COST-EFFECTIVE MAXIMUM POWER POINT TRACKING FOR BATTERY CHARGING APPLICATIONS

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***Abstract* – This paper proposes a method to track the optimal operating condition of a PV module by estimating the maximum available power through a simple linear equation, whose parameters are derived from off-line measurements. The method is suitable for battery charger circuits fed by a photovoltaic module and presents a good compromise between ease of implementation and effectiveness. The strategy was tested on a dc-dc buck-boost converter and was validated by experimental results from a 55W PV Module.**

***Keywords* - Photovoltaic module, Maximum Power Point tracking, Battery Charger.**

I. INTRODUCTION

The field of photovoltaic (PV) systems has become quite broad, with many different applications and converter types [1]. There are four major application into which existing PV systems fit: large-scale grid connected systems – with power outputs ranging from tens of kilowatts to hundreds of kilowatts [2]; remote applications, where a much smaller photovoltaic plant is used to drive loads in remote areas [3][4]; low power applications, for use in residential areas where solar arrays are mounted on the roof of the dwelling [5][6][7]; hybrid systems, composed by a PV installation combined with another energy source [8]. Most of these applications use batteries to store the excessive generated energy to be used during peak load or poor environmental conditions [9].

Because PV modules present a nonlinear power characteristic depending on the load condition, a system fed by a PV module must contain a maximum power point tracking (MPPT) circuit. Indeed, numerous MPPT methods have been presented in the last years [10].

Most of the methods are focused on tracking the maximum power condition of a PV module by satisfying the condition $dP_{PV}/dV_{PV} = 0$, where P_{PV} and V_{PV} represent the PV module output power and voltage, respectively. The Perturb and Observe [11][12][13] and the Incremental Conductance [14][15] methods both make use of this relation and have been extensively used. Due to the complexity of the required mathematical operations, a DSP or a microcomputer are more suitable to execute them, which increases their cost.

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Another way of tracking the MPP is through estimation. The optimal value of the PV voltage (V_{MPP}) or current (I_{MPP}) is estimated as a function of cell short circuit current (I_{SC}) [16][17], open circuit voltage (V_{OC}) [18][19][20] or temperature (T) [21]. Although these solutions are generally much cheaper and simpler, they are based on rough estimations that vary from module to module and can differ excessively from the true MPP depending on the operation condition. Therefore, their use has been limited to small scale PV applications.

In [22], it was observed that the values of V_{MPP} and I_{MPP} can be approximated by a linear function. It is possible to demonstrate that the origin of this fact is the effect of the PV module series resistance R_s, and it is more evident for high irradiation conditions This is visible in Fig. 1, which presents simulated results of the equivalent electrical model of a PV cell, presented in Fig. 2. In Fig. 1 the maximum power points were traced for three different R_S values.

In this paper, it is demonstrated that at high irradiation condition the series resistance also gives origin to an almost linear relation between V_{MPP} and P_{MPP}, where P_{MPP} is the PV output power at the MPP. From this fact, it was derived an MPPT method, which estimates the maximum available power as a linear function of the module voltage. A simple system to compensate for temperature variation is used, which only requires the periodic sensing of V_{OC}.

Furthermore, the proposed method is suitable for battery charger circuits fed by PV module. For this case, the charging current is used to sense the power given to the circuit.

Experimental results performed in a prototype present good accuracy in the MPP estimation, specially for high conditions of irradiation, and confirm the method as a simple and cost-effective solution for the MPPT.

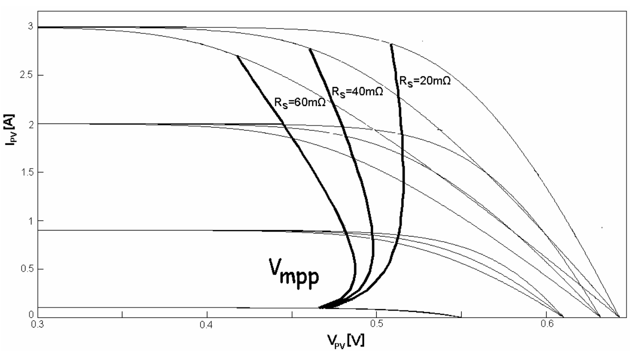

Fig. 1 – Maximum power points (black line) in simulated IxV curves of a silicon PV cell for three different values of R_S.

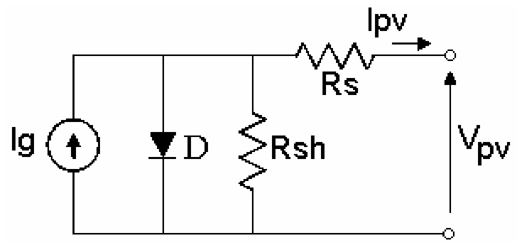

Fig. 2 – Electrical equivalent model of a PV cell.

II. THE PROPOSED MPPT METHOD

Considering the model presented in Fig. 2, it is possible to demonstrate that, for high levels of irradiation (high I_g), the relation between the optimal values of voltage and current can be approximated by:

$$\begin{aligned} V_{MPP} &= \underbrace{-I_{MPP} \cdot R_s + V_{OFFSET}}_{VLR} \\ V_{OFFSET} &= V_{OC} - K_1 \end{aligned} \tag{1}$$

where K_1 is weakly dependent on temperature. Equation (1) is called Voltage Linear Reference (VLR). As shown in Fig. 3, the value of VLR tends to the MPP for the high irradiation conditions.

Moreover, simulation of the equivalent model of the PV cell suggests an almost proportional relation between I_{MPP} and the maximum available power P_{MPP}, which slightly varies with respect to temperature condition or the R_S value, as shown in Fig. 4. Thus, it is possible to define a constant K_2 such as:

$$I_{MPP} \approx K_2 \cdot P_{MPP} \tag{2}$$

By replacing (2) in (1) and rearranging the terms, the maximum power available can be estimated as a function of the V_{MPP} value as:

$$P_{MPP} = \underbrace{m_{PLR} \cdot V_{MPP} + q_{PLR}\left(V_{OC}\right)}_{PLR} \tag{3}$$

where:

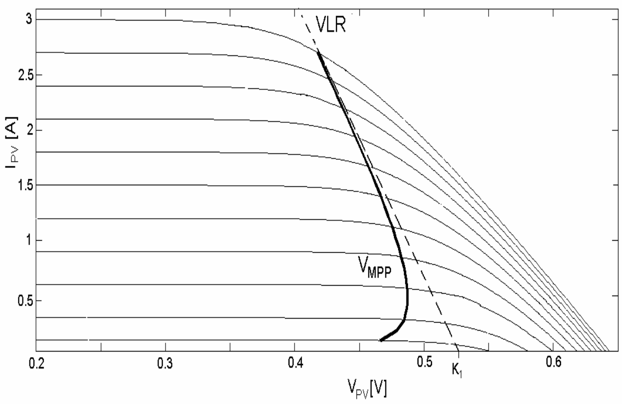

Fig. 3 – Maximum power points and the VLR in the simulated *I x V* curves of a PV cell.

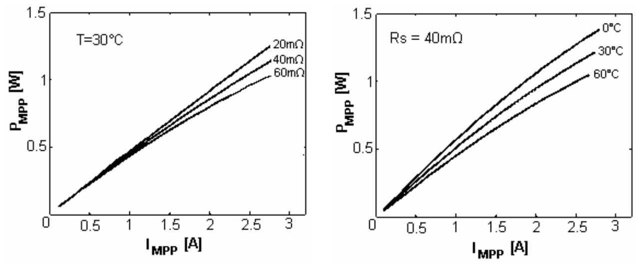

Fig. 4 – The almost linear relation between I_{MPP} and P_{MPP} for different conditions of (a) series resistance and (b) temperature.

$$\begin{cases} m_{PLR} = -\dfrac{1}{K_2 \cdot R_S} \\ q_{PLR}\left(V_{OC}\right) = K_3 \cdot V_{OC} + K_4 \end{cases} \tag{4}$$

and:

$$\begin{cases} K_3 = \dfrac{1}{K_2 \cdot R_S} \\ K_4 = -\dfrac{K_1}{K_2 \cdot R_S} \end{cases} \tag{5}$$

The right side of (3) is defined as the Power Linear Reference (PLR) and it is graphically represented in Fig. 5. Just as with the VLR, the value of the PLR approximates to the MPP with the increase of the irradiation.

Moreover, since K_1, K_2 and R_S are weakly dependent on the temperature condition, the PLR shift with respect to temperature is compensated by the periodic sensing of V_{OC}. Thus, the variation of the PLR with respect to temperature is:

$$\frac{dPLR}{dT} \approx \frac{dq_{PLR}\left(V_{OC}\right)}{dT} \approx \frac{1}{K_2 \cdot R_S} \cdot \frac{dV_{OC}}{dT} \tag{6}$$

Fig. 6 presents the maximum power points for three conditions of temperature and the respective PLRs. For the same conditions of illumination, the V_{OC} shift due to temperature variation is proportional to PLR shift, as predicted by (6).

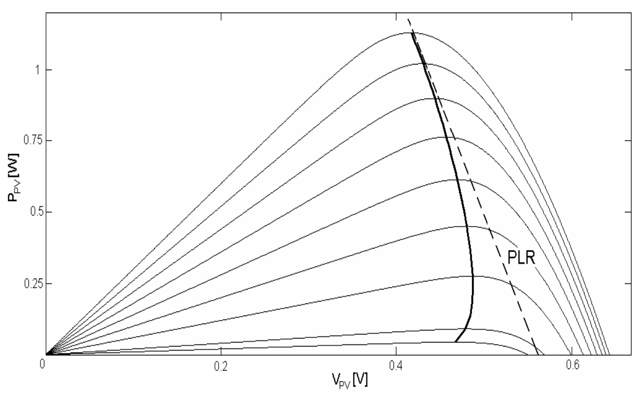

Fig. 5 – Simulated P x V curves and the PLR.

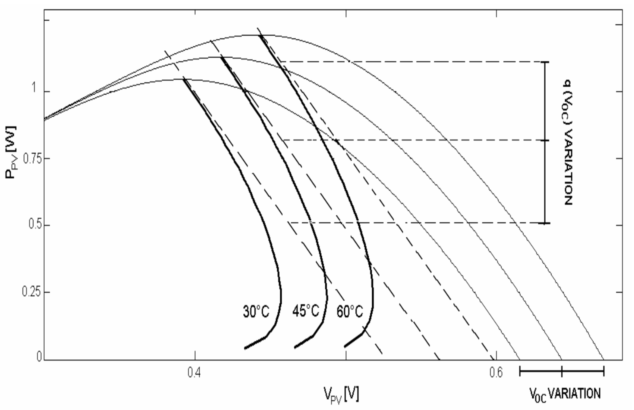

Fig. 6 – Simulated maximum power conditions for three temperature conditions and the respective PLRs.

Even if the parameters R_S, K_1 and K_2 are not known, they can be defined experimentally anyway, as it will be described in Section III.

III. APPLICATION TO A BATTERY CHARGER CIRCUIT

In a battery charger circuit, assuming a converter with efficiency η, for a PV module fed battery charger, the charging current i_o is given by:

$$i_o = \frac{\eta \cdot v_{MOD} \cdot i_{MOD}}{V_{batt}} \tag{7}$$

where:

V_{batt} battery voltage
v_{MOD} PV module voltage
i_{MOD} PV module current

Moreover, considering V_{batt} and η constant, the I_o x V_{pv} curve and P_{PV} x V_{pv} curve will have the same shape. Indeed, a PV module with M paralleled strings each made of N series connected cells that feeds a battery charger circuit will operate in the vicinity of its maximum power condition if the charging current is controlled at a value i_o^* calculated as:

$$i_o^* = \underbrace{m \cdot v_{MOD} + q\left(V_{OC.MOD}\right)}_{CLR} \tag{8}$$

where:

$$m = \frac{M \cdot \eta}{V_{batt}} \cdot m_{PLR}$$
$$q\left(V_{OC.MOD}\right) = \frac{M}{N} \cdot \frac{\eta}{V_{batt}} \cdot q_{PLR}\left(V_{OC}\right) = K_5 \cdot V_{OC.MOD} + K_6 \tag{9}$$

and $V_{OC.MOD}$ is the PV module open circuit voltage. Analogously, the right side of (8) is called Charging Current Linear Reference (CLR). By controlling the current delivered to the battery it is possible to prevent damage due to overcurrent and to add any given charging algorithm to the control strategy.

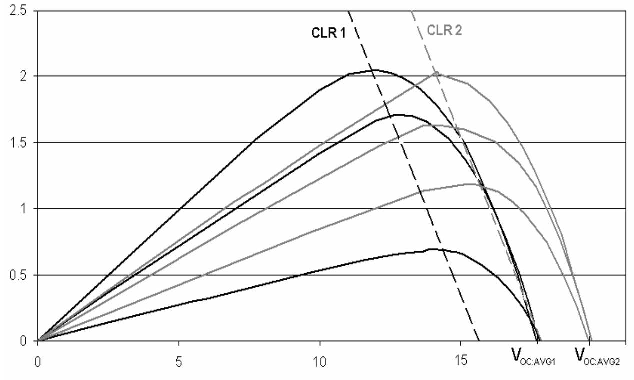

Fig. 7 – Experimental results in a 36-cell PV Module along two days with different air temperatures and their respective CLRs.

To determine K_5 and K_6, i_o x v_{pv} curves are measured for several conditions of irradiation along two days with different air temperatures and the respective CLRs are defined graphically, as shown in Fig. 7. Please note that the slope m is unique for both CLRs.

Since CLR1 and CLR2 are given by:

$$\begin{aligned} CLR1 &= m_1 \cdot V_{PV} + q_1 \\ CLR2 &= m_1 \cdot V_{PV} + q_2 \end{aligned} \tag{10}$$

the terms of $q(Voc)$ are analytically derived as:

$$\begin{cases} K_5 = \dfrac{q_2 - q_1}{V_{OC.AVG2} - V_{OC.AVG1}} \\ K_6 = q_1 - K_5 \cdot V_{OC.AVG1} \end{cases} \tag{11}$$

where $V_{OC.AVGn}$ is the mean value of all measured V_{OC} along the n^{th} day.

Once all the required parameters are defined, the charging current reference value will be calculated as described by the flowchart presented in Fig. 8.

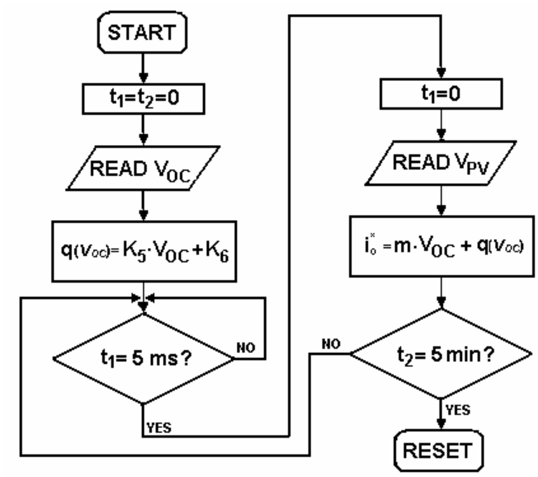

Fig. 8 – Flowchart of the i^*_o computation.

IV. EXPERIMENTAL RESULTS

The proposed strategy was implemented in a battery charger prototype based on the buck-boost topology, fed by a 36-cell PV module from Helios Technology. The parameters of the PV module (at 1Sun and 25°C) and the component values of the converter are presented in Table 1.

Table 1
Parameter values of the tested PV module and the component values of the converter

PV Module	
Parameter	**Value [Unit]**
PV Module Power	55[W]
Number of Cells	36
Open Circuit Voltage	20.9[V]
Short Circuit Current	3.8[A]
Buck Boost Converter	
Component	**Value [Unit]**
Input filter capacitor	56 [µF]
Filter inductor	130[µH]
Output Capacitor	470 [µF]
Switch	IRF4710
Diode	STPS20H100CT

The value of i_o* is calculated as described in Fig. 8 by an 8-bit PIC microcontroller. An analog circuit controls i_o through a proportional-integral controller, as shown in Fig. 9. The battery charger prototype is shown in Fig. 6.

Fig. 11 presents output current curves for different conditions of irradiation, the calculated CLRs (according to the value of V_{OC}) and their intersection points. The CLR color is the same of the respective curve. Please note that three of the curves (red, blue and green) present the same V_{OC} and thus their CLR are represented by the same line. As predicted by the method description, the estimation error increases with the irradiation decrease. This is also visible in Fig. 12, which depicts the mean power extracted from the module, the power available at its MPP under the same conditions and the ratio between them, i.e., the effectiveness of the MPPT.

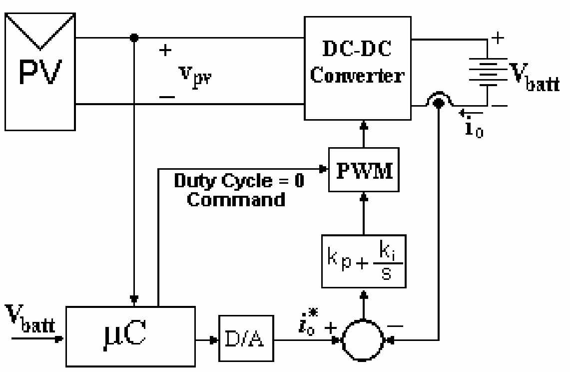

Fig. 9 – Battery charger prototype with the proposed strategy.

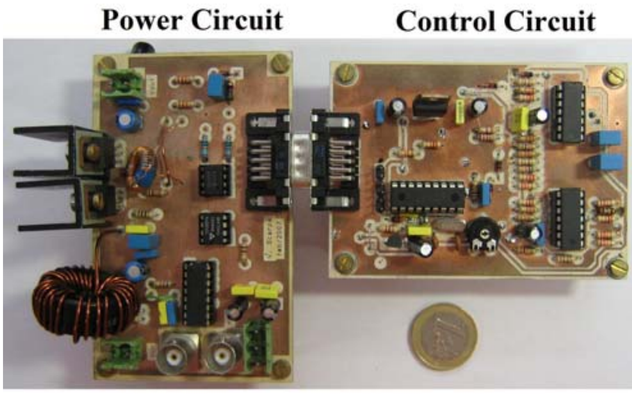

Fig. 10 – Battery charger prototype and the control board where it is implemented the proposed MPPT method.

V. CONCLUSION

In this paper, a method to track the maximum power point of a battery charger circuit fed by a PV module was proposed. This is done by controlling the charging current, making use of the almost linear relation between the optimal values of module voltage and power. To demonstrate the validity of the strategy, a prototype was set-up and experimental results were performed, presenting high levels of effectiveness for the highest irradiation conditions.

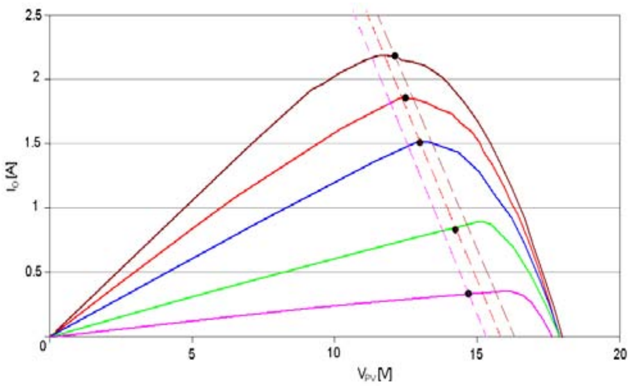

Fig. 11 – Charging current curves and prototype points of operation and the correspondent calculated CLRs for different conditions of irradiation.

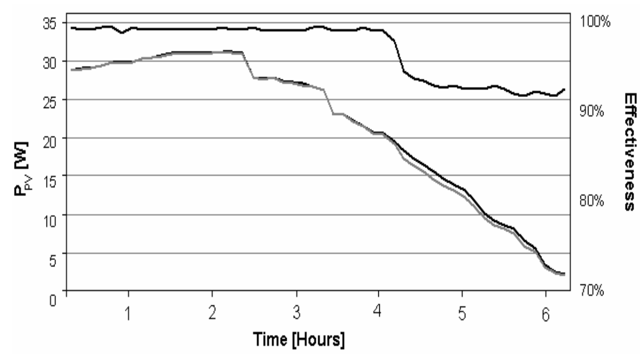

Fig. 12 – Maximum available power (lower black line), mean extracted power (grey line) and the effectiveness of the MPPT (upper black line).

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