Mathematical Model of Solar Battery for Balance Calculations in Hybrid Electrical Grids

Sergiy O. Tymchuk, Doctor of Science, Professor
Department of Automation and Computer-Integrated Technologies
Kharkiv Petro Vasylenko National Technical University of Agriculture
Kharkiv, Ukraine
stym@i.ua

Sergii O. Shendryk, PhD student
Department of Computer Science
Sumy State University
Sumy, Ukraine
s.shendryk@cs.sumdu.edu.ua

***Abstract*—The results of mathematical modeling of a current–voltage characteristic of a solar battery are presented in this paper. It is assumed that power losses caused by nonidentity of solar cell characteristics, commutation, uneven temperature distribution and illumination can be taken into account integrally if the current–voltage characteristic of the solar battery is built on the basis of the current-voltage characteristics of solar cell groups. Mathematical functions for determination of the current-voltage characteristic of a group of solar cells are obtained as a result of processing the experimental data of several groups of solar cells within a wide range of temperatures and illumination.**

Keywords— mathematical model; solar battery, current-voltage characteristic, balance calculation, hybrid electrical grid

I. Introduction

We face with an increase of electricity rate in the modern world. The reason is that the price of non-renewable energy resources of the planet is constantly rising. The use of both traditional and alternative energy sources is one of the ways for solving this problem.

Complex electricity generation provided by two or more energy sources simultaneously is much more effective for ensuring the stability of electrical energy intake in an electrical grid of small cottage communities, country houses and small private business rather than the use of these energy sources separately.

Electrical grids which contain beside traditional source one or more alternative sources (in most cases solar batteries and wind-powered generators) are called hybrid electrical grids.

In order to describe the functioning of a solar battery as a part of a hybrid electrical grid, it is necessary to have a mathematical model of its current-voltage characteristic.

Traditionally a solar battery current-voltage characteristic is built on the basis of use a current-voltage characteristic of a single solar cell [1-4]. The prevalence of this approach can be explained by the relative simplicity of studying the characteristics of solar cells. However, during calculation of large area solar battery, difficulties arise in determining the various losses caused by nonidentity of the solar cells, commutation of solar cells, uneven temperature distribution and solar battery illumination etc. Usually these losses are taken into account by introducing different coefficients, as in [5, 6]. Detailed studies to determine all possible losses in the solar battery result in a significant complication of the mathematical model of the current-voltage characteristic, as in [6].

Thus, the approach in which the solar battery current-voltage characteristics are built not on the basis of the single solar cell current-voltage characteristic, but on the basis of the solar battery small panel current-voltage characteristic consisting of solar cell several groups seems to be reasonable. In this simple way, it is possible to consider integrally the losses caused by nonidentity of the solar cells, switching of the solar cells in the groups and switching of the groups.

II. Basic Equations

It is seen from analysis of references [1, 6] that the description of operation modes of a group of solar cells results in building of a current-voltage characteristic that considers the relation between the output parameters (current, voltage) and external operating conditions (illumination, temperature). A light current-voltage characteristic of a single solar cell is described by equation [1]

$$I = I_{s/c} - k_1 \exp(k_2(U - U_{xx})), \quad (1)$$

where I – solar cell current strength;

$I_{s/c}$ – short-circuit current strength;

U – solar cell voltage;

U_{xx} –voltage of no-load operation condition.

This equation can be used as a basis for description of current-voltage characteristic of a group of solar cells.

k_1 and k_2 are coefficients determined by passing of current-voltage characteristic through points: short circuit, no-load operation condition and optimal point (current intensity I_{opt} and voltage U_{opt} at maximum power), i.e. these conditions for the group of solar cells can be written in the following way

$$I_{gr} = \begin{cases} I_{s/c} \quad where\ U_{gr} = 0; \\ 0 \quad where\ U_{gr} = U_{xx}; \\ I_{opt} \quad where\ U_{gr} = U_{opt}. \end{cases} \tag{2}$$

Because of the overdetermination of the system (2), coefficient k_1 can be calculated from an equation similar to that given in [6]:

$$k_1 = I_{s/c} U_{gr} / U_{xx}, \tag{3}$$

which simultaneously meets two conditions (2).

Now, from the third condition (2), we find

$$k_2 = \ln((I_{s/c} - I_{opt}) / k_1) / (U_{opt} - U_{xx}) \tag{4}$$

Substituting (3) and (4) in (1), we obtain a mathematical description of the current-voltage characteristic of a group of solar cells:

$$I_{gr} = I_{s/c} \left\{ 1 - \frac{U_{gr}}{U_{xx}} \exp \left[\frac{\ln \left(\left(1 - \frac{I_{opt}}{I_{s/c}} \right) \frac{U_{xx}}{U_{opt}} \right) (U_{gr} - U_{xx})}{(U_{opt} - U_{xx})} \right] \right\}. \tag{5}$$

Accordingly, we obtain the function for calculation of solar cell group power

$$W_{gr} = I_{gr} \cdot U_{gr} \tag{6}$$

The parameters $I_{s/c}$, U_{xx}, I_{opt} and U_{opt} used in (5) is a function of illumination and temperature. The form of these functions was determined by processing the experimental data.

III. Experimental Data Processing

Experimental data for the development of a mathematical model of the current-voltage characteristic of a solar cell were obtained on the basis of a study of sixteen groups of silicon solar cells with an area of 0.0403 m^2 (0.12 m x 0.336 m) within the temperature range (12-70)°C and illuminations (550-1260 W/m^2). Accounting for losses caused by nonidentity of solar cells is achieved by the presence of solar cells of different sizes. Accounting for losses caused by uneven temperature distribution on the area of solar cell group is achieved by special test facilities devices that allow to change the temperature over the area of the solar cell group within ±1°C of the average temperature. Accounting for switching losses is achieved because each sola cell group is commutated from several standard groups.

The peculiarity of the experiment was that the values of I_{opt}, U_{opt} were not measured directly, but values were measured in several points of the current-voltage characteristic located near optimal point. Therefore, the first stage of processing the experimental data consisted in determining the values of I_{opt}, U_{opt}. The computational program developed for this purpose implements the approximation of the current-voltage characteristic points measured at each temperature and illumination level with a standard deviations not exceeding the accuracy of the experiment. Here, according to the approximating equation, I_{opt}, U_{opt} are determined, every time corresponding to specific values of temperature (T) and illumination (E).

The second stage of processing consisted in formulating regression functions for each group separately.

$$\begin{aligned} I_{s/c} &= \alpha + \beta E_{gr} + \delta T_{gr} + \gamma E_{gr} T_{gr}, \\ U_{xx} &= \alpha_1 + \beta_1 E_{gr} + \delta_1 T_{gr} + \gamma_1 E_{gr} T_{gr}, \\ I_{opt} &= \alpha_2 + \beta_2 E_{gr} + \delta_2 T_{gr} + \gamma_2 E_{gr} T_{gr}, \\ U_{opt} &= \alpha_3 + \beta_3 E_{gr} + \delta_3 T_{gr} + \gamma_3 E_{gr} T_{gr} \end{aligned} \tag{7}$$

MS EXCEL regression analysis algorithm was used to determine polynomial coefficients (7).

The third stage of processing consisted in formulating the general functions (7) for all the solar cell groups. This was done by averaging the coefficients of the regression functions obtained in the second stage of the processing.

And at the fourth stage of processing the validity of the received mathematical formulations was determined

Table 1 shows the values of the regression functions coefficients and the standard deviations of the processing. And the standard deviation of functions for I_{opt}, U_{opt}, includes the errors of preliminary processing in the first stage, and Fig. 1 shows the results of processing the experimental data in obtaining the functions (7).

TABLE I. Regression coefficients

Function	α_i	β_i	δ_i	γ_i	σ_i
$I_{s/c}$	$1.384 \cdot 10^{-2}$	$1.689 \cdot 10^{-3}$	$1.924 \cdot 10^{-3}$	$1.233 \cdot 10^{-6}$	$5.722 \cdot 10^{-2}$
U_{xx}	2.955	$-6.931 \cdot 10^{-5}$	$-1.08 \cdot 10^{-2}$	$1.325 \cdot 10^{-6}$	$6.721 \cdot 10^{-2}$
I_{opt}	$1.571 \cdot 10^{-2}$	$1.528 \cdot 10^{-3}$	$1.478 \cdot 10^{-3}$	$2.211 \cdot 10^{-7}$	$4.803 \cdot 10^{-2}$
U_{opt}	2.469	$-1.748 \cdot 10^{-4}$	$-1.366 \cdot 10^{-2}$	$4.183 \cdot 10^{-6}$	$7.300 \cdot 10^{-2}$

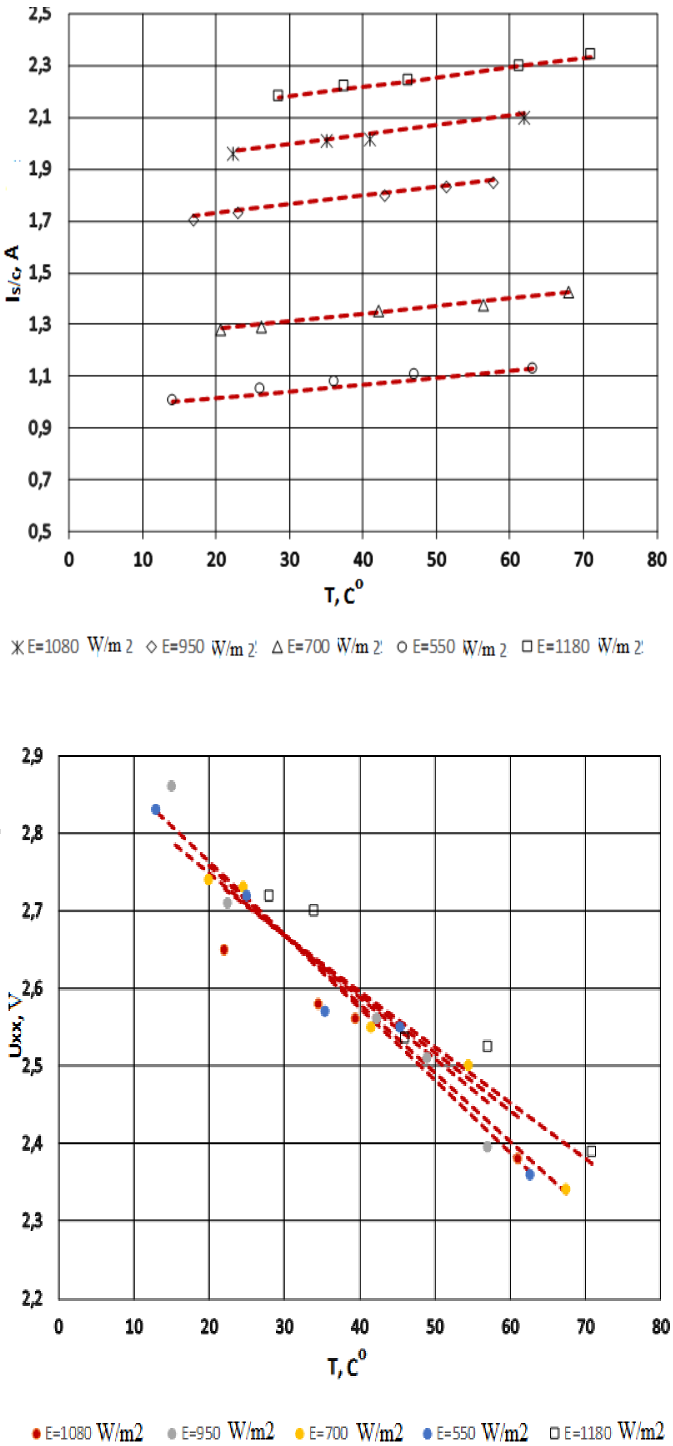


Fig. 1. Regression functions for calculation of the parameters included in the current-voltage characteristic of the solar cell group

To validate the accuracy of the mathematical model of the current-voltage characteristic of the solar cell group (5) considering the obtained functions (7), additional calculations were carried out within the fourth stage of processing. Here, we determined the residual dispersion and the standard deviation of the mathematical model of the current-voltage characteristic of solar cell group from the initial experimental points of the current-voltage characteristic of all sixteen solar cell groups.

As a result, within the temperature range 12-71 ° C and illumination 550-1260 W/m^2 for sixteen groups of silicon solar cells, the residual dispersion of the formulation was 0.00757, and the standard deviation was 0.087. The error corresponding to the standard deviation of 0.087, in the worst case, does not exceed 6%, and the average modulus relative error is 3.3%.

Fig. 2 shows functions (5) and (6), as well as the experimental data of one of the solar cell groups.

Knowing the size of the solar cell groups used in a particular solar battery, it is possible to calculate the current-voltage and current-power characteristics for it by adjusting the basic electrical parameters included in equation (5) and equation (6) as

$$
\begin{aligned}
U_{gr1} &= U_{gr}\frac{l}{0{,}12},\\
I_{s/c1} &= I_{s/c}\frac{d}{0{,}336},\\
U_{xx1} &= U_{xx}\frac{l}{0.12},\\
I_{opt1} &= I_{opt}\frac{d}{0{,}336},\\
U_{opt1} &= U_{opt}\frac{l}{0.12},
\end{aligned}
\qquad (8)
$$

where l is the size of the solar cell group, which defines the number of solar cells connected in sequence within the group, d is the size of the solar cell group, which determines the number of solar cells connected in parallel.

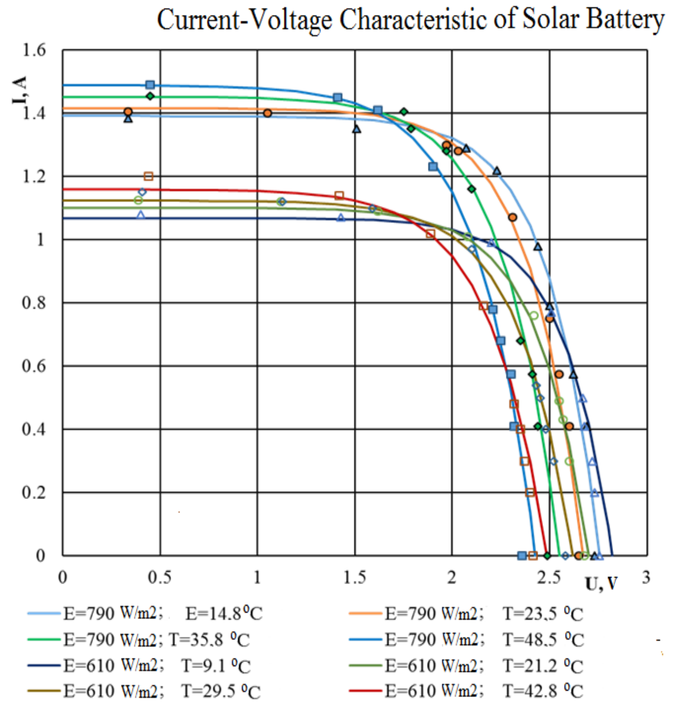
In a simplified version, it is possible to determine the characteristics of the solar batteries as a whole, taking the corresponding dimensions of the battery as l and d in (8).

When using the mathematical model of solar batteries in balance calculations of hybrid electrical grids, it is proposed to use the forecasted integrated models as initial data on illumination and temperature, as given in [7]. And for the tasks of on-line control - the data of a short-term weather forecast.

Conclusion

As a result of the studies, we propose to calculate the balance of a solar battery in the hybrid electrical grids using the approach based on the following assumption: in order to estimate all possible power losses of large solar batteries the solar battery current-voltage characteristic are built on the basis of regression functions obtained by processing the experimental data of solar battery small panels current-voltage characteristic consisting of several groups of solar cells.

As a result of processing experimental data of sixteen silicon solar cell with an area of 0.0403 m^2 within temperature range (12-70) °C and illumination (550-1260 W/m^2), the functions of the main parameters of the current-voltage characteristic of the solar cell groups: $I_{s/c}$, U_{xx}, I_{opt} and U_{opt} on the illumination and temperature are defined.



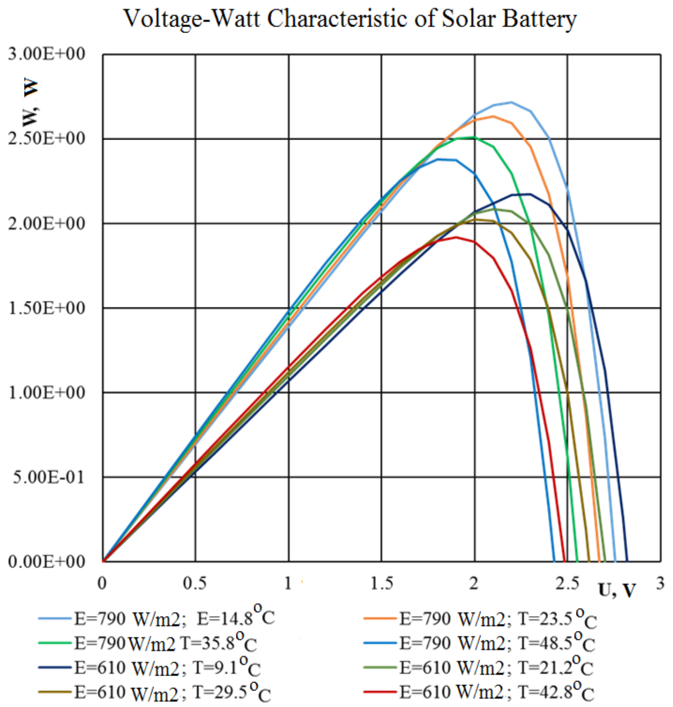


Fig. 2. Predicted electrical characteristics of the solar cell group

To determine the coefficients of regression functions, a multi-stage procedure was used with the MS EXCEL regression analysis. The residual dispersion and the standard deviation of the mathematical model of the current-voltage characteristic of the solar cell group from the initial experimental points of the current-voltage characteristic of all sixteen solar cell groups were determined.

Functions that allow to calculate these parameters for a solar cell of any area are proposed. The presented mathematical model makes it possible to calculate the current-voltage characteristic of ground solar battery with a simple solar positioning system with an average modulus relative error of no more than 3.3%, which is acceptable in balance calculations as well as in on-line control and decision support.

Operation modes of a solar cell group is described by means of a current-voltage characteristic taking into account the function between the output parameters (current, voltage) and external operating conditions (illumination, temperature). Also, the conditions of passing the current-voltage characteristic through characteristic points: short circuit, no-load conditions and optimal point (the optimum value of the current intensity I_{opt} and the optimum value of the voltage U_{opt} at maximum power) are considered.

The processing error of the experimental data and the approximating functions obtained during the regression analysis is negligible.

The proposed mathematical model of a solar battery can be used for balance calculations of hybrid electrical grids as well as for solving problems of on-line control of solar batteries

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