TECHNICAL TRANSACTIONS | **CZASOPISMO TECHNICZNE**
CIVIL ENGINEERING | BUDOWNICTWO

4-B/2015

ANDRZEJ SMOLEŃ*

PERFORMANCE ANALYSIS OF THE HYBRID POWER SYSTEM USED FOR SUPPLYING THE AUTONOMIC ROAD LIGHT INSTALLATIONS

ANALIZA WYDAJNOŚCI HYBRYDOWEGO UKŁADU ZASILANIA AUTONOMICZNEGO SYSTEMU OŚWIETLENIA DROGOWEGO

Abstract

The performance of hybrid power system used for supplying power to the autonomous road light system is analyzed in this paper. The calculations were based on data describing the typical climatic conditions in the selected location on Polish territory. The power flow simulation results were presented. The results show that the efficiency of micro-wind turbine is low. This leads to the conclusion that there is no economic justification to use it in such systems.

Keywords: autonomic, road light, hybrid, simulation, photovoltaic

Streszczenie

W artykule przedstawione zostały wyniki analizy wydajności hybrydowego układu zasilania autonomicznego systemu oświetlenia drogowego. Obliczenia przeprowadzone zostały metodą symulacji komputerowej na podstawie danych opisujących typowe lata meteorologiczne w miejscowości Szczecinek. Ponadto przedstawiony został przewidywany poziom naładowania zasobnika energii systemu. Otrzymane wyniki świadczą o niskiej przewidywanej wydajności mikro-turbiny wiatrowej. Prowadzi to do wniosku, iż jej zastosowanie w analizowanym układzie nie ma uzasadnienia ekonomicznego.

Słowa kluczowe: autonomiczny, oświetlenie, hybrydowy, symulacja, fotowoltaika

DOI: 10.4467/2353737XCT.15.403.5034

* Eng. Student Andrzej Smoleń, Department of Electrical and Computer Engineering Fundamentals, Faculty of Electrical and Computer Engineering, Rzeszow University of Technology.

Denotations

G_{STC} – solar radiation under STC conditions 1000 [W/m^2]
G_c – hourly average of solar radiation [W/m^2]
I_{scmr} – short-circuit current of module under under STC conditions [A]
V_{ocmr} – open-circuit voltage under STC conditions [V]
dV/dT – module voltage temperature coefficient [-]
dI/dT – module current temperature coefficient [-]
I_{mppSTC} – maximum power point current of module under STC conditions [A]
T_{pv} – PV module temperature [K]
N_s – number of cells connected in series
R_{sm} – module series resistance
n – P-N junction quality coefficient [-]
l_m – number of modules in PV panel
V_d – velocity of wind, which start the turbine
V_o – a minimum value of wind speed, at which the turbine reaches the rated power
V_g – wind speed limit, at which the turbine turns off
N_n – wind turbine nominal power
γ – Rayleigh distribution shape coefficient 2 [-]
A – rotor surface [m^2]
ρ – typical air density 1.225 [kg/m^3]

1. Introduction

In recent years, autonomic road light systems became much more popular. The power supply unit uses renewable energy from wind and the Sun. Installation of such systems is not preceded by a long-term analysis of the location when it comes to renewable energy potential. For this reason a lot of this applications do not fulfill its function properly, especially when the configuration was selected incorrectly. Considered supply system comprises: photovoltaic panel, micro wind turbine and a lead-acid battery. Quasi-static mathematical models of each component were used to simulate the system. Such an approach requires the input data in a form of time series average values describing the temperature, wind speed, solar radiation and system load. For the purposes of this study the data describing typical climatic conditions (TCC) in Szczecinek (Poland) were used.

2. Method

2.1. Photovoltaic panel

In order to calculate the expected energy yield of the photovoltaic panel it is necessary to calculate the temperature of its modules for each step in the simulation. For this purpose the single layer PV thermal models described in [1] were used. In this approach the temperature of the module is treated as a linear function of the solar radiation with straight angle of incidence. The influence of forced convection was neglected in this model, for increased accuracy the simulation step in which the wind speed exceeds $1\frac{\mathrm{m}}{\mathrm{s}}$ were calculated using the other model described in [2]. Values of natural convection coefficient $h = 25.3\frac{\mathrm{W}}{\mathrm{m^2K}}$ and the forced $h_1 = 6\frac{\mathrm{W}}{\mathrm{m^2K}}$ have been adopted in accordance with [3]. The influence of module temperature for open circuit voltage was taken into account.

$$V_T = \frac{dV}{dT} T_{PV} \tag{1}$$

The temperature-caused change of module current was calculated as:

$$I_T = \frac{dI}{dT}\left(T_{PV} - T_{STC}\right) \tag{2}$$

To calculate the time series energy produced by a photovoltaic panel, on the basis of [4], [5] and [6] the quasi-static PV model was created. The method of calculation of the hourly average generated power is presented below.

The current of module under the given conditions of solar radiation is given by:

$$I_{\mathrm{scm}} = \frac{G_{\mathrm{c}}}{G_{\mathrm{STC}}\left(I_{\mathrm{scmr}} + I_{\mathrm{T}}\right)} \tag{3}$$

The average value of the open circuit voltage is given by:

$$V_{ocm} = V_{\mathrm{ocmr}} + \frac{\mathrm{dV}}{\mathrm{dT}}\left(T - T_{STC}\right) nN_s V_T log\left(\frac{I_{\mathrm{scm}}}{I_{\mathrm{scmr}}}\right) \tag{4}$$

The average value of module MPP current, under given conditions is calculated as:

$$I_{\mathrm{mpp}} = \frac{I_{\mathrm{mppSTC}} G_{\mathrm{c}}}{G_{\mathrm{STC}} + I_{\mathrm{T}}} \tag{5}$$

The average value of module voltage corresponding to the same conditions is given by:

$$V_{\mathrm{mpp}} = nN_s V_T log\left(\frac{1 + I_{\mathrm{scm}} - I_{\mathrm{mpp}}}{I_{\mathrm{scm}} e^{\frac{V_{\mathrm{ocm}}}{nN_s V_T}} - 1}\right) - I_{\mathrm{mpp}} R_{sm} \tag{6}$$

The average value of generated power is calculated as:

$$P_g = V_{\mathrm{mpp}} I_{\mathrm{mpp}} l_m \tag{7}$$

Additionally the conversion loses (contacts and wires resistance) are about 5 percent of produced energy [4]. Module parameter values have been adopted in accordance with the note sheet of BP-Solar-380. The relations have been analyzed in Mat-lab. Exemplary calculations results carried out for the PV panel which rated power is 240 W are presented below.

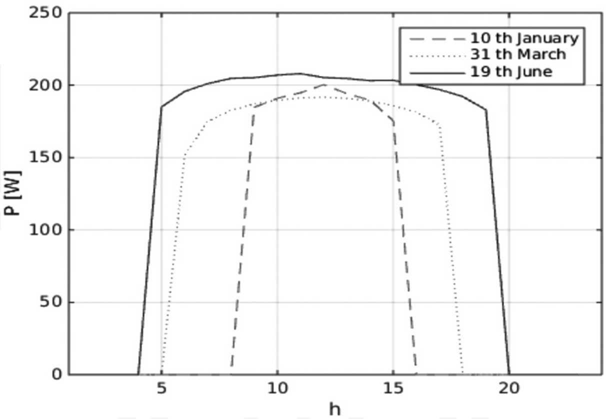

Fig. 1. The hourly average value of power generated by PV module with angle of elevation 30° and south orientation

The results show that the total daily value of generated power depends mostly on ratio of the length of day and night. Occurring in the course of the year, changes of this ratio are most important for the autonomic road light systems, where load increases relatively to the length of nights.

2.2. Estimate of the energy yield of micro wind turbine

In a considered system the micro-wind turbine is mounted directly on the lamppost. For this reason the axis of the rotor is usually located at an altitude between 7 to 11 m above the ground. It is very important for the amount of energy supplied to the turbine by the air stream. According to [7] the measurements were performed at similar heights above the ground. According to [8] wind velocity distribution as a function of time, a density function can be approximated by Weibull or Rayleigh. The practical possibilities of using wind energy are limited by the construction of turbine and this can be estimated with a method given in [8] as follows:

The amount of energy produced by the turbine into the wind speed range from V_d to V_o was calculated as:

$$E_1 = \frac{3}{2} N_n T \int_{V_d}^{V_0} \left[\left(\frac{V}{2} \right)^{(3-1)} \mathrm{e}^{-\left(\frac{V}{2}\right)^3} \right] \sin\left(\frac{\pi}{2} \frac{V - V_d}{V_0 - V_d} \right) dV \tag{8}$$

For the wind speed range from V_o to V_g:

$$E_2 = \frac{\gamma}{\beta} N_n T \int_{V_0}^{V_g} \left(\frac{V}{\beta} \right)^{(3-1)} \mathrm{e}^{-\left(\frac{V}{\beta}\right)^3} dV \tag{9}$$

The total energy produced by micro-turbine in a given period of time:

$$E_c = E_1 + E_2 \tag{10}$$

To the future calculations the Rayleigh distribution was used, where $\beta = 1.1258$ coefficient is taken as an example according to [7]. On this basis, values of annual energy yield were estimated for a turbine with rated power 400 W. The calculations were conducted for different values of turbine starting speed (V_d).

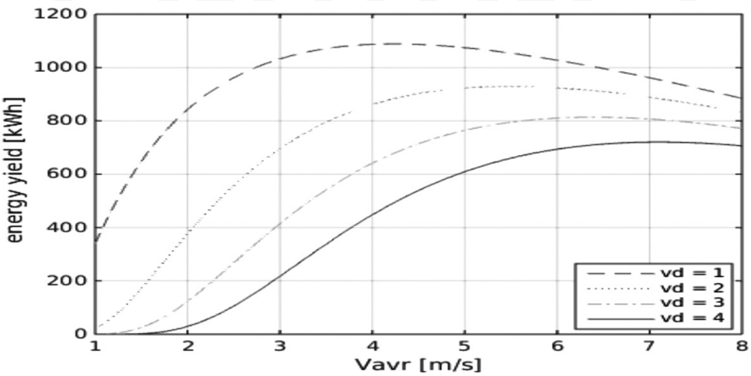

Fig. 2. Annual yield of turbine as a function of average wind speed, for different values of V_d

The results show that the values of V_d affect the annual yield of turbine, especially for low wind speeds. The most frequently value of this parameter, reported by the manufacturers, is about 2 $1\frac{\text{m}}{\text{s}}$. For the purpose of this study the experimental verification of parameter V_d has not been made. For this reason, for further calculations V_d = 3 m/s were adopted. The parameters of considered turbine are as follows:

– turbine has a three-bladed rotor
– rotor blade design provides a maximum value of power coefficient $C_p = 0.4$
– rotor diameter is 1.5 m

For those parameters the minimum value of V_o is approximately given by:

$$V_0 = \sqrt[3]{\frac{N_n}{\rho A C_p}} \tag{11}$$

For a rated power N_n = 400 W the value of V_o = 7.73 $1\frac{\text{m}}{\text{s}}$ is assumed to the further calculations. For the purpose of energy flows, simulations of the hourly energy yield of turbine were calculated using the method presented above for each average value of wind speed. The hourly average value of generated power was calculated by dividing it by corresponding time unit.

2.3. Energy storage

For the purpose of power flow simulation in systems with energy storage the kinetic model of battery was developed in National Renewable Energy Laboratory (USA). The model has been described in details in [4]. This model considers the limitations of available power stored in the battery, in the case of rapid unloading and access to free capacity of the battery during charging. The dependences was implemented in Mat-lab in accordance with [4]. Additionally the charging and discharging loses were treated as constant and equal. The value of these processes: efficiency coefficient was assumed as 0.8. The parameters of the model were adopted for a lead-acid battery in accordance with Homer software database.

2.4. System load

The LED lamps with rated voltage of 12 V, are most frequently used as a load of autonomic road light systems. Load power between 20 to 120 W is usually used in such installations, 80 W was adopted to the further calculations. In order to simulate the system energy flows, the hourly time series of energy consumption was created with following assumptions:

- the light source operates from dusk to dawn
- the load power is constant during simulation step (the influence of temperature is neglected)

Distribution of daily averages load power has been calculated.

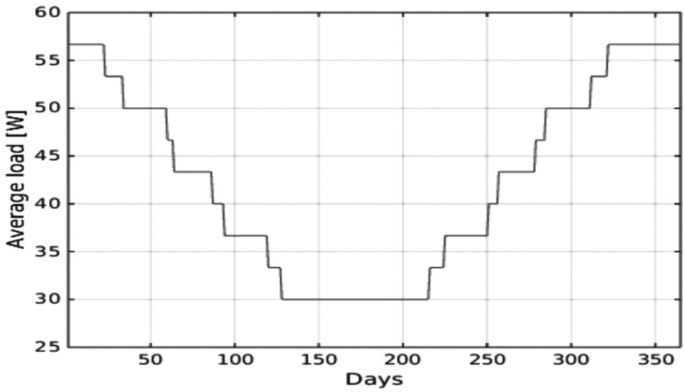

Fig. 3. Daily averages of load power [W]

3. Results

The simulation was performed with a quasi-static approach which means that all of variables are constant during the simulation step. The simulation process is based on energy conservation law, the system energy balance is calculated for each step and on this basis the battery state of charge is determined. According to [4] such calculations can provide acceptable accuracy at time step 1 h. For this reason the hourly averages of generated and consumed power were used. The considered system configuration is:

- photo-voltaic panel is composed of three modules with a total capacity 240 W
- micro wind turbine rated power is 400 W
- nominal load power is 80 W
- battery capacity is 2400 Wh

In order to compare the performance of each energy sources during the year, the daily averages of their power generation were calculated.

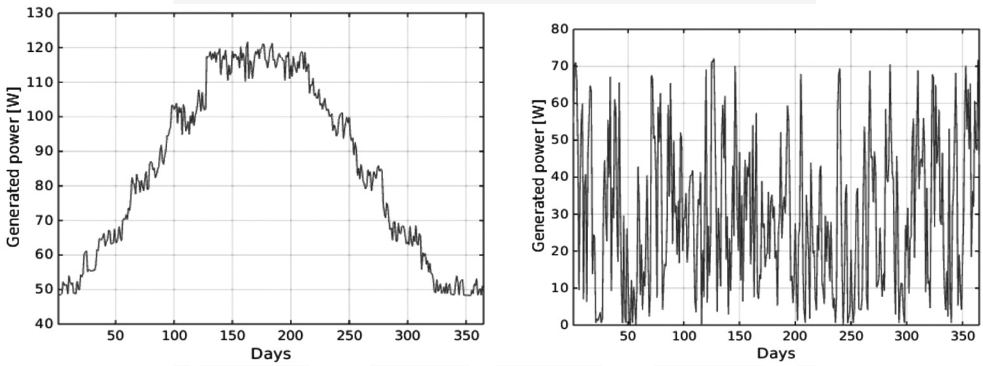

Fig. 4. Daily averages of photovoltaic collector output (left) and micro wind turbine output (right)

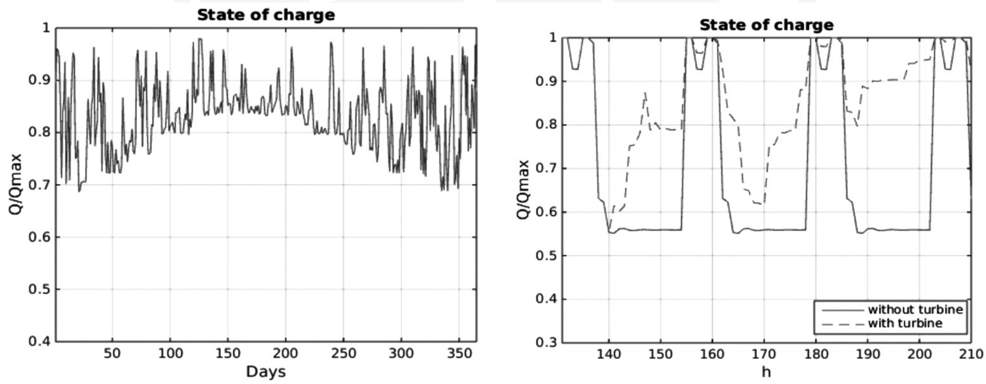

Fig. 5. Battery state of charge – daily averages (left), and without wind turbine support (right)

The results show that the differences between the collector performance in winter and summer period are significant. It is particularly important in view of annual load profile of considered system. The daily averages of power generated by micro-wind turbine practically do not exceed 70 W, with rated power 400 W. The calculated annual average of turbine output power is only 29.43 [W]. For reference, the average output power of photovoltaic panel is more than three times higher, and equals 89.62 W. In order to assess whether the system is able to work autonomously, the battery state of charge was calculated.

4. Conclusions

The considered configuration of standalone road light system could be able to work autonomously, but the influence of ambient temperature for a total battery capacity was neglected in this study. The battery state of charge does not fall below 0.4. It is important in the view of battery service life [9]. In accordance with the expectations the wind turbine has a greater share in energetic balance of system in a winter period and during the nights. The contribution of wind turbine yield, in total energy balance of the system is slight and unpredictable. For this reason it is doubtful to consider it in optimization calculations of battery capacity. This leads to the conclusion that there is no economic justification to support such systems by a micro wind turbine.

References

[1] Bardhi M., Grandi G., Tina G. M., *Comparison of PV Cell Temperature Estimation by Different Thermal Power Exchange Calculation Methods*, 2012.
[2] Mattei M., Notton G., *Calculation of the polycrystalline PV module temperature using a simple method of energy balance*, Renewable Energy vol. 31, 553–567.
[3] Faiman D., *Assessing the outdoor operating temperature of photovoltaic modules*, Progress in Photovoltaic: Research and Applications vol. 16, 307-315.
[4] Manwell J., *HYBRID2 – A Hybrid System Simulation Model – Theory Manual*, National Renewable Energy Laboratory, 1997.
[5] Caster L., Silvester S., *Modeling Photovoltaic Systems using PSpice*, John Wiley & Sons, 2002.
[6] Marciniak W. , *Przyrządy półprzewodnikowe i układy scalone,* WNT, Warszawa 1987.
[7] Narowski P. G., *Dane klimatyczne do obliczeń energetycznych w budownictwie*, Ciepłownictwo, Ogrzewnictwo, Wentylacja, vol. 11, 2006.
[8] Gumuła S., Knap T., Strzelczyk P., *Energetyka wiatrowa*, Kraków 2006.
[9] Czerwiński A., *Akumulatory, baterie, ogniwa*, WKiŁ, 2005.

used for analyses purposes. Modelling of different air exchanges is the subject of authors' future works.

References

[1] Nowak-Dzieszko K., Rojewska-Warchał M., *Analiza symulacyjna komfortu cieplnego w wielkopłytowym budynku wielorodzinnym,* Materiały Budowlane 8/2014, 47 – 49.

[2] Nowak-Dzieszko K., Rojewska-Warchał M., *Simulation analysis of microclimate conditions in a multi – family large panel building*, Technical Transactions, vol. 3-B/2014, Cracov University of Technology Press.

[3] Nowak-Dzieszko K., Rojewska-Warchał M., *Influence of shadings systems on the microclimate conditions in the large panel building,* Technical Transactions, vol. 3-B/2014, Cracov University of Technology Press.

[4] Nowak-Dzieszko K., Rojewska-Warchał M., *Thermal Comfort of the individual flats of multi – family panel building*, Technical Transactions, vol. 5-B/2014, Cracov University of Technology Press.

[5] Rozporządzenie Ministra Infrastruktury z dnia 12 kwietnia 2002 w sprawie warunków technicznych, jakim powinny odpowiadać budynki i ich usytuowanie (Dz.U. nr 75, poz. 690 z późn. zm. ogłoszonymi w Dz.U. z 2003 r. Nr 33, poz. 270, z 2004 r. Nr 109, poz. 1156, z 2008 r. Nr 201, poz. 1238, z 2009 r. Nr 56, poz. 461, z 2010 r. Nr 239, poz. 1597, z 2012 r. poz. 1289 oraz z 2013 r., poz. 926.

[6] Rozporządzenie Ministra Transportu, Budownictwa i Gospodarki Morskiej z dnia 5 lipca 2013 r. zmieniające rozporządzenie w sprawie warunków technicznych, jakim powinny odpowiadać budynki i ich usytuowanie (Dz.U. z 13 sierpnia 2013 r., poz. 926).

[7] PN-EN ISO 7730 Ergonomics of the thermal environment. Analytical determination and interpretation of thermal comfort using calculation of the PMV and PPD indices and local thermal comfort criteria.

[8] PN-83/B-03430 Wentylacja w budynkach mieszkalnych zamieszkania zbiorowego i użyteczności publicznej – Wymagania.

[9] Nowak, K., *Modernizacja budynków a komfort cieplny pomieszczeń*, Energia i Budynek, 29–33.