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Computer Aided Model for an Off-grid Photovoltaic System Using Batteries Only

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***Abstract*— This article will present an off-grid photovoltaic energy system based on a photovoltaic element (PV), or a group of PVs, integrated in a solar battery (SB), directly connected to an electrical battery (EB) having no DC-DC adapter (use of adapters is the most common solution existing now on in this domain). This SB must be properly adjusted to the EB, not only as voltage, but it must provide also the same amount of energy as the system when operating at its classically detected maximum power operating point. This proposed technical solution is more economically justified, compared to the classic one: SB+DC-DC+EB, due to the simple fact that the DC-DC converter is no longer required at all. A simple mathematical model for the current-voltage characteristics is also presented, followed by a comparison between the classic DC-DC converter-based solution and the newly proposed one, without DC-DC converter.**

Keywords*— *CAD Model Electric Battery, Maximum Power Point, Solar Battery

I. INTRODUCTION

Nowadays, all renewable energy sources have gathered more and more importance worldwide. The PV systems are representing a very important and dynamic category from the renewable electric energy generation point of view [1], [2], [3], despite their price and complexity, of course, mostly in countries having many sunny days. But PV systems must operate in many other environments, too.

Within the literature, there are several approaches dealing with solar–electric energy conversions [3], [4], [5], [6]. All these approaches are sustained by the fact that the PV system intends to operate at maximum power operating points [7], [8]. A DC-DC converter is necessary to be installed between the solar battery (SB) and electric battery (EB), to achieve this goal. Thus, the system becomes expensive and, generally, not economically feasible.

By varying the terminal SB equivalent load resistance, it is investigating the operation possibility in the maximum power operating point neighbourhood. However, not knowing this point an operation below the maximum power is achieved [9], [10].

All the equivalent resistance load variation methods are implying high costs, complex electronic equipment meaning DC-DC converters [11]. Thus, in case of several applications these investments are totally unprofitable.

The power provided by the Sun is continuously changing even during daytime, and the system SB+DC-DC+EB (shown in Fig. 1) has to be continuously controlled in such a manner that assures the maximum power operating point.

Cheap and efficient equipment must be realized (as presented in the current paper) in order to reduce the PV systems' costs [2].

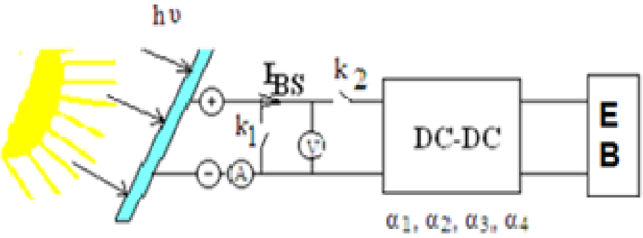

Fig. 1. The complete SB+DC-DC+EB classic solution

By voltage-current characteristics mathematical modelling, SB+EB system operation efficiency estimation is proposed (achieved through computing the obtained energy).

The maximum power operating point P_{max} coordinates (U_{OPTIM}, I_{OPTIM}) are changing in time, depending on the environment conditions (solar radiation intensity). Thus, the module terminal equivalent load has to be correlated with the solar radiation intensity [11], [12].

Measuring the solar radiant power P_S the fundamental quantities characterizing the SB operation in maximum power operating points are able to be determined:

- optimal load resistance R_{OPTIM} using SB mathematical model or using the simplified version by the ratio between the idle and short-circuit voltages (Fig. 2) [4];
- useful maximum available electric power P_{OPTIM} ;
- I_{OPTIM} current and U_{OPTIM} voltage corresponding to the maximum power operating point.

The determination of coordinates for the Maximum power operating point P_{OPTIM} (Fig. 2) is based on SB (or PV module) external characteristics $U = f(I)$ that are changing based on atmospheric nebulosity.

These characteristics are valid for regular 44-48 V panels available on the market.

This principle insures optimal operation of the PV system in all weather conditions.

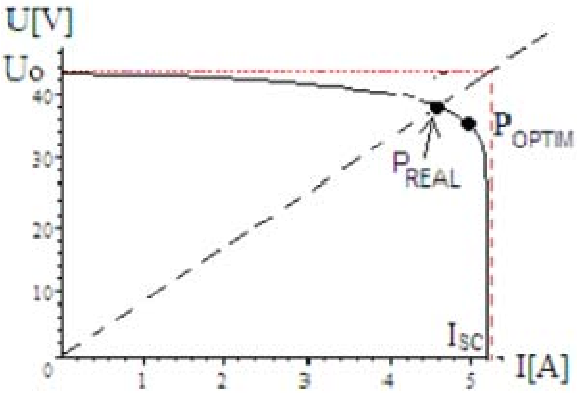

Fig. 2. External characteristics U = f(I) for a standard PV panel

In the following part of our paper, the difference between the SB obtained energy directly generating on the EB and the available maximum one is computed. Thus, the SB external characteristics *U(I)* are mathematically modelled.

II. Mathematical Model of the External PV Pannel Characteristics

The proposed mathematical model for the external characteristics $U = f(I)$ has the following form:

$$U(I) = (d - T \cdot f) \cdot \left(\cos\left(\frac{a \cdot I - g \cdot T}{P_s^b} \right) \right)^c \tag{1}$$

where: a, b, c, d and g – designing constants computed based on the experimental external characteristics [7]; P_S – solar radiant power; I – generated current. The determination of the maximum power operating point coordinates is performed by cancelling the power $P = U \cdot I$ derivative:

$$U_{OPTIM} = (d - T \cdot f) \cdot \left(\cos\left(\frac{a \cdot I_{OPTIM} - g \cdot T}{P_s^b} \right) \right)^c \tag{2}$$

and:

$$P_{OPTIM} = U_{OPTIM} \cdot I_{OPTIM} \tag{3}$$

The resulted family of voltage-current characteristics offers us the possibilities for continuous service of that panel for a certain voltage and for a certain current.

Considering the $T = 273 + 25$ K absolute temperature, the SB external characteristics at 25 degrees Celsius are described by the following functions [4]:

$$U(I) = 41 \cdot \left(\cos\left(\frac{3.14}{8} \cdot I \cdot \frac{883}{P_S} \right) \right)^{0.15} \tag{4}$$

where P_S – is a certain radiant power (taken as a variable parameter, as presented in Fig. 3.

It is normal that, as well as the solar radiant power is increasing, the converted power also increases, and, for a certain voltage, the panel can provide a higher current, due to a higher converted power (depending on the hour on the day and on meteorological and environmental conditions).

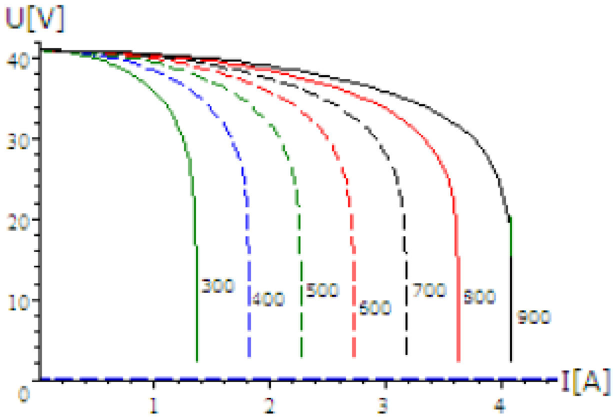

Fig. 3. External characteristics having radiant power as parameter

The main goal of this paper is to determine the maximum power point and to adjust directly the panel parameters, in order to function in these conditions.

III. Maximum Power Operating Points for a Classic System with DC-DC Convertors

The use of a DC-DC converter is requested to operate within the maximum power operating points. It is situated between the SB and the EB. The maximum power operating point coordinates (U_{OPTIM} , I_{OPTIM}) are determined cancelling the derivative [4]:

$$\frac{dP}{dI} = \frac{d}{dI} \left(41 \cdot \left(\cos\left(\frac{3.14}{8} \cdot I \cdot \frac{883}{P_S} \right) \right)^{0.15} \cdot I \right) \tag{5}$$

This classic structure is shown in Fig.4., which is identical with Fig.1., but with no measuring devices on service.

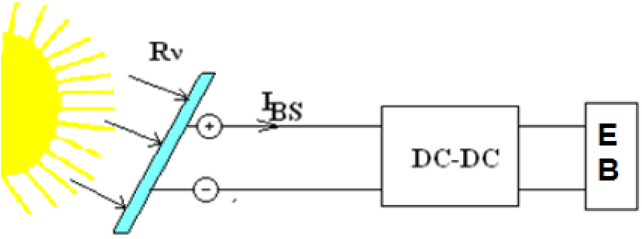

Fig. 4. The simple SB+DC-DC+EB classic solution.

This is the worldwide most common solution for solar energy conversion, tracking, at each moment, the maximum power operating point.

In equations (6) and (7) we will present the computational method for obtaining the optimal charging power. Battery supplying voltage could be easily modified.

For a radiant power $P_1 = 900W$, we will obtain:

$$\frac{dP}{dI} = \frac{d}{dI}\left(41\cdot\left(\cos\left(\frac{3.14}{8}\cdot I\cdot\frac{883}{P_S}\right)\right)^{0.15}\cdot I\right) =$$
$$= -1.0\cdot10^{-9}\cdot\frac{2.3683\cdot10^{9}\cdot I\cdot\sin(0.38509\cdot I) - 4.1\cdot10^{10}\cdot\cos(0.38509\cdot I)}{\cos^{\frac{17}{20}} 0.38509\cdot I} = 0 \tag{6}$$

It provides an optimal current $I = 3.5533\ A$.

From the next group equations, we will obtain:

$$U = 41\cdot\left(\cos\left(\frac{3.14}{8}\cdot3.5533\cdot\frac{883}{P_S}\right)\right)^{0.15} = 32.232\ V \tag{7}$$

In case of the maximum radiant power (for 1 h/day):

For $P_1 = 900\ W$ we will obtain: $P = 114.52\ W$;

We will consider each effective solar power hour having an average radiant power decreasing with 100 W, applied for $t_i = 1$ *hour* (9 effective radiant hours).

- for $P_2 = 800\ W$ it yields: $P = 101.8\ W$;
- for $P_3 = 700\ W$ it yields: $P = 89.080\ W$;
- for $P_4 = 600\ W$ it yields: $P = 76.354\ W$;
- for $P_5 = 500\ W$ it yields: $P = 63.629\ W$;
- for $P_6 = 400\ W$ it yields: $P = 50.902\ W$;
- for $P_7 = 300\ W$ it yields: $P = 38.177\ W$;
- for $P_8 = 200\ W$ it yields: $P = 25.452\ W$;
- for $P_9 = 100\ W$ it yields: $P = 12.726\ W$.

Daily total energy has the following value:

$$W = \Sigma\,(P_i\cdot t_i) = 3.4587\ MJ = 0.96\ kWh \tag{8}$$

This is an estimation of the total energy provided by a single panel during an average sunny day with 9 effective radiant hours, when the DC-DC converter is tracking the maximum power point.

IV. MAXIMUM POWER OPERATING POINTS FOR A SOLAR BATTERY GENERATING DIRECTLY OVER AN ELECTRIC BATTERY

In some cases, the solar energy storage is performed directly within electric batteries (EB) (SB over EB, as presented in Fig. 5).

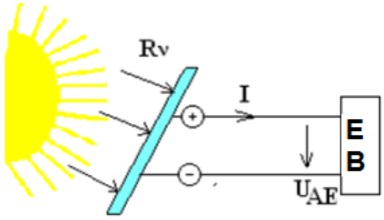

Fig. 5. Solar Battery (SB) over Electric Battery (EB)

For example, the EB voltage could be multiple of ordinary 12 V batteries: $U_{AE} = k\cdot12\ V$. In this case the system operation is far from the maximum power operating points, as described in Fig. 6.

The values for P_1 (minimum radiant power) and P_2 (maximum radiant power) operating points are obtained at the intersection between the SB external characteristics $U = f(I)$ with the ones of the EB voltage $U = U_{EB} + r\cdot I$, where r – EB circuit resistance, U_{EB} – EB terminal voltage.

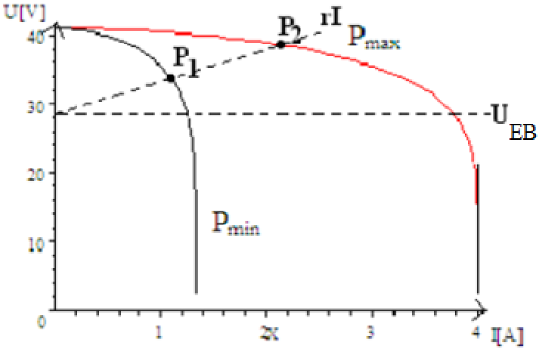

Fig. 6. Operating points of the SB+EB system

Electric battery idle voltage (U_{EB}) determination is another important step when using this new system.

The electric batteries' cells have the idle voltage around $2\ V$. Voltage corresponding to the maximum power operating points for $P_S = 900\ W$ is $U_{OPTIM} = 32.232\ V$. Thus, $32 / 2 = 16$ cells are selected for the EB. In case of $U_{EB} = 32\ V$ and EB internal resistance $r = 0.1\ \Omega$, the same results are obtained as for the maximum power operating point.

The equivalent electric schema is presented in Fig. 7.

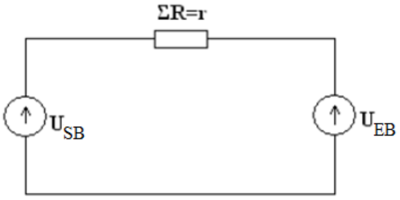

Fig. 7. Electric schema of the SB+EB system

The values for P_1 (minimum radiant power) and P_2 (maximum radiant power) operating points are obtained based on the SB external characteristics $U(I)$, is the considered voltage response, $U = U_{EB} + r\cdot I = 32 + 0.1\cdot i$, as presented below:

- for $P_1 = 900\ W$ it yields: $P = 112.11\ W$;
- for $P_2 = 800\ W$ it yields: $P = 101.8\ W$;

- for $P_1 = 700\ W$ it yields: $P = 89.079\ W$;
- for $P_3 = 600\ W$ it yields: $P = 76.353\ W$;
- for $P_4 = 500\ W$ it yields: $P = 63.628\ W$;
- for $P_5 = 400\ W$ it yields: $P = 50.901\ W$;
- for $P_6 = 300\ W$ it yields: $P = 38.175\ W$;
- for $P_7 = 200\ W$ it yields: $P = 25.449\ W$.
- for $P_8 = 100\ W$ it yields: $P = 12.724\ W$.

Daily total energy has the following value:

$$W = \Sigma (P_i \cdot t_i) = 3.4239\ MJ = 0.95\ kWh \tag{9}$$

The energy difference between these cases is:

$$\Delta W = 3.4587 \cdot 10^6 - 3.4239 \cdot 10^6 = 34800\ J \tag{10}$$

It represents around *1 %*, thus a small difference, practically negligible for the common applications, especially if the DC-DC converter efficiency is considered, when introduced, it certainly could overpass the *1 %* obtained here for the SB-EB only.

V. CONCLUSIONS

In this article, a solar battery generating energy over an electrical battery has been analysed in comparison with its operation at maximum power operating point.

The system SB+EB is more economically than the SB+DC-DC+EB system due to its simplicity. We analysed the differences between the amount of energy stored within the EB, for the two cases (having or not a DC-DC convertor), for a standard daylight of 9 radiant hours.

After all calculations, we notice that the difference between these amounts of energies is less than 1 *%*. It has been demonstrated that the DC-DC converter may be avoided. Thus, a cheaper conversion system has been obtained, operating at increased efficiency conditions.

This study will continue by taking in consideration other radiant power values, different than the average one.

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