Abstract — The article is focused on specific issues arising for a photovoltaic panel (PV). In this case, the short circuit current is measured to determine the value of prescribed current corresponding to maximum power point. The results obtained by imposing a load resistance with this method are energy maximum possible, thus justifying the usefulness of this process very simple and inexpensive applied in practice.

I. INTRODUCTION

In the category of renewable energy, solar power systems are becoming increasingly used in obtaining clean electricity [1], [5], [6].

Most of the specialized literature focused on solar energy conversion systems based on photovoltaic effect assumes that PV system operates in the maximum power point [9], [11], [12].

By modifying the equivalent load resistance connected to the PV terminals is attempted that system operation is as close to maximum power point. Due to the fact that this maximum power point is not known exactly, the operation is performed always below the maximum power [3], [8], [9].

The presented control approach is quite simple being based only on short-circuit current measurement with ampermeter A, after closing switch K (as is depicted in Figure 1).

The proposed method is comparable, in terms of energy, with solutions based on the maximum power point MPP coordinates.

Maximum power point coordinates \( P_{\text{OPTIM}}, \) (Voltage: \( U_{\text{OPTIM}}, \) Current: \( I_{\text{OPTIM}} \)) are changing over time depending on weather conditions (\( P_s \) solar radiation intensity) and therefore equivalent load across the PV module must be correlated with the intensity of solar radiation [10],[11],[13].

Determining the MPP coordinates is based on PV external characteristics \( U = f(I) \) (depicted in Figure 2), features that change depending on atmospheric cloud.

The mathematical model used for external characteristics, in the general case for the radiant solar power \( P_s \) and a solar battery temperature \( T \), is given by [4]:

\[
U(I) = (d - T \cdot f) \cdot \left( \cos \left( \frac{a \cdot I - b}{P_s} \right) \right)^c
\]

where: \( a, b, c, d, f \) and \( g \) are manufacturing constant that can be determined using the PV experimental external characteristics.

Determining the coordinates of the maximum electrical power point \( P_{\text{OPTIM}} \), respectively the voltage \( U_{\text{OPTIM}} \) and the current \( I_{\text{OPTIM}} \), is performed by canceling the derivative of electrical power \( P = U \cdot I \), thus:

\[
\frac{dP}{dI} = \frac{d}{dI} \left( (d - T \cdot f) \cdot \left( \cos \left( \frac{a \cdot I - b}{P_s} \right) \right)^c \right) = 0
\]

The current \( I_{\text{OPTIM}} \) can be obtained from the above equation resulting the voltage \( U_{\text{OPTIM}} \), electrical power \( P_{\text{OPTIM}} \) and load resistance \( R_{\text{OPTIM}} \):

\[
U_{\text{OPTIM}} = (d - T \cdot f) \cdot \left( \cos \left( \frac{a \cdot I_{\text{OPTIM}} - b}{P_s} \right) \right)^c
\]

\[
P_{\text{OPTIM}} = U_{\text{OPTIM}} \cdot I_{\text{OPTIM}}
\]

\[
R_{\text{OPTIM}} = \frac{U_{\text{OPTIM}}}{I_{\text{OPTIM}}}
\]
Thus, results the dependence of maximum power point voltage $U_{OPTIM}$ and current $I_{OPTIM}$ by solar radiant power $P_s$ depicted in Figure 3.

The analysis of the above results conducts to the following remarks:

- The value of optimal voltage $U_{OPTIM}$ change slightly with $P_s$.
- The current $I_{OPTIM}$ changes linearly with $P_s$.

II. TYPICAL PV CONTROL SYSTEMS

Most of the proposed structures for controlling solar energy conversion systems (composed from PV panel, DC-DC converters and electric accumulator EA) presented in the specialized literature [1],[4],[7],[9] are developed in order to assure that maximum power is captured. These control structures are based on electric power measurement: $P=UI$ and changing the load resistance of PV, in order to provide maximum power.

There will be presented various PV control structures all based on a constant solar radiant power $P_s = 1000[W/m^2]$.

A. Resistance changes in steps according to $\Delta P$

This version of PV control is based on measuring the provided electric power from time to time and changing the load resistance depending on:

$$\Delta P_e = P_e(k) - P_e(k-1)$$

where $P_e(k)$ represents the electric power measured at moment $t_k$.

By changing load resistance in steps according with:

$$R(k) = R(k-1) - K(P_e(k) - P_e(k-1))$$

There is obtained in the first phase, an operation point $P_1$ near the maximum power point $P_{OPTIM}$, ->, then the operating point moves towards $P_4 \rightarrow P_5$ -> while the load resistance increases, as depicted in Figure 4.

Therefore, the control structure of the PV + DC-DC + EA system, in this form, does not provide maximum power point operation.

B. Resistance changes at time steps

This version of PV control is based on changing the load resistance after a time $t$ as follows:

$$R_K = R_{K-1} - K_1 \cdot \Delta P_e - K_2 \cdot \int_0^t \Delta P_e \cdot dt$$

The load resistance variation in this case is similar with the one depicted in Figure 5.

This fact led to a continuous power point variation as can be noticed in Figure 6.

From the above results is can be noticed the inefficiency of the control system in the sense that it cannot assure the operation in the maximum power point, energy losses being around 2%.

III. PV CONTROL SYSTEMS BASED ON SHORT-CIRCUIT CURRENT MEASUREMENT

A. Study case

The external characteristics for a PV operating at the temperature $T = (273 + 25)K$ are given by the relation [2]:

$$U(I) = \left(42.7 + 0.3 \cdot \frac{P}{883} \cdot \cos \left(\frac{446.32}{P_{MPP}}\right) \right)^{\frac{1}{2}}$$

(9)
Considering different values for the solar radiant power, the corresponding short-circuit current can be determined based on PV external characteristics depicted in Figure 7 resulting the values presented in Table I.

### Table I. PV Short-Circuit Current

<table>
<thead>
<tr>
<th>$P_s$ [W/m²]</th>
<th>883</th>
<th>883/2</th>
<th>883/4</th>
<th>883/6</th>
<th>883/8</th>
</tr>
</thead>
<tbody>
<tr>
<td>$I_{SC}$ [A]</td>
<td>4.6</td>
<td>2.3</td>
<td>1.2</td>
<td>0.8</td>
<td>0.6</td>
</tr>
</tbody>
</table>

The current corresponding to the optimal operation point can be determined throughout the cancellation of power derivative:

$$\frac{d}{dt}(U \cdot I) = 0$$  \hspace{1cm} (10)

For $P_s = 883$[W/m²] from (9) and (10) results:

$$\frac{d}{dt}(U \cdot I) = \frac{d}{dt}(43(\cos(0.34431 \cdot I))^{7.3737\times10^{-2}} \cdot I) = 0$$  \hspace{1cm} (11)

thus

$$5.4585 \times 10^8 I \sin 0.34431 I - 2.15 \times 10^{10} \cos 0.34431 I = 0$$

Having the solution $I = 4.25 [A]$.

Similarly, the other optimal values for the PV provided current are obtained, as presented in Table II.

### Table II. PV Optimal Point Current

<table>
<thead>
<tr>
<th>$P_s$ [W/m²]</th>
<th>883</th>
<th>883/2</th>
<th>883/4</th>
<th>883/6</th>
<th>883/8</th>
</tr>
</thead>
<tbody>
<tr>
<td>$I_{OPTIM}$ [A]</td>
<td>4.25</td>
<td>2.125</td>
<td>1.0625</td>
<td>0.70832</td>
<td>0.53124</td>
</tr>
</tbody>
</table>

Given the values of $I_{SC}$ and $I_{OPTIM}$ the following ratio can be calculated:

$$\frac{I_{OPTIM}}{I_{SC}} = 0.911$$  \hspace{1cm} (12)

Thus, through the measurement of $I_{SC}$ current it is possible to develop an efficient, but simple and very economical, control structure for the PV system.

### B. PV control system’s structure

The presented control structure, depicted in Figure 8, is much simpler than other PV control methods and is based on the measurement of short-circuit currents $I_{SC}$ and direct computation of the maximum power point current. Its performances are similar with those achieve through of the maximum power point current $I_{OPTIM}$ estimation based on external characteristics, but the implementation is much simplified.

As it was shown, at different solar radiation power values there are obtained external characteristics. It can be noticed the pronounced dependence of short circuit currents values $I_{SC}$ of the level of solar radiation given by $P_s$, as depicted in Figure 7.

By measuring the short-circuit currents $I_{SC}$ and through DC-DC converter control there is realized the prescribed load resistance value. Since changing of $P_s$ is quite slow there is no question of achieving rapid response from the control structures.

By comparing the set-point with the actual load current is obtained the error $\Delta I$, which is the input into the REG controller (Figure 8). The load resistance changing is performed by switching the thyristors angle command of DC-DC converter.

### C. PV control system’s dynamical regime

For $P_s = 883$[W/m²] results:

$$R_{INITIAL} = U_0 / I_s = 43.4 / 4.599 = 9.3499 \Omega$$  \hspace{1cm} (13)

and the following initial conditions are obtained:

- $\{I(0) = 4.0469 [A]\}$ from

$$43(\cos(0.34431 \cdot I))^{7.3737\times10^{-2}} = 9.3499 I$$

- $\{U(0) = 37.833 [V]\}$ from

$$U = 43(\cos(0.34431 \cdot 4.0469))^{7.3737\times10^{-2}}$$

By modifying the solar radiant power toward $P_s = 883/2$[W/m²], the final conditions are obtained: $R_{FINAL} = U_0 / I_{s2} = 42.85 / 2.34299 = 18.31 \Omega$.

The external characteristic for this solar radiant power is given by:

$$U(I) = 42.85(\cos(0.34431 \cdot I - 2))^{7.3737\times10^{-2}}$$  \hspace{1cm} (14)

The entire PV conversion system (PV + DC-DC + EA) can be equivalent with the RL circuit $(R = R_{FINAL} = 18.31 \Omega, L = 0.11 [H])$, obtaining:

$$U_s = RL \frac{dI}{dt}$$  \hspace{1cm} (15)

For $P_s = 883/2$[W/m²], the maximum current being
\[ I_{sc} = 2.2596[A], \] lower than \[ I(0) = 4.0469[A], \] PV will not provide current, thus resulting the current variation from the differential equation:

\[
\begin{cases}
0 = 18.31I + 0.11\frac{dI}{dt} \\
I(0) = 4.0469
\end{cases}
\]

The current variation in this regime is depicted in Figure 9.

From above results:

\[ I(t) = 4.0469 \exp(-166.45t) \]

(17)

And for the moment \[ \{ I = 3.5011 \times 10^{-3}[s] \} \] results

\[ I = I_{sc} = 2.2596[A] \]

and PV will generate current on the load resistance \[ R_{FINAL} = 18.31[\Omega] \].

Finally, the current value is obtained from equation

\[ U(t) = R_{FINAL} \cdot I \]

(18)

Then

\[ 42.85(\cos(0.34431 \cdot I \cdot 2))^7.373\times10^{-2} = 18.31 \cdot I \]

Resulting \[ \{ I = 2.0457[A] \} \]

The time variation for the current depicted in Figure 10, when PV generates current, can be obtained from equations:

\[
\begin{cases}
42.85(\cos(0.34431 \cdot I \cdot 2))^7.373\times10^{-2} = 18.31I + 0.11\frac{dI}{dt} \\
I(0) = 2.2596
\end{cases}
\]

(19)

It can be noticed that in a very short time (under 0.01 [s]), the PV current reaches the final value.

IV. CONCLUSIONS

In this paper there is presented a PV control structure that assure an increased energy efficiency by computing the maximum power point based on the short-circuit current measurement.

The results obtained by imposing an optimum load current justify the usefulness of this process very simple and low-priced to be implemented. The presented control system assures that the maximum energy is provided at a low cost given by electronic equipment due to the simple method to obtain the optimal current reference.

ACKNOWLEDGMENT

This project was developed through the Partnerships in priority areas - PN II, with the support of ANCS, CNDI - UEFISCDI, project no. 36/2012.

REFERENCES