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Numerical Experimental Validation of a Proposed MPPT Algorithm with Dynamic Hysteresis for PV Systems

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Abstract. In the last decades, the renewable energies have had a highly positive effect on the daily life. This due to the necessity of reducing the common fuel energies that have negatively impacted the environment. Among all the available renewable energies, the solar energy is one of the most common. This energy is obtained through Photovoltaic (PV) systems. Thus, in previous years, new techniques of Maximum Power Point Tracking (MPPT) to raise the quality of the energy provided by PV panels have been proposed. Since the energy provided by the PV cells depends on the external environmental conditions, as temperature or sun irradiance, the MPPT methods should be adequate to deal with these external changes by maintaining the desired power level. Hence, this paper proposes a recent hysteretic dynamic technique to extract the maximum power from a PV panel array by employing a Boost DC/DC converter to supply energy to an inductive load. Here, a comparative study between the results obtained with the well known Perturb and Observer (P&O) algorithm and by using our dynamic hysteretic MPPT method is analyzed, specifically when the PV panel is submitted to fast variations in temperature and irradiance. It will be proved through numerical experiments realized in MatLab/Simulink that our hysteretic MPPT algorithm provides a better achievement of the maximum power of the PV panel in comparison to the conventional Perturb and Observer method.

Key words

Photovoltaic panel, maximum power point tracking, dynamic hysteresis model, DC/DC converters, power quality.

1. Introduction

Within the recent past it has been well known that conventional energy sources, as petroleum or natural gas, are not more a good option due to they have negatively impacted the life on earth [1], [2]. This is why, recently, the demand of renewable energies has been increased to deal with the climate change and to reduce the common use of fuel energy sources. In particular, solar energy is one of the most common renewable sources and as a consequence of this, an enormous amount of studies has been dedicated to it, with the aim of optimizing the power produced by the photovoltaic systems. Some advantages of the solar energy with respect other renewable options are for instance that the energy conversion process does not need fuel burning or moving parts [2]–[4]. Moreover, PV panels provide long effective life, low maintenance cost and high reliability [5]. However, the efficiency of energy conversion is still considered a challenge to be defeated. Thus, it becomes necessary to develop new techniques to extract the maximum power from the PV panels in order to increase the maximum efficiency operation of the PV systems. [2], [6], [7].

The energy provided by a PV cell depends on the operating conditions, mainly the sun irradiance and the temperature. If these conditions are uniform there is a unique peak where the PV power is maximized, this peak is known as Maximum Power Point (MPP) and it is achieved by invoking an adequate Maximum Power Point Tracking algorithm [8], [9]. In the state of the art, there is a considerable amount of Maximum Power Point Tracking methods, a deep description and comparison of the existent MPPT methods has been published in several papers [4], [5], [10]–[26]. Nevertheless, the most common algorithms are those based on a climbing technique, for instance, the Perturb and Observer method (P&O) [4], [13], [16], [24]; the Incremental Conductance algorithm (InC) or the Hill Climbing (HC) technique [27], [28]. In this paper, the P&O is invoked as a reference algorithm for comparison purpose since it is the most popular method and a simple one in the PV field.

In addition to the PV panel and the MPPT algorithm, a photovoltaic system also requires a suitable power conversion stage between the terminals of the PV panel and the user load [11], [23]. For applications that require DC energy, the conversion stage is realized by a DC/DC converter, which manipulates the load seen by the PV panel when its duty cycle is modified through the MPPT algorithm [29]. Hence, the maximum power point is adapted to the PV conditions, while the converter output keeps up the voltage and the current levels according to the load requirements [13], [23], [29], [30].

This paper proposes a scheme where the MPPT algorithm is based on a dynamic hysteresis model. The hysteresis provides memory effect, among other characteristics that yield a suitable performance of the PV system. In this manner, the aim of this paper is to contribute with a scheme that could be implemented in real photovoltaic applications. Numerical experiments show that the performance of the proposed technique stands out over the performance of the system when the Perturb and Observer method is invoked. These experiments were realized under fast changes in irradiance and temperature, which is a notable contribution of this paper since it is a current issue in the PV research area [13], [31]. Moreover, it will be seen that the power extracted from the PV array when our technique is implemented has a better performance in comparison to the one obtained with the P&O algorithm, since the natural oscillation of the P&O is considerably attenuated.

This paper is organized as follows. Section 2 describes the main design stages of a PV-MPPT system, basically these are the PV cell and the DC/DC converter. On the other hand, Section 3 states the Perturb and Observer algorithm and the hysteretic MPPT method. Meanwhile, the numerical experiments and the analysis of the corresponding results are exposed in Section 4. Finally, some concluding remarks are given in Section 5.

2. Photovoltaic-MPPT System

In this Section, first, the PV electrical and mathematical model is presented in order to study its basic operation. Afterwards, the conversion stage is exhibited by emphasizing the Boost DC/DC converter employed in this paper.

A. Photovoltaic Modelling

The photovoltaic modelling has been the object of study in the last years since some MPPT algorithms are based on it [10], [23]. The equivalent electronic circuit of a PV cell is summarized in Fig. 1. This model can be seen as a current source with series and parallel resistors connected to a single diode [2], [5]. From Fig. 1, R_{sh} is the shunt resistance, R_s is the serial resistance, I_{PV}, I_d, I_{sh} and I_{ph} are the PV array output current, the current through the diode, the current in parallel resistance and the current generated by the sun incident light, respectively. Finally, V_{PV} is the PV module output voltage [15], [28], [29].

The equation that describes the PV output current (I_{PV}) of the solar cell yields:

$$I_{PV} = I_{ph} - I_d - I_{sh}, \tag{1}$$

Furthermore, I_d is given by [23]:

$$I_d = I_0 \cdot (e^{q\frac{(V+IR_s)}{nKT}} - 1), \tag{2}$$

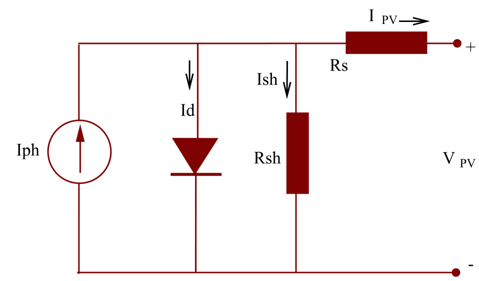

Fig. 1. Simplified equivalent circuit of a photovoltaic cell.

where I_0 is the saturation current, q represents the electron charge, and K is the *Bolzman constant*. Moreover, n is the diode factor and T is the temperature on the P-N junction of the diode. The current I_{ph} can be expressed as follows [23]:

$$I_{ph} = \frac{G}{Gstc} \cdot (I_{sc,ref} + \mu_{sc}(T - T_{stc})), \tag{3}$$

where μ_{sc} is the temperature coefficient of the short circuit current, G is the irradiation effect, G_{stc} is the irradiation effect in specific operating conditions (defined as standard conditions [29]), and $I_{sc,ref}$ is the short circuit current at a given reference temperature. On the other hand, the saturation current is given by [23]:

$$I_0 = C \cdot T^3 \cdot e^{(-\frac{E_{gap}}{kT})}, \tag{4}$$

where E_{gap} is the band gap of the semiconductor material and C is the temperature coefficient [23]. Therefore, the PV current can be rewritten as:

$$I_{PV} = I_{ph} - I_0 \cdot [e^{q\frac{(V+IR_s)}{nKT}} - 1] - \frac{V + R_s I_{PV}}{R_{sh}}. \tag{5}$$

B. Boost-Converter

The conversion stage in photovoltaic systems is necessary to provide quality energy with the characteristics required by the load. Besides, this stage allows to overcome the undesired effects on the output PV power imposed by the environmental perturbations, and to achieve, as well as possible the maximum power point [12], [29]. This maximum power production is based on the adjustment of the load, through the conversion stage, seen by the PV panel, which is subjected to the mentioned non-uniform environmental conditions. Depending on the application, the

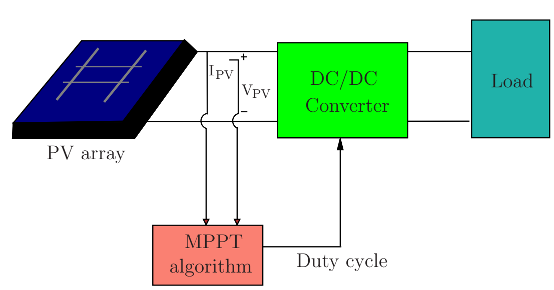

Fig. 2. Scheme of a PV system with conversion stage.

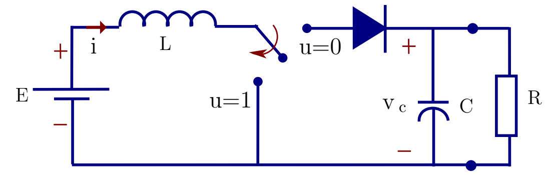

Fig. 3. General power electronic scheme of the Boost converter [34].

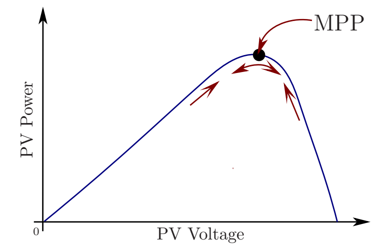

Fig. 4. Characteristic curve voltage vs power for the P&O algorithm.

conversion stage is realized by a DC/DC converter which is controlled through a duty cycle adequately adjusted by the MPPT algorithm [4], [12], [13], [29]. The representative connection scheme of the converter interacting with the PV array, the load and the MPPT algorithm is shown in Fig. 2.

In PV systems implementation, the selection of the suitable DC/DC converter depends on the load requirements. The most common structures of DC/DC converters are: the *Buck Converter*, which steps down the voltage from its input supply to its output [32]; the *Boost Converter*, which will be invoked in this paper and explained later; and the combined *Buck-Boost Converter (Cûk Converter)*, that is a fusion between the behavior of both converters [32]. On the other hand, in some recent papers, emulators of converters have been used to fulfill the objective of manipulating the load seen by the panel [29], [33].

By recalling the Boost converter configuration, its general electric scheme is the one presented in Fig. 3. Where R is the user load that in some cases, depending on the application, can be also an inductive load. L is the input circuit inductance, C is the capacitance of the output filter and V_c is the output voltage in the capacitance [34]. Moreover, E is the supplied voltage, and in the particular case of PV systems this voltage is the one given by the PV panel. The basic principle of the Boost converter is to step up the output voltage from its input supply.

3. MPPT Algorithms

In this section two MPPT algorithms are described and analyzed. The first one is the standard Perturb and Observer method, the second one is our Hysteretic MPPT algorithm. These both techniques will be employed in our numerical experiments in order to realize a comparative study between both methods. These comparisons will be exposed in Section 4.

A. *Perturb and Observer Algorithm*

One of the most common MPPT algorithms is the Perturb and Observer method due to its simplicity [35]. Its basic principle consists of periodically measure the voltage and current from the PV panel in order to estimate the PV power. Thus, an adequate perturbation is redefined and the corresponding output power is compared with the previous perturbing cycle [16], [23], [36]. Hence, the perturbation is calculated at every sample time and when the maximum power point is reached the power oscillates around this

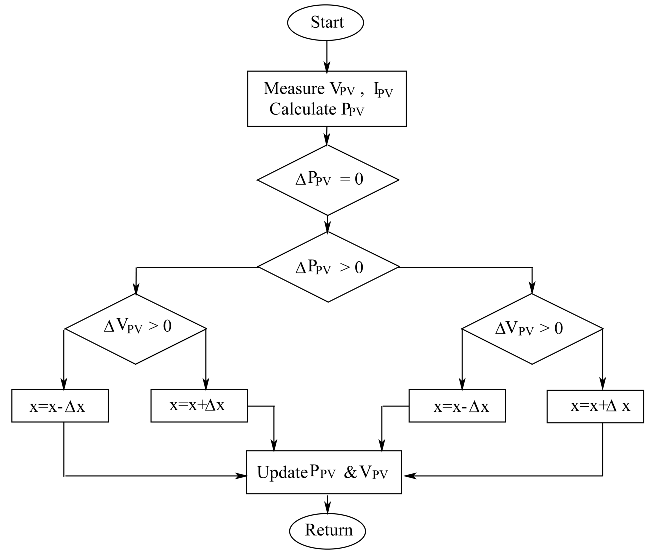

Fig. 5. Flowchart of the standard Perturb and Observer (P&O) [11].

peak (see Fig. 4). However, due to its nature of constantly perturbation, this method presents the disadvantages of important power lose when the maximum power is closely achieved [4]. Another important disadvantage of this method is that it normally fails when the PV system is subjected to fast changes in temperature or sun irradiance [13], which is a natural situation of the PV panels in general. Figure 5 shows the classical flowchart of the standard P&O algorithm.

B. *Hysteretic MPPT Algorithm*

The proposed Hysteretic MPPT algorithm incorporates, as its name says, a dynamic hysteresis model. This employs

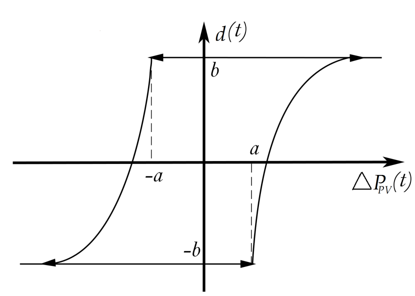

Fig. 6. Hysteresis loop.

information from the PV panel, specifically its voltage and current [29]. Due to a hysteretic dynamic system has a memory effect, its output depends on the past state of its variables and its input. This feature provides greater stability in the panel terminals. Thus, the output generated by the algorithm will present fewer oscillations when the maximum power point is closely achieved.

The model of the dynamic MPPT algorithm employs signum functions as a representation of a memory action. Furthermore, it requires information form the PV voltage V_{PV} and the PV current I_{PV} in order to estimate the PV power P_{PV}. The dynamic hysteretic equation is as follows [29]:

$$\dot{d}(t) = \alpha[-d(t) + b\text{sgn}(\Delta V_{PV} + a\text{sgn}(\Delta P_{PV})], \quad (6)$$

where a and $b \in R^+$ are the hysteresis loop parameters and $d(t)$ is the internal variable of the model. For instance, Figure 6 shows a characteristic hysteresis behavior by varying ΔP_{PV} and keeping constant ΔV_{PV} with respect to $d(t)$. In Equation (6), the transition time-rate between b and $-b$ is governed by the real positive parameter α. Hence, these parameters can be properly adjusted in order to set the response time or the hysteresis width. Actually, ΔV_{PV} and ΔP_{PV} are the inputs to the hysteresis system. Then, ΔP_{PV} and ΔV_{PV} collaborate jointly to drive the hysteresis loop behavior to fulfill the MPPT objective [29]. Thus, the equation (6) is presented as a newfangled MPPT algorithm.

4. Numerical Experiment Results

In this section the simulation results are presented. The numerical experiments were realized in Matlab/Simulink. First of all, the PV array implemented was the SunPower SPR serie 305-E built of strings of 66 PV modules connected in parallel, each string consists of 5 modules connected in series. The characteristic curves, $I-V$ and $P-V$, are exhibited in Fig, 7, for the specific PV array employed in the simulations. These curves are very useful to know where the MPP is located according with the conditions that the panel is subjected. These graphics were obtained with two levels of irradiance: 250 W/m^2 and 450 W/m^2. Note that for these two levels there are two maximum power points respectively, the first one is near to 2.5x10^4 W and the other one is around to 4.5x10^4 W. Later on it will be seen that these power values are closely achieved with the proposed technique.

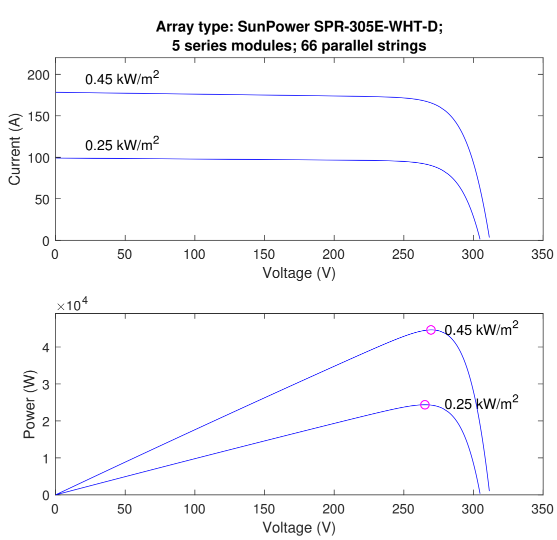

Fig. 7. Photovoltaic array characteristic curves $I-V$ and $P-V$ for two irradiance levels.

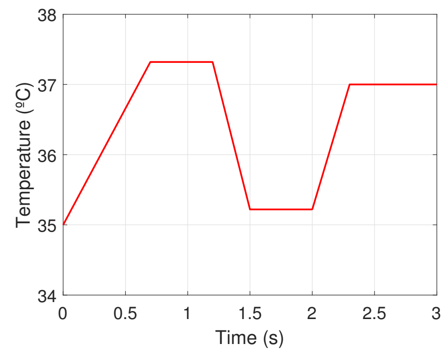

Fig. 8. Environmental temperature variation.

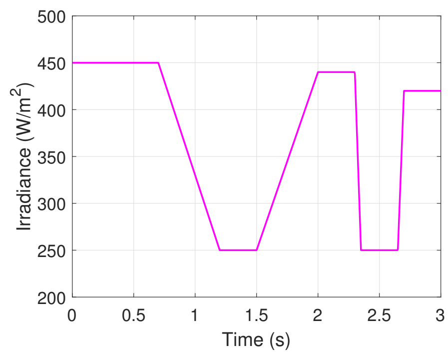

Fig. 9. Environmental irradiance variation.

Figure 17 and Fig. 18 show the both MPPT schemes build in Simulink, the one with the P&O method and the one with the hysteretic proposal, respectively. The first one contains a MatLab Function block with the P&O algorithm. The second one has a model diagram block of equation (6). Furthermore, both systems employ the same Boost

TABLE I

BOOST CONVERTER PARAMETERS.

Component	Value
Switching frequency	50kHz
Inductor, La	200μH
Serie resistance of inductor, Ra	0.5Ω
Input and output capacitors, Ci and Co	220μF
Resistance load, Rb	250Ω
Inductance load, Lb	100μH

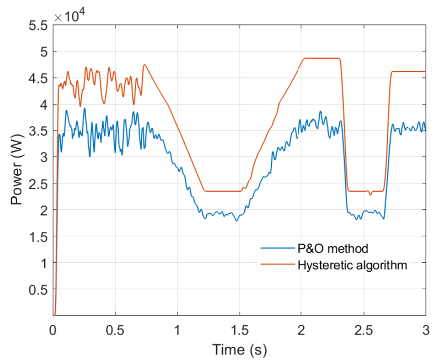

Fig. 10. The output generated PV power.

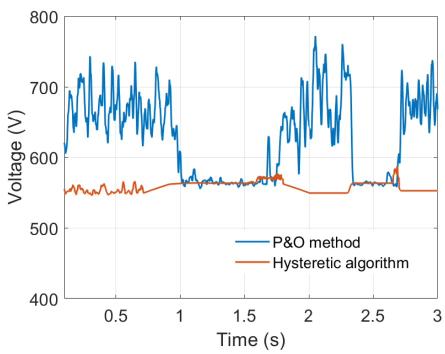

Fig. 11. The output voltage at the user load.

converter parameters exhibit in Table I. On the other hand, the hysteresis parameters values are: $a = 0.5$, $b = 0.5$ and $\alpha = 0.5$. These values were fixed by the trial and error technique.

For the first set of experiments, the conditions of temperature and irradiance of the PV array are shown in Fig. 8 and Fig. 9 respectively. The result of this experiment is depicted in Fig. 10. This highlights the fact that the proposed scheme with hysteresis has a better performance by extracting the maximum power of the PV panel. Although there is a transitory time where the power oscillates, after this, the quality of the generated PV power is better.

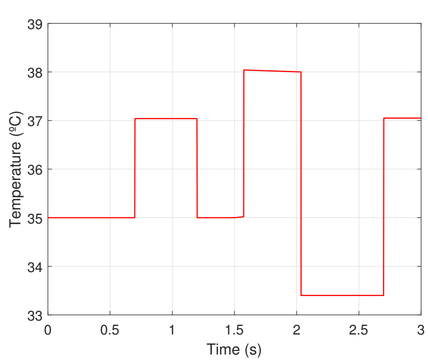

Fig. 12. Fast environmental temperature variation.

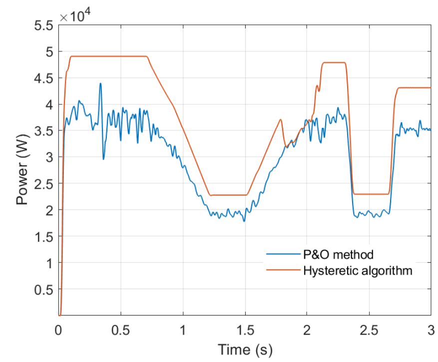

Fig. 13. The output generated PV power.

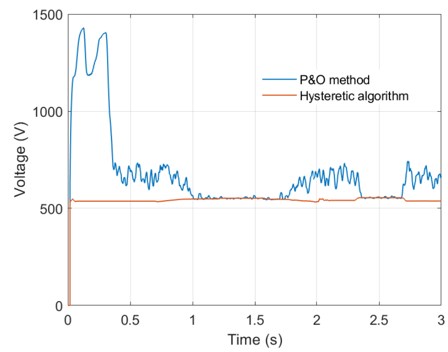

Fig. 14. The output voltage at the user load.

Besides, it is notable that the value of the maximum power is achieved, according to the curves presented in Fig. 7. On the other hand, in the case of the P&O method, the power is constantly oscillating and it is due to the nature of the algorithm and the maximum power point is not achieved. In addition, Fig. 11 gives the output voltage of the Boost converter. This voltage is important since is the one supplied to the load. The features that has to have this voltage depend on the application, but in general, it is expected that the output voltage is stable without abrupt changes. Fig. 11 shows that the output voltage obtained with our method does not have abrupt changes and the quality of this signal is better than the one obtained by employing the conventional P&O method.

Additionally, another experiment was realized by programming the temperature with fast changes as is shown in Fig. 12, and the employed irradiance is the same than in the previous experiment. The generated output PV power is depicted in Fig. 13. In this figure, just like in the previous case, the maximum power extracted by invoking the proposed algorithm is higher and with better quality than the one obtained with the Perturb and Observer method. Besides, the output voltage, in Fig. 14, provided with the hysteretic algorithm also has a notable better performance since the voltage generated by using the P&O algorithm presents a high overshoot and a long transitory time. Finally, one more experiment was implemented by using the same

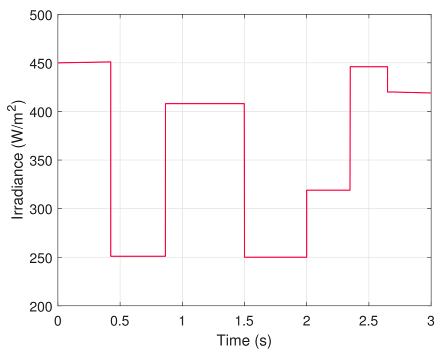

Fig. 15. Fast environmental irradiance variation.

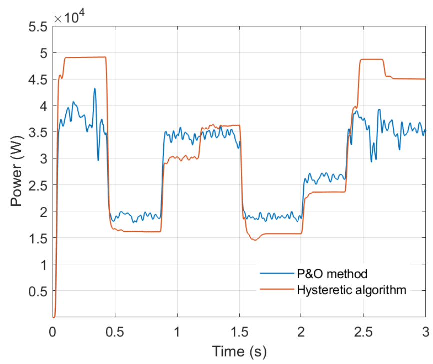

Fig. 16. The output generated PV power.

temperature profile given in Fig. 12. Moreover, in this case the irradiance was computed with fast changes as is shown in Fig. 15. This is an important validation since these phenomena are very common in PV systems, for instance, these abrupt changes may be provoked by fast shading conditions. Hence, an acceptable MPPT algorithm has to be capable to deal with the perturbations in the PV panel. The result of this numerical experiment is presented in Fig. 16. In this figure it is possible to observe that the power extracted by employing our proposal is not the higher one on each level. Nevertheless, the power extracted by invoking the hysteresis MPPT algorithm has better quality which is a significant characteristic required by the PV systems in general.

5. Conclusions

In this paper was proposed a scheme where the MPPT algorithm is based on a dynamic hysteretic model. The characteristics of the dynamic hysteresis applied to an MPPT algorithm allowed to obtain, in most cases, the maximum efficiency of the PV panel. Moreover, the quality of the PV generated power is remarkable in comparison to the power produced by employing the standard P&O method. On the other hand, the numerical experiments were realized by invoking an inductive load in order to perform a reality PV systems implementation. The experimental results motivate future work on real applications where the user load require specific conditions of the voltage provided by the PV panel. Finally, numerical experimental validation employs fast changes in the irradiance, which may emulate fast shading conditions in the PV panel. To the best knowledge of the authors, this is a current and prevalent objective in the field of maximum power seeking in photovoltaic systems.

Acknowledgments

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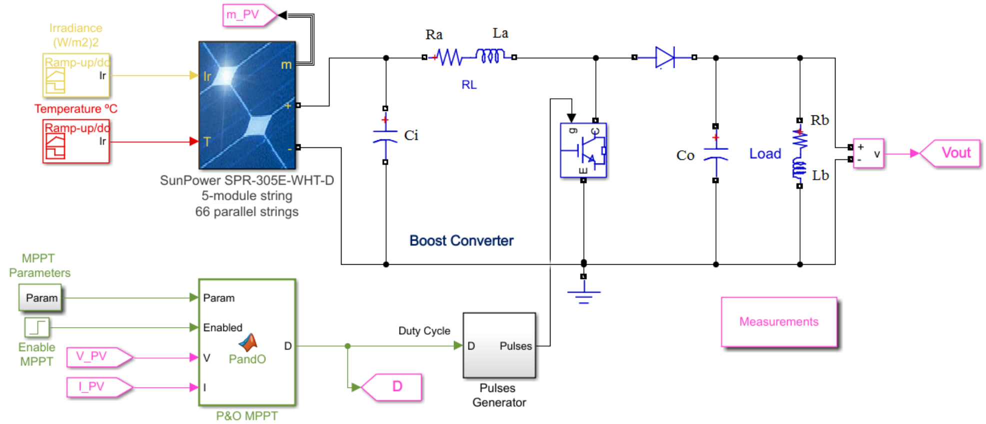

Fig. 17. PV system by employing Perutb and Observer algorithm.

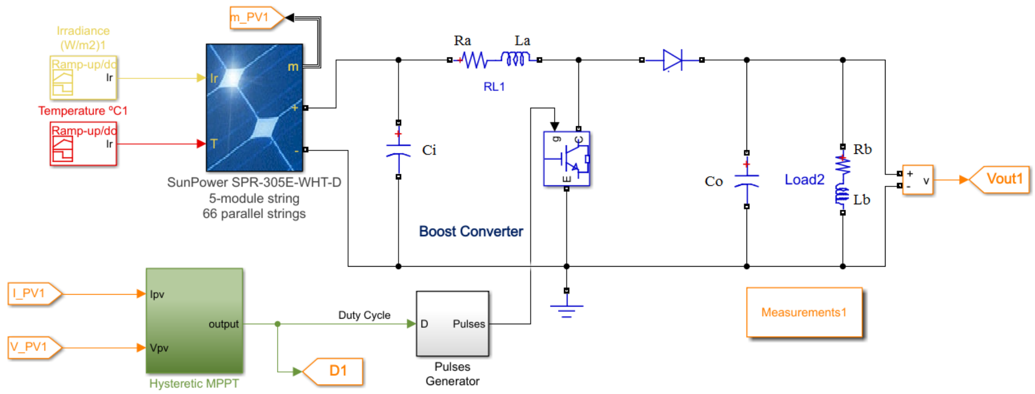

Fig. 18. PV system by employing the hysteretic MPPT algorithm.

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