A Maximum Power Point Tracker Implementation for Photovoltaic Cells Using Dynamic Optimal Voltage Tracking

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Abstract— **A maximum power point tracker (MPPT) for photovoltaic (PV) cells, PV modules (PVM) and PV arrays is presented using a dynamic optimal voltage estimator to estimate the voltage at which a PV cell generates its maximum power, and, using a DC-DC converter, to force the PV cell to reach and operate at voltage in a finite time and to stay there for all future time. The optimal voltage estimator reads the temperature at the surface of the PV array and the solar irradiance that reaches it surface to estimate the maximum power voltage point. A sliding mode controller, implemented in a low cost microcontroller, uses the estimated optimal voltage to generate a control signal which forces the PV cell to track and operate at this estimated optimal voltage for all future time. The procedures for the design, simulation, implementation and results are presented in this paper.**

I. Introduction

The use of renewable energy systems as an alternative way to produce electricity has been increasing during the past years [1]. The need of a cleaner, more efficient and cheaper method for generating electric power is helping this growth. Among all the renewable energy systems, the use of solar cells is one of the most common system. Photovoltaic is the technology that uses solar cells or an array of them to convert solar light directly into electricity. The power produced by the PV array depends directly of factors that are not controlled by the human being as the cell's temperature and solar irradiance.

PV arrays have only one operating point where the product of the voltage and the current results in a maximum power point(MPP). PV arrays, if connected directly to the load, will only operate at that maximum power point when the load is equal to the division of the values of voltage and current that results in a maximum power. Fig. 1 shows that for an specific PV array power curve, operating at standard conditions, the maximum power point will be reached only when a load equal to 3Ω is connected to the PV array ; otherwise, due to load mismatching, the PV array will operate at a suboptimal power point. The maximum power operation point depends on variable factors such as the cell temperature and solar irradiance which change the value of the load at which the PV array generates its maximum power (Fig. 2). Due to this, a device capable of tracking the maximum power operating point and force the PV array to operate at this point is required. A maximum power point tracker is a device capable of detecting the maximum power point and forcing the system to reach and operate at this point.

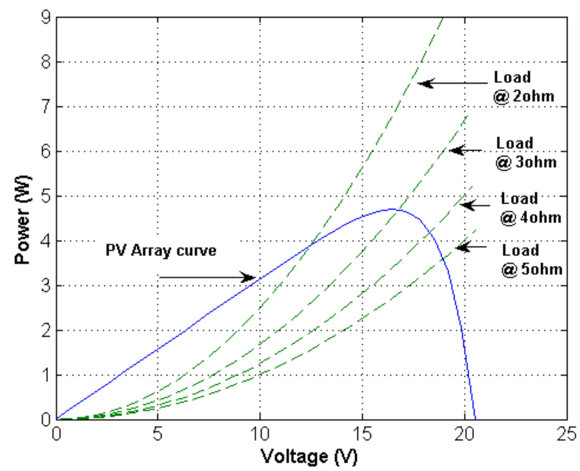

Fig. 1. PV Array Power Curve and different resistive load power curves in a direct matching.

In this paper a maximum power point tracker, using a sliding mode control algorithm, is presented. With this algorithm the system is always forced to track and reach the optimal voltage point, in a finite time, and stay there for all future time in order to optimize the power generation from any PV array. As previous results, simulations of this method can be found in [2], while the validation, for the PV equations used in this paper, is studied in [3].

II. Existing Methods

A very common method used is the Perturb and Observe algorithm [4] [5]. Perturb and Observe algorithm measure the converter's output power in order to modify the input voltage by modifying the converter's duty cycle. Other common method is the hill-climbing method [6] [7]. This method is based on a trial and error algorithm where the voltage is increased until the voltage where the PV array exhibits a maximum power is reached. Other MPPT algorithms sample

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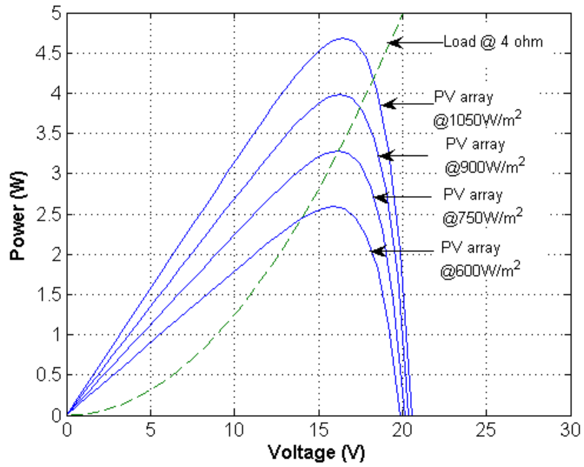

Fig. 2. PV Array Power Curve for different Irradiance Levels.

the open circuit voltage and operate the PV array at a fixed percent of this voltage. The incremental conductance algorithm is another method to track the MPP [8] [9] [10]. Other methods that have been used to obtain the MPP are parameters estimations [11], neural networks [12] and Linear Reoriented Coordinates Method (LRCM) [13], an implementation of this method can be found in "in press" [14].

III. Proposed Method

Fig. 3 shows the proposed scheme for the MPPT. This system uses a PV array composed of s in series and p in parallel PV modules. It is connected to a converter in order to decrease the desired voltage. After that, is connected directly to the load. Measurement of the PV array voltage, Irradiance and Temperature on the PV array surface are taken in order to estimate the optimal voltage for the maximum power, and then a non linear MPPT algorithm takes this value to produce the signal for driving the switching element of the DC/DC converter.

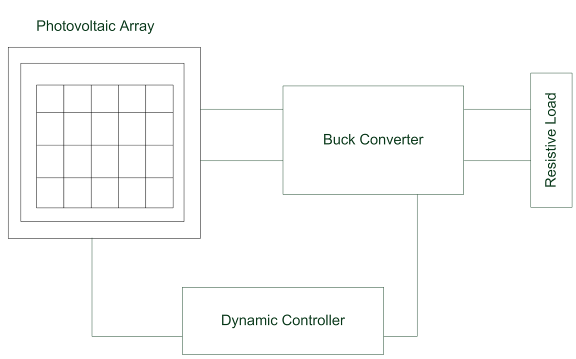

Fig. 3. General Scheme for the proposed method

A. Photovoltaic Cell Equations

Equations (1)-(4) presented in this work are based in [13]. These equations describe the behavior of the curve for any PV array under different values of temperature and solar irradiance and using values that can be obtained directly from any manufacturer's datasheet. I_x and V_x represent the short circuit current and open circuit voltage at a given temperature and solar irradiance. V is the PV array output voltage, T is the PV array temperature, T_N is the standard conditions temperature, E_i is the effective solar irradiance at the PV array, E_{in} is the standard condition solar irradiance, TCV is the open circuit voltage temperature coefficient and T_{Ci} is the short circuit current temperature coefficient. V_{max} is the open-circuit voltage at 25^oC and more than $1200W/m^2$. V_{min} is the open-circuit voltage at 25^oC and less than $1000W/m^2$. b is the characteristic constant and is unique to each PVM, s and p are numbers of in series and in parallels modules with the same electrical characteristics.

$$I(V) = \frac{pI_x}{1 - exp(\frac{-1}{b})}\left[1 - exp\left(\frac{V}{bsV_x} - \frac{1}{b}\right)\right] \quad (1)$$

$$I_x = p\frac{E_i}{E_{i_N}}\left[I_{sc} + TC_i(T - T_N)\right] \quad (2)$$

$$V_x = s\frac{E_i}{E_{i_N}}TCV\left(T - T_N\right) + sV_{max} -$$

$$s\left(V_{max} - Vmin\right)exp\left(\frac{E_i}{E_{i_N}}\ln\left(\frac{V_{max} - V_{op}}{V_{max} - Vmin}\right)\right) \quad (3)$$

$$while \;\; |b_{n+1} - b_n| > \epsilon$$

$$b_{n+1} = \frac{V_{op} - V_{oc}}{V_{oc}\ln\left[1 - \frac{I_{op}}{I_{sc}}\left(1 - exp\left(\frac{1}{b_n}\right)\right)\right]} \quad (4)$$

B. Optimal Voltage Equation

It can be seen in (1) that there is only one value of current for each value of voltage. As said before, the maximum power point correspond to a single voltage, V_{op}, or, since for each value of voltage there is a value of current, a single current, I_{op}. In this case we just have to find one of them. By multiplying (1) times V we obtain a power equation, presented in (5).

$$P(V) = V \cdot I(V) = \frac{V \cdot I_x}{1 - exp\left(\frac{-1}{b}\right)}\left[1 - exp\left(\frac{V}{bV_x} - \frac{1}{b}\right)\right] \quad (5)$$

By differentiating (5) with respect to V, equaling it to zero and solving it for V, (6) is obtained. Using this equation the optimal voltage for any solar cell or panel can be estimated.

$$Vop = b \cdot V_x\left(lambertw\left(2.7138exp^{\frac{1}{b}}\right) - 1\right) \quad (6)$$

C. *Sliding Mode Control*

A sliding mode controller is a variable structure control where the dynamics of a non linear system is altered via the application of a high frequency switching control and the trajectories of the system are forced to reach a sliding manifold or surface, where it exhibit desirable features, in finite time and to stay on the manifold for all future time. Equation (7) presents a sliding surface that will accomplish the objective as a maximum power point tracker.

$$\sigma = V - V_{op} \tag{7}$$

The sliding mode will be controlling the duty cycle of a switching device. So the switching device will have two operation state:

$$On, \ 1 \quad V - V_{op} > 0$$
$$Off, \ 0 \quad V - V_{op} < 0$$

A control law that guarantees us that our controller will behave in that way is given by (8).

$$u = \frac{1}{2} + \frac{1}{2} sign(V - V_{op}) \tag{8}$$

IV. Implementation

The MPPT method presented in this article was easily implemented using a low cost microcontroller from Microchip family PIC 16F687X running at a frequency of 20 MHz. Lectures from the PVM surface temperature(T), PVM solar irradiance(E_i) and the PVM voltage(V) were done by ADC ports of the microcontroller. The Implementation of the mathematical functions such as division multiplication and exponential functions was made using a C language compiler, PIC C from $HI-TECH\ C$.

The schematics of the implemented circuit is shown in Fig. 4. A flow chart of the programming sequence for the microcontroller is presented in Fig. 5.

V. Results

Two tests were done to verify the effectiveness of the MPPT implementation. Both of them were developed under controlled irradiance levels; showing the dynamical behavior of the system..Both Experimentations were developed using a BP Solar PVM, model: SX305M.

The first experiment consider load variations from 10Ω to 100Ω with a fixed irradiance level of $409W/m^2$ and an average temperature of 48^oC. Fig. 7 and Fig. 8 show the dynamic behavior in the PVM voltage and PVM Power, while Fig. 9 shows the power and voltage delivered to the load

In the second experiment a step change in the irradiance level, from $409W/m^2$ to $102W/m^2$, was introduced to the system when a resistive load of 100Ω is connected to it. Fig. 11 to Fig. 13 show the dynamical behavior in the PVM power, PVM voltage, PVM surface temperature, and Fig. 12 shows the power delivered to the Load.

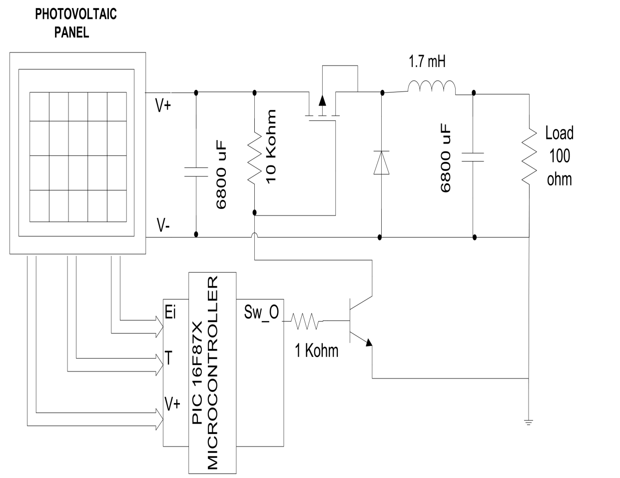

Fig. 4. Circuit Schematic

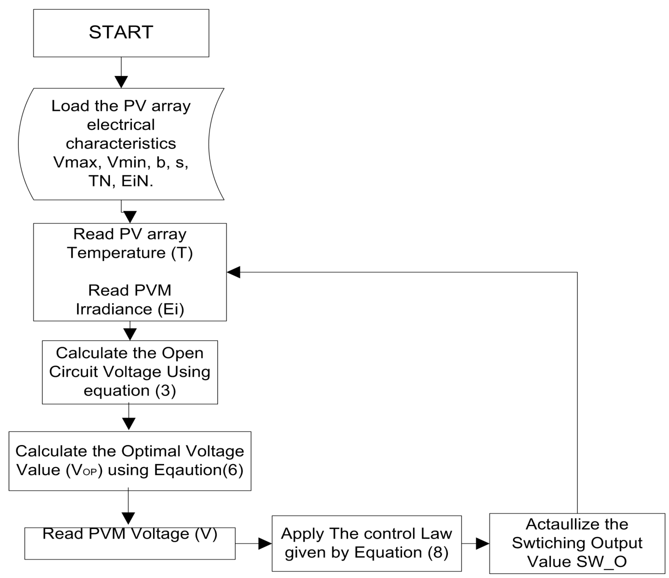

Fig. 5. Flow Chart For the Microconntroller Application

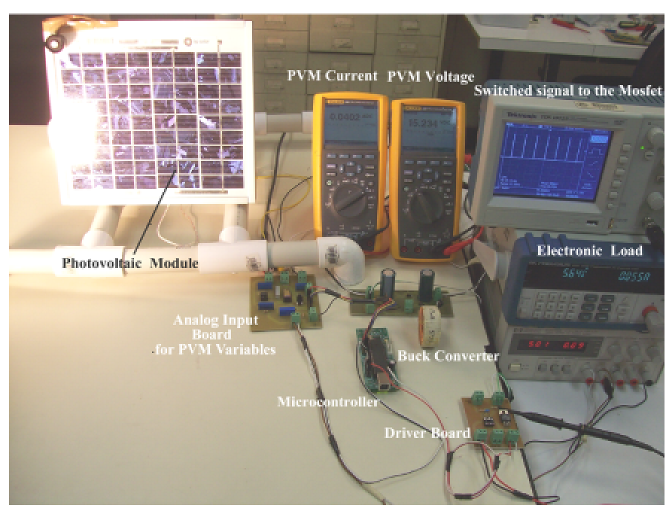

Fig. 6. Experimental Setup

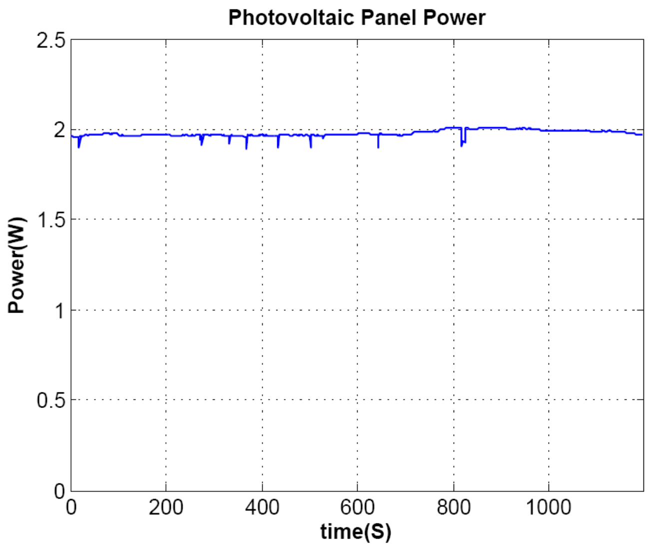

Fig. 7. PVM Power for different load changes

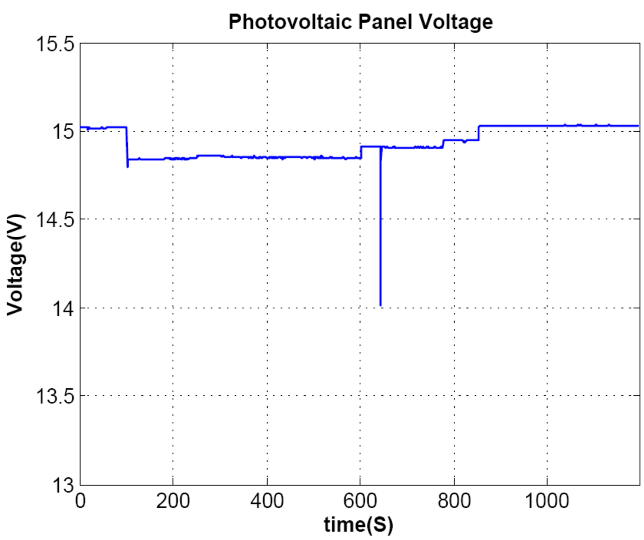

Fig. 8. PVM Voltage for diferent load changes

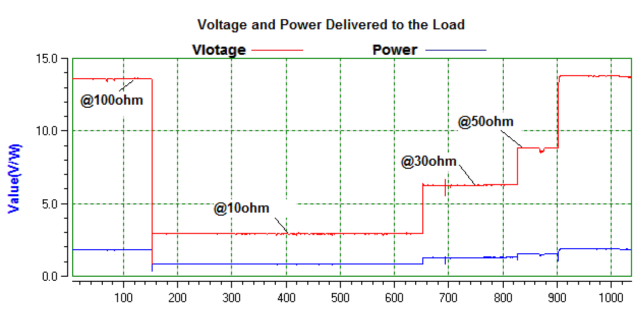

Fig. 9. Output Power for different Load changes

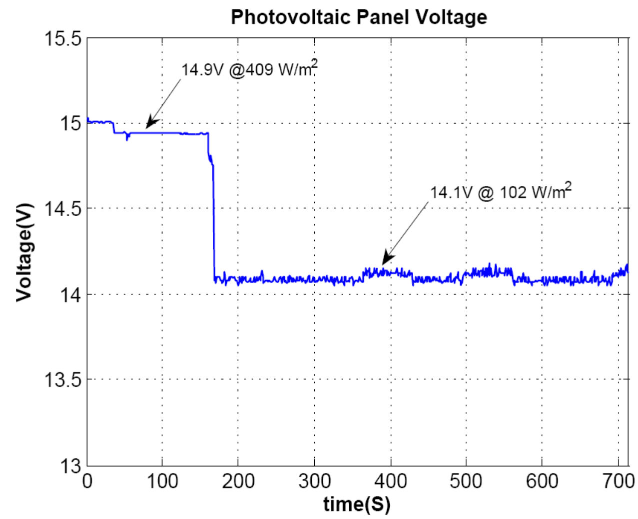

Fig. 10. PVM Voltage for a step variation in the irradiance level

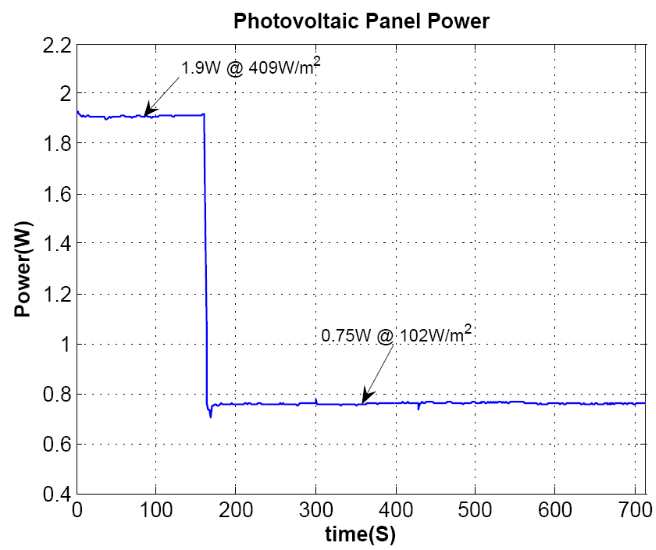

Fig. 11. PVM Power for a step variation in the irradiance level

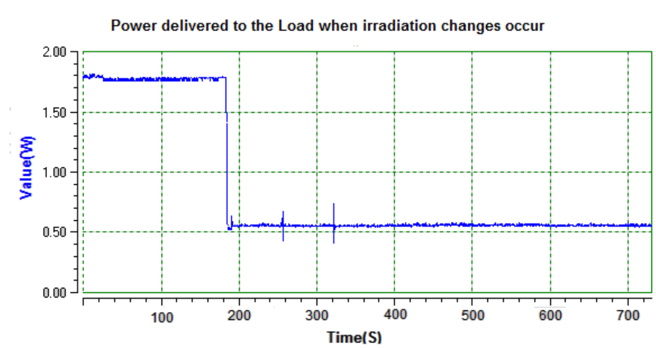

Fig. 12. Load Power for a step variation in the irradiance level

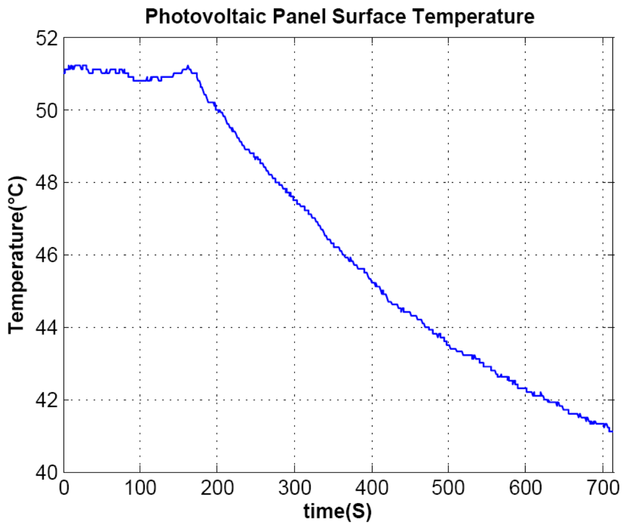

Fig. 13. PVM surface temperature behavior for a step variation in the irradiance level

TABLE I
COMPARISON BETWEEN OPTIMAL VOLTAGE VALUES ESTIMATED (EST), REAL, OBTAINED ON CIRCUIT(OC)

E_i	T	V_{op}(Est)	V_{op}(Real)	V_{op}(OC)
102 W/m^2	38.8 C	14.4202 V	14.85 V	14.2 V
409 W/m^2	49.5 C	14.953 V	15.3 V	15.01 V

TABLE II
COMPARISON BETWEEN MAXIMUM POWER POINTS ESTIMATED REAL AND OBTAINED ON CIRCUIT(OC)

Ei	T	P_{max}(Real)	P_{max}(OC)	Error
102 W/m^2	38.8 C	0.775 W	0.76 W	3.22 %
409 W/m^2	49.5 C	1.89 W	1.86 W	1.58 %

Table I and Table II present the average optimal values for the voltage and power in the PVM at steady state conditions. In both tables, the "real" measures refer to the values for which the module is driven to the maximum power with a direct load matching, while the "on circuit" measures(OC) are the values obtained with the implemented system. $(V_{op}(est))$(Table I) is the theoretical simulated optimal voltage for the given conditions.

VI. CONCLUSION

A novel maximum power point tracking method, capable of estimate the optimal voltage at which the solar cell produces its maximum power, has been presented. The equation for estimating the optimal voltage showed very low and acceptable errors percentage at estimating the optimal voltage and current for different solar cells. The implementation in a low cost microcontroller and its effectiveness for load variations and irradiance variations has been shown. The sliding mode controller was capable of tracking the optimal voltage and forced the PVM to reach that voltage point in a finite time. It also forced the solar module to keep operating at that voltage for all future time. The sliding mode controller was capable of extracting the maximum power available from the solar module under different temperature, irradiance and load conditions.

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