Modeling of solar batteries operating modes

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Abstract. For the solar power engineering development it is essential to determine the photovoltaic plant energy indicators by modeling the solar batteries operating modes. To obtain an adequate solar battery model, we need to determine its main parameters on the basis of an equivalent electric circuit. Modeling the solar battery operating mode, it is necessary to take into account the influence of its heating temperature. We propose a combined research algorithm in MS Excel with the installed add-on “Search for a solution” for modeling of solar battery operating mode. We have given the results of modeling the solar battery operating mode where the calculated solar battery maximum power including its heating, satisfactorily matches with the experimental data. The research shows that excluding the solar battery heating, the maximum power value and, accordingly, its efficiency are overestimated in comparison with the experimental data. Moreover, the results of modeling excluding its heating do not provide the required accuracy and the modeling mistakes are more than 30% especially at relatively high values of solar radiation. The given model allows to determine the equivalent circuit parameters and determine the solar battery maximum power depending on the considered factors of its heating temperature and the incoming solar energy.

1. Introduction

Nowadays, the role of renewable energy in the world is growing. The development of renewable energy sources (RES) using, in particular, solar, is one of the priority areas [1-4].

In the conditions of the renewable electric power industry development, we need to make research related to the design, development and analysis of the power plants operating modes. In this regard, we determine the main parameters of the elements that transform renewable energy into other useful types of energy [5,6].

The construction of a solar power plant (SPP) is a promising direction in the development of distributed generation. At the same time, solar batteries (SB) made of silicon cells are most widely used in a photovoltaic system (PVS) [7,8].

Research and modeling of the SB operation modes, as the main component, is an important stage to choose and to determine the PVS energy parameters. Designing a PVS, we aimed to obtain an adequate SB model based on an equivalent circuit that describes its main characteristics. Consequently, the basic SB parameters must be established.

The reliability of the SB parameters depends on its type, the used technology and the quality of solar cell (SC). Then, to determine the SB parameters, it is advisable to use the data from the SC technical specification. The SB passport presents experimental data on electrical and thermal characteristics which the manufacturer must provide in accordance with the requirements of Underwriters Laboratories (UL) [9]. In the SB technical documentation, the manufacturer provides the
following experimental data obtained under standard testing conditions (STC): radiation intensity $\lambda = 1000 \text{ W/m}^2$, solar spectrum AM 1.5, temperature $T = 25 ^\circ \text{C}$:
- rated peak power $P_{\text{MPP}}$, W;
- voltage at the maximum power point $V_{\text{MPP}}$, V;
- current at the maximum power point $I_{\text{MPP}}$, A;
- open-circuit voltage $V_{\text{OC}}$, V;
- short-circuit current $I_{\text{SC}}$, A;
- temperature coefficient at the open-circuit point $k_V$, V/ºK;
- temperature coefficient at the short circuit point $k_I$, A/ºK.

The given technical data are insufficient to construct the required external characteristic (EC), SB volt-watt or volt-ampere characteristic. Moreover, the given SB parameters correspond to one value of solar radiation and temperature, taken as the reference values. In fact, during the SB operating, the amount of solar radiation and its temperature vary over a wide range.

Thus, in order to determine the SB equivalent circuit parameters and its maximum power, we have made a mathematical model which should reproduce the operating modes and SB energy characteristics under changing operating modes. The urgent task is to determine SB parameters and the accuracy of modeling its operating modes.

2. Materials and methods

The SB design and operating principle are described in detail in various studies [10-13]. In the SB themselves, the silicon plates are connected in series by flat conductors to obtain the required parameters for current and voltage.

A number of scientific studies are devoted to the development of SB mathematical models and the determination of their parameters [10-17]. We can see the simplest solar cell as a “sandwich” of two $p$ and $n$ type semiconductor wafers which generate an electric current under the influence of solar radiation.

As a result of the solar energy conversion into electricity, the dependences of the SB electrical parameters were established. Figure 1 shows the SB EC, the dependence of current and power on voltage [8].

![Figure 1. SB external characteristics.](image)

On EC we can select the maximum power point (MPP). The voltage and the current values in MPP depend on various factors: the spectral light source composition, the ray angle, the SB temperature, etc. All the mentioned parameters, especially the temperature, constantly change over time which leads to a corresponding change in the shape of the graph and MPP position on it.

The mathematical models on the basis of equivalent electric circuits are mostly widespread to study the SC parameters and operating modes. The equivalent circuit of a perfect SC is shown in Fig.2.
This model quite simply calculates SC EC. The fact is that the modeling accuracy will be low due to its relative simplicity.

In real solar cells the energy losses are inevitable and to increase the accuracy an equivalent circuit is used, shown in Fig. 3.

Other two or three diodes equivalent circuits, requiring the determination of a larger number of undiscovered parameters, are known. In these conditions, we must make a compromise solution between the complexity and the accuracy of modeling.

The article considers the equivalent circuit of a real solar cell with one diode and two resistances (Fig. 3) which is a compromise between simplicity and accuracy of the model.

Modeling the SB operating mode, we are to take into consideration the level of the incoming solar energy. Solar radiation is characterized by power and spectral composition. These characteristics can be measured and its duration for hourly intervals can be estimated with a certain degree of probability [18,19].

When modeling, we consider the effect of temperature on the SB energy characteristics. Consequently, increasing the SB temperature decrease the generated power [20].

Thus, during daylight hours, the incoming solar energy, the SC temperature and the associated energy characteristics will be changeable. This leads, in particular, to take into account changes in the SB power to evaluate it in the MPP and the SB efficiency and accurate operating modeling.

The SB development should be based on the principle of maximum simplicity and convenience for the user. It is necessary to obtain a reliable model of the SB operation mode using the passport data. It is important to check the modeling results with experimental data obtained during various SB types testing.
3. Results and discussions
Modeling the SB operating mode, it is relevant to obtain EC, the values of the current and the voltage at the points of short-circuit, open circuit and MPP. These values are necessary to select the parameters of some PVS components (charging controller, accumulator, etc.).

To provide SB EC under specified operating conditions, the equivalent circuit parameters must be known. They can be determined on the basis of a mathematical model with sufficient accuracy.

Modeling the SB operating mode, we have proposed a combined calculating algorithm which is implemented in an MS Excel table with the installed add-on “Search for a solution”.

To check the proposed model, we used the technical specification data of the CM TCM-30A [21]. Table 3 shows the equivalent circuit parameters obtained from the mathematical modeling results.

To test the ability of the model to display EC in SB real operating conditions, the characteristics were calculated in changing the solar radiation power and the temperature. The results of the study, using the example of SB TCM-30A, are shown in Fig. 4. On the graphs, markers indicate the experimental data and the lines correspond to the calculated characteristics.

| Table 1. Estimated parameters of the SB equivalent circuit TCM-30A. |
|------------------|------------------|
| Parameter        | Meaning          |
| Io, A            | 9.98 * 10^-8     |
| IPH, A           | 8.214            |
| A                | 1.3              |
| Rs, Ом           | 0.2226           |
| RsH, Ом          | 451.66           |

The data analysis proves that the results of modeling the SB type TSM-30A operating mode well matches to the experimental data. The relative mistake in modeling SB EC does not exceed 5%.

The absolute mistakes in modeling the SB type TSM-30A data at different illumination and temperature do not exceed 0,11 A. At that, the maximum mistake is observed in modes close to open circuit and short circuit. This difference is not so critical since PVS, due to control, operate in the SB maximum power, so it is most important to ensure high accuracy of SB modeling near MPP.

A model advantage is the high accuracy of the SB energy characteristics modeling when the temperature changes. This is ensured by the fact that a more accurate analytical expression proposed in [22] is used to determine the reverse diode current.

Figure 4. Modeling results and experimental data of EC TSM-30A in solar radiation and temperature changing.

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To determine the influence degree of the SB temperature on its parameters, mainly on the maximum power value, we have generated the graphs of changes in the polycrystalline SC parameters with a rated maximum power of 30 W during August 2018 using the developed model. The research maximum power value data are given on Fig. 5 and 6. We have also shown the solar radiation power changes (H) and SB heating temperature (t_{sh}).

![Figure 5](image-url)  
*Figure 5. The changes of SB maximum power, its temperature and solar radiation during a day.*

We can see from the given data that the nature of the change in the SB maximum power, received empirically (P_m) and using the developed model (P_{m2}), repeat the daily variation of the solar radiation power. At noon, we expect the maximum solar radiation power according to the reflected radiation and the SB heating temperature.

The calculated SB maximum power with its heating corresponds to the experimental data. In this case, the value of the SB maximum power excluding its heating (P_{m1}) turns out to be overestimated in comparison with the experimental data, especially at noon, at high values of the solar radiation power. At this time, the maximum SB output with an area of 0.25 m^2 is observed and more power losses should be expected which reduces its efficiency. The calculated efficiency based on the results of the SB modeling excluding its heating also turns out to be overestimated. Its value is almost independent of the solar radiation power magnitude (Efficiency 1), though in reality the efficiency changes significantly (Test efficiency) and it is lower than the efficiency excluding its heating (Fig. 6).

![Figure 6](image-url)  
*Figure 6. SB efficiency changing.*
Modeling the SB operating mode including its heating gives results that are more adequate to the real values (Efficiency 2). Only in the morning and evening hours, with relatively small values of solar radiation and insignificant SB heating, the mistakes in calculating the maximum power and the efficiency excluding heating decrease.

The SB maximum power calculating mistakes are shown in Fig. 7. It can be seen that considering the influence of the SB temperature allows to reduce the calculating mistakes to no more than 5% (Mistake 2), which is adequate for engineering calculations. The modeling results of the SB operating mode excluding its heating do not provide the required accuracy (Mistake 1) and the calculating mistakes are more than 30% especially with relatively high solar radiation power values.

Consequently, according to the data, we should take into account the influence of SB heating on its operation. So, we must make a calculation using the SB temperature coefficients of the short-circuit current and the open-circuit voltage. In this case, the relative mistake in SB modeling parameters will not exceed 5% which is adequate for engineering calculations.

![Figure 7. The SB maximum power calculating mistakes.](image)

Comparative results of modeling the SB operation mode with experimental data are given in Table 2.

| P_{nominal}, W | H, W/m² | Δt₂₅, °C | P_{experience}, W | P_{model}, W | Mistake, % |
|---------------|---------|-----------|------------------|--------------|------------|
| 29.7          | 555     | 12.1      | 15.0             | 15.77        | -4.92      |
| 29.7          | 700     | 15.3      | 18.3             | 19.03        | -4.0       |
| 29.7          | 860     | 20.5      | 19.6             | 18.65        | 4.87       |
| 29.7          | 980     | 22.0      | 22.6             | 21.5         | 4.9        |

The analysis of the given data shows that an increase of solar radiation level raises the SB temperature (relative to the accepted 25°C) and the generated maximum power. The proposed model accurately describes the SB operation mode including its temperature. The discrepancy between the experimental and the theoretical data does not exceed 5%.

4. Conclusion
The article presents the results of the researches devoted to the improvement of modeling SB methods. We have chosen a simple model providing a sufficient accuracy in modeling the SB operating modes.
based on a comparative analysis of the known mathematical models. Using the proposed model can simplify the mathematical description of the research object.

Studying the SC equivalent circuit and the mathematical model we have determined the factors influencing its energy characteristics. Modeling results and experimental data have proved the relationship of these factors.

An important factor affecting the SB energy characteristics is its heating temperature. At the same time, the SC temperature increasing decreases its efficiency and the generated power. We have established the influence of solar radiation on the SC heating. The developed model makes it possible to determine the SC equivalent circuit parameters and the SC maximum power depending on the considered factors. The research results have shown good convergence of theoretical and experimental data, the mistake of the proposed model does not exceed 5%.

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