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Article · June 2011

DOI: 10.1109/ICCEP.2011.6036361

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Comparative Analysis of MPPT Techniques for PV Applications

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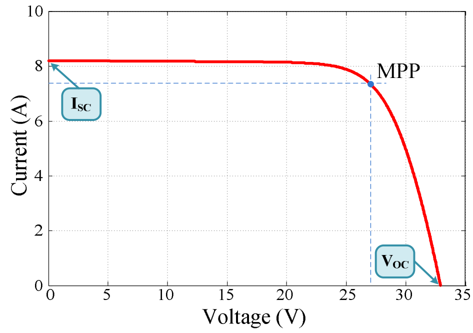
***Abstract*--This paper presents a careful evaluation among the most usual MPPT techniques, doing meaningful comparisons with respect to the amount of energy extracted from the photovoltaic (PV) panel, PV voltage ripple, dynamic response and use of sensors, considering that the models are first implemented via MatLab/Simulink®, and after a digitally controlled boost DC-DC converter was implemented and connected to an Agilent Solar Array simulator in order to verify the simulation results. The prototype was built, the algorithms are digitally developed and the main experimental results are also presented, including dymanic responses and the experimental tracking factor (TF) for the analyzed MPPT techniques.**

***Index Terms*--MPPT Techniques, PV Applications, Tracking Factor for MPP, Digital Control.**

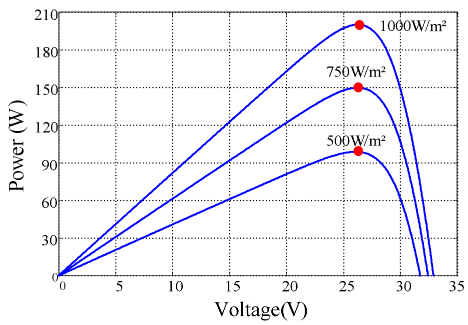
I. Introduction

The growing energy demand coupled with the possibility of reduced supply of conventional fuels, along with growing concerns about environmental preservation, has driven research and development of alternative energy sources that are cleaner, renewable and produce little environmental impact. Among the alternative sources the electrical energy from PV is currently regarded as the natural energy source more useful, since it is free, abundant, clean, distributed over the Earth and participates as a primary factor of all other processes of energy production on Earth [1]. Moreover, although the phenomena of reflection and absorption of sunlight by the atmosphere, it is estimated that solar energy incident on the surface of earth is of the order of ten thousand times greater than the world energy consumption. According to expertises previsions the PV energy will became the most important reneable energy source until 2040, reaching almost 28% off all world energy consumed [2]. In this context, the concept of distributed energy generation, became a real and present technical possibility, promotin various researches and standardizations in the world. Despite all the advantages presented by the generation of energy through the use of PVs, the efficiency of energy conversion is currently low and the initial cost for its implementation is still considered high, and thus it becomes necessary to use techniques to extract the maximum power from these panels, to achieve maximum efficiency in operation. It should be noted that there is only one point of maximum power (MPP - Maximum Power Point), and this varies according to climatic conditions. The photovoltaic power characteristics is nonlinear, as shown in Fig.1, which vary with the level of solar irradiation and temperature, which make the extraction of maximum power a complex task, considering load variations. To overcome this problem, several methods for extracting the maximum power have been proposed in literature [3-14], and a careful comparison of these methods can result in important information for the design of these systems. Therefore, this paper aims to assess the main MPPT techniques presented in the literature using models in Matlab/Simulink®, doing depth comparisons between them with regard to the amount of required sensors, voltage ripple in steady state, startup of the method and amount of energy extracted.

This work was supported by FAPESP, CAPES and CNPq.



(a)



(b)

Fig. 1. (a) PV Current versus Voltage Characteristic, and (b) Power Characteristic for Different Levels of Irradiation.

II. Main MPPT Techniques

This paper covers the Fixed Duty Cycle, Constant Voltage, Perturb and Observe (P&O) and Modified P&O, Incremental Conductance (IC) and Modified IC, Ripple Correlation and System Oscilation methods, which are briefly described in this section. The Fixed Duty Cycle represents the simplest of the methods and it does not require any feedback, where the load impedance is adjusted only once for the maximum power point and it is not adjusted again.

The Constant Voltage method uses empirical results, indicating that the voltage at MPP (V_{MPP}) is around 70% to 80% of the PV open circuit voltage (V_{OC}) for the standard atmospheric condition. Among the points of MPP (varying atmospheric conditions), the voltage at the terminals of the module varies very little even when the intensity of solar radiation changes. However the V_{MPP} strictly modifies with temperature changes. So, the operating point is never exactly at the MPP and different data have to be adopted and tested for different environmental conditions and regions. An interesting point is the necessity of only one voltage sensor and it presents very good performance for low insulation. Because of this reason this method can be combined with others to increase efficiency.

The P&O method operates periodically incrementing or decrementing the output terminal voltage of the PV and comparing the power obtained in the current cycle with the power of the previous cycle. If the voltage varies and the power increases, the control system changes the operating point in that direction, otherwise change the operating point in the opposite direction. Once the direction for the change of current is known, the current is varied at a constant rate. This rate is a parameter that should be adjusted to allow the balance between faster response with less fluctuation in steady state. The flowchart of this algorithm is presented in Fig. 2. A modified version is obtained when the steps are changed according to the distance of the MPP, resulting in higher efficiency. A frequent trouble in P&O methods is that the output terminal voltage of the PV is perturbed every MPPT cycle even when the MPP is reached, resulting in loss of power.

The IC method is based on the fact that the power slope of the PV is null at MPP (dP/dV = 0), positive in the left and negative in the right, as shown in Fig. 1(b). Due to this condition, the MPP can be found in terms of the increment in the array conductance. Using (1) it is possible to find the IC conditions presented by (2).

$$\frac{dp}{dv} = \frac{d(v.i)}{dv} = i + v\frac{di}{dv} = 0 \qquad (1)$$

$$\frac{\Delta i}{\Delta v} = -\frac{i}{v}(a), \frac{\Delta i}{\Delta v} > \frac{i}{v}(b), \frac{\Delta i}{\Delta v} < \frac{i}{v}(c) \qquad (2)$$

Where (2.a) represents the condition at MPP, (2.b) represents the condition in the left and (2.c) in the right of MPP.

This method searches the MPP in the same way as P&O, and also features a modified version, but it is not necessary to calculate the PV output power and presents very good transient performances when subjected to rapidly changes in atmospheric conditions. The flowchart of the IC algorithm is presented in Fig. 3.

The Beta method is the approximation of the point of maximum power through the equation of an intermediate variable β (3).

$$\beta = \ln(I_{PV} / V_{PV}) - c.V_{PV} \qquad (3)$$

Where: c = (q/(σ. K.T.Ns)) is a constant that depends on the electron charge, the quality factor of the junction panel, the Boltzmann constant, temperature and amount of photovoltaic cells in series. As the operating conditions change, the value of β at the optimum point remains almost constant. Thus, β can be continuously calculated using the voltage and current of the panel and inserted on a conventional closed loop with constant reference, as shown in Fig. 4.

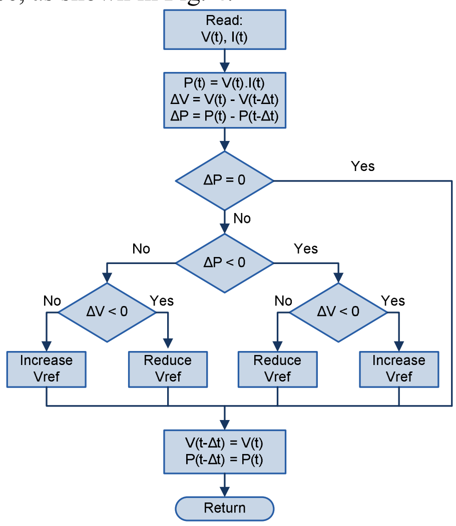


Fig. 2. Flowchart of the P&O Algorithm.

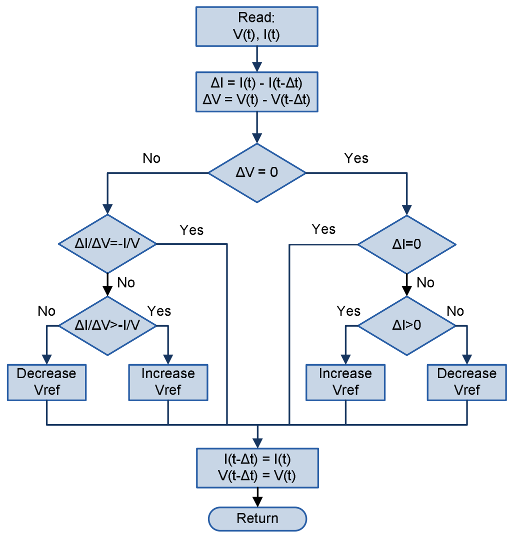


Fig. 3. Flowchart of the IC Algorithm.

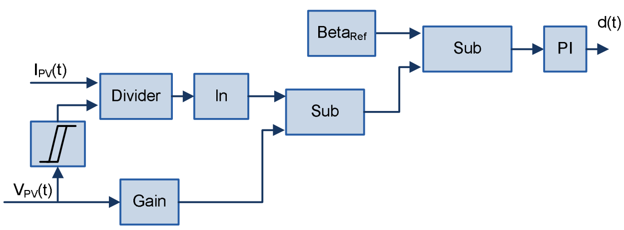


Fig. 4. Implementation of Beta Method.

The System Oscillation method is based on the principle of maximum power transfer and it uses the oscillations to determine the optimum point of operation. At the MPP the ratio of the amplitude of the oscillation and the average voltage is constant. This method requires only the sensing of the array voltage and its implementation is basically characterized by the use of filters. So, this method can be easily implemented with only analogical circuitries.

The Ripple Correlation is also based on the principles of maximum power transfer and it uses the oscillations in power throught all pass filters to obtain the optimal point. In other words, the high-frequency ripple in power and voltage is then captured using high-frequency filters, which are used to compute dP/dV. Then, the sign of this derivative is used in a signum function to indicate the right region of operation and an integrator also ensures the MPP.

III. Simulation Results

The average model of the DC-DC boost converter was used to simulate the load variation controlled via Matlab/Simulink®, and was added a fluctuation in the average model in order to represent the effect of the inductor ripple current. All tests were performed considering the same temperature and irradiation with positive and negative steps. Fig. 5 shows the responses of the best MPPT algorithms evaluated where the maximum available power is highlighted in blue color, and the graph in red is the PV power extracted.

Aiming to compare and adjust appropriately each algorithm according to the application it becomes necessary to provide performance measures that can be used for comparison criteria. Beyond the typical measures of dynamic responses, there are also additional metrics that are used in these cases. Because the transmitted energy is essential for the use of PV as an energy source, a very important measure is the tracking factor, which is the percentage of available energy that was converted. The ripple voltage in steady state is also of vital importance, as there is a limit of ripple so that the panel will remain effectively at the MPP. Other factors such as ease of implementation, number of sensors and cost are also desirable. The tracking factor is depicted in Fig. 6, and according to it P&O and IC modifieds, Ripple Correlation and Beta methods stands out, and the Beta method can extract the greatest amount of energy from the PV, being in the order of 98.8%.

Ripple comparisons in steady state of the power extracted are shown in Fig. 7(a), where the Ripple Correlation and Beta methods stands out for having the slightest ripple in steady state. MPPT methods should also be compared with respect to its dynamic response, i.e. how they behave when the power panel is minimal and quickly changed to the nominal condition. Just to test, the resulting degree of power varies instantaneously from 10W to 200W, and can be evaluated using Fig. 7(b).

According to the results presented, it appears that Beta and modified IC methods stands out, and it is the modified IC method which presents less time to reach the steady state (time of the order of 0.2 s). Just to highlight the methods IC and P&O had almost the same indices of quality, since they are based on the same principle of searching for MPPT, which is dP/dV null at MPP.

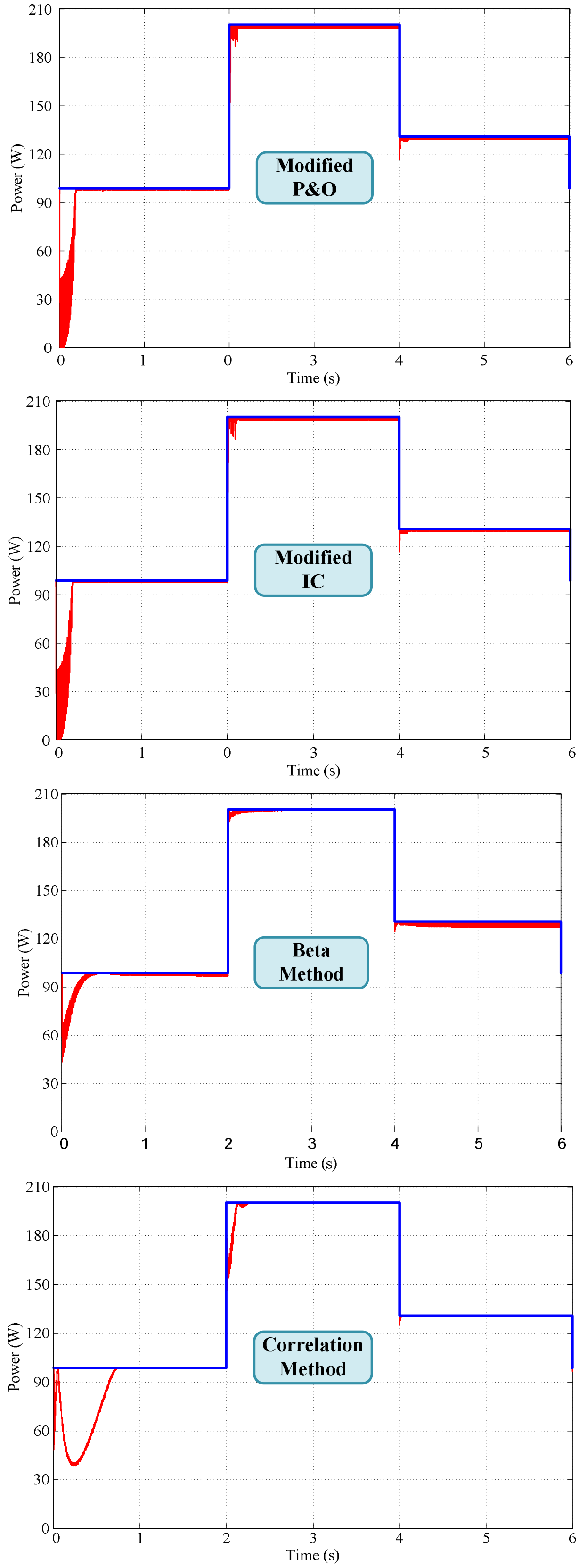


Fig. 5. Power Extracted from the PV panel with the Best MPPT Techniques.

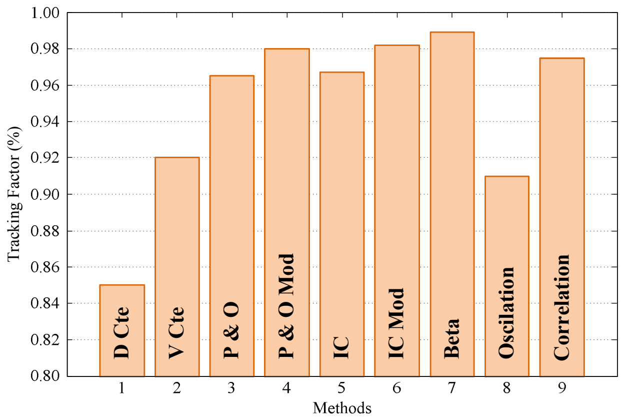
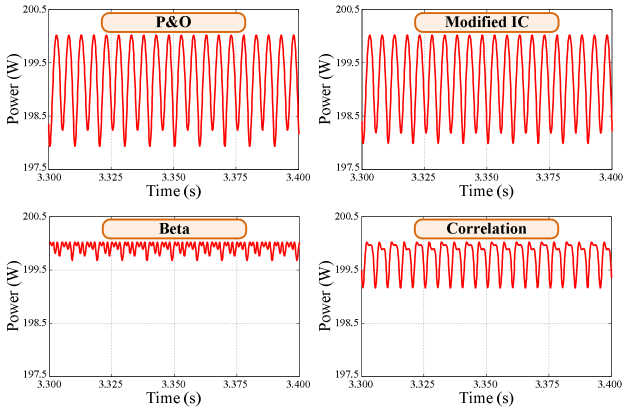
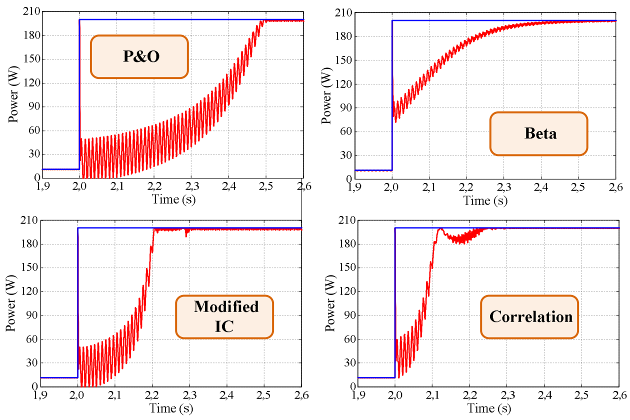


Fig. 6. Percent of Energy Extracted from PV Panel.



(a)



(b)

Fig. 7. (a) Power Ripple in Steady State, and (b) MPPT Dynamic Behavior.

IV. Experimental Results

The implemented prototype and the experimental arrangement are shown in Fig. 8. The algorithms are digitally implemented in the dsPACE ACE1104 plataform, wich emulates a DSP TMS230F240 core, and the main results are presented in this section.

The irradiation and temperature steps are configurable using the Agilent E4350B PV emulator via GPIB-USB and Agilent Interactive I/O interface.

Fig. 8. Experimental Arrangement - Laboratory Setup.

The methods were first evaluated in relation to its initialization, i.e., how they behave when submitted to full insulation starting from the zero state, and after positive and negative steps of power were applied. It is possible to verify the Beta Method dynamics response in Fig. 9, the Vcte dynamic response in Fig. 10, P&O dynamics response in Fig. 11 and IC response in Fig. 12.

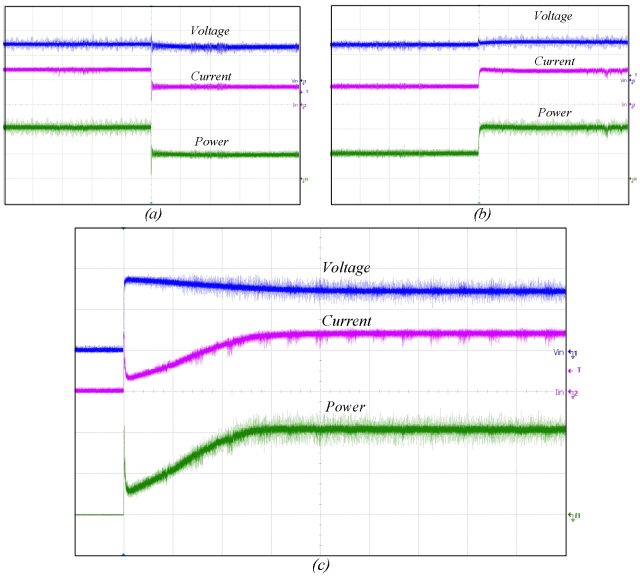


Fig. 9. Dynamic Behavior of Beta Method. (a) Negative Step (200W-100W); (b) Positive Step (100W-200W); (c) Inicialization (0W-200W). Scales: Voltage (20V/div); Current (5A/div); Power (100W/div) and Time: (a) e (b) (20ms/div) e (c) (200ms/div).

According to the dynamic responses, all experimentally eavaluated methods presented very good performance. All of then changed the PV output power in less than 20ms when submitted to a power change (100W-200W and vice-versa). Only Vcte method presented a poor inicialization spending 1.6s to reach the maximum power from off state. The Beta method presented a good initialization time being of aproximattely 500ms. Experimentally the inicialization of IC and P&O methods presented the best performance, but the on time perturbations represent loss of power in steady state because PV output voltage are always perturbed as easily observed in Figs. 11 and 12, respectively.

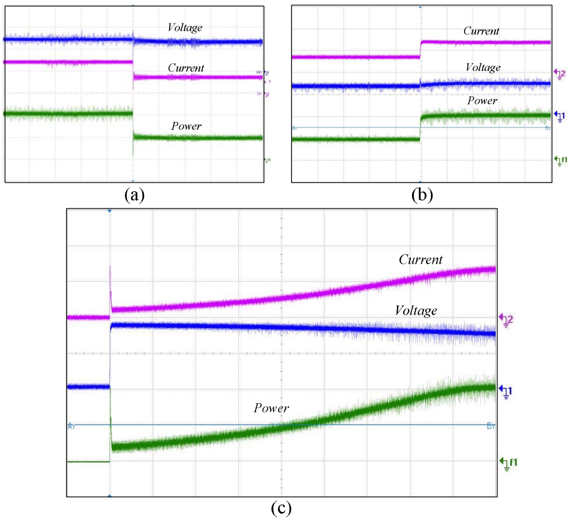


Fig. 10. Dynamic Behavior of Vcte Method. (a) Negative Step (200W-100W); (b) Positive Step (100W-200W); (c) Inicialization (0W-200W). Scales: Voltage (20V/div); Current (5A/div); Power (100W/div) and Time: (a) e (b) (20ms/div) e (c) (200ms/div).

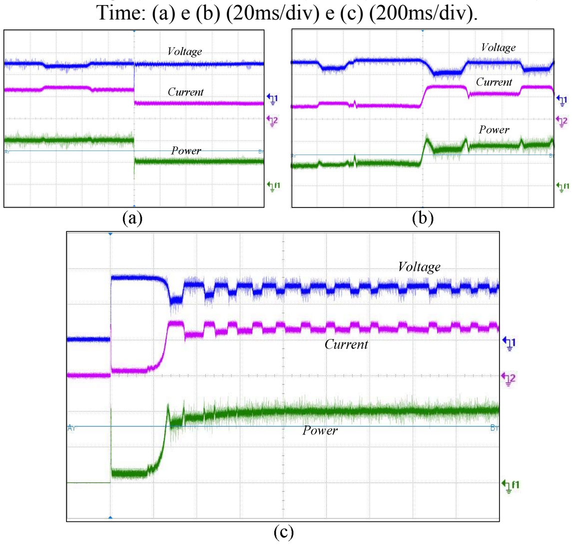


Fig. 11. Dynamic Behavior of P&O Method. (a) Negative Step (200W-100W); (b) Positive Step (100W-200W); (c) Inicialization (0W-200W). Scales: Voltage (20V/div); Current (5A/div); Power (100W/div) and Time: (a) e (b) (20ms/div) e (c) (200ms/div).

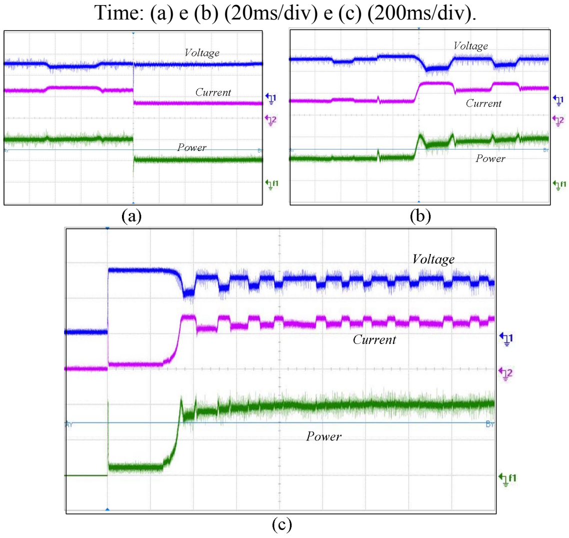


Fig. 12. Dynamic Behavior of IC Method. (a) Negative Step (200W-100W); (b) Positive Step (100W-200W); (c) Inicialization (0W-200W). Scales: Voltage (20V/div); Current (5A/div); Power (100W/div) and Time: (a) e (b) (20ms/div) e (c) (200ms/div).

In order to compute the Tacking Factor (TF), an aquicstion management system was implemented through C++ Builder. Using this system it was possible through remote program for the Array Emulator with a set of irradiation and temperature curves emulating some profiles of power. These profiles of power can be aleatory adjusted or follow some irradiation or temperature settings, according to environmental conditions from a specific region. The communication was done through GPIB-USB to exchange data from Computer and Array Emulator.

The evaluation of power extracted from the Photovoltaic Emulator (E4350B) through the converter with the MPPT algorithms can be observed in Figs. 13 to 15, where P_{MAX} (red chart) represents the maximum available power of the Photovoltaic Emulator and P_{MPPT} (green chart) represents the energy that could be converted by the converter. The analyzed methods were adjusted to provide its best performance with the same set of irradiation and temperature steps. In this context, the Beta method stands out with 98% of energy extracted, the P&O method reach 96% and Vcte stays at 92%. The experimental results are almost the same as the simulated ones, showing the potential of the analytical procedure. The commercially specifications for the photovoltaic module applied to the Array Simulator are presented in Table I.

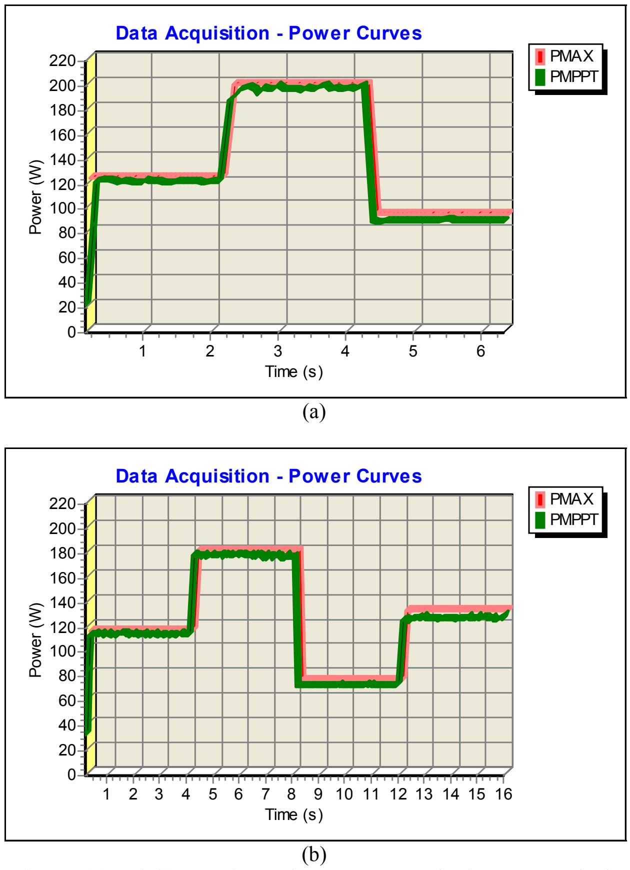


Fig. 13. (a) and (b) Experimental Power Extracted using Beta Method.

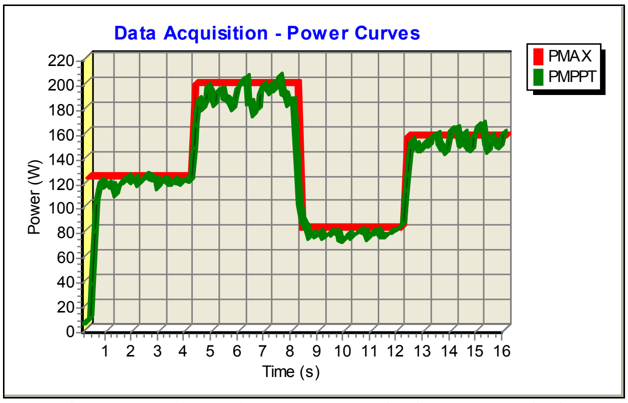


Fig. 14. Experimental Power Extracted using P&O Method.

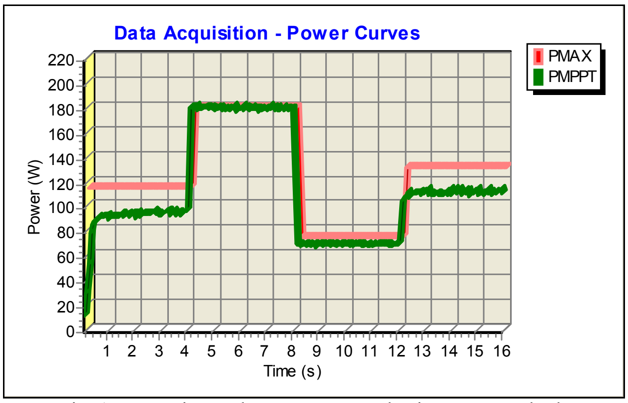


Fig. 15. Experimental Power Extracted using Vcte Method.

TABLE I
PV ELECTRICAL PARAMETERS

Maximum Power	P_{max} = 200Wp
Voltage at MPP	V_{MPP} = 26.3V
Current at MPP	I_{MPP} = 7.61A
Open Circuit Voltage	V_{oc}= 32.9V
Short Circuit Current	I_{sc} = 8.21A
Temperature Coeficient of I_{sc}	$\alpha = 3.18\text{x}10^{-3}$ A/°C

V. CONCLUSIONS

This paper presented a carreful evaluation among some interesting and important MPPT Algorithms presented in literature, but in a deeper manner mixing simulation, discussions and experimental results. The simulation procedure also reached the expectation giving similar results as the experimental ones. The inicialization methods, MPPT ripple in steady state and the amount of energy extracted (Tracking Factor) from the photovoltaic panel were pointed out. It is necessary to highlight that the use of energy from photovoltaic panels is a reality, and its intensive use will very soon become extremely important in finding solutions to energy and environmental problems. In this context, the used MPPT techniques are of most importance to extract the maximum power available in PV. Among the methods evaluated, Beta was presented as an excellent solution regarding the best tracking factor, reduced and smaller ripple voltage in steady state, good transient performance and simplicity of implementation, resulting in the best overall performance among the techniques. Finally, it is noted that the Ripple Correlation, modifieds IC and P&O, also deserve mention as an alternative for good PV performance.

ACKNOWLEDGEMENT

The authors would like to thank FAPESP, CAPES and CNPq for support this work.

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