Power electronic supply system with the wind turbine dedicated for average power receivers

Tomasz Widerski¹, Adam Skrzypek²

¹ Lodz University of Technology, Wolczanska 211/215, 90-924 Lodz, Poland; tomasz.widerski@p.lodz.pl
² ABB Sp. z O.O., Placydowska 27, 95-070 Aleksandrow Lodzki, Poland

E-mail: tomasz.widerski@p.lodz.pl

Abstract. This article presents the original project of the AC-DC-AC converter dedicated to low power wind turbines. Such a set can be a good solution for powering isolated objects that do not have access to the power grid, for example, isolated houses, mountain lodges or forester's lodges, where they can replace expensive diesel engine generators. An additional source of energy in the form of a mini-wind farm is also a good alternative to yachts, marinas, and tent sites, which are characterized by relatively low power consumption. This article presents a designed low power wind converter that is dedicated to these applications. The main design idea of the authors was to create a device that converts the very wide range input voltage directly to a stable 230VAC output voltage without the battery buffer. Authors focused on maximum safety of using and service. The converter contains the thermal protection, short-circuit protection and overvoltage protection. The components have been selected in such a way as to ensure that the device functions as efficiently as possible.

1. Power electronics solutions in wind energy area

1.1. The wind energy development

Based on current data and forecasts presented by experts, significant increases in energy prices from fossil fuels are expected. Developed countries have long recognized the problem and started intensive progress of alternative energy. Germany is the perfect example, where in 2014 the largest share of renewable energy production took place. Currently, wind turbines are the largest source of renewable energy. Over the last twenty years, there has been a noticeable rise of wind energy area in the world. The increase in the capacity of these power plants in the last twenty years was more than 9000% [1,2,3,4]. This phenomenon is best illustrated by the fact that the combined capacity of wind turbines installed in Poland alone in 2015 was higher than in 1995 worldwide [5,6]. Trends in the development of global wind power are illustrated in figure 1 [1,2]. The power growth of the installed wind power plant is about 20-30% per year and it can be assumed that this trend will continue.

Due to the huge interest in the generation of energy from wind farms, the production of components used for their construction is growing steadily and the number of companies involved in the development of this energy sector is growing. As a result, the cost of wind farms is reduced, which further accelerates the development of this sector.
It should also be noted that the generation of wind energy is increasingly available to individual people and small companies with limited budget. On the market there are companies producing small power plants below 30kW, which can be purchased at an attractive price. This allows to construct a small energy generator at the place where it is consumed. This is an attractive solution, due to the significant reduction of transmission losses. The advantages of using low power wind turbines are most evident in the supply of isolated non-grid facilities, such as lonely houses, mountain huts or forester’s houses, where they can replace expensive diesel engine generators. An additional source of energy in the form of a mini-wind farm is also a good alternative to yachts, marinas and tent sites, which are characterized by relatively low power consumption.

1.2. Converters for high power generators

One of the biggest problems of wind energy is the variability of the generators output voltage electrical parameters. As the wind speed changes, the rotation speed of the turbine is changed and therefore the output voltage and amplitude are changed. To solve this problem, AC/DC converters are installing in wind generator plants to set the stability output voltage value, suitable for the energy consumers. These are switching circuits containing IGBT transistors or IGCT thyristors [7] (low power converters contain MOSFET transistors). An example of such a converter for handling large wind turbines is the PCS 6000 model developed by ABB company [8], whose block diagram is shown in figure 2. Depending on the configuration, the converted power can be up to 9MVA at 3.3kV output voltage and 98% efficiency.

The voltage generated in the generator (a) is converted by the thyristor rectifier (d). Between these blocks there is a necessary disconnector (b) to disconnect the generator from the converter for e.g. service the device. The filter (c) protects the generator from the hazardous overvoltages generated during the switching of the rectifier power diodes. High amplitude overvoltages can damage the insulation in the generator windings and lead to the failure of the entire power plant. The middle section (e) is responsible for eliminating the ripple voltage in the rectifier. Also included in this block is a converter discharging circuit made up of two IGCT thyristors. Another converter section is the inverter (f), which is not different from the rectifier. Its purpose is to generate a three-phase voltage with a sinusoidal waveform. In order to improve the quality of the output voltage, an LC low pass filter (g) is used to eliminate the higher order harmonics. The last element of the circuit is a three-phase transformer that transforms the average voltage to the mains voltage (often 15kV) and the grid disconnector (h).

**Figure 1.** Global wind power cumulative capacity. [source: GWEC]
1.3. Converters for low power generators

There are relatively few commercial solutions for small wind converters for low power wind turbines. An example is AirGenerator company, which offers wind converters from 1kW to 20 kW, 230VAC / 50Hz output voltage and 80% efficiency (depending on output power) [9].

The above mentioned wind converters are characterized by high stability of the output voltage parameters. Unfortunately, they require high-stable input voltage, hence the wind generator and converter cannot be directly connected. In this case, a rechargeable battery is used, whose role is to receive electricity from the generator when the output power is higher than that received. Consequently, the converter contains a battery charging regulator, whose purpose is to stabilize the voltage generated by the wind turbine. This problem is typical for low input voltage converters. For a 1 kW model, the supply voltage is 48VDC, which means high input currents, significant power losses during energy converting and, as a result, decrease efficiency. The efficiency of inverters increases considerably for higher power and higher input voltages [9].

Low power converters are significantly different from the high power converters designed to wind power plants. IGBT transistors are used in low power applications. They operate at frequencies from 1kHz to 40kHz (depending on the model) [10]. Increasing the switching frequency allows the generation of sinusoidal waveforms with small deformations. The output filter of this converter may be smaller and therefore cheaper. The converter also generates less noise.

The high power converter, as mentioned above PCS 6000 WIND, has a longer switching time than IGBT transistors, so the switching frequency is less than 1kHz for output 5kV voltage and 2.5kA current. This enables the reduction of the power losses and thus high efficiency. On the other hand, the output voltage is significantly deformed, which requires the use of a high-inductance filter, which generates large electromagnetic interferences. In addition, due to high losses (over 100kW for full output power), liquid cooling of the switching devices and chokes is used. This solution complicates the mechanical construction (external radiator), electrical scheme (additional sensors and cooling system controls) and increases costs. The control circuit of the converter controls many subsystems and sensors, which is extremely complicated compared to low power converters. However, this is necessary because of the risk of fire or breakdown.

Figure 2. PSC 6000 WIND converter topology (a – generator, b – generator disconnector, c – input filter, d – rectifier, e – capacitors bank and discharging system, f – inverter, g – output filter, h – output disconnector) [8].
2. Project of low power wind converter

Based on the information presented above, the authors have developed a converter designed to convert energy from an unstable source such as a small wind generator. The main authors design idea was to create a device that converts the very wide range input voltage directly to a stable 230VAC output voltage without the battery buffer. Most commercial wind power converters include battery charging systems or are dedicated to connect to the power grid [11,12,13,14,15,16]. There are few solutions that would allow to supply more complex facilities (several receivers) and at the same time were relatively cheap and without charging systems or phase synchronization. The solution is to use dedicated converters for special applications, such as powering the receivers on the yacht [17,18], but they are usually very expensive, because they must meet very high criteria for resistance to weather conditions or safety. In addition, the solutions on the market usually have a rather high input voltage level at which the converter starts works (usually 100-150V or higher) [13,19]. An additional problem is the fact that the manufacturers limit the universality of the proposed converters. Usually, they are dedicated to wind turbines offered by a given manufacturer. The converter designed by the authors has a very wide range of input voltages, thanks to which it gives the output voltage even at low input voltages, and is able to cooperate with any type of wind generator, which makes the solution extremely versatile.

2.1. General design assumptions

The converter design is based on the following assumptions:

- Device safety (the protection of user, external environment and internal components of the converter; the overvoltage protection from the high voltage from generator and the output short-circuit protection).
- Use of three-phase rectifier in the input. (possibility of cooperation with different wind generators).
- Input voltage from 0 to 330V (after rectifier).
- Output voltage 230VAC.
- Continuous output power at 1kW.
- Auxiliary 12V power supply for switching transistors drivers (galvanic isolating power supply).
- Engineering solutions that reduce the price of the device and increase its reliability.
- Achieving the highest possible performance.
- Quiet operation and relatively small dimensions.
- Simple interface for easy operation by serviceman.

The converter block diagram, including the power switches and the most important passive components, is shown in figure 3. The power of the converter is divided into three parts: rectifier, voltage converter and inverter together with the output filter.

![Figure 3](image-url)
The rectifier section has three input connectors for single-phase or three-phase voltage. The overcurrent protection is located in this section too. The aim of this one is to protect the generator against damage in the event of a converter malfunction. At the output of this section there is a bank of capacitors filtering the voltage and stabilizing the parameters of the converter. The choke between the rectifier bridge and the capacitors reduces the ripple of the current flowing between them, thus increasing the life span of the wind turbine and reducing the electromagnetic interference generation.

The next section is a boost converter that increases the input voltage to about 325V. The value of this voltage allows inverter generate a sinusoidal waveform with an effective voltage close to 230VAC. The driver controlling the operation of the switching transistor measures the output voltage and sets the value of PWM coefficient of gate impulse. The frequency of the MOSFET switch is about 70kHz. Another task of the system is to control the current value drawing from the wind turbine, which makes it possible to use the generator optimally and to prevent it from overheating. This section also includes the converter unloading switch when the unit turns off. The energy accumulated in the capacitors is decomposed on a resistor connected in series to the discharge transistor.

The last section of the wind converter is a inverter, which convert DC voltage for AC voltage (sinusoidal). For the output waveform to have a sinusoidal shape, the switching transistors should work at a frequency of 20kHz. The input choke of the inverter reduce the switching losses of the power transistor and reduce the electromagnetic interference that occurs when operating with heavy loads. At the output of the inverter there is a LC filter modifying the rectangular waveform generated by the inverter to a sinusoidal waveform. The higher the inductance value of the choke and capacitor capacitance, the more accurate the sinusoidal waveform, but also the greater the voltage drop across the filter (higher heat loss and lower output voltage).

2.2. Block diagram of the designed converter

Due to the large size of some components, a few blocks of the wind converter are divided into smaller modules, such as the placement of the inverter and the filter along with the output circuit on the various PCB board. A block diagram illustrating the connections between the modules is shown in figure 4. The schematic contains also an isolated power supply and a main microcontroller based on the Atmega16A. The task of the microcontroller is:

- Control of relays placed in front of the rectifier (disconnecting the generator and converter if the input voltage is too high).
- DC voltage measurement before and after the inverter.
- Starting up the boost converter and limiting the maximum current through it.
- Temperature measurement of switching elements located in the boost converter and inverter. This solution allows the control of the switching devices cooling fan and protect the system from overheating.
- Control of inverter power transistors.
- Control of capacitors battery discharge transistor.
- Starting the isolated power supply.
- Control of relays located on the output of the wind converter (converter and load disconnection).
- Measurement of the output voltage of the converter.
- Output current measurement (short circuit detection on load).

An isolated power supply is needed to ensure proper control of the inverter transistors. In addition, this power supply supplies the bank of the filter capacitors and the boost converter. It is designed as a set of DC/DC converters. Galvanic isolation provides small impulse transformers. Due to the low power consumed by the controllers and the efficiency of the power supply over 80%, it does not introduce significant power losses to the entire wind converter.
Between the generator and the rectifier there is additionally short circuit protection in the form of a three-phase overcurrent turn-off switch with a maximum current of 6A. Also between the output circuit of wind converter and the load is a single phase turn-off switch with a maximum current of 6A. The main capacitors are discharged via the earthing switch. The control system has the ability to receive signals from the sensors that signal the opening of the converter case and to activate the main capacitor discharge circuits, which significantly reduces the risk of electric shock. To enable communication with the converter driver, the project provides an operator interface consisting of:

- Power switch for control circuit,
- Power switch for other modules,
- Converter reset button,
- Main converter switch,
- Indicator light for the control system supply,
- Indicator light for other modules power supply,
- Warning indicator light for low level of inverter input voltage,
- Warning indicator light for earthing connected and disconnecting converter from the generator or load,
- Indicator lamp for correct operation of wind converter (capacitors voltage above 30V, converter connected to generator and loads, inverter and boost converter power transistors working).
- Warning light,
- Safety switch,
- An ammeter measuring the current taken from the generator (behind the rectifier).

2.2.1. Boost converter

One of the most important converter circuits is the boost converter. Due to the selected topology presented in figure 5 [10,20,21,22] and the nature of the work, it is the module with the lowest efficiency. This is effect of unfavorable switching conditions of the power semiconductor (high voltage and current) and voltage drops on the inductance and diode. The alternative is to use a transformer converter with higher efficiency, but in this case the converter may not directly work with unstable input voltages like...
wind turbines (without battery buffer) [10,22,23]. For this reason, a simpler topology of the boost converter has been used at the expense of lower efficiency, which is evident at low input voltages. The converter works in CCM mode (Continuous Current Mode) [22].

![The electrical diagram of the boost converter.](image)

**Figure 5.** The electrical diagram of the boost converter.

The MOSFET transistor (IRFP460) is switching at 70 kHz and PWM from 10% to 97%. The power lost in the transistor, for PWM = 97%, is 10.77 W. The boost converter control circuit includes a short-circuit protection and a feedback circuit that controls the output voltage. During testing of the described block with a resistive load of 800 W, the correct output voltage (Uout = 329 V) was reached at the input voltage of 250 V, as shown in table 1. It should be noted that the high level of output voltage stabilization and increase of efficiency with the increase of input voltage. During the measurements, slight increase in temperature was observed on the power components (up to 45°C), which indicates the low power losses and thus the high energy efficiency of the inverter.

| Vin [V] | Iin [A] | Vout [V] | Iout [A] | η [%] |
|--------|--------|---------|---------|-------|
| 100.2  | 2.08   | 170.1   | 1.15    | 94.2  |
| 150.4  | 2.17   | 235.0   | 1.33    | 95.6  |
| 200.0  | 2.21   | 283.0   | 1.48    | 94.4  |
| 250.0  | 2.20   | 329.0   | 1.59    | 94.9  |
| 275.0  | 1.98   | 329.0   | 1.58    | 95.5  |
| 300.0  | 1.80   | 329.0   | 1.58    | 96.0  |

2.2.2. Inverter

The single phase inverter has the form of a H bridge, consisting of four power transistors IRF740, as shown in figure 6 [10,20,21]. The input and output filters of the inverter are located on a separate PCB board. The main assumptions of the inverter design include:

- Input voltage 325VDC (max 400VDC),
- Minimum output current 4A for Uout = 230VAC,
- MOSFET switching frequency inverter 20kHz,
- Galvanic isolation between the control circuit and power transistors by optocouplers.

It was important to fit the large radiators for MOSFETs. Their effectiveness largely depends on the efficiency of the inverter. The power losses, calculated for one 20kHz switched transistor, amounted to 4.65 W. Due to the increase in RDSon resistance along with the temperature, only a forty degree increase in the temperature of the junction was allowed, which necessitates the use of larger heat-sinks. This allows a short overload of the inverter, but increases the cost, weight and size of the device. To avoid these disadvantages, authors were decided to use a cooling fan. The power consumption of the additional fan (2 W) is disproportionately lower compared to the increase in power losses on the switching elements.
Figure 6. The electrical diagram of the inverter.

In order to cool down only when the inverter or boost converter is overheated, it was decided to use NTC thermistors as temperature sensors mounted on the heat sink of the boost converter transistor and on the heatsink of one of the inverter transistors. This solution reduces power losses and allows the converter to run quietly at low loads.

2.2.3. Controlled system

The control module is the most expanded module in the converter. It monitors the current operating parameters of the wind converter and sends the control signals to the other modules: inverter, boost converter and discharge circuit. Its block diagram is shown in figure 7. It includes the Atmega16A microcontroller and steering-measurement systems (control of output voltage, load current, power supply voltage, radiator temperature, inside and outside of the case temperature and rotation speed of the wind turbine) [24]. In addition, it controls the relays disconnecting the wind converter from the generator and the load, the cooling fan and controls the opening of the case. In order for the converter to work long enough after power failure, the system is equipped with a supercapacitor bank. All control blocks are based on simple and effective solutions [25], therefore the whole system is cheap and not very extensive.

Figure 7. The block diagram of the control system.
2.3. Microcontroller software

A very important part of the project is the software of the microcontroller controlling the work of the converter blocks. In the case of this wind converter project, the Atmel microcontroller with AtmelStudio 6.2 was chosen. Programming language “C” has been used in the application [26,27]. The programmer AVRISP MkII was used to upload the compiled file to the microcontroller.

Figure 8 shows a flowchart control algorithm. The first instructions in the program are the definitions of the variables and configurations of the respective microcontroller registers. The next step is to start the A/D converter and the interrupt enable bits. The last step of configuring the microcontroller is to determine the mode of operation of the individual terminals (as input or output). All these operations are performed only once after the microprocessor is started.

The program analyses the inputs of the microcontroller and converts measurements obtained from the A/D converter. On this basis, it determines if an alarm should start and the main wind converter blocks should switched off. Based on the received signals, the microcontroller controls the digital outputs.

![Figure 8. Algorithm of control program. (red - decision blocks, violet - blocks executed only during program initialization, yellow - interrupt, green - blocks executed during main loop operation).](image_url)
3. Inverter tests

The main aim of the inverter test with different load is to check the thermal response of the system. Components such as inverter and boost converter power transistors or the output filter choke, produce appreciable amounts of heat during the current flow. As part of the tests, their case temperatures were measured by digital multimeter with thermocouple. The first test was performed with an inductive load 2.75 mH. The main capacitors were charged to approximately 51 V and then the inverter was started with a 1/8 sinusoidal inverter so as to achieve a rated current of 4 A. The ambient temperature was 27.5°C and the fan was off. The following temperature values were measured:

- The inverter power transistor achieve 55°C, resulting in an increase in the $R_{DSon}$ resistance and a decrease the output current to 3.7 A. Raising the voltage to 55 V increases the output current and automatically causes a further increase switch transistors temperatures and the process repeats. Activation of cooling fan immediately reduces the temperature of the inverter's heatsink, after a 20 minutes their temperature stabilizes at 30°C and the current rises to 4.3 A (at 55 V on the capacitors).
- The measurement of the choke temperature after about 10 minutes indicated stable value of 38°C.

As part of the next test, authors forced the overloaded of the system. The capacitor voltage has been increased to about 74 V using the same load and output current achieves 6 A. Due to the risk of damage to the converter, the test was carried out while the fan was running. The following temperature increases have been reported:

- The inverter transistors have reached 36°C (at an ambient temperature of 27.5°C). This confirms the effectiveness of forced cooling.
- The choke has reached 55°C after about 5 minutes, which is already a high value for this type of element (6 A rated current of the choke).

Measurements made during the tests show that the semiconductor power components are not even close to the maximum temperature values given in the catalogue notes [28,29,30]. The main limitation in this case is excessive overheating of the output filter choke, but only after 150% of the converter overload.

The last test checked the electrical breakdown endurance of the inverter block. The mains capacitor voltage has been increased to 335 V and the load has been exchanged for resistance load. The output current of the wind converter was 3.42 A. The test confirmed the correct operation of the device and none of the power components showed excessive overheating. This is indicated by the temperature of the inverter transistors and the output filter choke shown in table 2. The test also checked the quality of the output circuit under load. The oscillogram of the output voltage of the wind converter is shown in figure 9.

| Table 2. Temperatures of inverter power transistor and filter inductor for different input voltage and load (with working fan) |
|---------------------------------------------------------------|
| **Vin**=55V **Iout**=4,3A | 30°C | 38°C |
| **Vin**=74V **Iout**=6A | 36°C | 55°C |
4. Conclusions
The purpose of this work was to design a power converter for a low power wind generator and small and medium 230VAC loads. The authors have developed switching blocks (boost converter and inverter), additional filter systems and a control system to monitor wind converter operation, prevent failures and ensure safe use and service. The whole is controlled by a microcontroller, which works based on the author's software. It is worth highlighting that the whole project also takes into consideration the aspects of the safety of the converter and the minimization of losses on the semiconductor and inductance elements. In addition, information on testing individual blocks is included.

Although the designed converter meets the initial requirements and covers the safety problems, there are several issues that can be developed to improve the quality of this wind converter. The most important modification of this one to be considered in the future is the replacement of MOSFET transistors on IGBT transistors or SiC-based components. This solution will increase the power of the inverter without changing the heat sink and cooling system. The use of IGBT switches will enable at least double the maximum power of the converter and reduce losses. However, that it leads to the redesign the remaining circuits, especially inside the boost converter.

Another possibility of this converter development concerns the communication with PC computer by Bluetooth. The HC-06 module is optionally installed on the PCB controller board when designing the printed circuits. An application running on the computer would allow to track the current parameters of the converter working and control the individual components such as inverter or boost converter. In addition, the program would record errors occurring during the operation of the device, which would significantly facilitate detection of any malfunction and repair it.

The last potential development is design a module, which may be able to provide energy from outside power grid to the inverter power supply. Thanks to this, in the case of weak winds, the energy would be partially taken from the grid, which would allow the receivers demanding a continuous power supply. The use of such a module would greatly increase the versatility of the converter, since it would enable almost all types of receivers.

5. References
[1] Renewable Energy Technologies: Cost Analysis Series, Volume 1: Power Sector, Issue 5/5 Wind Power (IRENA Working Paper), June 2012, https://www.irena.org/documentdownloads/publications/re_technologies_cost_analysis-wind_power.pdf (access 26.03.2017)
[2] GWEC - global statistic, http://gwec.net/global-figures/graphs/ (access 26.03.2017)
[3] The European Wind Energy Association - EWEA, *Wind in power 2015: European statistics*, February 2016, https://www.ewea.org/fileadmin/files/library/publications/statistics/EWEA-Annual-Statistics-2015.pdf (access 26.03.2017)

[4] *Renewables 2016 Global Status Report* (by REN21), http://www.ren21.net/wp-content/uploads/2016/06/GSR_2016_Full_Report.pdf (access 26.03.2017)

[5] Energy Regulatory Office (Poland) – map of RES, http://www.ure.gov.pl/uremapozemap.html (access 26.03.2017)

[6] *Global Wind 2006 Report* (by GWEC) http://gwec.net/wp-content/uploads/2012/06/gwec-2006_final_01.pdf (access 26.03.2017)

[7] ABB product brochure 2015 *IGCT – integrated gate-commutated thyristors*; http://www.brown.edu/Departments/Engineering/Courses/ENGN1931F/ABB_Flyer_IGCT_2015.pdf (access 27.03.2017)

[8] ABB product brochure 2016 *PCS6000 wind turbine converter Medium voltage, full power converter, up to 12 MW*; http://new.abb.com/power-converters-inverters/wind-turbines/utility-scale/pcs6000 (access 28.03.2017)

[9] *Przydomowe elektrownie wiatrowe* (by AirGenerator) http://generatory-wiatrowe.pl/produkt/y/elektrownie-wiatrowe/ (access 28.03.2017)

[10] Ke Ma 2015 *Power Electronics for the Next Generation Wind Turbine System* (Switzerland: Springer International Publishing)

[11] Teodorescu R, Liserre M, Rodriguez P 2011 *Grid Converters for Photovoltaic and Wind Power Systems* (John Wiley & Sons Ltd published)

[12] Fattah Hassanzadeh, Hossein Sangrody, Amin Hajizadeh, Shahrrokh Akhlaghi 2017 *Back-to-back Converter Control of Grid-connected Wind Turbine to Mitigate Voltage Drop Caused by Faults*, Conference: 49th North American Power Symposium, September 2017, https://www.researchgate.net/publication/318205807_Back-to-back_Converter_Control_of_Grid-connected_Wind_Turbine_to_Mitigate_Voltage_Drop_Caused_by_Faults (access 08.03.2018)

[13] Nayar Ch, Dehbonei H, Chang L, 2005 *A Low Cost Power Electronic Interface for Small Scale Wind Generators in Single Phase Distributed Power Generation System*, (AUPEC 2005 Australasian Universities Power Engineering Conference, Australia, 25 -28 September, 2005), http://citeseerx.ist.psu.edu/viewdoc/summary?doi=10.1.1.574.1392 (access 10.03.2018)

[14] Blaabjerg, F., Iov, F., Chen, Z., & Ma, K. 2010 *Power Electronics and Controls for Wind Turbine Systems*, (In Proceedings of the IEEE Energy Conference and Exhibition, ENERGYCON 2010, Bahrain) http://vbn.aau.dk/files/46616844/Power_Electronics_and_Controls_for_Wind.pdf (access 10.03.2018)

[15] Krishnamoorthy H, Rana, D, Garg P, Enjeti PN and Pitel I, Fellow *Wind Turbine Generator–Battery Energy Storage Utility Interface Converter Topology With Medium-Frequency Transformer Link*, (IEEE TRANSACTIONS ON POWER ELECTRONICS, VOL. 29, NO. 8, AUGUST 2014), http://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=6689314 (access 10.03.2018)

[16] Mayouf M, Abdessemed R *Comparative Study of a Small Size Wind Generation System Efficiency for Battery Charging*, (SERBIAN JOURNAL OF ELECTRICAL ENGINEERING Vol. 10, No. 2, pp. 261-274, June 2013), http://www.journal.ftn.kg.ac.rs/Vol_10-2/03-Messaoud-Abdessemed.pdf (access 10.03.2018)

[17] ECOSOLAR - commercial offer, http://www.ecosolar.pl/inwertery-windy-boy-c-75_76.html (access 07.03.2018)

[18] e-MARINE SYSTEMS - manufacturer's offer, https://www.emarineinc.com/categories/Inverters (access 07.03.2018)

[19] Meere R, Ibrahim I, Ruddy J, O'Loughlin C and O'Donnell T 2016 *Scaled Hardware Implementation of a Full Conversion Wind Turbine for Low Frequency AC Transmission*, (Energy Procedia Volume 94, pp. 182-190, September 2016)
[20] Barlik R and Nowak M 2014 Energoelektronika: Elementy, Podzespoły, Układy (Warsaw: Warsaw University of Technology publisher)
[21] Nowak M and Barlik R 2013 Poradnik inżyniera energoelektronika, tom 1 (Warsaw: WNT publisher)
[22] Schmidt-Walter H, Wenzel H, Zänker T, Morgan R and Kegan J. Design of Switch Mode Power Supplies http://schmidt-walter-schaltnetzteile.de/smps_e/smpe_e.html (access 27.03.2017)
[23] Sanjaya Maniktala 2006 Switching Power Supplies – A to Z, (Burlington USA: Newnes, Elsevier Inc.)
[24] Atmega16 datasheet http://www.atmel.com/images/doc2466.pdf (access 27.03.2017)
[25] Nowak M, Barlik R and Rąbkowski J 2014 Poradnik inżyniera energoelektronika, tom 2 (Warsaw: WNT publisher)
[26] Borkowski P 2010 AVR&ARM7. Programowanie mikrokontrolerów dla każdego (Gliwice: Helion publisher)
[27] Francuz T 2015 Język C dla mikrokontrolerów AVR. (Gliwice: Helion publisher)
[28] IRF740 datasheet http://www.vishay.com/docs/91054/91054.pdf (access 27.03.2017)
[29] IRFP460 datasheet http://www.irf.com/product-info/datasheets/data/irfp460a.pdf (access 27.03.2017)
[30] DTMSS-40 chokes datasheet http://feryster.pl/assets/nowa/pdf/dlawiki/dtmss40.pdf (access 27.03.2017)