Michał ROLAK[1], Radosław KOT[1], Mariusz MALINOWSKI[1], Zbigniew GORYCA[2], J. Tomasz SZUSTER[3]

Politechnika Warszawska, Instytut Sterowania i Elektroniki Przemysłowej(1), Politechnika Radomska, Instytut Automatyki i Telematyki(2), Politechnika Warszawska, Wydział Mechaniki i Energetyki Lotnictwa (3)

AC/DC converter with Maximum Power Point Tracking algorithm for complex solution of Small Wind Turbine

***Abstract**. This paper presents a complex solution of Small Wind Turbine for AC/DC converter with Maximum Power Point Tracking Algorithm. The different topologies of converters are presented and compared to chose optimal solution. Chosen Maximum Power Point Tracking methods are introduced, described and simulated. Some important phenomenon which occurred during designing process of the wind rotor and permanent magnet synchronous generator are described either.*

***Streszczenie:** Artykuł przedstawia proces projektowania małej elektrowni wiatrowej z przekształtnikiem AC/DC do śledzenia mocy szczytowej MPPT (ang. Maximum Power Point Tracking). W pracy zostały przedstawione i porównane różne topologie przekształtników, jak również opisano i wykonano badania symulacyjne wybranych algorytmów MPPT. Ponadto pokazano problemy pojawiające się podczas procesu projektowania elektrowni wiatrowej ze szczególnym uwzględnieniem zagadnień dotyczących turbiny wiatrowej, generatora i samego przekształtnika AC/DC. (**Przekształtnik AC/DC z algorytmem śledzenia mocy szczytowej w zastosowaniu do małej elektrowni wiatrowej**)*

Keywords: Small Wind Turbine, Maximum Power Point Tracking, Permanent Magnet Synchronous Generator, AC/DC converter
Słowa kluczowe: mała elektrownia wiatrowa, algorytm śledzenia mocy szczytowej, generator synchroniczny z magnesami trwałymi,

Introduction

Nowadays it is easy to see increasing role of renewable energy and its growing interest in whole produced energy, mainly because of ecological reasons. The state of the art is that the wind farm market is widely known and almost explored. However, it is focused mostly on the high power (hundreds of kilowatts) power station. There is still a gap in low power plant applications. It is so-called small wind turbines (SWT) which swept area is smaller than 200m^2, and generating power is in the ranges of 1-15kW (residential) and 15-100kW (light commercial). The more precise definition and directives are described in standard PN-EN 61400-2:2006 [1]. Moreover there is still a need to set a low power self-sufficient system next to household to assure some independence just in case of grid blackout. This paper presents general solution for SWT, but it focuses mainly on wind turbine, generator and maximum power point tracking system (MPPT).

System

The small wind turbine is a complex system which provides the energy for the utility grid as well as for the local, stand-alone loads. One of the goals of presented solution is modularity which allows to configure system easily to user accordance. General system is presented in Figure 1 and consist of following modules:

Module 1 - Small wind turbine with low speed permanent magnet synchronous generator (PMSG);

Module 2 - AC/DC converter with maximum power point tracking system (MPPT);

Module 3 - DC/AC converter to couple system to the grid (with possible islanding operation mode);

Module 4 – DC/DC converter to use the excess of produced energy for heat water in boiler or to charge batteries.

Wind rotor

Wind rotor has to assure proper power production according to typical wind conditions. SWT design is a multiobjective process and only some selected issues were described. In current case rotor radius of 3.75m was found by optimization. Rotor geometry was chosen in order to fulfill some requirements:

- highest SWT overall efficiency for chosen range of mean long-term wind speed,
- high energy yield,
- reasonable load factor.

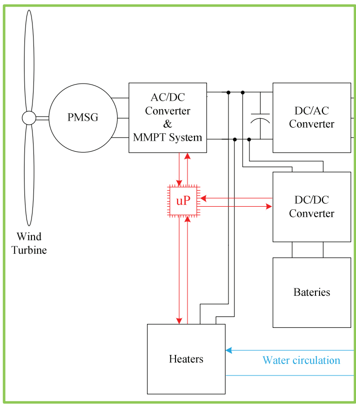

Fig. 1. General idea of Small Wind Turbine

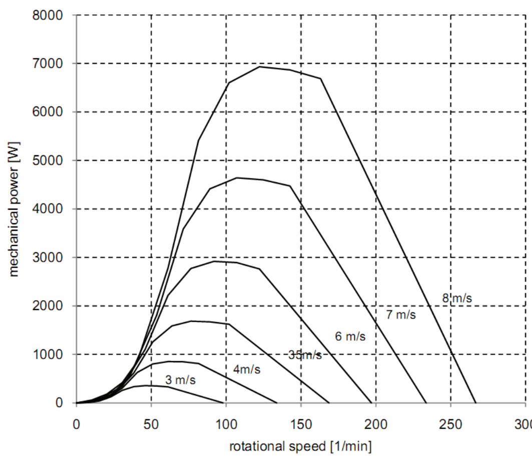

Fig. 2. Relation between rotor mechanical power of wind rotor and rotational speed at given constant wind speed.

One of the most important wind rotor characteristic is so-called available power characteristic i.e. dependence between 'shaft' mechanical power and rotational speed for given mean 10 min wind speed as parameter. Such characteristic was shown in Figure 2. Power curve, i.e. relation between SWT output (power) and mean 10 minutes wind speed for designed wind rotor is shown in Figure 3a.

The most interesting thing from economical point of view is a quantity of energy which can be obtained. Relation between annual energy yield long-term mean wind speed was presented in Figure 3 b.

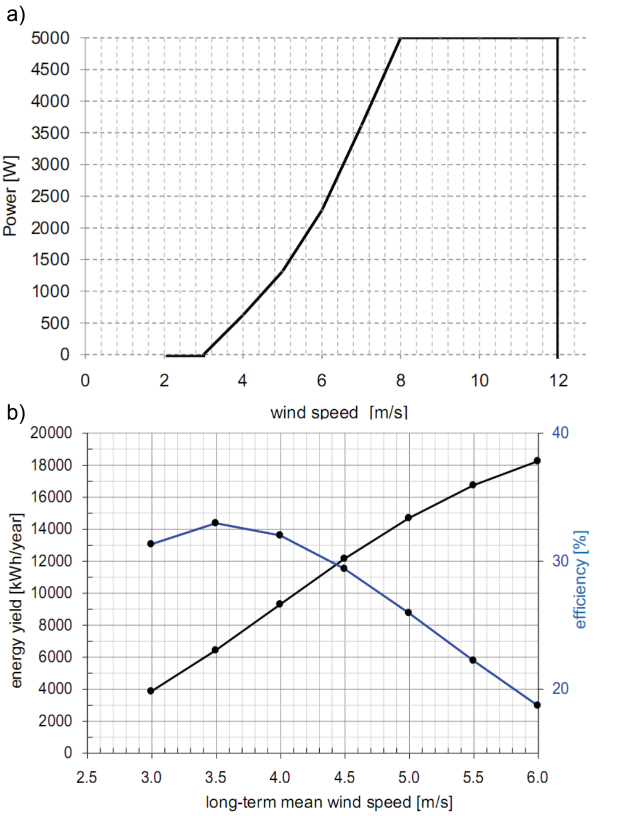

Fig. 3. a) Power curve, b) Overall efficiency of SWT and energy yield vs. long-term mean wind speed.

As it was mentioned before, designed wind rotor has to be precisely matched to the given generator to assure suitable rotational speed from given wind speed to achieve rated electrical power. A permanent magnets synchronous generator has an unfavorable phenomenon called cogging torque which has significant influence on the efficiency of the system. Friction torque has the same effect. Relative decrease of energy yield vs. sum of cogging and friction torques was depicted in Figure 4.

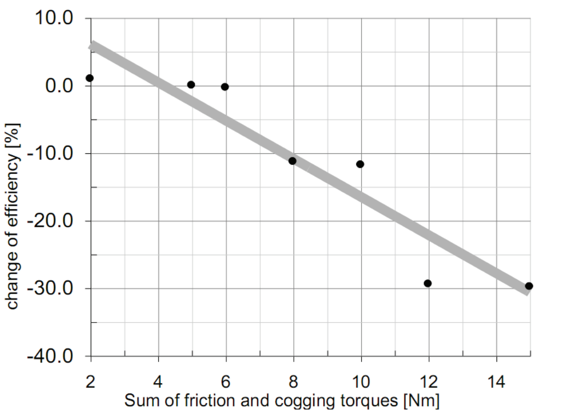

Fig. 4. Influence of the sum of cogging and friction torques on relative change of SWT energy yield.

Worth of note is a fact that errors in the blades' geometry reproduction process, contamination or icing can reduce wind rotor energy yield even up to 20%. Mentioned conditions allowed to design proper turbine's blade geometry. Its view was shown in Figure 5

Fig. 5. Designed SWT's blade view

Permanent Magnet Synchronous Generator

To achieve assumed rated power (5kW) at low wind speed there is a need to use low-speed PMSG (150rpm). It means a great number of poles, and this in turn, introduces a high value of cogging torque. Properly designed magnetic circuit allows to minimize this disadvantage. The designed generator has 40 neodymium magnetic bars what usually cause a strong cogging torque, which achieve value higher than several percent of nominal electromagnetic torque (450 Nm). To reduce this unfavorable phenomenon, odd number of poles and stator's grooves was used. To simulate and to solve a magnetic circuit a finite elements method was employed, what is described in [2]. Figure 6a presents magnetic flux distribution for given rotor position and Figure 6b shows a received cogging torque depending on rotor angle.

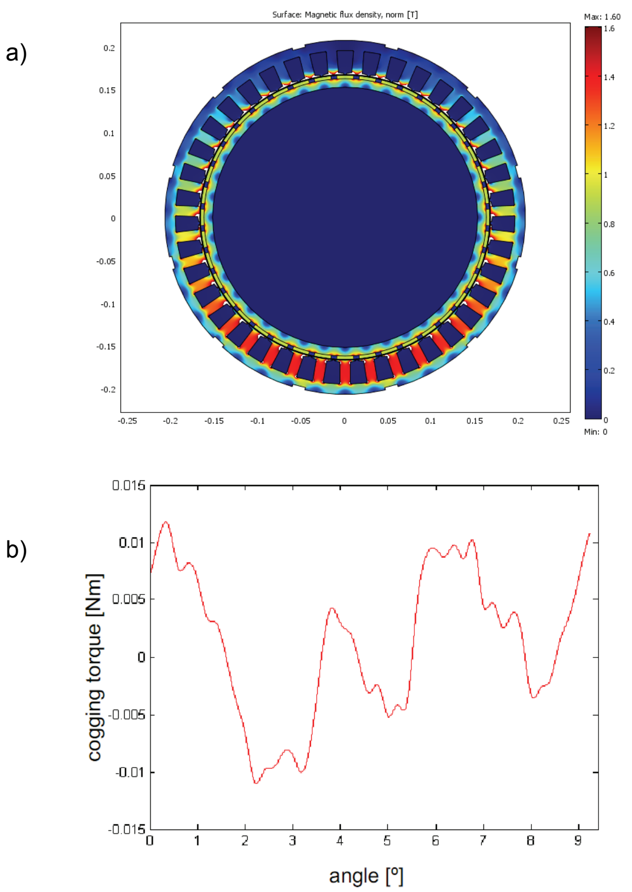

Fig. 6. a) Magnetic flux distribution for given rotor position, b) Cogging torque value received for designed machine [2]

It is easy to see that its value was minimized. In whole industry, it could be seen a trend to minimize volume of built devices. The prototype of the generator with significantly reduced size (470 x 350mm) and weight (84kg) was built and is shown in the Figure 7. It presents rotor with magnetic neodymium bars (Figure 7a), stator windings (Figure 7b) and full prototype (Figure 7c).

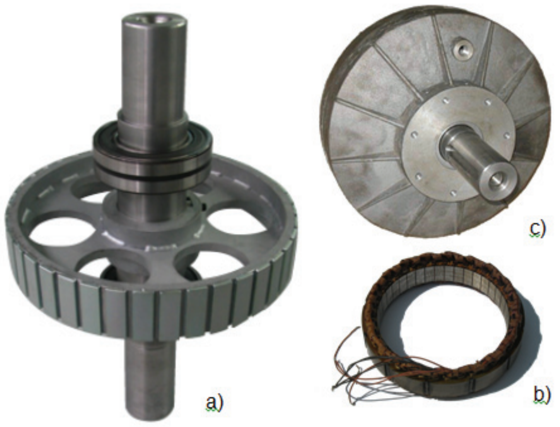

Fig. 7. Prototype of designed PMSG [Patent number P-392342]

Converters topologies

Quantity of power, which could be received versus rotational speed of the shaft corresponds to different wind's speed. It means that by proper control of the rotor's speed it is possible to obtain maximum power for each wind speed (Figure 8).

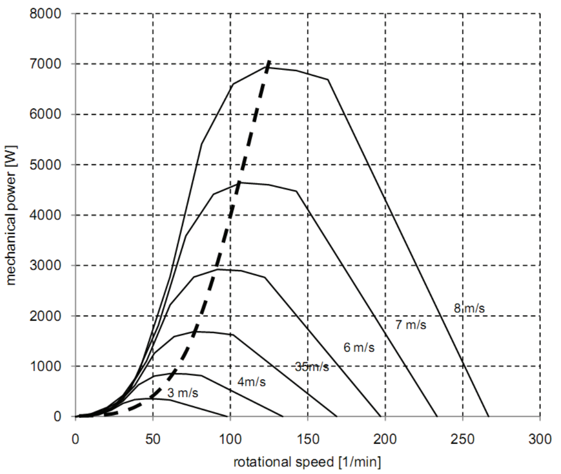

Fig. 8. MPPT's general idea

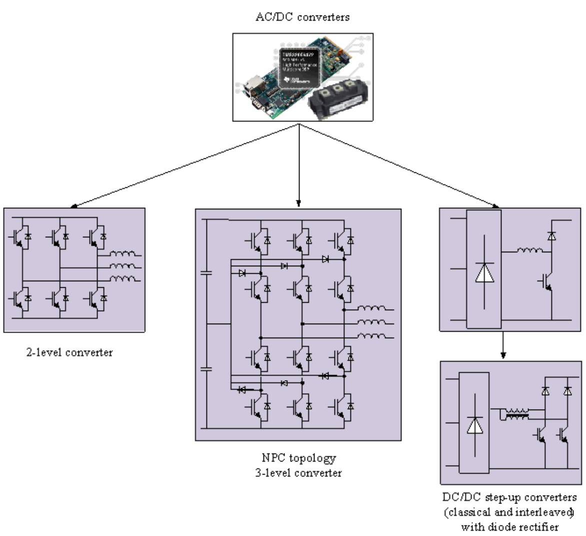

Fig. 9. AC/DC converters topologies division

Speed control can be obtain by use one of following converter chosen among the different topologies shown in Figure 9. A different device has its own advantages and disadvantages. It can be done by using a 2- or 3 - level converters [3],[4]. The other solution could be 6-pulse diode rectifier which rectifies the generator's voltage, and control of current is done by the DC/DC converter such a step-up or interleaved step-up converter [5], [6].

In presented paper the classic and interleaved step-up converters for MPPT was used. The main reason of this choice is its simplicity and its price.

Design of converter and inductance was supported by Figure 10a and Figure 10b based on equation (1).

$$\Delta i = \frac{U_0 (1 - D) D}{Lf} \tag{1}$$

where: Δi – current ripples, U_0 supply voltage, D-duty cycle, L –inductance, f-switching frequency.

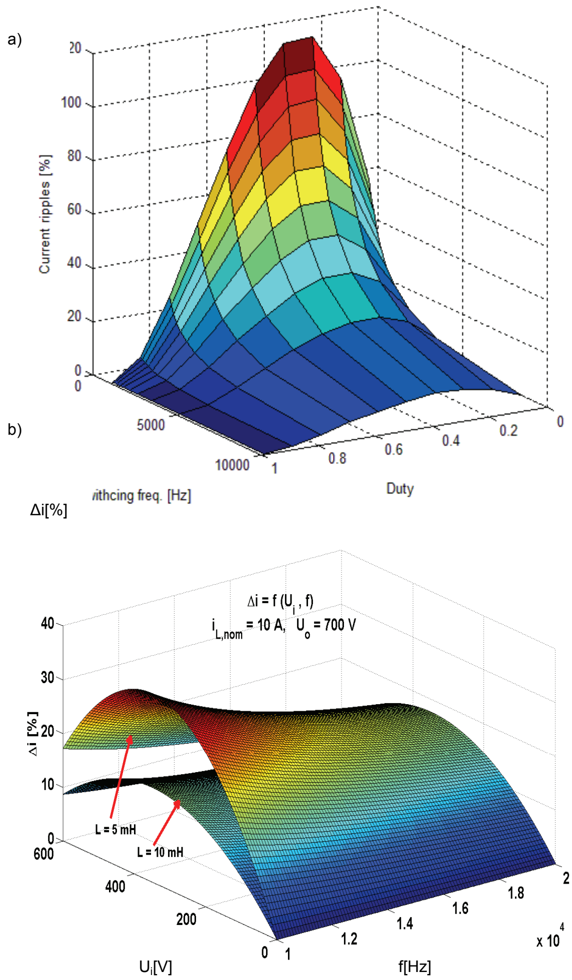

Fig. 10. a) Current ripples versus switching frequency and duty cycle of step-up converter, b) Current ripples for different inductor values

Control

However, each topology needs a MPPT algorithm to efficient work. Different ways to implement it to the converter are shown in Figure 11. They are described precisely in [7-10].

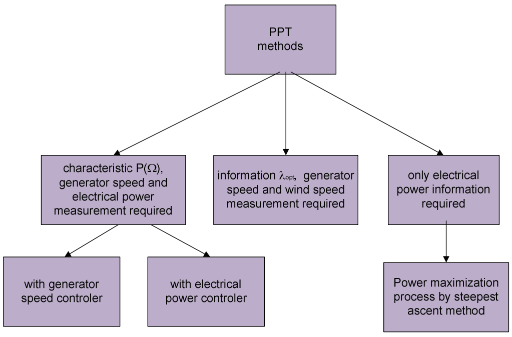

Fig. 11. MPPT algorithms division

The method based on P(Ω) characteristic is the simplest one. General idea of this method is shown in Figure 12a. It needs information about shape of the curve of maximum points – the same as it was shown in Figure 8.
This method requires the rotor speed and electrical power measurements. It is easy to obtain the equation describing required curve by mathematical way and use it in control strategy. Nevertheless, the problem starts in real applications, where for different blades geometry there is a need to calculate another characteristic.

The second method uses a relation between λ_{opt} and wind speed to calculate certain value of the rotor speed. This strategy base on equation (2):

$$\omega^* = \frac{\lambda_{opt} v}{R} \quad (2)$$

where: ω^* - reference rotational rotor speed, λ_{opt} – tip speed ratio coefficient, v-wind speed, R – rotor radius.

Algorithm idea is depicted in Figure 12b and it is deeply described in [10].

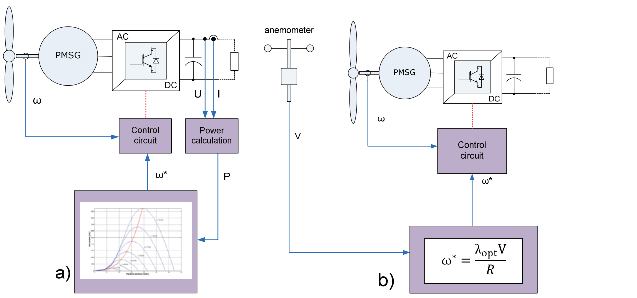

Fig. 12. a) MPPT method based on P(Ω) characteristic, b) λ_{opt} MPPT method

The third method uses iteration algorithm to check that system operates on the maximum or not. For given operation point control circuit increase the generator's speed by a given step value and check if the new power value is greater that the last or not. If yes, it increases the speed and looking further for the maximum. If new value of power is lower than previous one it decrease rotor speed. This method is the most promising because it increases reliability of the system through the elimination of the wind speed sensor and generator's speed measurement. General idea of this method is depicted in Figure 13.

Simulation results

Figure 14 shows the simulation models for 2 different topologies (step-up and interleaved step-up, respectively). They consist of wind source, wind rotor, PMSG, 6-pulse diode rectifier with classic or interleaved step-up dc/dc converter and control circuit.

The comparison between classical step-up and interleaved topology is shown on Figure 15. Interleaved topology has two inductors which inductance values are half of inductance put in classical step-up topology. Frequency and duty cycle were the same for both converter types. The output current ripples frequency is higher in interleaved topology – Figure 15b.

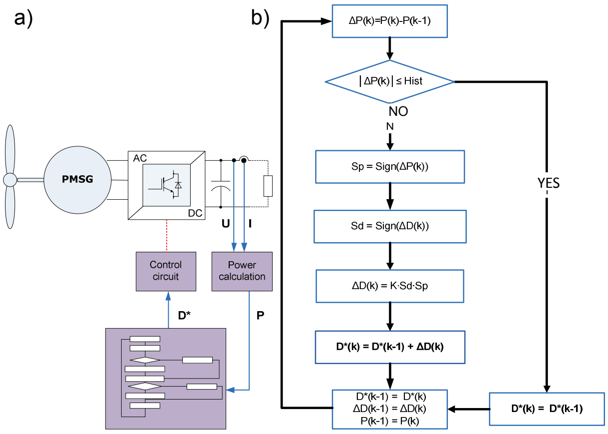

Fig. 13. a) Incremental MPPT algorithm, b) Incremental MPPT flowchart of algorithm applied to classical step-up converter
where: P-current power value, ω- rotational speed, k – incremental calculation step, $Hist$ –hysteresis, Sd –duty sign value Sp – power sign value, D-duty cycle

To show how much energy can be extracted from the wind by using proper control strategy waveforms in Figure 16 was presented. It shows power production with and without MPPT algorithm. It shows how the system tracks the maximum power point according to changes of wind speed. Moreover, it can be seen that the average active power production increase from 1444,4 [W] up to 2646 [W] for MPPT algorithm. The comparison between method based on P(Ω) characteristic and incremental MPPT is depicted in Figure 17. It shows that results are similar (slightly lower dynamic of incremental MPPT), but the reliability of the system increase through the rotational speed sensor elimination.

Summary

- The interleaved converter can diminish values of inductances which in turn, reduce significantly cost and volume of the device. Operating frequency of both circuits is the same, but particular inductor values in each branch in interleave topology are lower, which in turn allows built more packed and compact device. Moreover, conduction losses in interleaved topology are lower because of lower current value in each branch. In addition interleaved topology with mutual inductances allows to reduce currents ripples in each branch of converter.
- The incremental Maximum Power Point Tracking algorithm is most suitable for Small Wind Turbine. The reason is wind speed sensor elimination, which improve a reliability of the system and reduce costs. Moreover, this method needs neither knowledge of wind rotor characteristic nor lambda parameter. It means that this algorithm is mechanically independent and can be used for any type of wind rotor.

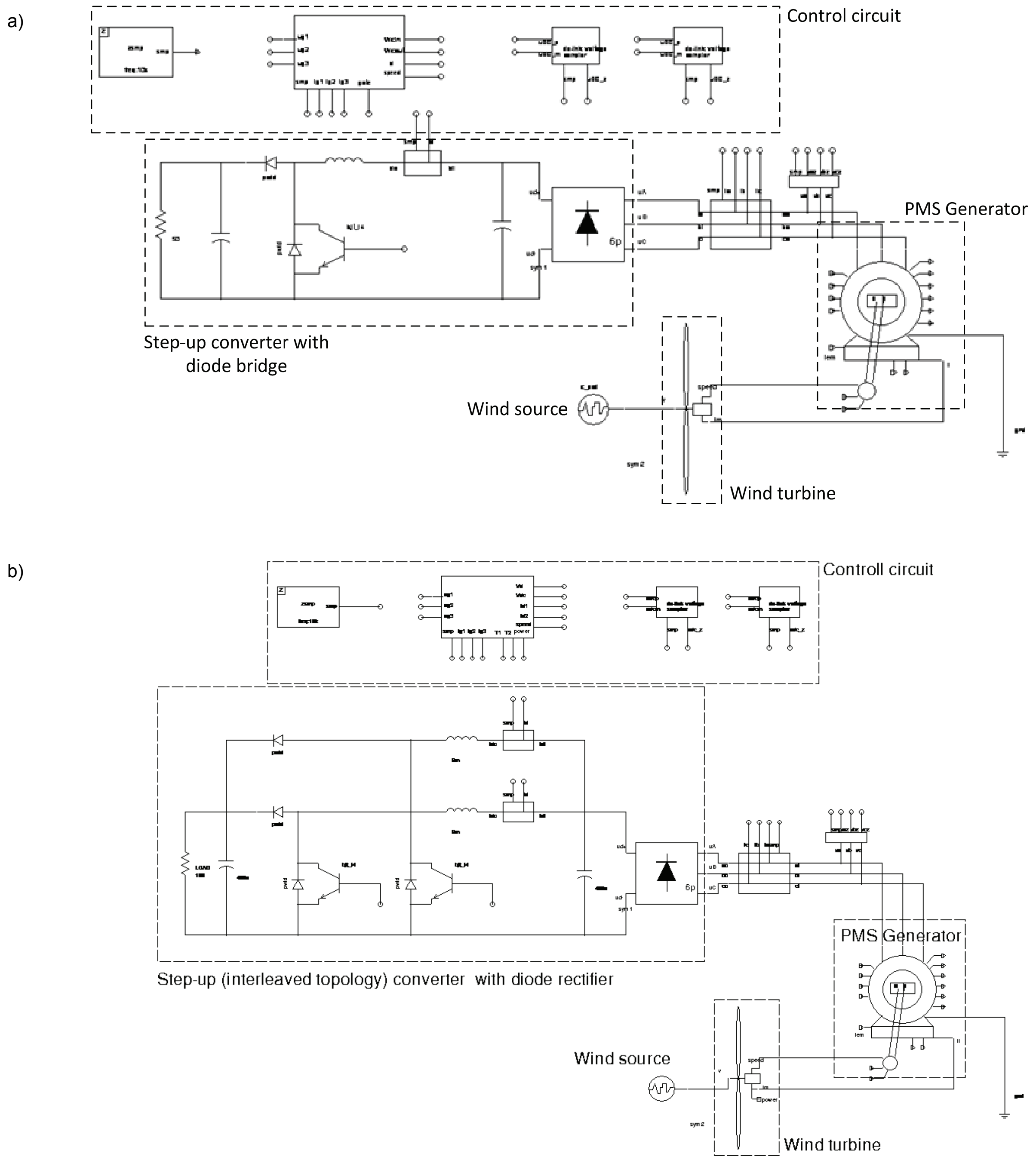

Fig. 14. Simulation models: a) System with classic step-up converter, b) System with Interleaved step-up converter

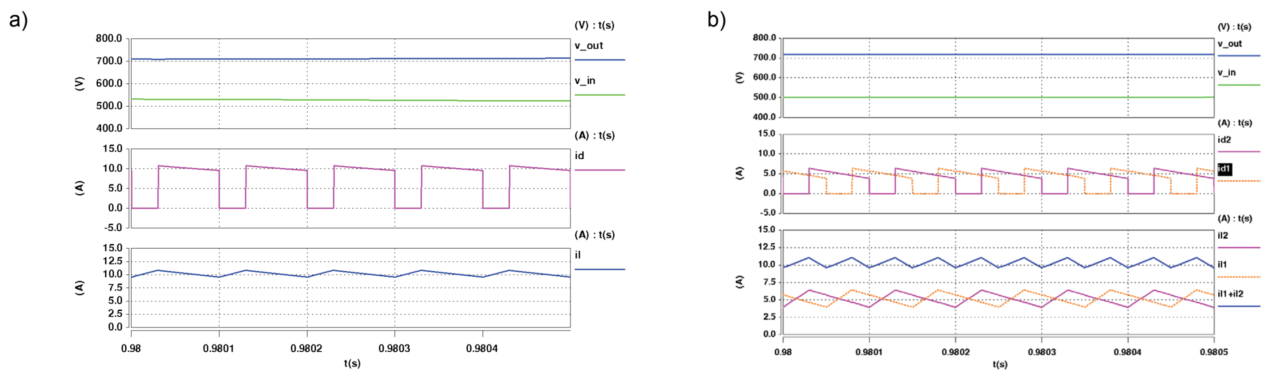

Fig. 15. Comparison between (a) step-up and (b) interleaved step-up converters. Waveforms from top: input and output voltage, output current; input current.

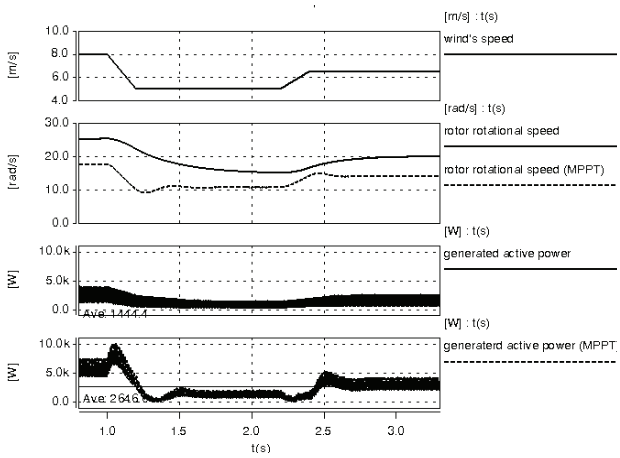

Fig. 16. Comparison of SWT operation with MPPT (dotted line) and without MPPT (solid line). From the top: wind speed, rotational speed of rotor, active power without MPPT, active power with MPPT.

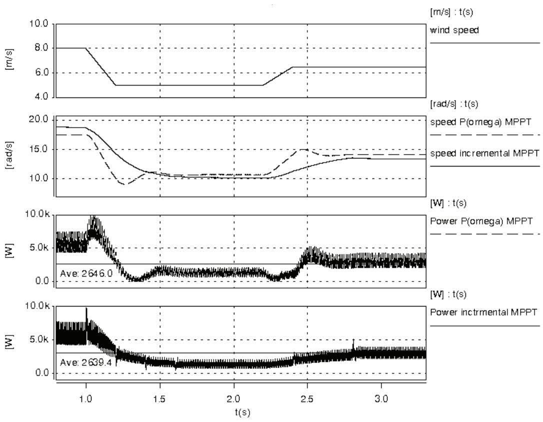

Fig. 17. MPPT systems comparison: incremental (dotted line) and based on P(Ω) characteristic (solid line). From top: wind speed, rotational speed of rotor, active power with method based on P(Ω) characteristic, active power with incremental MPPT method.

N R01 0015 06/2009 "Complex solution for low speed small wind turbine with energy storage module for distributed generation systems" and sponsored by The National Centre for Research and Development

REFERENCES

[1] International standard PN-EN 61400-2:2006
[2] Goryca Z., Ziołek M., Malinowski M., Cogging Torque Of The Multipolar Generator With Permanent Magnets, *Maszyny Elektryczne Zeszyty Problemowe*, Vol 88/2010, (2010),
[3] Malinowski M., Sensorless Control Strategies for Three-Phase PWM Rectifiers, *Ph. D. Thesis*, (2001), http://www.isep.pw.edu.pl/icg/pdf/phd/mariusz_malinowski.pdf
[4] Malinowski M., Stynski S., Kolomyjski W., Kazmierkowski M., Control of Three-Level PWM Converter Applied to Variable-Speed-Type Turbines, *Industrial Electronics, IEEE Transactions on,* Volume 56, (2009), Issue: 1, Page(s): 69-77
[5] Destraz B., Barrade P., Rufer A., A new interleaved multi-channel DC/DC converter specially dedicated to low voltage, high current applications, *International Conference on Power Electronics, Intelligent Motion and Power Quality*, Nuremberg, Germany, (2006),
[6] Wang Ch., Investigation on Interleaved Boost Converters and Applications, *Ph.D Thesis,* July 21st, (2009),
[7] Esmaili R., Xu L. and Nichols D. K., A New Control Method of Permanent Magnet Generator for Maximum Power Tracking in Wind Turbine Application, *Power Engineering Society General Meeting*, Vol. 3, (2005), Page(s): 2090 - 2095
[8] Koutroulis E., Kalaitzakis K., Design of a Maximum Power Tracking System for Wind-Energy-Conversion Applications, *Industrial Electronics, IEEE Transactions on,* Volume *53,* (2006), Issue 2, Page(s): 486 - 494
[9] Hui J. xand Bakhshai A., A New Adaptive Control Algorithm for Maximum Power Point Tracking for Wind Energy Conversion Systems, *Power Electronics Specialists Conference*, (2008), Page(s): 1069 - 1074
[10] Drugă M., Nichita C., Barakat G., Dakyo B., Ceangă E., A Peak Power Tracking Wind System Operating with a Controlled Load Structure for Stand-Alone Applications, *EPE '09*, (2009), Page(s): 1 - 9

Authors:
mgr inż. Michał Rolak, Politechnika Warszawska Instytut Sterowania i Elektroniki Przemysłowej, ul. Koszykowa 75, 00-662 Warszawa, E-mail: rolakm@ee.pw.edu.pl
mgr inż. Radosław Kot, Politechnika Warszawska Instytut Sterowania i Elektroniki Przemysłowej, ul. Koszykowa 75, 00-662 Warszawa, E-mail: radosław.kot@ee.pw.edu.pl
dr inż. Mariusz Malinowski, Politechnika Warszawska Instytut Sterowania i Elektroniki Przemysłowej, ul. Koszykowa 75, 00-662 Warszawa, E-mail: malin@isep.pw.edu.pl
mgr inż. Tomasz Szuster, Politechnika Warszawska Instytutu Techniki Lotniczej i Mechaniki Stosowanej, ul. Nowowiejska 24, 00-665 Warszawa, E-mail: jts_xl@wp.pl
prof. nadzw. dr hab. inż. Zbigniew Goryca, Politechnika Radomska, Instytut Automatyki i Telematyki, ul. Malczewskiego 29, 26-600 Radom, E-mail: tgoryca@kki.net.pl