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Minimisation of the LCOE for the hybrid power supply system with the lead-acid battery

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Abstract. The paper presents the methodology of minimisation of the unit cost of production of energy generated in the hybrid system compatible with the lead-acid battery, and used to power a load with the known daily load curve. For this purpose, the objective function in the form of the LCOE and the genetic algorithm method were used. Simulation tests for three types of load with set daily load characteristics were performed. By taking advantage of the legal regulations applicable in the territory of Poland, regarding the energy storing in the power system, the optimal structure of the prosumer solar-wind system including the lead-acid battery, which meets the condition of maximum rated power, was established. An assumption was made that the whole solar energy supplied to the load would be generated in the optimised system.

1 Introduction

In the recent years, a rapid increase in the number of renewable energy sources has been noticeable. The quantity of electricity produced in the European Union from renewable sources has been doubled in the period of the recent 15 years. This increase is caused, on the one hand, by the vision of exhaustion of fuels used in conventional power plants, and on the other hand, a decrease in the prices of renewable energy sources with the simultaneous increase in their effectiveness [1, 2]. It is not without significance that renewable sources do not have such a negative impact on the natural environment as the conventional solutions (particularly in terms of emission of harmful substances into the atmosphere).

The most popular renewable sources include wind farms and photovoltaic farms [3]. Unfortunately, these sources are characterised by high dependence on weather conditions and small efficiency [4,5]. For this reason, while designing the power supply systems built of such type of sources, the selection of their optimum configuration, which concerns the type and number of used sources and systems that store the energy and improve quality of the supplied energy is absolutely important [6-11]. On a global scale, what may also be the subject of optimisation is the location of the generation system and transmission lines [12-18]. It is also necessary to emphasise that in the process of solving technical problems, the more and more frequently decisive criteria include economic ratios. This refers to various engineering issues [14, 19-20].

For this reason the paper deals with the subject of optimisation of hybrid power supply systems based on the example of the solar-wind system with the lead-acid battery pack, designed to power loads with the known daily load curve. The economic ratio has been selected as the criterion of optimization. Attention is focused on prosumer systems, taking into account the applicable legal regulations in Poland [21].

2 Characteristics of the hybrid power supply system

The application of power supply systems which take advantage of independently operating sources of solar or wind type to ensure the continuity of operation of loads, usually requires the replenishment of energy from the power grid [22]. This is the result of the stochastic nature of changes in wind and solar energy and the occurrence of deterministic components which do not match with typical daily load curves of objects. The joint use of PV modules and wind turbines, that is the hybrid system, allows for the reciprocal compensation of shortages of electricity generated by both sources during a year. Momentary differences between generated and installed capacities are, however, an important problem in this type of power supply systems. With the assumption that the load is supplied only with electricity generated in the hybrid system, power interruptions may only be eliminated using one of two solutions: significant oversizing of the installed capacity of the system or the incorporation of energy storages into the system.

The present paper takes into consideration the solar-wind systems with the lead-acid battery pack, whose general structure is presented in Fig 1. Based on the legal regulations related to renewable prosumer systems, which are applicable in Poland, the energy storage is divided into two sections: the classic battery pack and the power system (an energy storage with the efficiency of 0.7 or 0.8 depending on the system's capacity) [21].

As well as PV modules (solar section) and wind turbines (wind section) the system incorporates the lead-

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acid battery pack intended for deep discharge as well as network inverter intended for synchronisation of electricity parameters with the power system. Because of the necessity to settle the amounts of energy collected from and discharged into the power grid, a bidirectional electricity meter is used in the system. The load is characterised by daily load curve $P_o(t)$.

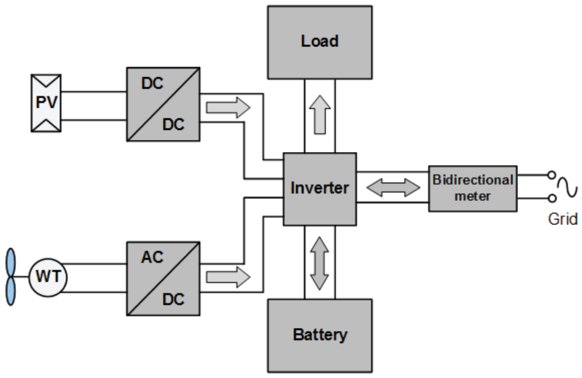

Fig. 1. Structure of the hybrid power supply system of solar and wind type, including the lead-acid battery pack and exchange of energy with the power system (PV – photovoltaic modules, WT – wind turbines).

The assumed algorithm of operation of the system covers the powering of the load directly from the solar and wind system, the additional charging of the energy storage from the PV panels and wind turbines, the drawing of energy from the energy storage in order to supplement the energy generated by the PV modules and wind turbines, the discharge of energy into the power system (production exceeding the demand) and its recovery in the case of the energy deficit from the solar-wind system and lead-acid energy storages. In Fig. 1 grey arrows mean the direction of flow of electricity. An assumption was also made that the charging of the storages with powers which exceed the permissible values causes a change in life L_C of the batteries in accordance with the following formula:

$$L_C = \begin{cases} \text{dla } (I_{AVG} > 0) \; 1000 - 0{,}34 \cdot \exp\left(26{,}2 \dfrac{I_{AVG}}{C_{20}}\right) \\ \text{dla } (I_{AVG} < 0) \; 1000 - 0{,}5 \cdot \exp\left(-37{,}23 \dfrac{I_{AVG}}{C_{20}}\right) \end{cases} \tag{1}$$

where:
C_{20} – rated capacity (20 hours),
I_{AVG} – average battery charging current (the negative value means discharge).

3 LCOE

The comparison of systems intended for electricity generation is possible, using many criteria. One of the most frequently used indicators is the unit cost of its generation [23]. It takes into account all the outlays incurred in the electricity production process (investment, operation, costs of fuel, etc.), also considering the variability of the value of money in time, credits, inflation, etc. Owing to the diversified approach to the method of defining of a unit cost of energy generation, several methods are used commonly of which the most important ones include: UNIPEDE developed by the International Union of Producers and Distributors of Electrical Energy and LCOE (Levelized Cost of Electricity) [10, 24, 25]. For the purposes of this paper, the second of the listed methods, popular in many countries of Europe, the U.S. and in international analyses is used.

The LCOE method uses the cost model in which the aspects of revenues related to the sale of energy and various forms of financial support for investments are omitted. The value of the LCOE represents the average cost of energy production converted into 1 kWh of energy generated in the system. This is the minimum price of energy, at which the sum of discounted revenues is equal to the sum of discounted costs spent on construction and operation, as well as financial costs considered most frequently during the lifetime of a unit. The overall relationship which describes the LCOE method does not take into account the systems in which energy storages were used, as well as the cases of use of the power system as a storage for the previously generated energy. In consideration of the above, it is necessary to modify the basic relationship [10, 24, 25], which assumes the following formula for the described system:

$$LCOE = \frac{\sum_{y=0}^{N} \dfrac{\left(I_{\mathrm{PV}\,(y)} P_{PV} + I_{WT\,(y)} P_{WT} + I_{ES\,(y)} A_{ES}\right)}{(1+r)^y}}{\sum_{y=0}^{N} \dfrac{A_{(y)}}{(1+r)^y}} + \frac{\sum_{y=0}^{N} \dfrac{\left(M_{\mathrm{PV}\,(y)} P_{PV} + M_{\mathrm{WT}\,(y)} P_{WT} + M_{\mathrm{ES}\,(y)} A_{ES}\right)}{(1+r)^y}}{\sum_{y=0}^{N} \dfrac{A_{(y)}}{(1+r)^y}} \tag{2}$$

where:
y – year index,
N – number of years of analysis (lifetime of the system),
$I_{PV(y)}$, $I_{TW(y)}$, I_{ES} – unit investment outlays (PLN/kW) for the solar and wind sections respectively,
$I_{ES(y)}$ – unit investment outlays (PLN/kWh) for the energy storage,
$M_{PV(y)}$, $M_{WT(y)}$ – unit operational costs (PLN/kW) for the solar and wind sections per year y respectively,
$M_{WT(y)}$ – unit operational cost (PLN/kWh) of the energy storage per year y,
P_{PV}, P_{WT} – power (kW) of the solar and wind sections,
A_{ES} – battery pack energy capacity (kWh),
$A_{(y)}$ – amount of energy (kWh) generated in the hybrid system, intended to supply the load with the known daily load curve during year y,
r – discount rate.

4 Mathematical model of the hybrid power supply

The development of the analytical model of the hybrid system characterised in section 2 requires the application of partial models: the PV module, the wind turbine and the energy storage, and their linking to the control algorithm. Such a model will be used to simulate the operation of the system. The values of wind speed v_w and irradiance G_r (measuring samples) from a period of one year, determined as mean values from the period of 36 seconds will be used as the excitation. The measuring data was made available by Mr. Krzysztof Markowicz from the Faculty of Geophysics at the Warsaw University and comes from the radiation transfer measurement station situated in the vicinity of Rzeszów. The said data will be used to establish the values of energy generated in the system, the energy transferred into the load, the storage and to or from the power system. The model requires complexity which allows for obtaining of accurate results of analysis in a short time.

4.1 PV modules

One of the standard electric models of a photocell [3, 22, 25-27, 28, 29] is used in the mathematical modelling of PV modules. In the analysed case, the double-diode model (DDM) was used; its structure is presented in Fig. 2. Its use guarantees significant accuracy of the mapping of the real behaviour of the PV installation during changes in irradiance and temperature, however it does not extend the time of analysis significantly.

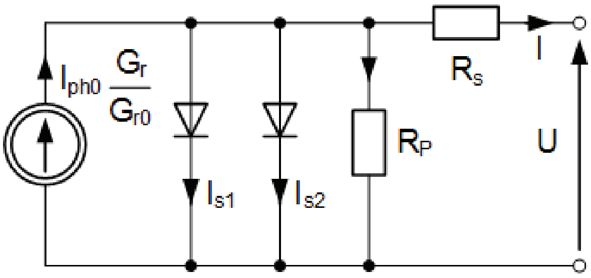

Fig. 2. Double-diode equivalent circuit of a photocell [28].

Power generated in the photocell P, with the set irradiance G_r, is determined upon solving of a non-linear equation that describes the dependence of current I on voltage U on terminals of element [10, 30, 31]:

$$I = I_{ph0}\frac{G_r}{G_{r0}} - I_{S1}\left[e^{\left(\frac{q(U+R_sI)}{N_1 k_B T}\right)} - 1\right] - I_{S2}\left[e^{\left(\frac{q(U+R_sI)}{N_2 k_B T}\right)} - 1\right] - \frac{(U+R_sI)}{R_p} \tag{3}$$

where:
I, U – current and voltage on the terminals of the photocell,
I_{ph0} – solar current generated at irradiance G_{r0},
G_r – real irradiance on the photocell surface,
I_{s1}, I_{s2} – saturation currents of the first and second diode,
N_1, N_2 – quality factors of the first and second diode,
R_s – series resistance,
R_p – parallel resistance,
k –Boltzmann constant,
T – photocell temperature,
q – elementary electron charge.

Knowing the number and method of connection of the PV module cells, the establishment of its current-voltage characteristics for irradiance G_r, requires the solving of equation (3). Determination of the family of characteristics I=f(U) for irradiance ranging between 50 W/m^2 and 1500 W/m^2 allows for the establishment of the characteristics of maximum power points as the function of irradiance MPP=f(G_r) being the numerical realization of the maximum power point tracking system. One of the most frequently used methods to solve equation (3) is the Newton-Raphson method.

4.2 Wind turbines

A wind turbine is a complicated mechanical-electrical system and the modelling of its operation in dynamic states belongs to complex and time-consuming tasks [14]. However, the use of the full mathematical model of the turbine is not always required. This also refers to the case under consideration in which it is only necessary to determine the amount of electricity generated in the wind section of the hybrid system during a period of one year [32]. In connection with the above, the simplified model of the wind turbine which covers only the modelling of its power curve P=f(v_w) was used in the conducted analyses. For this purpose, interpolation or approximation is used. For the purposes of this paper, splines were used. This allows for the indication of the corresponding wind turbine power for the measuring samples of wind speeds recorded to one decimal point.

4.3 Lead-acid batteries

Lead-acid batteries are most frequently modelled using circuit models, i.e. equivalent circuits built of electrical components, which reflect chemical phenomena that take place in an electrochemical cell. Such models consist of the source of voltage serially connected with the group of resistive-capacitive blocks (in parallel connection with each other, with time constants that reflect the inertia of electrochemical phenomena), the resistor (that reflects the resistance of electrodes, electrolyte and connections between the respective conductive elements inside the battery) and the coil (that reflects the inductance of internal circuits of the battery). Furthermore, such models take into account parasitic phenomena that take place in the cell (e.g. heat resulting from gasifying during electrolysis) by means of resistance connected in parallel [33].

Depending on the use of the battery, there is no need to take into account some of its elements in the circuit model. Because of low variability of the flowing current in the case under consideration, the circuit inductance may be omitted and one RC block is left in the main branch (Fig. 3) [34]. All the listed elements of the equivalent circuit are non-linear and change to a great extent depending on many factors such as the battery charge level, electrolyte temperature, or current which flows through the battery.

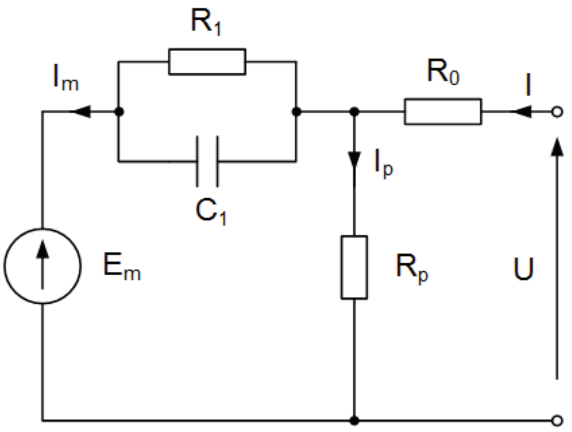

Fig. 3. Equivalent circuit of the lead-acid battery [33].

Their values are determined based on the formula presented in papers of [33-35], while the battery capacity is determined from the following formula:

$$C(I,T)=\frac{K_C C_{0*}\left(1+\dfrac{T_e}{-T_f}\right)^{\varepsilon}}{1+(K_C-1)\left(\dfrac{I}{I_n}\right)^{\delta}} \tag{4}$$

where:
K_C, C_{0*}, ε, δ – constants determined on the basis of battery specifications,
I – battery load current,
I_n – battery rated current.

The values of load and current on battery terminals during the charge and discharge process are determined by analysing the transient states in the circuit, using standard circuit methods.

5 Minimisation of the unit cost of generation of electricity from the solar and wind system with the electrochemical energy storage

The basic aim of the paper is to present the optimisation algorithm intended for establishment of the structure of the hybrid power supply system (described in chapter 2), which guarantees the continuous supply of electricity to the load with the set daily load characteristics and minimises the cost of energy generated in the system without drawing the energy from the power grid. At the same time, the sale of the surplus electricity is not taken into account (prosumer installation), except its “storage” in the power system in accordance with the applicable law [21].

The average unit costs of electricity generation determined in accordance with the standard of the so called levelized cost of energy (*LCOE*) were taken as the objective function [PLN/kWh] – formula (2). Based on the detailed analysis of this issue, it was found that the objective function was multimodal and the character of the task is that of optimization with restrictions. Five parameters which have a direct effect on the value of the objective function and which create the vector of decision variables **x** were indicated: x_1 – type of used PV modules, x_2 – number of PV modules, type x_1, x_3 – type of used wind turbines, x_3 – number of wind turbines, type x_2, x_5 – energy capacity of lead-acid battery pack. All the variables are of integer type and the restrictions result from the content of the database of turbines and PV modules, assumed rated power P_n of the system (e.g. structural limitations of the roof) and maximum time T_{MAX}, during a period of one year, in which the system may fail to supply energy to the load. The rated power of the optimised hybrid system P_{no} is determined by variables from x_1 to x_4.

Taking into account the restrictions, modified objective function $J_m(\mathbf{x})$ is the sum of the *LCOE* and the factor associated with standard penalties related to structural and functional restrictions [25,36,37]. In the case of the considered minimisation task, the modified objective function looks as follows:

$$J_m(\boldsymbol{x})=LCOE(\boldsymbol{x})+\sum_{i=1}^{m+n}F_{k(i)}(\boldsymbol{x},\rho_{K(i)}) \tag{5}$$

where:
m, n – number of structural and functional restrictions respectively,
$F_{k(i)}$ – penalty function for the i-th restriction,
$\rho_{K(i)}$ – scalar penalty factor of the i-th restriction.

Taking into account the nature of the task and the properties of the objective function, the genetic algorithm metaheuristics, which is effective for multi-modal tasks with restrictions was used to minimise the objective function (5) [29,35,36].

6 Results of optimisation and simulation tests

Based on the mathematical model of the hybrid power supply system presented in section 4 and the optimisation method proposed in section 5, the IT system designed for minimisation of the *LCOE* (2) was implemented in the MATLAB and MS Visual Studio 2015 environments. The genetic algorithm method implemented in the MATLAB environment allows for extensive modification of the method of operation of its respective blocks (selection, mutation, crossing, scaling, selection pressure, etc.) in relation to the basic algorithm. The performed calculations included the use of the elitist strategy (transfer of 1 individual) and random selection based on odds without repetitions. The restrictions are taken into account using the Augmented Lagrangian Genetic Algorithm (ALGA) which described in detail in the paper by [1]. Additionally, the selection probability was assumed in the conducted calculations at the level of 0.7 while the mutation probability amounted to 0.05. Based on the conducted preliminary tests, an assumption was made that a generation consists of 40 individuals, while 60 generations are altogether under analysis. Three loads with the average daily power of 3 kW and daily load profiles $P_o(t)$ presented in Fig. 4 (variants: I, II and

III) were selected for the calculations. An assumption was made that the maximum rated power of the solar-wind system may amount to $P_n = 20$ kW. It was also assumed that the optimised power supply system guaranteed the supply of electricity to the load all year round, and the power system is the second storage for energy generated in photovoltaic modules and wind turbines right after lead-acid batteries.

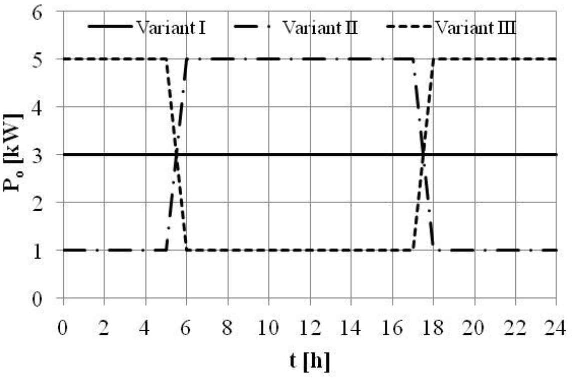

Fig. 4. Daily load patterns for the variants of the load analysed in the paper.

In order to establish the value of the *LCOE* the average unit investment and operational costs converted into 1 kW of installed power (solar and wind system) as well as the costs of one kWh of installed energy capacity of batteries given in the report [38] were used.

For each type of the load, a series of 5 optimisation calculations were carried out using the developed IT system. For each of them the rated power of the optimized system, the capacity of the solar and wind sections as well as the value of the *LCOE* and the energy capacity of the battery pack were determined.

Fig. 5 presents the pattern of the average value of the *LCOE* as a function of the number of a generation for five algorithm implementations and the case of the load with profile II. On the other hand, Table 1 lists the values of optimal solutions and the *LCOE* obtained for three daily load curves given in Fig. 4.

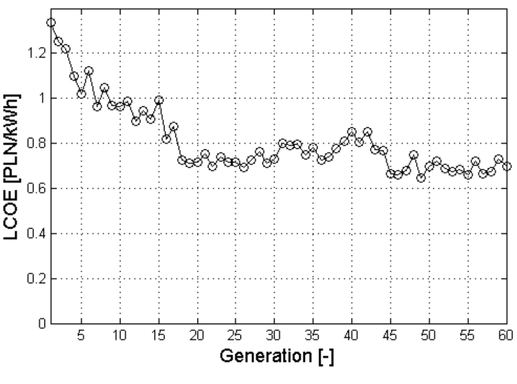

Fig. 5. Average values of the *LCOE* (from 5 algorithm) as the function of the number of a generation for load variant II.

No solution, which would fulfil the assumptions made, was found for variant III. The reason for this is the high demand for electricity at night when the power supply system is not supported by any photovoltaic sources.

Table 1. Parameters of optimal solutions for the analysed types of loads (Fig. 4) and $LCOE_{AVG}$ determined for 5 genetic algorithm implementations.

Parameters	Load variant		
	I	II	III
P_{no} [kW]	19.1	16.85	no solution
P_{PV} [kW]	4.1	1.85	no solution
P_{WT} [kW]	15.0	15.0	no solution
P_{PV}/P_{no} [%]	21.5	11.0	no solution
P_{WT}/P_{no} [%]	78.5	89.0	no solution
A_{EM} [kWh]	1	1	no solution
A_{EM}/P_{no} [kWh/kW]	0.05	0.06	no solution
LCOE [PLN/kWh]	**0.516**	**0.508**	no solution
$LCOE_{AVG}$ [PLN/kWh]	**0.519**	**0.512**	no solution

7 Conclusions

The developed algorithm and the calculation system enable the establishment of the optimal structure of the hybrid power supply system, for which the cost of generation of electricity used to power the load with the set daily load characteristics is minimal.

The used model of the hybrid system and the optimisation algorithm (genetic algorithm) are effective and enable the establishment of the global minimum for the multimodal objective function with restrictions despite the complexity of the task and the range of the area of acceptable solutions. Owing to the applied modifications of the genetic algorithm, high repeatability of results was obtained. The differences between the best and average values (from five algorithm implementations) are insignificant and amount to less than 1% (Table 1).

The optimisation calculations were carried out for three load variants (Fig. 4) with the average daily power of 3 kW. The hybrid system with the maximum rated power equal to 20 kW, the storage capacity with the maximum value of 100 kWh and assumption of the lack of purchase of energy from the network were searched. In the cases of load variants I and II, the system structure which fulfils the set requirements was found (table 1). In the case of variant III, a solution, which meets the assumed power supply criteria, does not exist.

In the analysed cases, the inclusion of the energy storage into the structure of the hybrid power supply system slightly increases the unit cost of electricity generation - *LCOE* (by about 3%), however, it allows the powering of the load all year round without drawing energy from the power grid. Owing to the use of the power system as additional energy storage, the capacity of the selected battery pack is small and amounts to 1 kWh (for variants I and II). Its annual operating time is short, which results in rare replacements of energy storages and reduction in operational costs. It also confirms the legitimacy of using electrochemical energy storages in the form of relatively cheap lead-acid batteries.

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