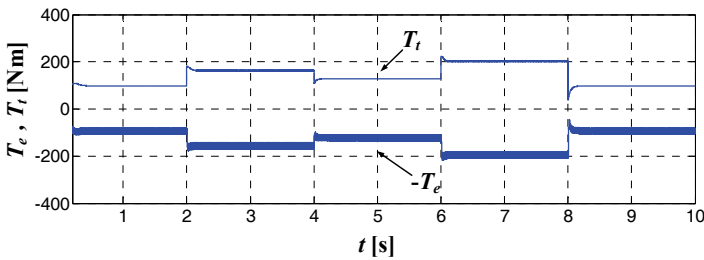


Fig. 8. Waveforms of electromagnetic torque T_e of PMSG and mechanical torque T_t of wind turbine

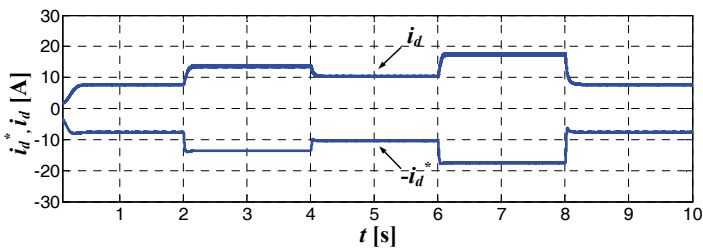


Fig. 9. Waveforms of reference dc current i_d^* and measured dc current i_d of Switch Mode Rectifier

Figure 9 shows the waveforms of reference dc current i_d^* and measured average dc current i_d of the DC/DC boost converter. It can be stated that the controlled current i_d is tracking the reference values i_d^* . In this way, the condition of MPPT control algorithm is fulfilled. Figure 10 shows the waveforms of the dc input v_d and output voltage v_{dc} of DC/DC converter. The waveforms confirm the boost operation of DC/DC converter because the output dc voltage is much greater than the input dc voltage.

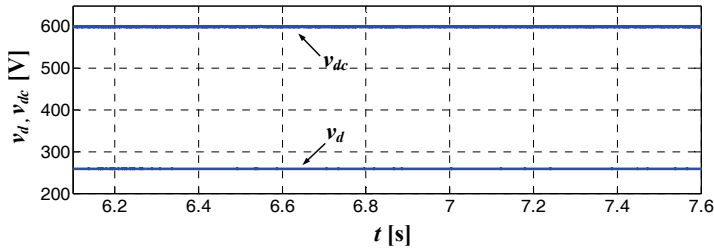


Fig. 10. Waveforms of dc link voltage v_d and dc link v_{dc} voltage

The simulation results for the operation and control of GSC are presented in Figs. 11 and 12. Figure 11 shows the components i_{gd} and i_{gq} of the grid current vector. It can be stated that the component i_{gq} is maintaining zero values, because in the control system it was assumed that only the active power will be delivered to AC grid. It is provided that the reference value of i_{gq} component of grid current vector should always be equal to zero. Simulation results presented in Fig. 11 show that this condition is fulfilled and the measured component i_{gq} of grid current vector is kept with great accuracy at a value close to zero.

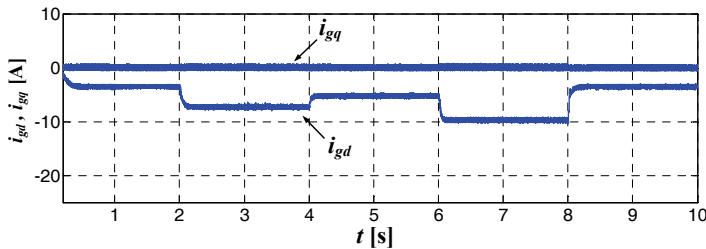


Fig. 11. Waveforms of grid current vector components i_{gd} , i_{gq}

Figure 12 presents the waveforms of phase voltage and grid current for one of the grid phases. It can be noticed that the waveforms of grid phase current and phase voltage are in phase. This confirmed that the only active power is delivered to AC grid and that the required condition for operation with unity power factor is fulfilled.

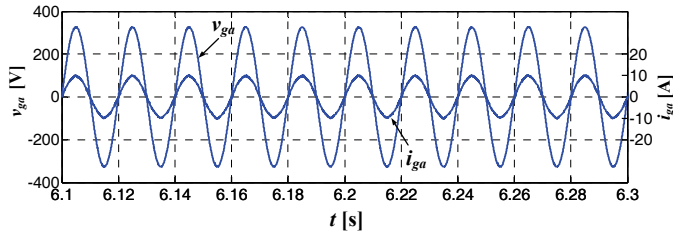


Fig. 12. Waveforms of grid phase voltage v_{ga} and grid phase current i_{ga}

5. CONCLUSIONS

The control structure approach of variable-speed wind turbine with direct-driven PMSG and converter system has been presented. In the control of DC/DC boost converter the MPPT algorithm has been applied. For control of Grid Side Converter, the VOC method has been applied. VOC control makes it possible to keep the DC link voltage to reference value and to adjust the quantity of the active and reactive powers delivered to the AC grid. Reactive power delivered into the AC grid is controlled to zero.

From the simulation results, it can be stated that the maximum power extraction control algorithm at the SMR confirmed the operation of the MPPT algorithm. The simulation results proved that the proposed control scheme of DC/DC converter and GSC have a good performance to obtain the maximum power from wind turbine and to obtain unit power factor, respectively. The high efficiency of the control system considered has been confirmed.

REFERENCES

- [1] EL HANI S., GUEDIRA S., EL ALAMI N., *Maximum Power Tracking Control Wind Turbine Based on Permanent Magnet Synchronous Generator with Complete Converter*, International Journal of Smart Grid and Clean Energy, 2014, Vol. 3, No. 1, 15–21.
- [2] GAJEWSKI P., PIENKOWSKI K., *Control of a Variable Speed Wind Turbine System With PMSG Generator*, Maszyny Elektryczne – Zeszyty Problemowe, 2015, Vol. 107, No. 3, 75–90.
- [3] GAJEWSKI P., PIENKOWSKI K., *Analysis of a Wind Energy Converter System with PMSG Generator*, Czasopismo Techniczne – Elektrotechnika, 2015, Vol. 8, No. 1-E, 219–228.
- [4] HUSSEIN M.M., SENJYU T., ORABI M., WAHAB A.A., HAMADA M.M., *Control of a Variable Speed stand Alone Wind Energy Supply System*, IEEE International Conference on Power and Energy PE-Con, Kota Kinabalu, 2012, 71–76.
- [5] KHATER F., OMAR A., *A Review of Direct Driven PMSG for Wind Energy Systems*, Journal of Energy and Power Engineering, 2013, 1592–1603.
- [6] LAZAROV V., ROYE D., SPIROV D., ZARKOV Z., *New Control Strategy for Variable Speed Wind Turbine with DC-DC converter*, 14th International Power Electronics and Motion Control Conferences EPE-PEMC, 2010, 120–124.

- [7] MALINOWSKI M., MILCZAREK A., KOT R., GORYCA Z., SZUSTER T., *Optimized Energy-Conversion System for Small Wind Turbines: Renewable Energy Sources in Modern Distributed Power Generation System*, IEEE Power Electronics Magazine, 2015, Vol. 2, No. 3, 16–30.
- [8] MAYOUF M., ABDESSEMED R., *Comparative Study of a Small Size Wind Generation System Efficiency for Battery Charging*, Serbian Journal of Electrical Engineering, 2013, Vol. 10, 261–274.
- [9] ROLAK M., KOT R., MALINOWSKI M., GORYCA Z., *AC/DC Converter with Maximum Power Point Tracking Algorithm for Complex Solution of Small Wind Turbine*, Przegląd Elektrotechniczny, 2011, Vol. 87, No. 6, 91–96.
- [10] SAYEEF S., MENDIS N., MUTTAQI K., PERERA S., *Enhanced Reactive Power Support of a PMSG Based Wind Turbine for a Remote Area Power System*, 20th Australasian Universities Power Engineering Conference AUPEC, 2010, 1–8.
- [11] WU B., YONGQIANG L., NAVID Z., SAMIR K., *Power Conversion and Control of Wind Energy*, John Wiley & Sons, INP, Publication 2011.
- [12] YADAV M.K., UPADHAYAY A.K., *Power Flow Control of Permanent Magnet Synchronous Generator Based Wind Energy Conversion System with DC-DC Converter and Voltage Source Inverter*, International Journal of Electronic and Electrical Engineering, 2014, Vol. 7, No. 8, 803–814.