Modular Photovoltaic Generation Systems Based on a Dual-Panel MPPT Algorithm

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***Abstract*-- In this paper a modular structure for grid-connected photovoltaic generation systems is presented. The basic generation unit consists in a quasi-parallel connection of two PV panels, with a dedicated buck-boost (or fly-back) PWM converter. The chopper input voltage, i.e., the PV panels' voltage, is regulated according to a novel MPPT algorithm, based on a forced small displacement in the working points of the PV panels. Outputs of the several generation units are parallel connected to the dc-bus of a standard active power filter, linked to the electric network. The grid-inverter regulates the dc-bus voltage to a proper fixed value, injecting the power coming from the units into the mains. Each generation unit works as a stand-alone converter, i.e., signal connections among the units or between each unit and the main active filter are not required.**

I. Introduction

Solar energy is the most available source for renewable energy. As it is known, photovoltaic (PV) generation of electricity, using semiconductor technology, depends not only on solar irradiation but also on temperature of the PV cells. Since the cost of the electric energy from PV panels is still high, the scientific community is working for maximizing the PV conversion efficiency. In recent years the PV conversion efficiency have been increased of about 10% by cooling the PV cells by an hybrid electro-thermal solar panel system [1]. Mechanical trackers have been also adopted to provide the maximum irradiation on panels but they are quite expensive and rather unreliable.

Maximum power point trackers (MPPT) are electrical devices acting in order to force the operating point of the panel on its peak power. There are many studies dealing with MPPT and introducing different strategies for following the peak power point [2]. The "perturbation and observation" method (P&O) uses a simple feedback topology and operates in a manner that it is periodically incremented the array voltage; if the array power decreases the opposite perturbation is applied and so the peak power is continuously tracked [3]. The "incremental conductance" method determines the slope of the PV panel's characteristic and calculates the direction of MPP [4]. Methods such as the "ripple correlation control" can be applied to both small- and large-scale PV generation systems [5], [6]. There are also other methods like "pilot-cell" method [7], "fuzzy control" [8] etc.

Nowadays, PV systems can be realized by using module-integrated converters (MIC), with ac [9] or dc [10] output voltage, leading to some advantages when compared to centralized systems. In fact, module integration helps to eliminate the losses of centralized MPPT since each panel uses its own converter. Furthermore, it is flexible in changes of the overall power level, reducing both the development time and the whole system cost.

The solution proposed in this paper is based on a modular scheme in which each generation unit consists in a quasi-parallel connection of two PV panels and a single dc/dc converter (buck-boost or fly-back). All the units are directly connected in parallel to the dc-bus of the grid inverter, acting as an active filter, according to the block diagram of Fig. 1.

In particular, the proposed MPPT scheme does not require the calculation of the instantaneous power. In order to do this, operating points of the two PV panels are kept slightly different from each other, allowing sharing of data between them on the basis of instantaneous currents measurement. In this way, the MPPT algorithm is able to estimate the position of the operating point with respect to the MPP without the need of multiplications for power calculation. Furthermore, the need of memory operations is prevented as well.

The proposed scheme enforces cost competitiveness and compactness of the size, allowing a simple analog circuit implementation. Note that a single dc chopper for both the PV panels of each generation unit is adopted in this paper, whereas the similar solution presented in [10] requires a double dc chopper to drive the dual-panel generation unit.

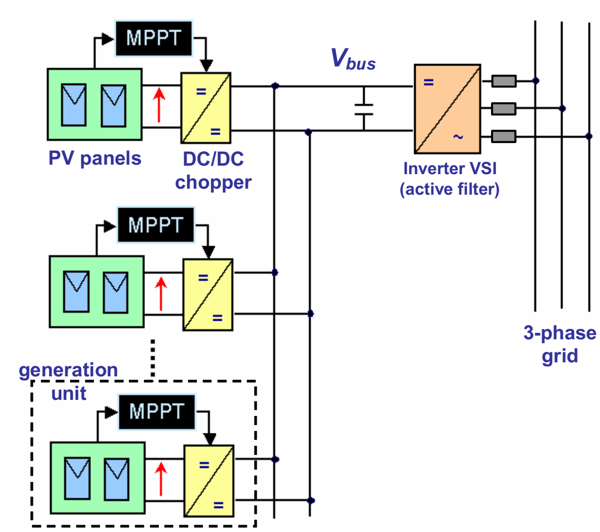

Fig. 1. Block diagram of the proposed PV generation system.

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II. General Description of the Generation Unit

For each generation unit, the proposed control scheme is based on the regulation of the voltage (V_{dc}) of the two quasi-parallel PV panels, in order to follow the MPP, according to the block diagram shown in Fig. 2.

The regulation of V_{dc} is obtained by means of a standard buck-boost converter (Fig. 3) considering V_{dc} as its input voltage, and the common bus voltage V_{bus} as its output voltage. Note that V_{bus} is kept constant by the grid inverter, and it can be considered as an external parameter in analyzing the buck-boost behavior.

Assuming the duty-cycle δ as the input variable and the voltage V_{dc} as output variable, the averaged dynamic behavior of the buck boost converter is represented by the block diagram of Fig. 4. As stated above, the bus voltage V_{bus} can be treated as a fixed parameter, whereas the current I_{dc} coming from the PV panels represents a disturbance. Fast and reliable numerical simulations can be carried out by means of this simplified model, and a proper tuning of both the buck-boost inductance L and the input *dc* capacitance C can be done. The values L=0.1 mH, and C=25 μF will be adopted in the following of this paper.

In steady state conditions, the relationship between the desired panels voltage V_{dc}^* and the duty cycle δ can be written as

$$\delta = \frac{V_{bus}}{V_{bus} + V_{dc}^*} \qquad (1)$$

Although (1) is non-linear, it represents a monotonic decreasing relationship between V_{dc}^* and δ, suggesting the possibility to include this block in within a control loop, avoiding the need to evaluate V_{dc}^*.

III. Principle of Operation of the MPPT Algorithm

As known, the MPP for a PV panel can be identified by introducing the derivative of the power P with respect to the voltage V as

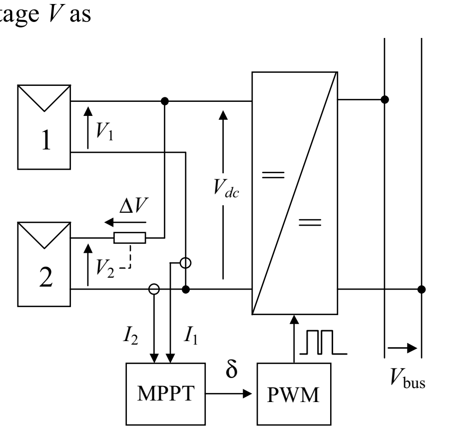


Fig. 2. Block diagram of a dual-panel generation unit.

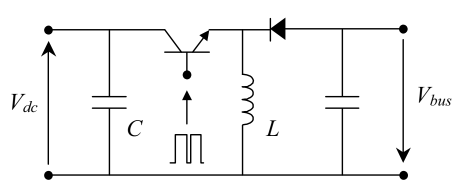


Fig. 3. Basic scheme of a standard buck-boost converter.

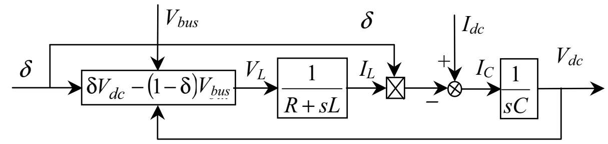


Fig. 4. Block diagram representing the averaged dynamic model of the book-boost converter.

$$\frac{dP}{dV} = 0 \, . \qquad (2)$$

The sign of dP/dV determines if the operating point is located on the left- or on the right-side of the MPP, whereas its absolute value determines the distance of the operating point from the MPP, according to the diagram represented in Fig. 5.

The solution proposed in this paper consists of determining the sign of dP/dV by considering two identical PV panels whose operating points are displaced by the small voltage drop ΔV>0, as shown in Fig. 2. In this way, the MPP condition is reached when P_2=P_1, whereas the operating point is located on the left- or on the right-side of the MPP when $P_2 > P_1$ or $P_2 < P_1$, respectively, as represented in Fig. 6. Being ΔV always positive, the sign of dP/dV can be determined as:

$$sign\left(\frac{dP}{dV}\right) = sign\left(P_2 - P_1\right) \qquad (3)$$

Introducing in (3) voltages and currents according to the scheme shown in Fig. 2, and considering the voltage drop ΔV, yields

$$sign\left(\frac{dP}{dV}\right) = sign\left((1+\frac{\Delta V}{V_1})\, I_2 - I_1 \right). \qquad (4)$$

The implementation of (4) requires at least an analog multiplier. In order to avoid this drawback, an adjustable voltage drop ΔV proportional to the PV panel voltage has been considered, $\Delta V = k' V_1$, yielding to

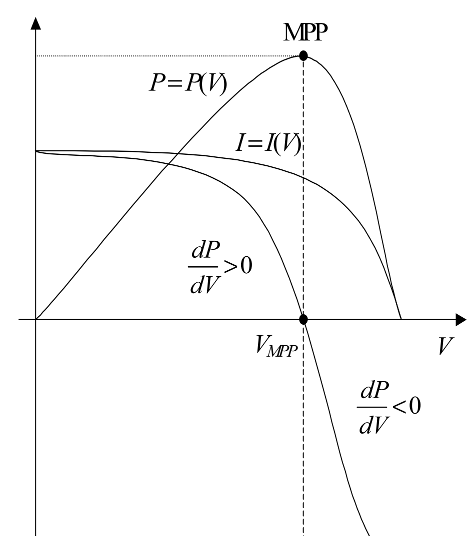


Fig. 5. Current I, power P, and power derivative dP/dV as function of the PV voltage.

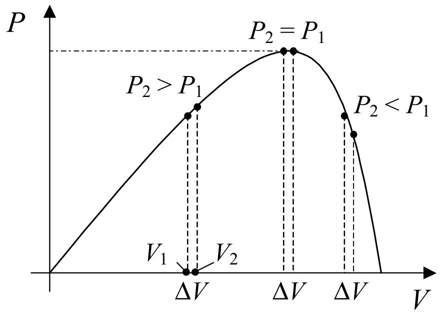


Fig. 6. Operating points of the panels displaced by the voltage drop ΔV.

$$sign\left(\frac{dP}{dV}\right) = sign\left((1+k')\,V_1 I_2 - V_1 I_1\right) = sign\left(I_2 - kI_1\right) \quad (5)$$

being $k = 1/(1+k')$. In this way, it is possible to determine the position of the operating point with respect to the MPP by the estimation of $sign(I_2 - kI_1)$, without the need of multiplications for power calculation.

Since $I_2 - kI_1$ represent a monotonic increasing function of dP/dV, it can be used within a control loop instead of dP/dV to determine the reference panels' voltage V_{dc}^*. Taking into account the inverse relationship between V_{dc}^* and δ expressed by (1), the buck-boost converter can be directly driven toward the MPP by the duty-cycle resulting from a simple PI regulator $K_p + K_i/s$ as shown in Fig. 7.

The qualitative relationship between the power generated by the PV unit and the duty-cycle δ is represented in Fig. 8, where the value $\delta = \delta_{min}$ corresponds to open circuit ($V = V_{oc}$) and the value $\delta = 1$ correspond to short circuit ($V = 0$).

Note that the regulator requires only the measurement of the currents I_1 and I_2, whereas the constant parameter k can be determined by a preliminary tuning of the scaling factor of the current I_1.

The voltage drop ΔV, i.e., the value of k' ($\Delta V = k' V_1$), should be chosen greater enough to handle sufficient signal amplitudes and for compensating the small differences between the *I-V* characteristics of the two PV panels. On the other hand, too large values of ΔV determine a large displacement of the steady-state operating points of the PV panels with respect to their MPP (see Fig. 6) and unacceptable additional power losses ($\Delta P = I_2 \Delta V$).

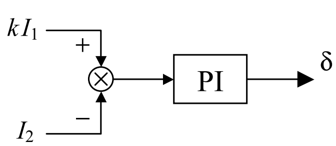


Fig. 7. Simple block diagram for generating the duty-cycle δ.

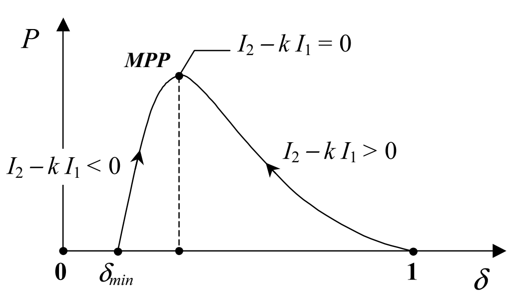


Fig. 8. Relationship between the PV power and duty-cycle.

IV. Results

The proposed modular generation system has been implemented by considering a couple of Shell SQ150-C photovoltaic solar modules. The main electrical characteristics are given in Table I. For the numerical tests, the *I-V* panels characteristics have been fitted by using a modified single exponential model [11], [12], leading to the curves depicted in Figs. 9 (a) and (b).

The model has been implemented in the Simulink environment of Matlab and a complete set of simulation results has been carried out to emphasize the dynamic performance of the proposed MPPT algorithm. The main system parameters are shown in Table II.

TABLE I
SHELL SQ150-C: DATA AT STANDARD TEST CONDITIONS
(*irrad. level 1000 W/m², spectrum AM 1.5, cell temp. 25°C*)

Open circuit voltage	V_{OC}	43.4 V
Short circuit current	I_{SC}	4.8 A
Peak power	P_{MPP}	150 W
Peak power voltage	V_{MPP}	34 V
Peak power current	I_{MPP}	4.4 V
Temperature coefficients:	$\alpha\, P_{MPP}$	-0.45 %/°C
	$\alpha\, V_{MPP}$	-152 mV/°C
	$\alpha\, I_{SC}$	+2m A/°C
	$\alpha\, V_{OC}$	-152mV/°C

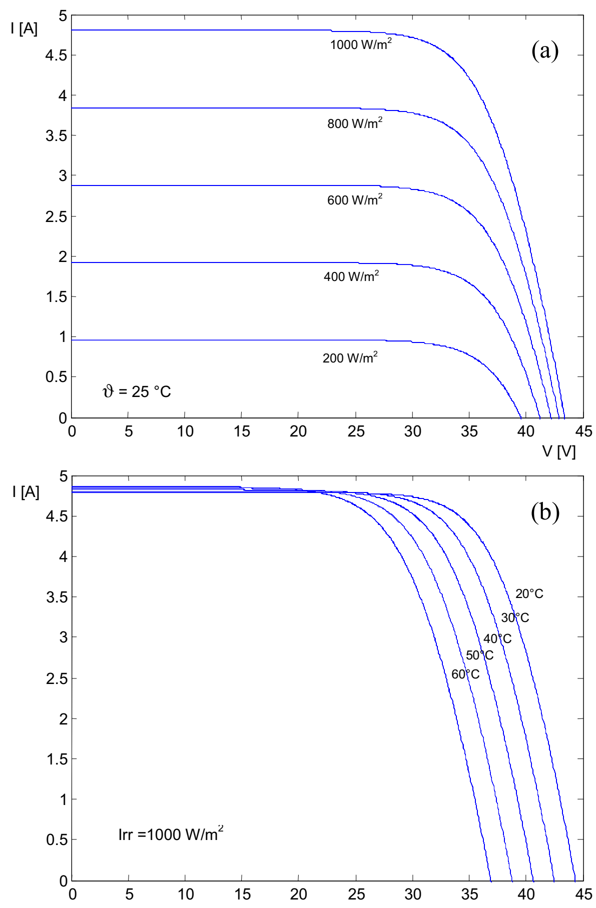


Fig. 9. Modeled *I-V* characteristics of the SQ150-C solar module:
(a) for different irradiance levels;
(b) for different cell temperatures.

In all the following diagrams, reference is made to the electric parameters of the PV panel #1, i.e., V_1, I_1, P_1. The corresponding parameters of the PV panel #2 are rather redundant and they are not shown.

The start-up transient of a generation unit is firstly analyzed. In particular, the control signal is applied to the buck-boost starting from the open circuit condition (V_1=V_{OC}), leading to the voltage and the current waveforms depicted in Fig. 10. It can be noted that the MPP condition is reached with a smoothed transient in less then 100 ms. The settling time can be handled by adjusting the parameter of the PI regulator shown in Fig. 7.

In Figs. 11 and 12 a solar irradiance transient and a cell temperature transient are separately considered, whereas in Figs. 13 a combined irradiance-temperature transient is presented. In all cases, both the time behaviors of voltage and current, and the operating point trajectory on the *P-V* plane are shown with reference to linear transients having rise and fall times of 50 ms.

In particular, Figs. 11 show a transient between the solar irradiances 1000 W/m^2 and 500 W/m^2 at the constant cell temperature of 25 °C. In Fig. 11(a) the PV panel voltage V_1 is zoomed in to emphasize the small voltage variations. Note that both the voltage and the current reach the steady-state condition corresponding to the MPP in about 50 ms without appreciable oscillations. Fig. 11(b) shows that the rise and the fall trajectories in the *P-V* plane practically coincide.

Figs. 12 show a transient between the cell temperatures 60 °C and 25 °C at the constant solar irradiance of 1000 W/m^2. The current I_1 in Fig. 12(a) is zoomed in to emphasize the small PV current transient. Also in this case, both the voltage and the current reach the steady-state condition corresponding to the MPP in about 50 ms with a smoothed transient. Fig. 12(b) shows a small displacement between the rise and the fall trajectories on the *P-V* plane.

A combined irradiance-temperature transient between the values (1000 W/m^2, 60 °C) and (500 W/m^2, 25 °C) is presented in Figs. 13. In this last case, Fig. 13(a) shows that the operating point reaches the new *I-V* characteristic in about 50 ms, and the MPPT algorithm takes less then 100 ms to drive the operating point to the new MPP. For this reason, the rise and the fall trajectories in the *P-V* plane follow a different path, as shown in Fig. 13(b).

V. Different I-V Characteristics of PV panels

In practical applications, the *I-V* characteristics of the two PV panels slightly differ one from the other, despite of the same commercial model is chosen from the same factory. As an example, experimental investigations on a set of nine Shell Solar SQ150 PV panels have been performed. The results have shown that, close to the standard test conditions (see Table II), the short circuit currents, I_{SC}, practically coincide, whereas the open circuit voltages, V_{OC}, are collected within a range of about 0.5 V (a similar range has been found for the MPP voltage).

In order to account for the *I-V* characteristics mismatch, it has been verified that, for a correct behavior of the MPPT regulator, the voltage drop ΔV should exceed twice the difference between the open circuit voltages of the two PV panels (absolute value).

With reference to Shell SQ-150, it has been found that a voltage drop ΔV = 1.2 V (k' = 0.04) guarantees good performances for any random combinations of two PV panels belonging to the testing set.

Table II
Main System Parameters

Buck-boost inductance	L	0.1 mH
Equivalent series resistance	R_L	31 mΩ
Voltage drop coefficient	k'	0.01
PI proportional gain	K_p	1
PI integral gain	K_i	50
Output dc voltage	V_{bus}	80 V
Switching frequency	f_S	10 kHz

VI. Conclusion

This paper shows that it is possible to build a modular generation structure suitable for grid-connected photovoltaic generation systems by introducing a dual-panel configuration with an embedded MPPT algorithm.

A single buck-boost converter is utilized to drive the operating point of the two PV panels toward the MPP. A fly-back converter can be adopted as well, in the case an electrical isolation and/or a high voltage transfer ratio is required.

The proposed MPPT algorithm, based on a forced small displacement in the working points of the PV panels, shows good dynamic performance despite of the simplicity of its hardware implementation. In particular, the whole control system of each generation unit (two PV panels plus one buck-boost converter) can be realized with standard analog circuitry, avoiding the need of memories and multipliers.

Each generation unit works as a stand-alone unit, i.e., signal connections among the units or between each unit and the grid inverter are not required, improving reliability and flexibility of the whole PV generation system.

A complete set of realistic numerical simulations carried out by means of the Simulink tool of Matlab is given

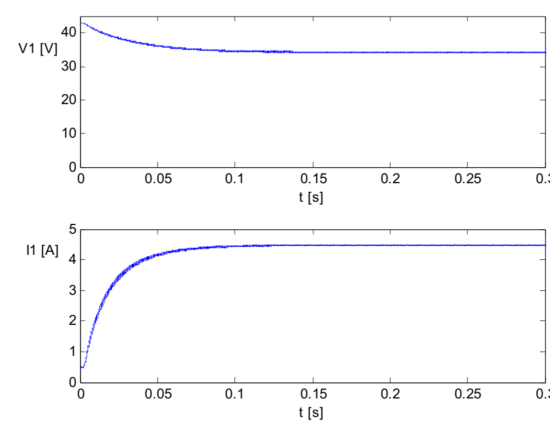
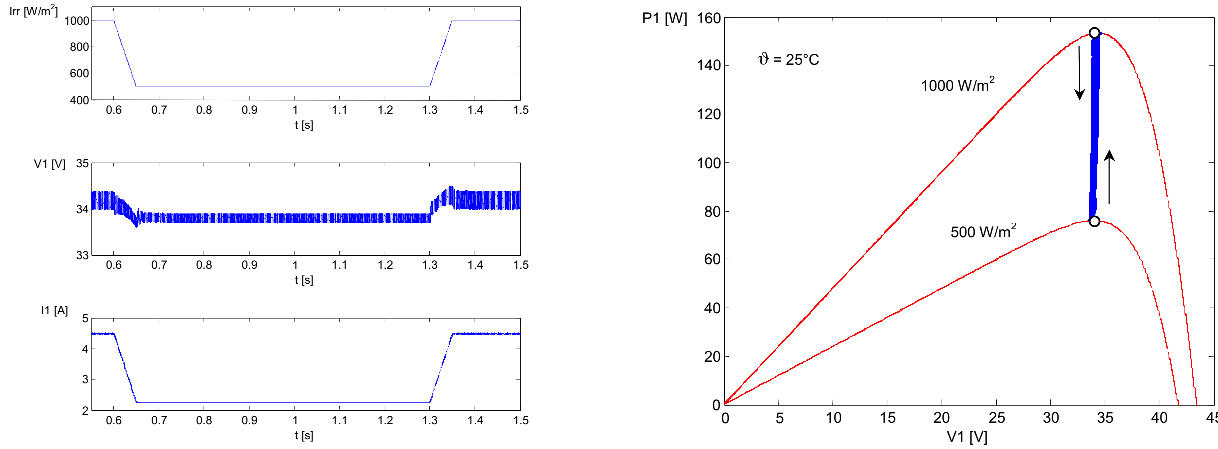
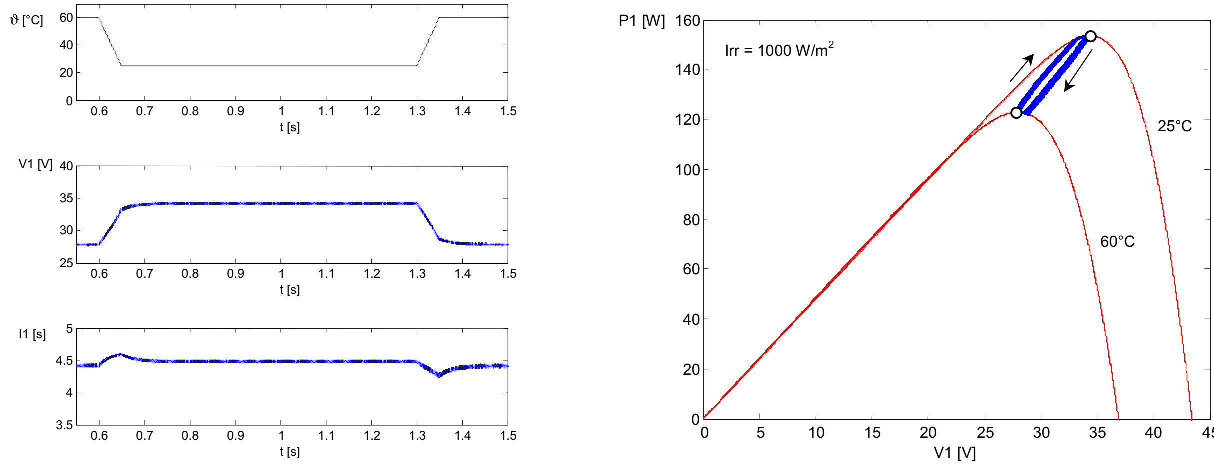


Fig. 10. Voltage and current waveforms during the start-up of the MPPT algorithm (Irr = 1000 W/m^2, ϑ=25 °C).



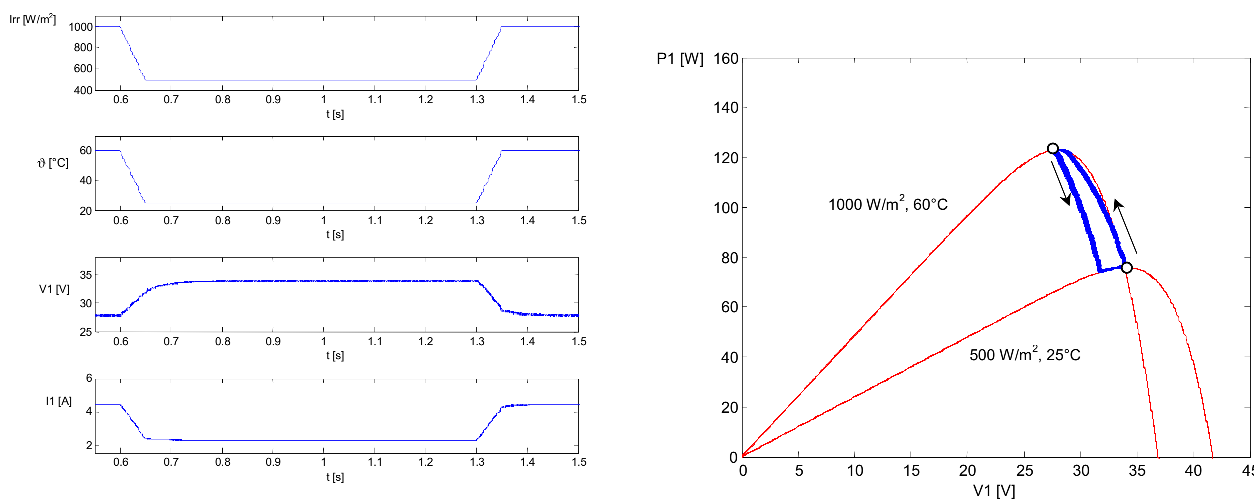
(a) (b)

Fig. 11. Irradiance transient at constant cell temperature: (a) irradiance, voltage, and current waveforms, (b) trajectory on the *P*-*V* plane.



(a) (b)

Fig. 12. Temperature transient at constant solar irradiance: (a) temperature, voltage, and current waveforms, (b) trajectory on the *P*-*V* plane.



(a) (b)

Fig. 13. Combined irradiance-temperature transient: (a) irradiance, temperature, voltage, and current waveforms, (b) trajectory on the *P*-*V* plane.

in the paper. The effectiveness of the MPPT algorithm has been proven also in presence of a practical mismatch in the *I*-*V* characteristics of two commercial PV panels.

Preliminary experimental tests on a generation unit prototype confirm the good static and dynamic performances of the proposed PV generation system.

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