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Analysis of the possibilities of introducing autonomous hybrid power supply system into stand-alone residential building

Streszczenie. *Dzięki dynamicznemu rozwojowi systemów zasilania źródłami energii odnawialnej, w szczególności układów fotowoltaicznych oraz wiatrowych, powstały nowe możliwości dotyczące wykorzystania tych układów w budynkach pasywnych oraz zaimplementowania do obecnie istniejących. W związku z ciągle rosnącymi cenami energii elektrycznej oraz poszukiwaniem ekologicznych źródeł energii, powstają koncepcje oraz projekty wykorzystania systemów hybrydowych do stworzenia autonomicznego zasilania budynków.*

Abstract. *Due to the dynamic development of power systems supplied with renewable energy sources, especially solar and wind energy objects, new possibilities have appeared in the aspects concerning applying such systems in passive houses and implementing them into existing buildings. Taking into account continuous increase in energy prices and the need of searching for the ecological energy sources it is necessary to develop the idea and elaborate technical projects using hybrid power systems as the way to create autonomous power supply system. (**Analiza możliwości wykorzystania hybrydowego autonomicznego systemu zasilania w budynku mieszkalnym**).*

Słowa kluczowe: fotowoltaika, energia wiatrowa, zasilanie hybrydowe, energia słoneczna.
Keywords: photovoltaics, wind energy, hybrid power supply, solar energy.

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1. Introduction

It is known that steadily growing level of technological development causes increase in the demand for electricity, which is actually essential in everyday life. Due to such rapid growth of the demand for electricity and the necessity of reducing the effects of the usage of fossil fuels at the same time a lot of researches have been carried out in order to find the alternative ways of producing energy. In recent years it was possible to observe dynamic development of the research projects which concerned introducing new technologies using power of sun or wind into the process of electricity generating for residential building purposes. The outcomes of those projects shown that in the result of combining photovoltaic systems with wind turbines it is possible to create the system which will ensure higher reliability of the power supply and enable to design autonomous power supply system, dedicated for residential buildings. Insolation in Poland depends on location of analyzed area and ranges between 900 and 1200 kW/m^2 per year [3, 7, 4], whereas amount of wind energy possible to obtain would be about 2100 W per year, assuming keeping wind speed on the level of 15 m/s for 1 m propeller swept area. Certainly, amounts of energy projected above as possible to obtain will depend on the local weather conditions, in which mentioned parameters will vary as the function of time. Considering autonomous power supply system dedicated for residential buildings it is necessary to optimize the hybrid power supply system with regards to multi-variant variables determining the level of supply system reliability. Additionally, it is assumed that in case of temporary break in renewal energy supply, all the demand for electricity will be met by the energy stored in the power batteries. For the purposes of electricity storage, nominal power of each individual load should be calculated on the basis of the energy balance of the whole power supply system. Certainly, in order to estimate the amount of energy which is possible to generate in described system it is necessary to make periodic measurements of an insolation and windiness on a given area. On the basis of achieved results it will be possible to estimate values of the essential technical parameters of the system, such as nominal power of the photovoltaic generators and wind turbines. After performing such calculations it will be possible to select an appropriate devices dedicated to cooperate with generators, such as the set of power batteries, charge controllers, inverters and devices protecting against overloads and short circuits. In case of assuming high level of power supply reliability rate it is possible to introduce emergency generating unit which will increase the level of certainty of the unstoppable power supply from the system.

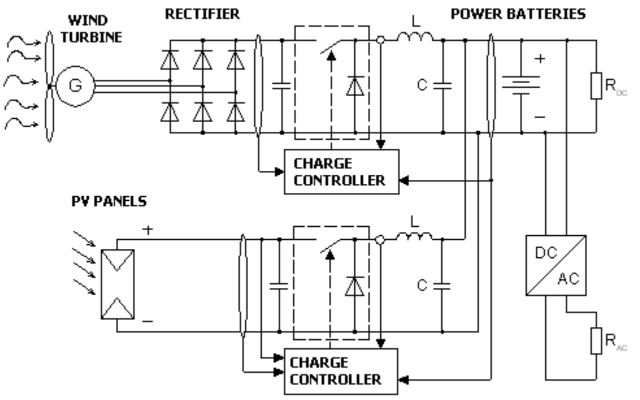

Fig.1. Scheme of the hybrid power supply system

2. System components

In the Fig.1. scheme of the tested hybrid renewal energy supply system has been shown. Presented system consists of the wind turbine of 2 kW nominal power, photovoltaic (PV) system of 2.3 kW nominal power as the primary power source, power batteries system of 48V nominal voltage and inverter, which is used in order to transform 48V DC voltage into 230V AC signal. In addition described system has been equipped with charge controllers, which task is to optimize the process of batteries charging. Output of the inverter is connected to the main power supply of the existing electrical system in the analyzed building.

2.1 Photovoltaic generators

Photovoltaic panel consists of many individual cells, which have been connected each other in order to achieve higher values of voltage and power. It is possible to increase the level of electric current on the output of PV panel by realizing parallel connection between single modules. Photovoltaic panels usually operates under output voltage of 12V or 24V [1], and 240V in case of systems connected to the power network. Due to the fact that crystalline silicon is the most often applied material in the process of PV cells production [5], silicon-based PV cells represent 95% of all available devices. Monocrystalline cells are usually applied in photovoltaic panels which nominal power is not greater than 150 - 200 W, whereas polycrystalline cells are commonly used in order to ensure nominal power at the level above 200W in one photovoltaic module. The number of possible applications of photovoltaic systems is unlimited and it only depends on the designer's creativity level. The main advantages of implementing systems containing photovoltaic cells are the relatively high level of reliability and the possibility to obtain free-of-charge electricity for living purposes as the result of the clean, quiet and unattended generation process. For those reasons PV cells are becoming increasingly common either as a part of the civil installations connected directly to the power network or as an autonomous power systems. In both mentioned cases the nominal efficiency of the whole system primarily depends on the annual insolation rate which is possible to obtain at the installation site. It is commonly known that the greater is the number of sunny days and solar radiation stronger, the more electricity is possible to obtain using given PV system [4]. Considering practical aspects of PV systems operation, geographical direction and inclination angle of the PV panels are very important factors. Typical mistake appearing during the setting PV panel up is the wrong localization in relation to the sun, such as northern slope of the hill or square shaded by trees or buildings. An excellent places for installing PV panels are roofs and walls of all kinds of buildings. In present technical conditions it is possible to build the office block with walls entirely covered by photovoltaic cells (including glass surfaces such as windows). Electricity generation using solar cells is characterized by relatively high efficiency at the level of 13-18%. Such level of efficiency is due to the fact that inside the PV cell the energy of solar radiation is transformed into electricity without thermal losses [5]. However it needs to be underlined that the nominal power of a single photovoltaic cell is low. Therefore in order to achieve assumed power level it is necessary to setup serial or parallel connection of PV cells in a so called panels or modules. In such cases the value of nominal power is directly proportional to the area covered by the panel.

The equation applicable for the current-voltage characteristic of photovoltaic cell could be expressed by the following formula:

$$(1)\quad I = I_f - I_0\left\{\exp\left[\frac{q(U+IR_s)}{mkT}\right]-1\right\} - \frac{U+IR_s}{R_{sh}}$$

where: I – electric current produced by the PV cell, A; U – voltage between PV cell terminals, V; I_f – photocurrent (as a function of the temperature and insolation), A ; I_0 – junction saturation current (dependent on the temperature), A; q – elementary charge ($1{,}602\cdot10^{-19}$ C); m – diode quality factor (1...2); k – Boltzmann constant ($1{,}381\cdot10^{-23}$ $J\cdot K^{-1}$); T – temperature of the PV cell, K; R_s – serial resistance of the PV cell, Ω; R_{sh} – parallel resistance of the PV cell, Ω

After analyzing the dependency $I = f(U)$ of the photovoltaic cell it is possible to distinguish three characteristic points:

P_1 ($U = 0$, $I = I_z$) – point which determines value of the short-circuit current of PV cell,

P_2 ($U = U_0$, $I = 0$) – point which determines value of the open-circuit voltage of PV cell,

P_3 ($U = U_{max}$, $I = I_{max}$) – point which determines value of the voltage and current at the maximum power of PV cell.

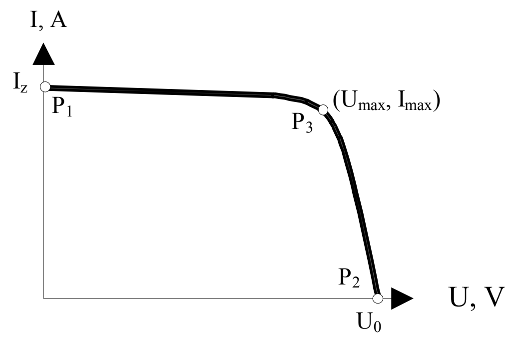

Fig.2. Current-voltage characteristic of the PV generator

Analysis of the Fig. 2. shows that between points P1 and P3 of presented dependency photovoltaic cells operates as the current source, whereas between points P2 and P3 it operates as the voltage source. Additionally the inclination angle of the characteristic between points P1 and P3 depends on parallel resistance R_{sh}, whereas between points P2 and P3 it depends on serial resistance R_s. I_s is also noticeable that in the point P3 of the characteristic presented in the Fig.2. it is impossible to classify PV cell neither as a typical current source nor voltage source [6].

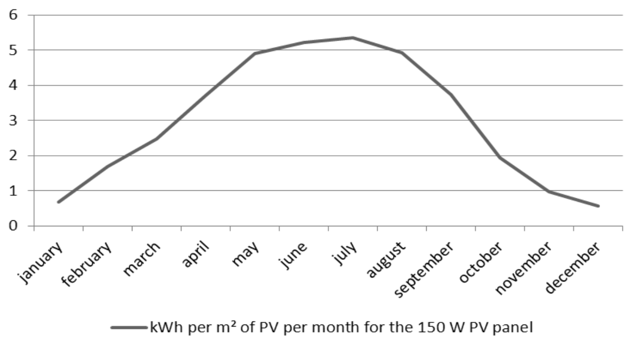

Fig.3. Amounts of the energy produced by the PV generator of the nominal power of 150W

In the Fig.3. the amount of electricity produced by the PV module as the function of time has been presented. Concerning the period of the highest insolation of the installation site, it can be seen that using the PV module of the area of 1 m2 it is possible to obtain more than 5 kWh of energy per month, whereas in the winter period those values are five times lower.

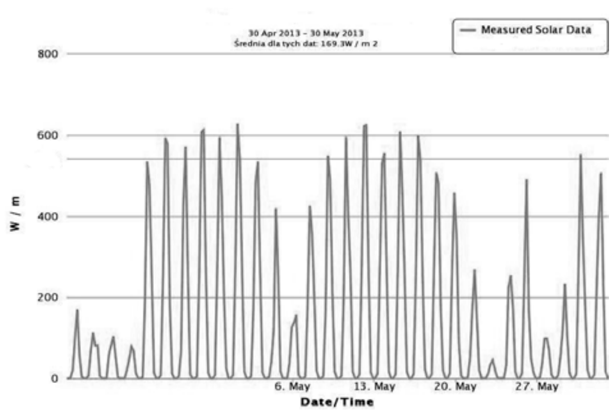

Fig.4. Insolation characteristic of the tested PV module installation site in May 2013

In the Fig.4. monthly insolation rate of the installation site as the function of time of the day has been demonstrated. It is possible to notice that at the beginning of month 4 days with low level of insolation rate have occurred, whereas in the next period measured values have dynamically increased. Average insolation rate in the presented period equaled 170 W.

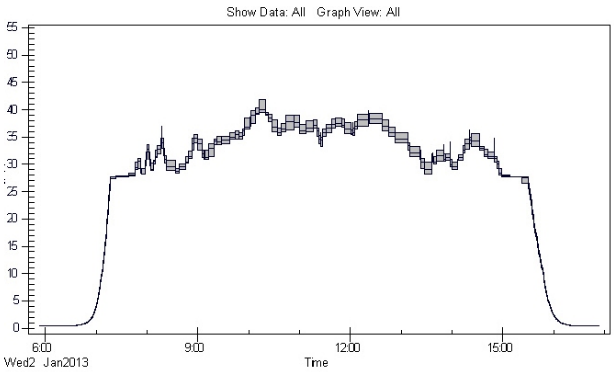

Fig.5. Time dependency of the PV generator voltage in the 2nd of January 2013

Figure 5. shows voltage data of the tested PV generator of the nominal power of 230W in relation to the period of time. In this case the testing time equaled 24 hours.

2.2 Wind turbines

General characteristics of the wind energy resources. Wind power is the one of the most dynamically developing sector of renewal energy industry in the world. Wind energy is produced using relatively simple technical solutions, such as wind turbines, which are part of the wind power plants. In such facilities kinetic energy of the wind is transformed into the electricity. It is estimated that in Poland about 40% of total country area could be used for wind power purposes [2], under the assumption that minimal economically viable generation is the level of 1000 kWh/m^2/year at the height of 30 m over the ground in the area of the class of the roughness "0" (which means ground smooth, unwooded and undeveloped). Average lifetime of small wind power plant is estimated at about 1800 hours per year [8]. In order to realize power generation purposes in such object the wind speed should equal at least 4 m/s. Performing analyses of maps of winds and wind resources it is necessary to consider that speed and direction of the wind in the analyzed point is the superposition of many different factors, which are strongly dependent on the local environmental conditions. Among those factors, the following are the most important:

- landform features,
- air temperature,
- land cover type (roughness),
- presence of water basins,
- wind direction.

Theoretically, the rate of efficiency of air stream energy usage could be equal 59.3%, however in practical applications it could reach the level of 50% at most.

Taking into account real efficiency rates of the mechanical and electrical components, the nominal power of the whole wind turbine system could be expressed by the following formulas:

for small power plant: $P = (0.00011)\, d^2 v^3$, kW

for large power plant: $P = (0{,}00022)\, d^2 v^3$[kW]

where:

d – diameter of the wind turbine wings [m]

v – wind speed [m/s]

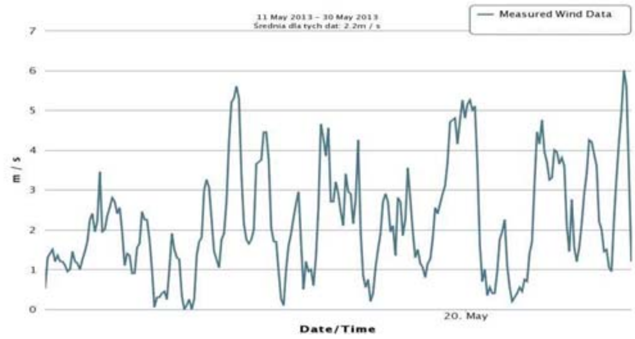

Fig.6. Air stream speed characteristic of the tested installation site in May 2013

According to the plot presented in the Fig.6. it could be stated that the plot contains stochastic data. After performing relevant measurements in the winter period it turned out that the shape of the obtained plot is similar to the one presented in the Fig.6, but recorded values of the air stream speed are much greater than in the summertime. Consequently, in the result of average measurement data calculations it is possible to determine the amount of energy produced in the precise period of time.

Important parameter which is often neglected in the process of estimating the amount of the generated wind energy is the direction of the blowing air stream. Fig.7. presents results of the measurements carried out in May 2013 at the installation site. As it can be seen the dominating wind direction was the north-west stream, which is essential during performing topological analysis of the terrain.

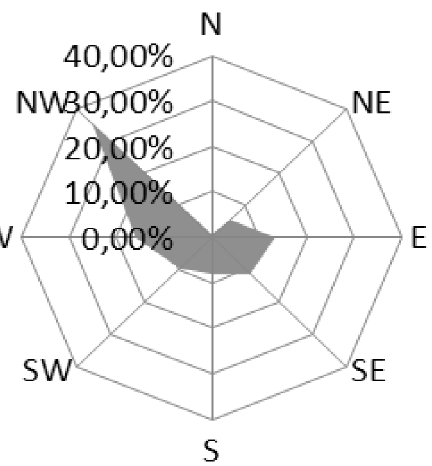

Fig.7. Percentage distribution of the wind directions: N 0,70% - north (N) - azimuth 0° (or 360°); NE 5.50% - north-east (NE) - azimuth 45°; E 13.30% - east (E) - azimuth 90°, SE 11.40% - south-east (SE) - azimuth 135°; S 8.00% - south (W) - azimuth 270°; SW 9.60% - south-west (SW) - azimuth 225°; W 16.00% - west (W) - azimuth 270°; NW 35.50% - north-west (NW) - azimuth 315°

3. Economic calculation of the system

In the research process the technical and economical analysis of application of the PV panels and wind turbine into power supply system of a stand-alone residential building has been conducted. It has been assumed that the total nominal power of devices installed in the considered object equals 12.5 kW, whereas demand for the peak power equals 4 kW. For the purposes of conducted research project and on the basis of information concerning availability of commercial products the hybrid system of the nominal power of 4.3 kW has been configured.

Technical parameters of the tested system are as follows:

- total power of the PV modules in the system: 2.3 kW,
- total power of the wind turbine: 2 kW,
- power of the single PV module: 230 W,
- total PV modules area: 16 m²,
- capacity of the batteries system: 1000 Ah
- power of the inverter: 4000 W
- system efficiency: 95%,
- output voltage: 230 V, 50 Hz,

On the basis of the current price-lists total cost of the system has been estimated at about 8 000 EUR (32 000 PLN).

Predicted annual amount of electricity produced by the wind generation system equals 3670 kWh, whereas annual amount of electricity produced by the PV generators equals 2136 kWh. It needs to be underlined that average consumption of electricity in the typical household equals about 2320 kWh per year. Taking into consideration that the average price of the 1 kWh on the energy market is the 0.60 PLN, the worth of total produced energy is the 3483.00 PLN per year. In the current economic conditions the period in which incurred investments will be paid back is about 9 years. Nonetheless, during the preparation of this proposal new legal restriction are on the way. In case of introducing new law imposing the obligation of purchasing energy surplus from the private sector by the state-owned companies the period mentioned above should be shortened by half.

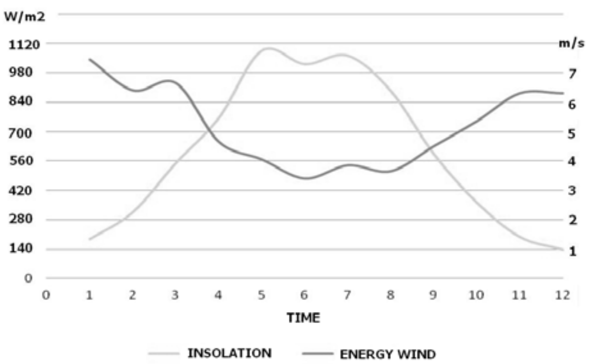

Fig.8. Annual distribution of the wind energy compared to the solar energy

As it can be seen from the Fig.8. wind turbine is perfectly complementary in relation to the solar panels. Considering autumn and winter period the number of windy days is much more greater than during the summertime. Wind turbine is able to produce about 2/3 of annual production during the cold semester, whereas PV panels generate 3/4 of the total annual production during the warm semester. For that reasons, after introducing the hybrid system it is possible to provide balanced production and stable energy supply throughout the year.

4. Conclusion

As the conclusion it is reasonable to state that in case of either newly constructed passive houses or already existing buildings it is possible to apply hybrid power generation systems producing electricity from renewal energy sources. Such power supply systems are becoming an alternative way of electricity generation in order to realize the idea of autonomously operating building. Certainly, very important factor is the climatic characteristic of considered location and the optimization of the related processes. Hybrid power supply system integrates wind power plant and photovoltaic cells, which ensures stable work of the whole system. Such solution is especially dedicated for the majority of locations in Poland. Additional advantage is the increased reliability due to the diversification of energy sources. From the economic perspective, the final conclusion is the observation that the most efficient power supply system based on the renewal power sources is the hybrid system, which enables to achieve stable level of generated energy during the whole year. Renewal energy systems, such as photovoltaic panel or wind generators are becoming more and more common as the way to meet the still growing needs for the ecological electricity. Mass production of the PV and wind generators causes the rapid decrease in their prices. At the same time the efficiency of such devices makes them a profitable investment.

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