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About Tracking the Maximum Power Point for a Battery Based Photovoltaic System

C M Vinga[1], F M Frigura-Iliasa[2, *], F I Balcu[2], M Frigura-Iliasa[1], D Vatau[1] and S Musuroi[1,3]

[1]POLITEHNICA University Timisoara/Faculty of Electrical and Power Engineering, 300223, Timisoara, Romania
[2]National Institute for Research. and Development in Electrochemistry and Condensed Matter/LERF, Timisoara, Romania
[3]Academy of Romanian Scientists, 300221, Timisoara Romania

*flaviu.frigura@upt.ro

Abstract. This paper aims to present an off-grid renewable energy system based on a photovoltaic element (PV), or a group of PVs, integrated in a solar battery (SB), directly connected to an electric battery (EB) with no DC-DC adapter (which is the most common solution existing on the market). The SB has to be properly adjusted to the EB, in order to provide 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.

1. 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].

Within the literature, there are several approaches dealing with solar–electric energy conversions [3], [4]. All these approaches are sustained by the fact that the PV system intends to operate at maximum power operating points [1], [2]. 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 [5]. All the equivalent resistance load variation methods are implying high costs, complex electronic equipment meaning DC-DC converters [6].

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 Figure 1) has to be continuously controlled in such a manner that assures the maximum power operating point.

Most of the photovoltaic systems operating worldwide are based on this principle of battery supplied throughout a DC-DC converter able to track (or not) the maximum power operation point.

There are many technical solution conceived to fulfil this tracking assessment, based on various algorithms ore presumptions, which are making them unpredictable sometimes.

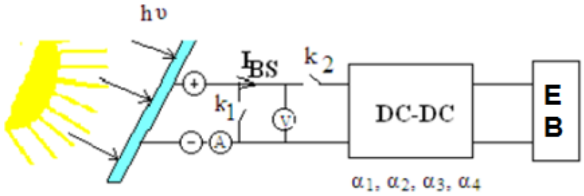

Figure 1. The complete SB+DC-DC+EB classic solution

Cheap and efficient equipment have to be realized (as presented in the current paper) in order to reduce the PV systems' costs [7]. 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 [8], [9].

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 (Figure 2) [10];
- useful maximum available electric power P_{OPTIM} ;
- I_{OPTIM} current and U_{OPTIM} voltage corresponding to the maximum power operating point.

Maximum power operating point P_{OPTIM} coordinates determination (Figure 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 a 44-48 V panels.

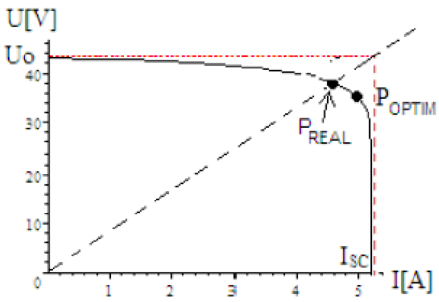

Figure 2. The complete SB+DC-DC+EB classic solution

In the following part of the paper, the difference between the SB obtained energy directly generating on the EB and the available maximum one will be computed. Thus, the SB external characteristics U(I) are mathematically modelled. By consequent, efficient equipment have to be put on place (as presented in this current paper) in order to reduce the PV systems' costs [11].

Price is an important issue for each photovoltaic system. Power electronic converters (like DC-DC ones or MPPT converters) are very expensive equipment, and, cost reductions have to be performed.

2. Mathematical Model for the External Characteristics

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

$$\frac{dP}{dI} = \frac{d}{dI}\left(41 \cdot \left(\cos\left(\frac{3.14}{8} \cdot I \cdot \frac{883}{P_S}\right)\right)^{0.15} \cdot I\right) \quad (1)$$

Where: a, b, c and d – design 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:

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

$$P_{OPTIM} = U_{OPTIM} \cdot I_{OPTIM} \quad (3)$$

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

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

Where P_S – is a certain radiant power (taken as a variable parameter, as presented in Figure 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.

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.

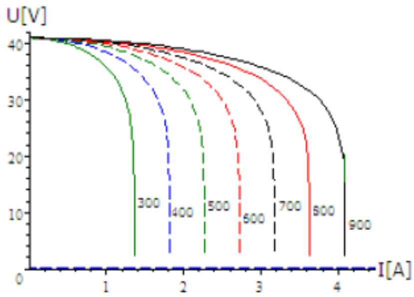

Figure 3. External characteristics considering radiant power as parameter

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.

3. 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:

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

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

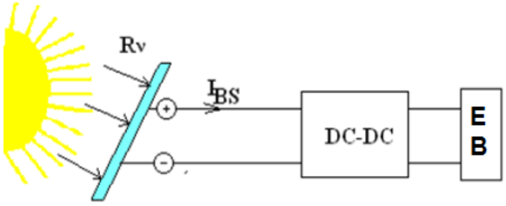

Figure 4. The simple SB+DC-DC+EB classic solution

This is the worldwide most common solution for solar energy conversion, tracking, at each moment, the maximum power operating point [12].

In equations (6), (7) and (8) 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:

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

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

From the next group equations, we will obtain:

$$2.3683\cdot 10^{9}\cdot I\cdot\sin(0.38509\cdot I) - 4.1\cdot 10^{10}\cdot\cos(0.38509\cdot I) = 0 \tag{7}$$

$$U = 41\cdot\left(\cos\left(\frac{3.14}{8}\cdot 3.5533\cdot\frac{883}{P_S}\right)\right)^{0.15} = 32.232\ V \tag{8}$$

By consequent, 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 useful hour having an average radiant power decreasing with 100 W, applied for $t_i = 1\ hour$ (9 effective radiant hours). Using the same relations as previous, we will obtain, for each effective hour, its corresponding electric output power:

- 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:

$$W = \sum P_i\cdot t_i = P_1\cdot 14400 + P_2\cdot 3600 + P_3\cdot 3600 + P_4\cdot 7200 + P_5\cdot 3600 + P_6\cdot 3600 + P_7\cdot 1800 + P_8\cdot 1800 + P_9\cdot 3600 = \\ = 114.52\cdot 14400 + 101.8\cdot 3600 + 89.08\cdot 3600 + 76.354\cdot 7200 + 63.629\cdot 3600 + 50.902\cdot 3600 + 38.177\cdot 1800 + \\ + 25.452\cdot 1800 + 12.726\cdot 3600 = 3.4587\cdot 10^{6}\ J \tag{9}$$

As final result:

$$W = \Sigma\,(P_i\cdot t_i) = 3.4587\ MJ = 0.96\ kWh \tag{10}$$

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4. Maximum Power Operating Points for a Solar Battery Generating Directly over an Electric Battery with no Converters

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

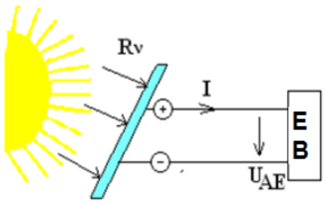

Figure 5. Solar Battery (SB) over Electric Battery (EB)

For example, in many cases, the EB voltage could be multiple of ordinary 12 V deep cycle batteries: $U_{AE} = k \cdot 12\ V$. In this case the system operation is far from the maximum power operating points, as described in Figure 6. 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 obtained from the EB voltage $U = U_{EB} + r \cdot I$, where r – EB circuit resistance, U_{EB} – EB terminal voltage. 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.

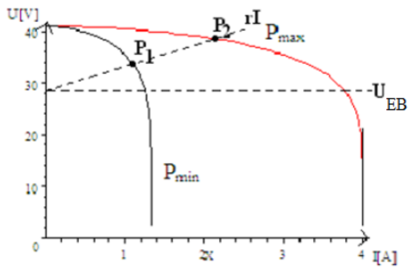

Figure 6. Operating points of the SB+EB system

The equivalent electric schema is presented in Figure 7.

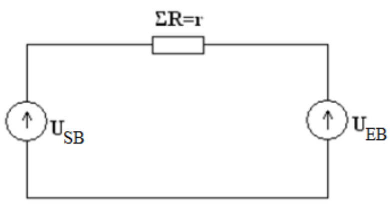

Figure 7. Electric schema of the SB+EB system

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: $P = 12.724\ W$.

The energy difference between these cases is:

$$\Delta W = 3.4587 \cdot 10^6 - 3.4239 \cdot 10^6 = 34800\ J \tag{11}$$

It represents *1 %.*, thus a small difference, practically negligible for the common applications, especially if the DC-DC converter efficiency is considered, that could overpass *1 %.*

5. 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 Central European ones.

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