Piotr Gajewski
Wrocław University of Science and Technology, Wrocław

STAND-ALONE WIND ENERGY CONVERSION SYSTEM WITH PMSG AND ENERGY STORAGE

AUTONOMICZNY SYSTEM PRZETWARZANIA ENERGII WIATRU Z GENERATOREM PMSG I UKŁADEM AKUMULACJI ENERGII

Abstract: The paper presents the stand-alone wind energy conversion system with permanent magnet synchronous generator (PMSG). The considered system is composed of wind turbine, PMSG, Switch Mode Rectifier (SMR), bidirectional DC/DC converter and Load Side Converter (LSC). The battery energy storage device is connected to the wind energy conversion system through the DC/DC bidirectional converter. In the control of SMR the maximum power point tracking (MPPT) algorithm including Hill Climbing Search method (HCS) has been applied. The application of HCS algorithm allows obtaining of the maximum power from the wind turbine independently from wind turbine power characteristics. The control of the LSC allows regulating the value of the amplitude and frequency of the load voltage. In order to obtain high power quality of energy the three-phase LC filter has been used in the output circuits of the LSC. The simulation studies have been carried out in order to evaluate the efficiency of the considered control strategy. The simulation results confirmed the high efficiency and high accuracy of the considered stand-alone wind energy conversion system.

Streszczenie: W artykule przedstawiono autonomiczny system elektrowni wiatrowej z generatorem synchronicznym o magnesach trwałych (PMSG). Rozpatrywany system składa się z: generatora PMSG, prostownika diodowego, przekształtnika DC/DC typu Boost, dwukierunkowego przekształtnika DC/DC oraz przekształtnika obciążenia. Do sterowania przekształtnika DC/DC typu Boost zastosowano algorytm śledzenia mocy maksymalnej MPPT z wykorzystaniem algorytmu HCS. Algorytm HCS pozwala na uzyskanie maksymalnej mocy z turbiny wiatrowej bez dokładnej znajomości charakterystyk turbiny wiatrowej. Do układu przetwarzania energii wiatru zastosowano również system baterii magazynujących energię z dwukierunkowym przekształtnikiem DC/DC. Przekształtnik obciążenia LSC pozwala na sterowanie wartością napięcia i częstotliwości na obciążeniu. Dla uzyskania wysokiej jakości energii, na wyjściu przekształtnika obciążenia zastosowano trójfazowy filtr LC. W celu potwierdzenia skuteczności rozpatrywanych metod sterowania przeprowadzono badania symulacyjne. Wykonane badania symulacyjne potwierdziły wysoką dokładność i skuteczność rozpatrywanych układów i algorytmów sterowania autonomicznego systemu przetwarzania energii wiatru.

Keywords: *wind turbine, PMSG, stand-alone system, battery energy storage, hill climbing search, simulation studies*
Słowa kluczowe: *turbina wiatrowa, PMSG, system autonomiczny, akumulacja energii, poszukiwanie punktu mocy maksymalnej HCS, badania symulacyjne*

1. Introduction

The stand-alone wind energy conversion system is the one of effective way to provide of the supply energy for small customers [4, 5, 9, 10]. For stand-alone wind energy conversion systems, the energy storage devices are necessary to storage electricity. These systems are also used to supply the load system during disappearance of the wind speeds, because the available wind power not always can deliver the required power to the applied load. The stand-alone wind energy conversion system is usually equipped with battery energy storage system. The battery energy storage system is required to supply the power according to the load requirements. This battery storage system can improve the efficiency of the whole system [5, 9]. The considered configuration of stand-alone wind energy conversion system with PMSG has been presented in Figure 1. The system consists of three basic converters: Switch Mode Rectifier (SMR), DC/DC Bidirectional Converter (BC) and Load Side Converter (LSC). The SMR consists of diode rectifier and DC/DC Boost converter.

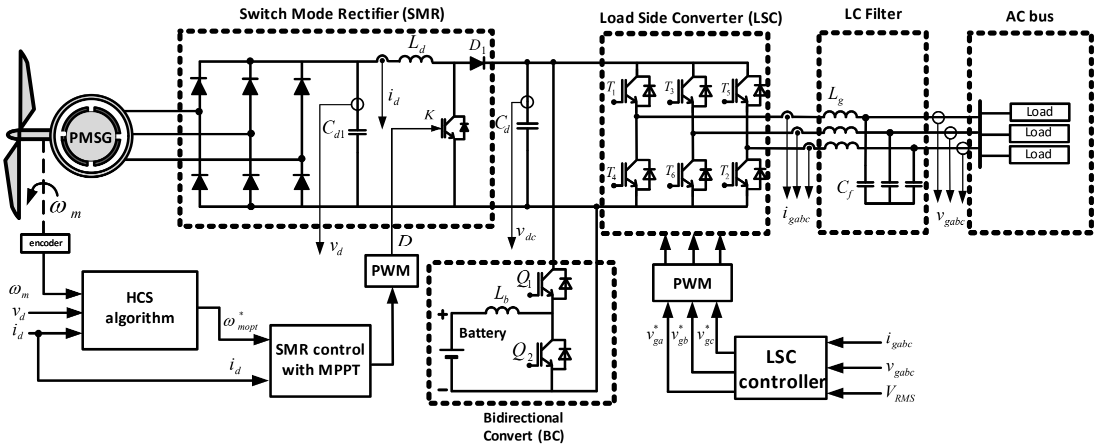

Fig. 1. Control diagram of the stand-alone wind energy conversion system with direct-driven PMSG

The diode rectifier is connected to the stator of the PMSG. The diode rectifier converters AC stator voltage of PMSG to the DC voltage.

Then the DC voltage of rectifier is transformed by DC/DC Boost converter. The DC/DC Boost converter also allows to control of the electromagnetic torque of PMSG and allows to step up the DC voltage in case of low wind speeds. The bidirectional DC/DC buck-boost converter consists of two transistor switches Q1 and Q2. The battery bank is connected to the DC-link through this converter.

The bidirectional DC/DC converter allows to storage the surplus energy in the battery, when the generated power from PMSG is higher than the required load power. In the case of low wind speeds, the demand load power can be higher than the generated power, then the battery system can supply the load [5, 9].

The main function of LSC is to stabilize the voltage amplitude and frequency of the load despite to the wind speeds variations. The detailed description of mathematical model of PMSG and wind turbine model are not considered in this paper. The description of mathematical model of PMSG and wind turbine can be found in the papers [1, 2, 3, 5, 8, 9].

2. Control of Switch Mode Rectifier

In the control of SMR the MPPT algorithm has been applied. This algorithm allows to obtain the maximum power from the wind. The control scheme of DC/DC boost converter has been presented in Figure 2. The control scheme consists of two control loops with PI controllers.

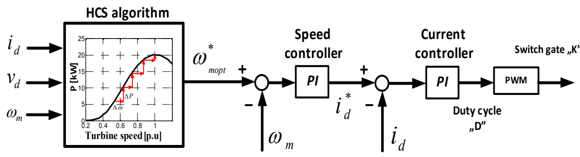

Fig. 2. The control strategy of DC/DC boost converter

The outer control loop regulates the angular rotor speed ω_m of the PMSG to follow the reference speed ω_{mopt}^*. The reference speed is obtained by application of HCS algorithm. The error signal is sent to PI speed controller. The output signal of PI speed controller determines the reference DC current of DC/DC Boost converter of SMR. Then the reference DC current i_d^* is compared with the measured DC current i_d of Boost converter. The error signal is sent to PI current controller. The output signal of this controller determines the reference duty cycle "D" of Boost converter. Then the duty cycle signal is sent to Pulse Width Modulator (PWM) block, which generates the control signals to the switch K of SMR. In the control of DC/DC Boost converter the HCS algorithm has been used. This algorithm is simple and fast and it can operate independently from wind turbine power characteristic [1, 5, 7, 9].

For the proper operation of the HSC algorithm, the measurement of the generated power is only required [1, 6]. In this case the required power is calculated on the base of the measured of the DC voltage v_d and the DC current i_d of the DC-link of the SMR.

The principle of HCS algorithm is based on perturbing of the turbine speeds in small steps ($\Delta\omega_m$) and observing the resulting changes of turbine mechanical power. The main problem of HSC is to determine the suitable step size of the increment . In the case of the large step size, the response of HSC will be very fast. However the large step size may cause signal oscillations around the maximum point of wind turbine characteristic. In the case of the small step size, the response of the algorithm will be very slow, but the efficiency of operation will be improved [1, 6, 7]. The flow chart of HCS algorithm has been illustrated in Figure 3.

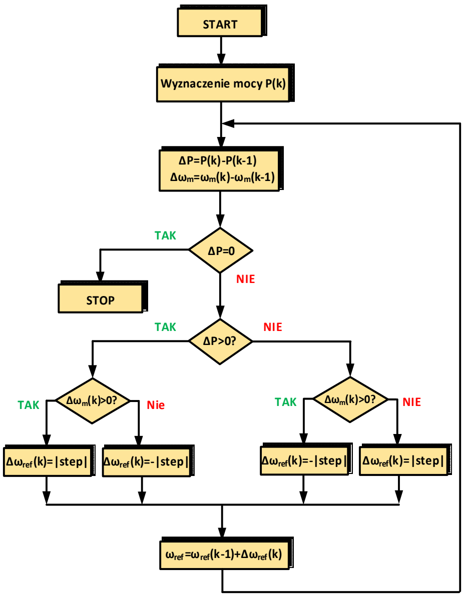

Fig. 3. The principle of HCS algorithm

In the control strategy of DC/DC Boost converter, it is assumed that, the PWM switching frequency of boost converter should be high. The low switching frequency may cause the problem with tracing the maximum power curve.

3. Control of DC/DC Bidirectional Converter

The bidirectional DC/DC converter is connected across the DC-link in order to adjust the power flow either to the battery bank or from battery to the load. The main function of DC/DC bidirectional converter is to stabilize the DC-link voltage and also to charge and discharge the energy from battery storage system [5, 9]. The battery storage system considered in this paper is composed of the 25 batteries in series connection. The rated voltage of each battery is equal to 12V, which gives total value about 300V. The ratting of the battery is assumed to equal 75Ah [5, 9].
The control scheme of DC/DC buck-boost converter has been presented in Figure 4. The control strategy of this converter consists of two control loops with PI controllers. The outer control loop regulates the DC link voltage. The reference DC link voltage v_{dc}^* is compared with measured DC voltage v_{dc} and the error is sent to the PI controller, which determines the reference battery current i_{dB}^*.

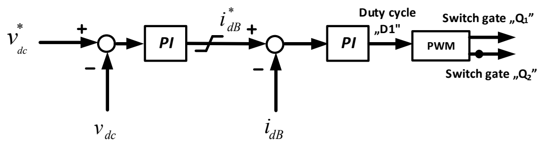

Fig. 4. The control scheme of DC/DC converter

The inner control loop regulates the battery current. The reference battery current i_{dB}^* is compared with measured battery current i_{dB} and the error is sent to PI controller, which determines the duty cycle “D1” of converter. Then the duty cycle signal is sent to PWM, which generates the required switching control signals of the transistor switches Q_1 and Q_2.

4. Control of Load Side Converter

In the stand-alone wind energy conversion system the three phase resistive load is connected through LC filter to the Load Side Converter (LCS). The main control objective of LSC is to regulate the value of the amplitude and frequency of the load voltage [4, 5]. The control scheme of LSC has been presented in Figure 5. The control scheme consists of four control loops with PI controllers.

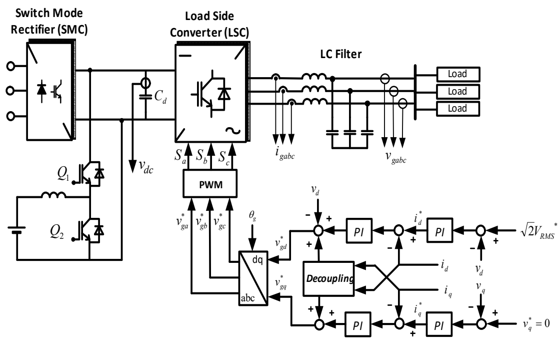

Fig. 5. The control scheme of LSC

The one of outer control loop regulates the amplitude of the voltage at the load. The second outer control loop is dedicated to control of instantaneous reactive power. In this control system the instantaneous reactive power is set to zero in order to obtain the operation at unit power factor. The reference load currents i_d^*, i_q^* are compared with the measured and transformed load currents

i_d, i_q. The error signals are sent to two inner PI controllers. In order to obtain better performance of the control strategy, the compensation terms are added. The references voltages v_{ld}^*, v_{lq}^* are transformed to the *abc* system and are sent to the block of PWM. The required switching signals for the LSC are generated through PWM block.
The information of angle position θ_e of the grid voltage vector is obtained from Virtual Phase Locked Loop (V-PLL). This position of angular voltage vector is used for coordinates transformations. Additionally, the passive LC filter has been added in the output of the LSC. The application of LC filter allows to eliminate the high frequency harmonics to improve the power quality.

5. Simulation Results

The simulation studies have been performed in Matlab/Simulink. Digital simulation studies have been made for the system with wind turbine parameters: rotor radius R - 4,4 m; maximum power coefficient C_{pmax} – 0,48; air density ρ - 1,225 kg/m^3; 3-phase PMSG parameters: rated power of PMSG P_g - 20 kW; stator dq-axis inductance L_d=L_q=L_s – 4,48 mH; stator resistance R_s – 0,1764 Ω; number of pole pairs p_b - 18; rated speed Ω_n - 211 rpm; stator rated phase current I_{sn} - 35 A.
The simulation results are presented in Figures 6-12. The assumed waveform of the wind speed has been presented in Figure 6. Figure 7 shows the waveforms of optimal ω_{mopt} and measured angular speed ω_m of PMSG. It can be noticed, that the generator speed is accurately adjusted to the waveforms of optimal speed ω_{mopt}.

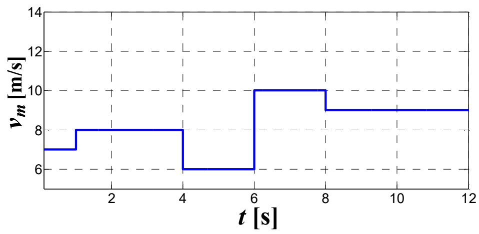

Fig. 6. Waveform of wind speed variations v_w

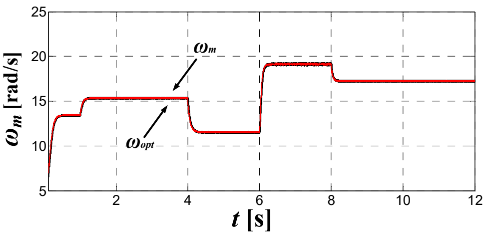

Fig. 7. Waveforms of reference speed ω_{opt} and angular rotor speed ω_m of PMSG

The waveform of power coefficient C_p has been shown in Figure 8. It is clear that the MPPT algorithm is fulfilled because the maximum value of power coefficient during the wind speed changes is obtained.

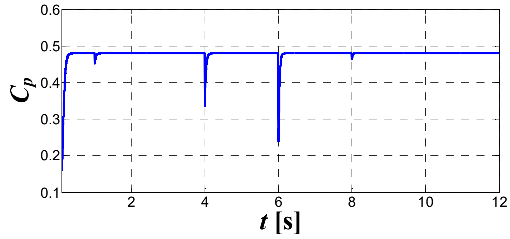

Fig. 8. Waveform of power coefficient C_p of wind turbine

The waveform of the battery load current I_{bat} has been shown in Figure 9. The direction of the current is changing depending on the state either the charging or discharging the battery bank. The response of the AC load current has been shown in Figure 10.

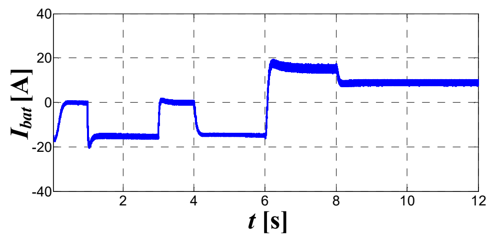

Fig. 9. Waveform of battery current I_{bat}

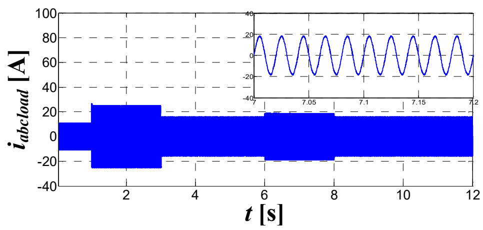

Fig. 10. Waveform of load current $i_{abcload}$

The waveform of DC-link voltage has been presented in Figure 11.

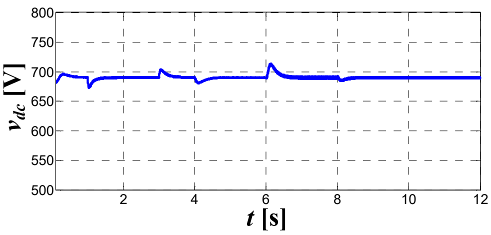

Fig. 11. Waveform of DC-link voltage v_{dc}

The generated power from wind turbine system P_{gen}, power of the battery storage system P_{bat} and the power of the load P_{load} have been presented in Figure 12. It can be noticed, that in the case of low generated power P_{gen} from wind turbine system, the proper operation of battery bank can be observed.

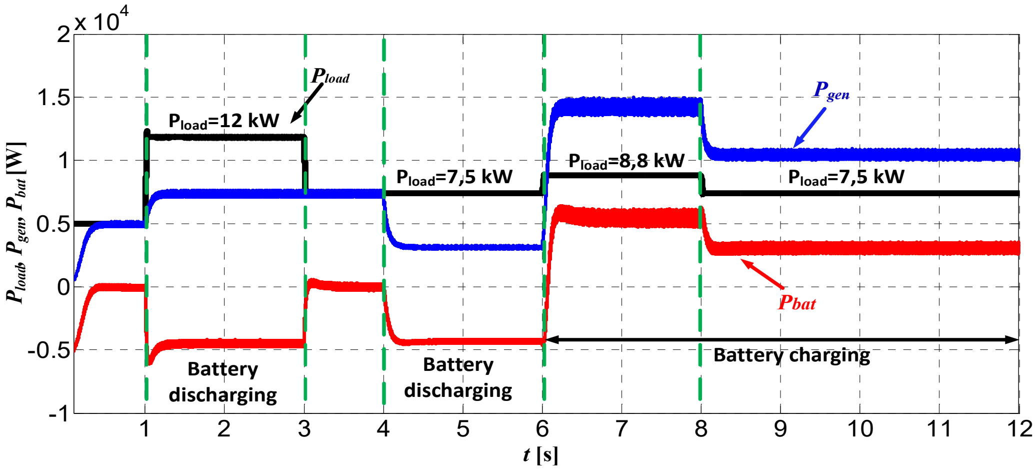

Fig. 12. Waveforms of generated power P_{gen}, load power P_{load}, battery power P_{bat}

In this case the three phase load is supplied through the battery bank and converter system. The discharging of the energy in the battery bank can be observed in the time periods 1-3s and 4-6s. When the generated power P_{gen} is greater than the load power P_{load}, the energy will be storaged in the battery bank.

6. Conclusions

The control strategy for stand-alone wind energy conversion system with battery energy storage has been considered in this paper. The application of HCS algorithm allows to obtain the maximum power from wind turbine. This algorithm operates independently from predefined wind turbine characteristics. The application of the DC/DC buck-boost converter with battery energy storage system has been used to balance between the powers obtained from the wind and the required power at the load. The power has been storaged in the battery bank in the case of the surplus generated power from wind turbine system. Whereas, the battery bank has been discharged in the case of low generated power from wind turbine system. The stand-alone system is used to supply to the autonomous three phase load. In the control of Load Side Converter the vector control method has been applied. The Load Side Converter allows to keep the value of load voltages and the value of the frequency at the desired level. According to the simulation results, it can be stated that the proposed control technique operates with high accuracy and high efficiency.

7. References

[1]. El-sebaii A.M., Hamad M.S., Helal A.A.: "A sensorless MPPT technique for a grid connected PMSG wind turbine system", Renewable Power Generation Conference (RPG 2013), 2013, str. 1-6.

[2]. Errami Y., Maaroufi M., Ouassaid M.: "Modeling and control strategy of PMSG based variable speed wind energy conversion system", International Conference on Multimedia Computing and Systems (ICMCS), 2011, str. 1-6.

[3]. Gajewski P., Pieńkowski K.: "Control of a variable speed wind turbine system with PMSG generator", Maszyny Elektryczne-Zeszyty Problemowe, nr 107, 2015, str. 75-80.

[4]. Haqye M.E., Muttaqi K.M., Negnevitsky M.: "Control of a stand-alone variable speed wind turbine with a permanent magnet synchronous generator", IEEE Power and Energy Society, 2008, str. 1-8.

[5]. Hussein M.M., Senjyu T., Orabi M., Wahab M.A.A., HAMANDA M.: "Control of a stand-alone variable speed wind energy supply system", Applied Sciences, 2013, str. 437-456.

[6]. Lalouni S., Rekioua D., Idjdarene K., Tounzi A.M.: "Comparative study between MPPT algorithm applied to wind energy conversion system", Electrical Power & Energy Conference (EPEC), 2009, str. 1-6.

[7]. Li X-P., Fu W-L., Shi Q-J., Xu J-B., Jiang Q-Y.: A fuzzy logical control strategy for PMSG wind generation system, Journal of Electronic Science and Technology, vol. 11, NO. 1, 2013, str. 72-77.

[8]. Molina M.G., Sanchez A.G., Lede A.M.R.: "Dynamic modeling of wind farms with variable-speed direct-driven PMSG wind turbines", Transmission and Distribution Conference and Exposition: Latin America (T&D-LA), IEEE/PES, 2010, str. 816-823.

[9]. Sayeef S., Mendis N., Muttaqi K., Perera S.: "Enhanced Reactive Power Support of a PMSG Based Wind Turbine for a Remote Area Power System", Universities Power Engineering Conference (AUPEC), 2010 20th Australasian, 2010, str. 1-8.
[10]. Wu B., Yongqiang L., Navid Z. Samir K.: "Power Conversion and Control of Wind Energy", John Wiley & Sons, INP., Publication 2011.