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New MPPT method for stand-alone photovoltaic systems operating under partially shaded conditions

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ABSTRACT

A new method to track the global maximum power point (GMPP) under partially shaded conditions (PSCs), for stand-alone photovoltaic (PV) systems, is introduced. Two loads, static and dynamic, have been used to evaluate the effectiveness of the method under different PSCs. Simulation results show that the developed method guarantees convergence to the GMPP under different PSCs and provides fast convergence in rapid variation of insolation conditions. To assess the performance of the developed algorithm, a comparison between two algorithms recently published has been carried out. It is shown that the developed method outperforms other methods found in literature both in terms of efficiency (95.80% and 95% for static and dynamic load) and response time (less than 0.25 s). Negligible oscillations around the MPP and easy implementation are the main advantages of the proposed method.

1. Introduction

Among the available renewable sources, solar energy is one of the most promising nowadays. The International Energy Agency (IEA) [1] estimates that by 2050, photovoltaics (PV) will provide around 11% of global electricity production and would avoid 2.3 Gt of CO_2 emissions per year. PV arrays have the advantage of directly converting light energy into electrical energy through semiconductors [2]. However, the low energy conversion efficiency of PV cells remains a barrier to the prolific growth of solar electricity and necessitates tracking the maximum power point (MPP) of the PV arrays to ensure harvesting the maximum possible energy.

PV cell has a highly nonlinear I–V characteristic varying with the irradiance and temperature. Under uniform insolation conditions, the P–V characteristic presents a unique point, the so-called the Maximum Power Point (MPP), in which the PV array operates with maximum efficiency and produces maximum output power. As the I–V characteristics of a PV vary with irradiation, under non-uniform insolation conditions, it is possible to have multiple local MPP and only one global MPP for the entire array. The non-uniform insolation occurs quite frequently due to clouds and shadowing from various items (leaves, electric poles) and from neighboring buildings.

Partially shaded PV modules typically exhibit additional difficulties in tracking the GMPP (global maximum power point). The operating point of the PV system tends to converge to a local MPP (most traditional MPPT algorithms converge to local maximum), which is not the global maximum output point on the P–V curve. Therefore, the power produced by photovoltaic systems is significantly reduced as well as the efficiency of the MPP tracking algorithm. In order to solve this problem, the issue of Partial Shading Conditions (PSC) has been addressed in different ways in literature. For example, a two-stage MPPT control method has been proposed by Kobayashi et al. [3], the first one moves the operating point to the vicinity of the real peak MPP to avoid converging to the local MPP and then the second one uses the dV/dI control algorithm. This method is rapid (response time = 0.3 s) and accurate, but it requires many sensors.

Karatepe et al. [4] estimated the equivalent circuit parameters of different irradiated modules in a PV array by using an Artificial Neural Network (ANN). The designed ANN-model is used to characterize the partially shaded PV module. The proposed model can provide sufficient degree of precision as well as solar cell-based analysis to control large-scale systems. However, the disadvantage of this method is that, the NN model should be trained periodically in order to ensure the convergence to the accurate MPP.

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Nomenclature

Terminology

ANN	Artificial Neural Network
DC motor	direct current motor
GA	genetic algorithm
IncCond	incremental conductance
MPPT	maximum power point tracking
MPP	maximum power point
PSC	partial shading condition
PV	photovoltaic
PVG	photovoltaic generator
PWM	pulse width modulator
STC	standard test conditions
SIF	shade impact factor

Symbols

G	irradiation (W/m^2)
I^*	output reference current (A)
I_{cc}	short-circuit current (I)
I_{PVK}	measured currant (A)
k_a	the armature constant
P_M	global maximal power point (W)
P_{PVK}	measured power (W)
R	Resistance (Ω)
R_a	resistance of armature (Ω)
T	Temperature (°C)
V^*	output reference voltage (V)
V_M	voltage at the global maximal power point (V)
V_{oc}	open-circuit voltage (V)
V_{PVK}	measured voltage (V)
W_A	weight function (1/V)
W_B	weight function (1/A)
w_m	the motor speed (rps)
$Z(s)$	transfer function of the battery

Greek

Φ	magnetic flux per pole (Wbr)

Ahmed and Miyatake [5] proposed a method using Fibonacci search algorithm to realize a simple control scheme that tracks the real MPP under PSCs. The Fibonacci search technique is similar to the Perturb and Observe (P&O) and hill climbing techniques and it was modified in order to apply it to the time-variant *P*–*V* characteristics of PV array. A new initialization function was introduced to start the search condition when sudden or partial changes in insolation are detected and carry out a wide search, which leads to the real MPP. However, this method does not ensure the convergence of the GMPP in some partial shadowing conditions.

A power compensation system for PV arrays for complicated non-uniform insolation conditions is developed by Karatepe et al. [6]. The proposed system uses DC–DC converters on each PV string in the PV array and enables the non-shaded PV modules to operate effectively at their normal maximum power point. The effectiveness of the proposed system is investigated and confirmed for complicated partially shaded PV arrays. However, power stage complexity and cost are increased in this technique. A new topology to reduce the effect of shading on the performance of individual photovoltaic modules is proposed by Ubisse and Sebitosi [7]. The proposed topology has been investigated in rural sub-Saharan Africa. It has been observed that, the impact of shading and staining on photovoltaic installations results in massive losses in the energy yield and can cause module damage as well.

Ji et al. [8] designed an MPPT algorithm based on the conventional incremental conductance (IncCond) with step-size variation. The step size is increases when the slope of the *P*–*V* characteristic curve exceeds a predetermined value, and it decreases again when the slope of power-voltage characteristic curve is less than the predetermined value. This algorithm uses a simple linear function for tracking the MPP under PSCs without any additional circuit. The step-size variation technique is applied to minimize the energy loss due to the oscillation in vicinity of MPP, as well as to improve the dynamic performance at rapid changes in irradiance level.

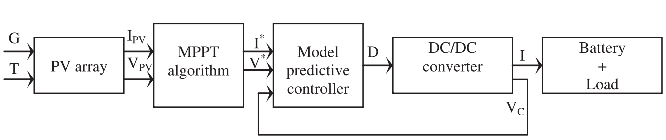

Fig. 1. The block diagram of a stand-alone PV system with MPPT controller.

Carannante et al. [9] made a comparison between measured power and the instantaneous maximum power reference value. For the shape of the *P*–*I* curve, two alternative fields can be determined. In the first field, the algorithm search the current of the MPP, by decreasing the measured current and imposing the operating current, while in the second field, the procedure is employed by imposing the actual current. This method is rapid but its implementation is complex.

Syafaruddin et al., [10] used a Radial Basis Function Neural Network (RBFNN) to estimate the global operating voltage in PV systems. The simulation results show that there is a significant increase of about 30–60% of the extracted power in one operating condition when the proposed method is able to shift the operating voltage of modules to their optimum values. However, the main disadvantage of this method is that considerable computational effort is required during the neural network training in order to ensure that the global MPPT process tracks the GMPP under PSCs, and the required data are often not available.

A Matlab-based modeling and simulation scheme suitable for studying the *I*–*V* and *P*–*V* characteristics of a PV array under a non-uniform insolation due to partial shading is developed by Patel and Agarwal [11]. Chen et al. [12] presented a novel MPPT method based on biological swarm chasing behavior to increase the MPPT performance. This method is only applicable when the entire module is under uniform insolation conditions, hence PSC is not considered. Villa et al. [13] made an exhaustive study of the available interconnections among the modules of a shaded photovoltaic field. A relationship between the interconnections of the PV modules and their power output is proposed through empirical connection laws.

Miyatake et al., [14] attempted to approach the GMPP using the particle swarm optimization (PSO) algorithm. The authors tried to realize a centralized MPPT control of the modular (multi-module) power generation system (PGS). These MPPT algorithms have good performance under various PSC; however, these methods are only suitable for systems that consist of multiple converters. Therefore, this system is not suitable for PGS, which commonly use one central high-power single-stage electronic converter for economical reasons and the relative simplicity of the overall system. A PSO-based MPPT algorithm for PGS operating under PSC is proposed by Liu et al. [15]. According to the authors, PSO-based method is a good candidate for MPPT algorithms under PSCs. The same technique

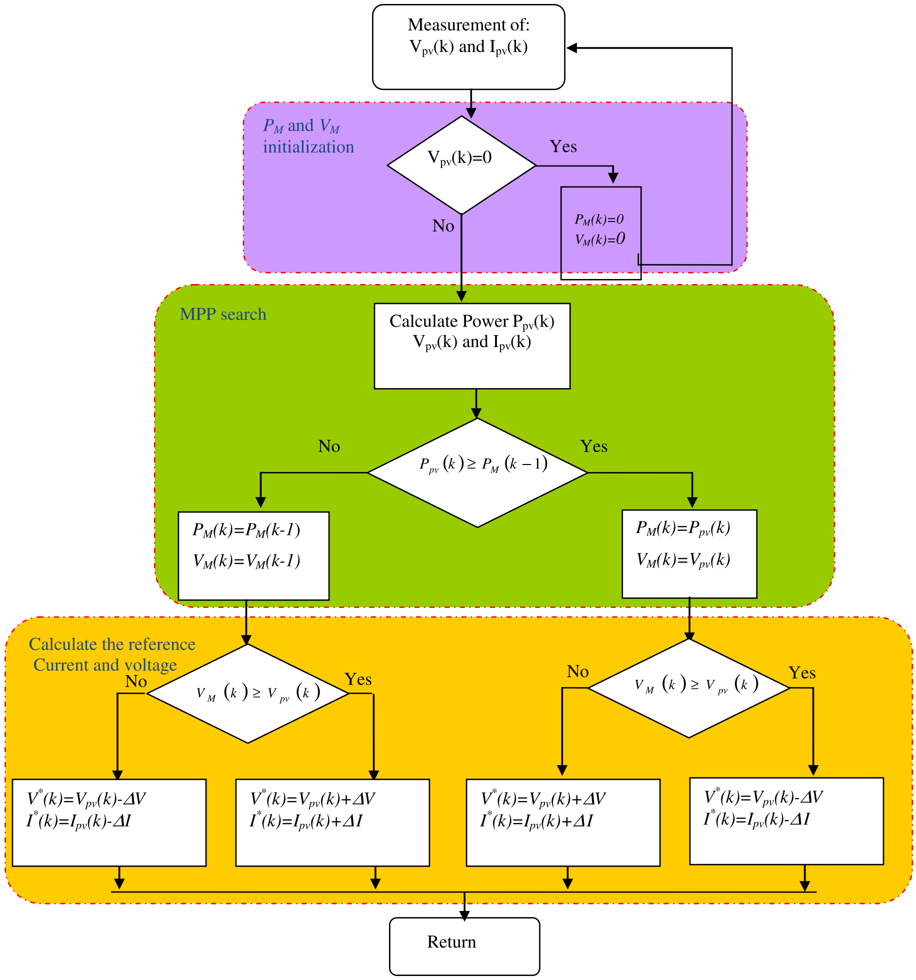

Fig. 2. Flowchart of the new MPPT algorithm.

(PSO) is also used by Ishaque et al. [16], in which a direct duty cycle control method is used instead the PI control loops. For the 10 h (daytime) irradiance and temperature profile, it yields an average MPPT efficiency of 99.5%.

Chowdhury and Saha [17] used an adaptive perceptive particle swarm optimization (APPSO)-based MPPT algorithm. However, PSO-based MPPTs exhibit significant algorithmic complexity, which increases the implementation cost of the GMPPT control system.

Koutroulis and Blaabjerg [18] developed a new method to track the GMPP, based on controlling a DC–DC converter connected at the PV array. The experimental results verify that the proposed global MPP method guarantees convergence to the GMPP under any PSCs.

Recently, a modified fuzzy-logic-based MPPT has been proposed to extract the GMPP under partially shaded PV system conditions [19]. The controller offers accurate convergence to the global maximum operating point under different PSCs. The results of the proposed MPPT exhibit a faster converging speed, less oscillations around the MPP under steady-state conditions, and no divergence from the MPP during varying weather conditions.

Finally, other methods developed are based on the modeling of the photovoltaic cell circuit parameters to determine the optimum connection and configuration of PV cells [20–22].

As can be understood from the above literature review, various methods of MPP tracking with PSC have been developed which vary in complexity, sensor requirement, speed of convergence, cost, range of operation, and ability to detect the GMPP under different PSCs. Hence, it is necessary to develop a method by taking into account the guarantee of convergence to the GMPP, accuracy and simplicity, i.e., feasibility to be implemented into programmable devices such as microcontroller, FPGA for real time applications, or dSPACE [23].

Therefore, in this paper, a new method to track the global MPP under different PSCs has been introduced. It combines a simple search algorithm with a model predictive control technique. Two loads static (resistive) and dynamic (DC motor) have been investigated in order to examine its potential to track the GMPP under different PSCs. To prove its performance, the introduced algorithm is then compared with two MPPT algorithms recently published in Refs. [8,19]. The designed algorithm is simulated and tested under Matlab/Simulink software.

2. Proposed method

A method is developed to track the global MPP under partially shaded conditions for stand-alone photovoltaic systems. It combines a new simple MPPT algorithm and the Model Predictive Controller (MPC) described in Refs. [24,25]. The block diagram of a stand-alone PV system with MPPT controller is depicted in Fig. 1. The MPPT algorithm aims to calculate the reference current I^* and voltage V^* that are used as input to the MPC and this is expected to improve photovoltaic system utilization efficiency under continuous changes in solar radiation overcoming disturbances and uncertainties.

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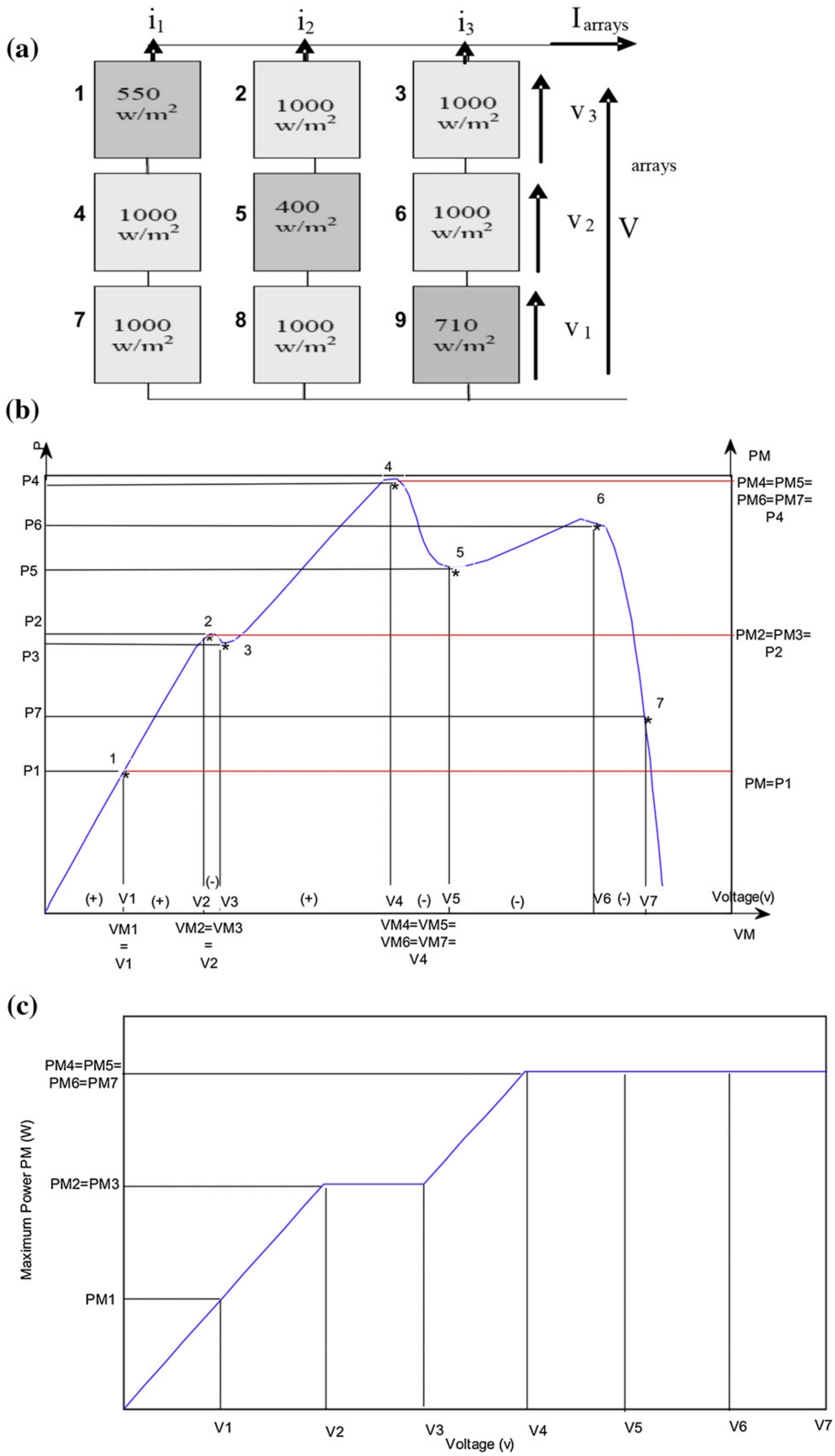

Fig. 3. (a) Photovoltaic array configuration used in this simulation study. (b) P–V characteristics of the PV array under non-uniform insolation conditions. (c) Maximum power point variation versus voltage.

2.1. Maximum power point tracker algorithm

The new MPPT algorithm is depicted in the flowchart shown in Fig. 2. Initially, when the simulation starts ($V_{pv} = 0$ V), the maximum power (P_M) is set to 0 W, and the maximum voltage (V_M) at this power is set to 0 V. Then, the PV array is simulated to obtain the values of the PV array current, voltage and power for the kth instant. Subsequently, a comparison between the actual power $P_{pv}(k)$ and the previous maximum power $P_M(k-1)$ is made to track the actual maximal power $P_M(k)$ and its voltage $V_M(k)$. If the actual power $P_{pv}(k)$ is superior to the previous maximum power $P_M(k-1)$, the actual maximum power $P_M(k)$ is equal to actual power $P_{pv}(k)$, otherwise the actual maximum power $P_M(k)$ maintains its original value. Finally, the algorithm calculates the reference current and voltage ($I^*(k)$, $V^*(k)$) by making a comparison between the measured voltage $V_{pv}(k)$ and the voltage at the maximum power $V_M(k)$. The reference outputs are defined as the increment of the PV system current and voltage measurements ($I_{pv}(k)$, $V_{pv}(k)$).

A detailed application example of the proposed algorithm for three-peak power, i.e., two local maximums and one global maximum that could occur in the P–V characteristic follows.

Fig. 3(a) shows a schematic diagram of the PV array employed which consists of three strings connected in parallel; each string has three PV modules connected in series. As depicted in Fig. 3(a), the diagonal PV modules 1, 5 and 9 receive non-uniform insolation levels of 550 W/m^2, 400 W/m^2 and 710 W/m^2 respectively, while the rest PV modules receive uniform insolation of 1000 W/m^2.

A few points from the P–V curve have been selected in order to test the algorithm. Fig. 3(b) shows the selected points with their coordinates ($P_{pv}(k)$, $V_{pv}(k)$, $P_M(k)$, $V_M(k)$) as well as the operation of references outputs [increment (+) or decrement (−)].

Thus, the calculation method of the GMPP is given as:

Case V of 0: PM0 = 0; VM0 = 0;
V1: if P1 > PM0 then PM1 = PM1; VM1 = VM1; end
V2: if P2 > PM1 then PM2 = PM2; VM2 = VM2; end
V3: if P3 < PM2 then PM3 = PM2; VM3 = VM2; end
V4: if P4 > PM3 then PM4 = PM4; VM4 = VM4; end
V5: if P5 < PM4 then PM5 = PM4; VM5 = VM4; end
V6: if P6 < PM5 then PM6 = PM5; VM6 = VM5; end
V7: if P7 < PM6 then PM7 = PM6; VM7 = VM6; end
End

More details about the developed algorithm are reported in the Appendix.

Fig. 3(c) shows the maximum power variation versus the photovoltaic voltage. As it can be observed the maximum power increase until the first local maximum (PM2) is detected, and then it remains at this value (V2 = V3), subsequently it increases again until the global maximum power (PM4) is reached and stabilizes at this point (V4 = V5 = V6 = V7).

2.2. Predictive controller implementation

The model predictive controller (MPC) used in this study was originally implemented by Kakosimos and Kladas [24] and it is based on the converter model. With respect to DC–DC converter topologies, the boost converter is considered as the most advantageous in this application because of its simplicity, low cost and high efficiency [24]. Fig. 4 shows a boost converter and its operating modes, which is used as the power stage interface between the PV array and the load.

The flowchart of the MPC technique, operating switch state, is shown in Fig. 5. More details about this technique can be found in Ref. [24].

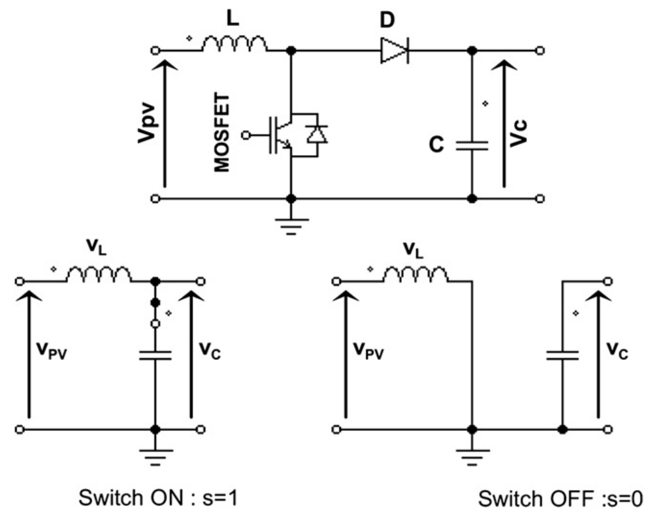

Fig. 4. Electrical circuit of the boost converter and its operating mode.

3. Method and results

In order to test the performance of the proposed MPPT method under PSCs, we have combined and simulated the new algorithm presented in Fig. 2 and the MPC presented in Fig. 5 under Matlab/Simulink environment, as shown in Fig. 6.

The main parts of the system are:

- *Block 1*: Photovoltaic generator with three strings connected in parallel, each string consists of three modules connected in series. The Photovoltaic modules type is BP SX150, and its specifications are reported in Table 1. The well-known one

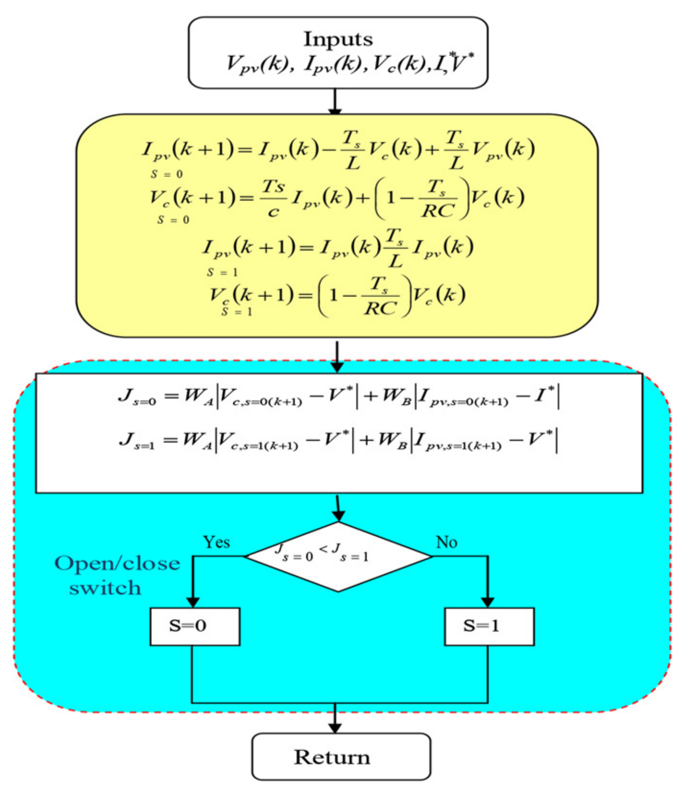

Fig. 5. Block scheme of the MPC technique operating switch state [24].

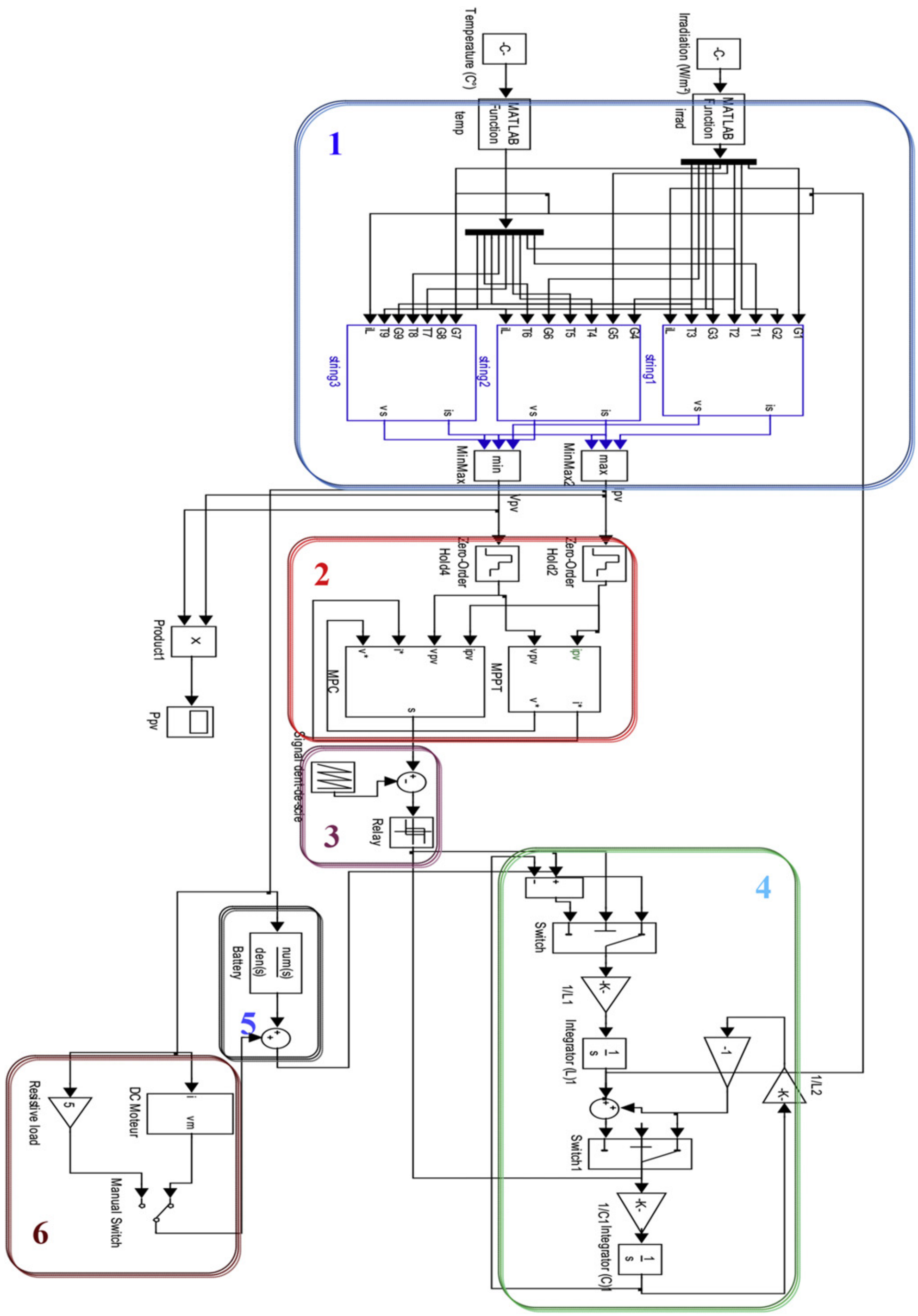

Fig. 6. Matlab/simulink block of the stand-alone PV system with MPPT method.

Table 1
PV module specifications.

Designation	BP SX150
Maximum power (P_{max})	150 W
Voltage at P_{max} (V_{PPM})	34.5 V
Current at P_{max} (I_{PPM})	4.35 A
Open-circuit voltage (V_{oc})	43.5 V
Short-circuit current (I_{sc})	4.75 A

- *Block 2*: Matlab/Simulink-based MPPT algorithm with MPC technique.
- *Block 3*: PWM signal (Pulse Width Modulation) is used to control the DC–DC converter.
- *Block 4*: DC–DC boost converter (see Fig. 4), the DC–DC specifications are reported in Table 2.

Table 2
DC/DC specifications.

Designation	Values and components
Capacitance (C)	100 μF
Inductance (L)	1.2 mH
Frequency (f)	20 kHz
Power MOSFET	IRF540
Power diode	STTA3006P/PI

- *Block 5*: A battery, an electrical model of a lead-acid battery is shown in Fig. 7 [27]. The transfer function of the battery is

$$Z(s) = \frac{900.336s^2 + 10.052s + 1.011}{3.336e^{-1}s^2 + 1.021s}$$

diode model described in Ref. [26] is used for modeling the PV module, because it requires only the available parameters.

The general form of this model is:

$$Z(s) = \frac{a_2s^2 + a_1s + a_0}{b_2s^2 + b_1s + b_0} \tag{1}$$

where:

$$\begin{cases} a_2 = R_{bs}R_{b1}R_{bp}C_{b1}C_{bp} \\ a_1 = R_{bs}R_{b1}C_{b1} + R_{bs}R_{bp}C_{bp} + R_{b1}R_{bp}C_{bp} + R_{bp}R_{b1}C_{b1} \\ a_0 = R_{bs} + R_{b1} + R_{bp} \\ b2 = R_{b1}R_{bp}C_{b1}C_{bp} \\ b_1 = R_{b1}C_{b1} + R_{bp}R_{bp} \\ b_0 = 0 \end{cases}$$

- *Block 6*: Two types of load are used:
  - Static load: resistor $R = 5\ \Omega$;
  - Dynamic load: the main equation that describes the voltage of DC motor as function of current is [28], $v = k_a w_m \Phi + R_a i$. The DC motor specifications are shown in Table 3.

Table 3
DC motor specifications.

Designation	DC motor
Resistance of armature (R_a)	0.04 Ω
The armature constant (k_a)	1368
Magnetic flux per pole (Φ)	2.63×10^{-2}Web
Motor speed (w_m)	6.67 rps

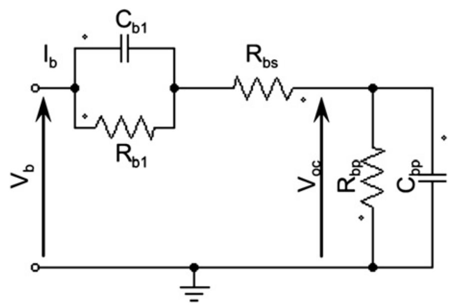

Fig. 7. Model of the battery.

To test the method a photovoltaic array with nine modules connected in series–parallel arrangement has been used. Four cases of partially shaded PV array have been examined, as reported in Fig. 8(a).

Case (a): all PV modules in the first string are shaded with non-uniform insolation.
Case (b): one PV module in each string is shaded with uniform insolation.
Case (c): one PV module in each string is partially shaded with non-uniform insolation.
Case (d): two PV modules in each string are shaded with uniform insolation.

The corresponding *P–V* characteristics for all cases are depicted in Fig. 8(b).

The response time, static error and the efficiency are used to verify the performance of the method. The tracking efficiency (η_{MPPT}) is an important parameter of an MPPT algorithm. This value is calculated as:

$$\eta_{PV} = \frac{\int_0^t P_{MPPT}(t)\mathrm{d}t}{\int_0^t P_{max}(t)\mathrm{d}t} \tag{2}$$

where PMPPT represents the output power of PV system with MPPT, and P_{max} is the output power at true MPP.

Fig. 9 shows the electrical circuit of the system. The PV generator is connected to a DC–DC boost converter, which could be easily controlled by a microcontroller-based MPPT control unit.

3.1. Non-uniform insolation

The results of the case (c) are presented here whereas results for the other cases are presented later. Fig. 10(a) shows the output power–voltage characteristic of the PV array considered. Under the partial shadowing condition considered, three power peaks have been observed at 450 W, 694.2 W and 630 W respectively, with shade impact factor (SIF) equal to 1.42.

To track the global maximum power from the PV array (694.2 W), the proposed MPPT algorithm is used. Fig. 10(b) depicts the maximum power P_M of the PV array and as can be seen, the proposed algorithm detected very fast all the maximum power points and stabilized in the global one, with a time responses less than 1 s. In addition, it can be observed that, the algorithm is more reliable in the case of static load, whereas a slight variation is observed in the case of dynamic load, which is due to the behavior of the DC motor.

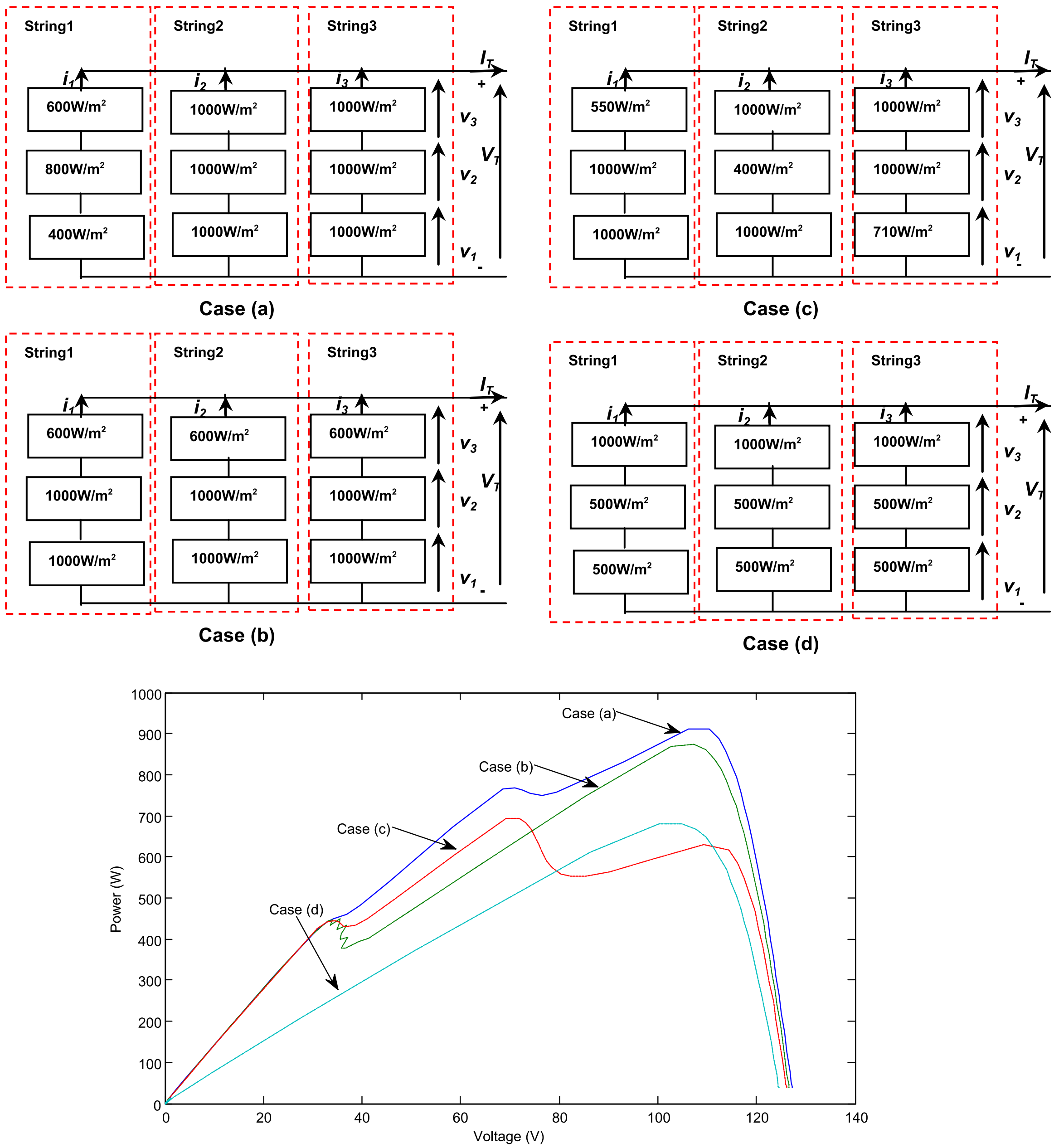

Fig. 8. (a) PV array with different partial shadow (4 cases). (b) *P*–*V* characteristics under different partially shaded conditions (four cases).

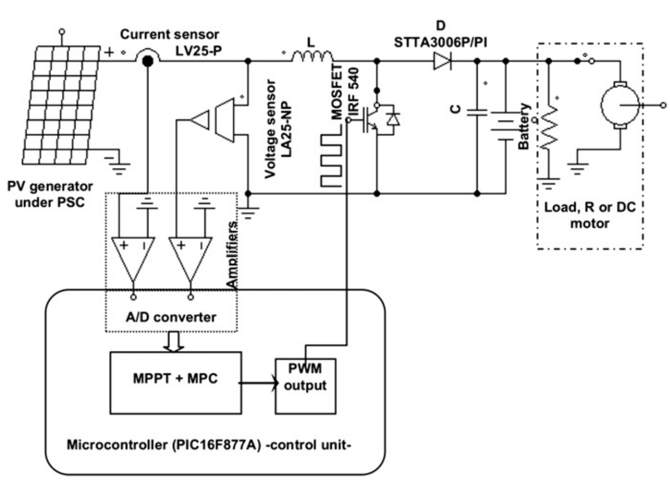

Fig. 9. Electrical circuit of the designed system with MPPT controller.

Fig. 11(a) and (b) shows the output references of current and voltage (I^*, V^*) imposed as inputs to the controller (MPC) and as it can be observed the output references varied until the global maximum power is detected, then they increase and remain at certain values. It should be noted that the static output references converge very fast with respect to the dynamic output references. However, the difference in time is about 0.02 s, which is negligible.

Fig. 12 depicts the output power of the proposed algorithm under non-uniform irradiation (case c) and as can be seen, the PV array power with static and dynamic load show fast response and good stabilization at the real MPP, however a slight difference in the transient is observed. The response time of the method is 0.246 s and 0.234 s for static and dynamic load respectively. As can be observed the response times of the proposed algorithm are different for the same insolation; hence, it depends on the type of the connected load to the DC–DC boost converter. Nevertheless, this difference in time is negligible in real time applications, thus the designed method performs well in both cases as the response

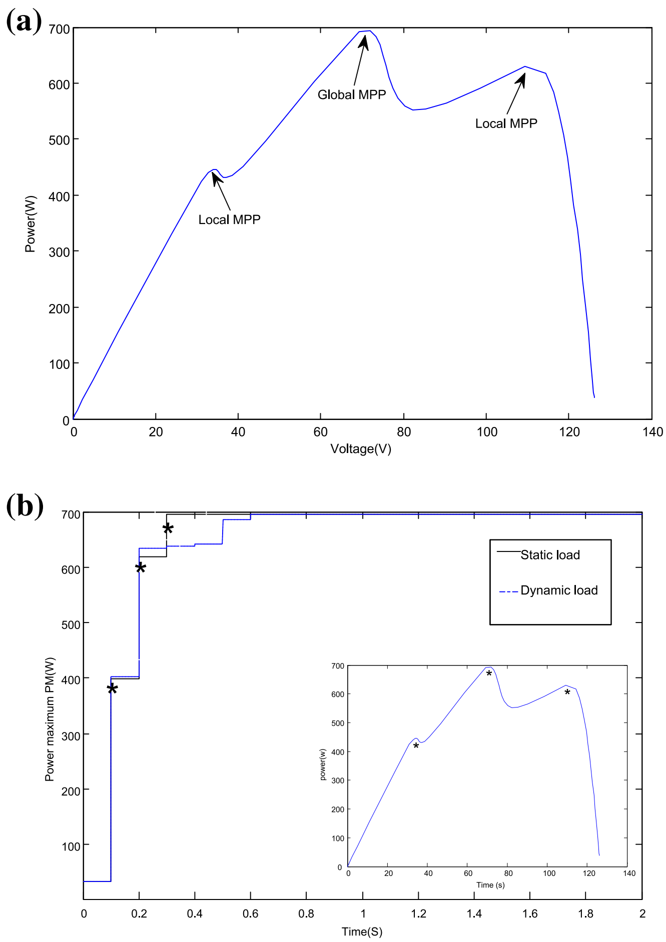

Fig. 10. (a) Output P–V characteristic of the PV array under non-uniform insolation conditions (case c). (b) Maximum output power P_M of the proposed algorithm under non-uniform insolation conditions (case c).

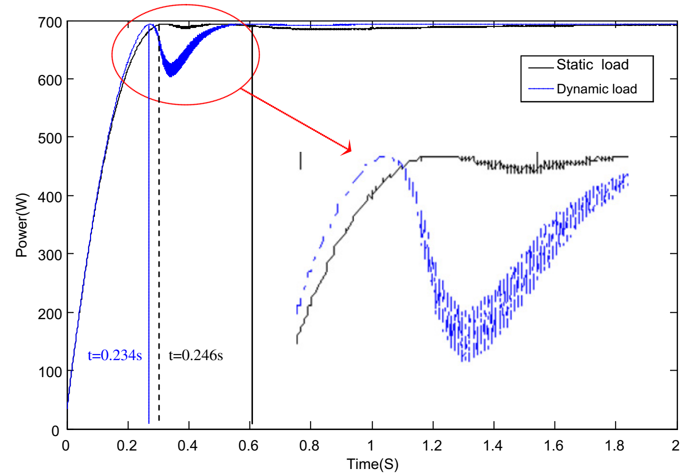

Fig. 12. PV array output power of the proposed method under non-uniform insolation (case c).

time is less than 1 s. Furthermore, the efficiency of the method is 95.8% and 95% for static and dynamic load respectively.

Fig. 13 shows the output power for the other cases (a, b and d) considered. The same remarks can be concluded, i.e., the algorithm tracks the global MPPT quickly, response time is less than 1 s, and its efficiency is about 95% for all cases investigated.

3.2. Rapid changes in insolation

In this section, the behavior of the proposed model under rapid changes in insolation is presented. Fig. 14(a) and (b) shows the insolation variations and the generated output power of the proposed algorithm, for both static and dynamic loads. The effects of the changes in solar insolation level are observed by imposing some stepwise increments and decrements only for the first PV module, while solar insolation in the rest PV modules are set to the standard test conditions ($T = 25$ °C and $G = 1000$ W/m^2). Thus, the solar insolation level starts from 700 W/m^2 then decreases to 600 W/m^2 after that increases to 950 W/m^2 and each change occurs after 2 s. With reference to Fig. 14(b), the proposed algorithm has a good time response (less than 1 s) to track accurately and maintains the real MPP after each step of insolation variation. In the case of static load, it can be observed that the proposed algorithm reach slowly the MPP compared to dynamic load and stabilize without oscillations. In the case of dynamic load, the algorithm takes a small amount of time to reach the MPP, but the estimated power oscillates and presents a small overshoot. It can also be concluded that in every insolation change, the true peak is localized very fast, within 0.24 s, and accurately (the efficiency is 96%).

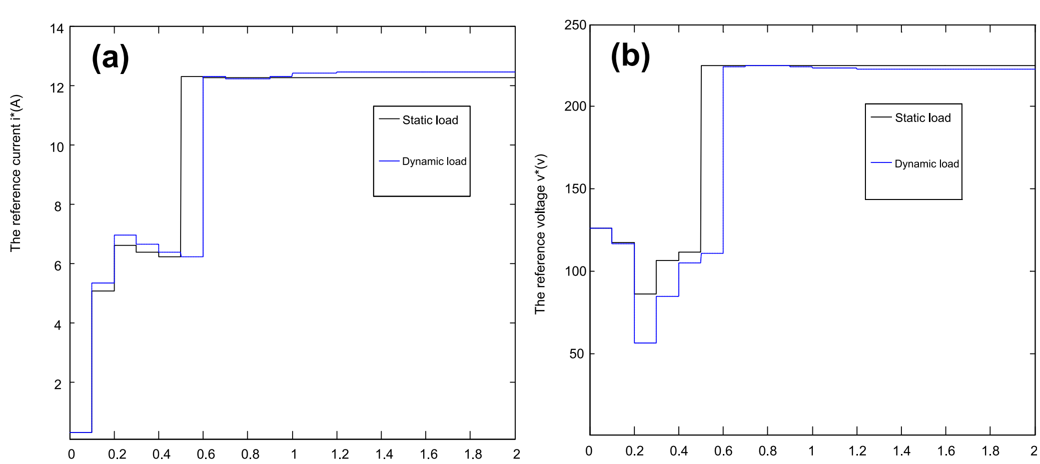

Fig. 11. (a) Output reference current (I^*) and (b) voltage (V^*) of the proposed algorithm under non-uniform insolation (case c).

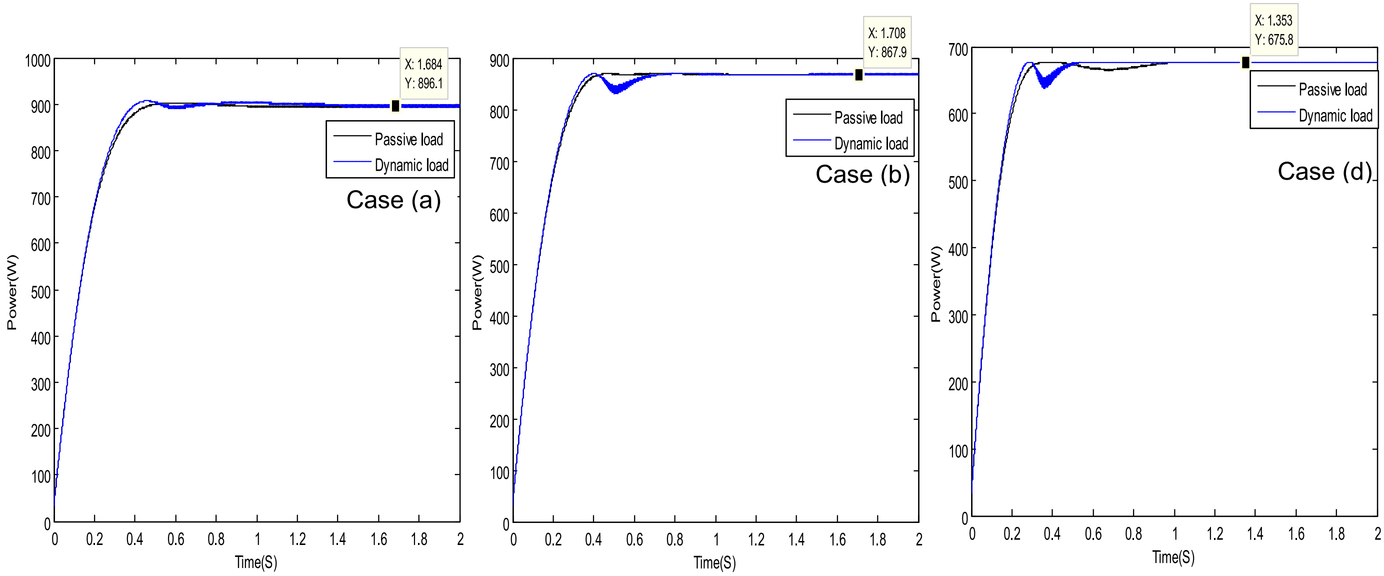

Fig. 13. PV array output power in different cases a, b and d.

3.3. *Comparative study*

In this section, a comparison of the performance of the proposed method with two algorithms published recently by Ji et al. [8] and Alajmi et al. [19] is presented.

The proposed method by Ji et al. [8] is based on the IncCond method with step-size variation and when a PSC is detected the MPPT method changes the voltage reference by a linear function. The method proposed by Alajmi et al. [19] is based on fuzzy-logic and hill climbing technique in which the controller scans and

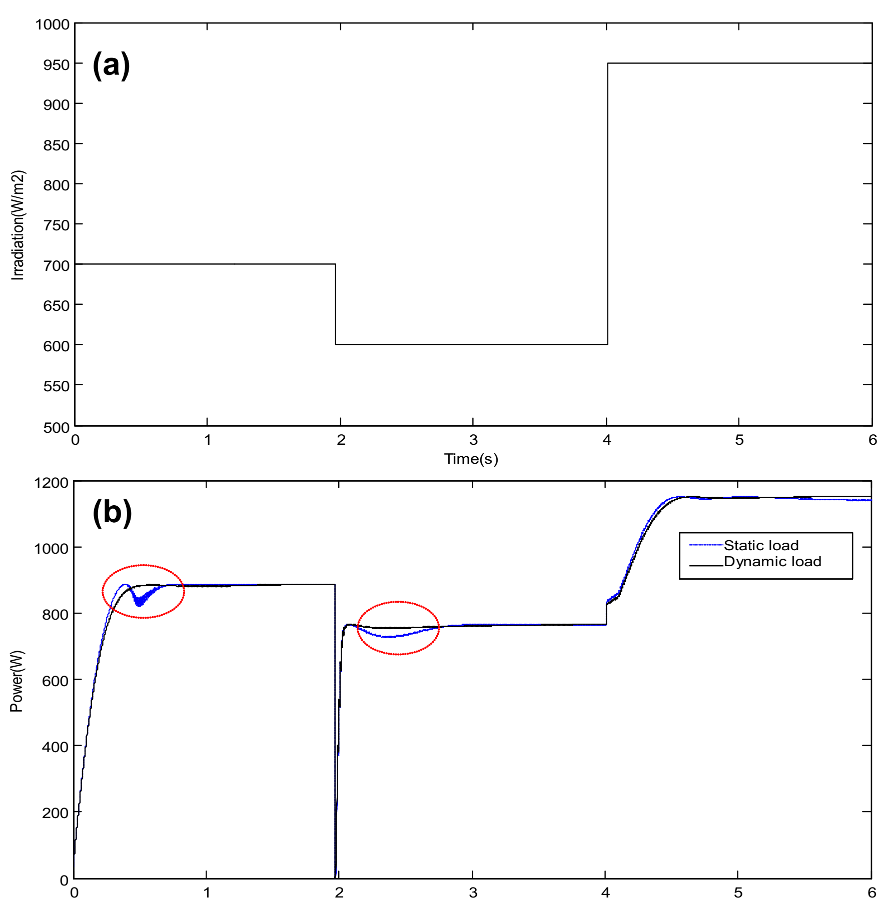

Fig. 14. (a) Insolation variations, (b) generated PV array output power of the proposed MPPT algorithm.

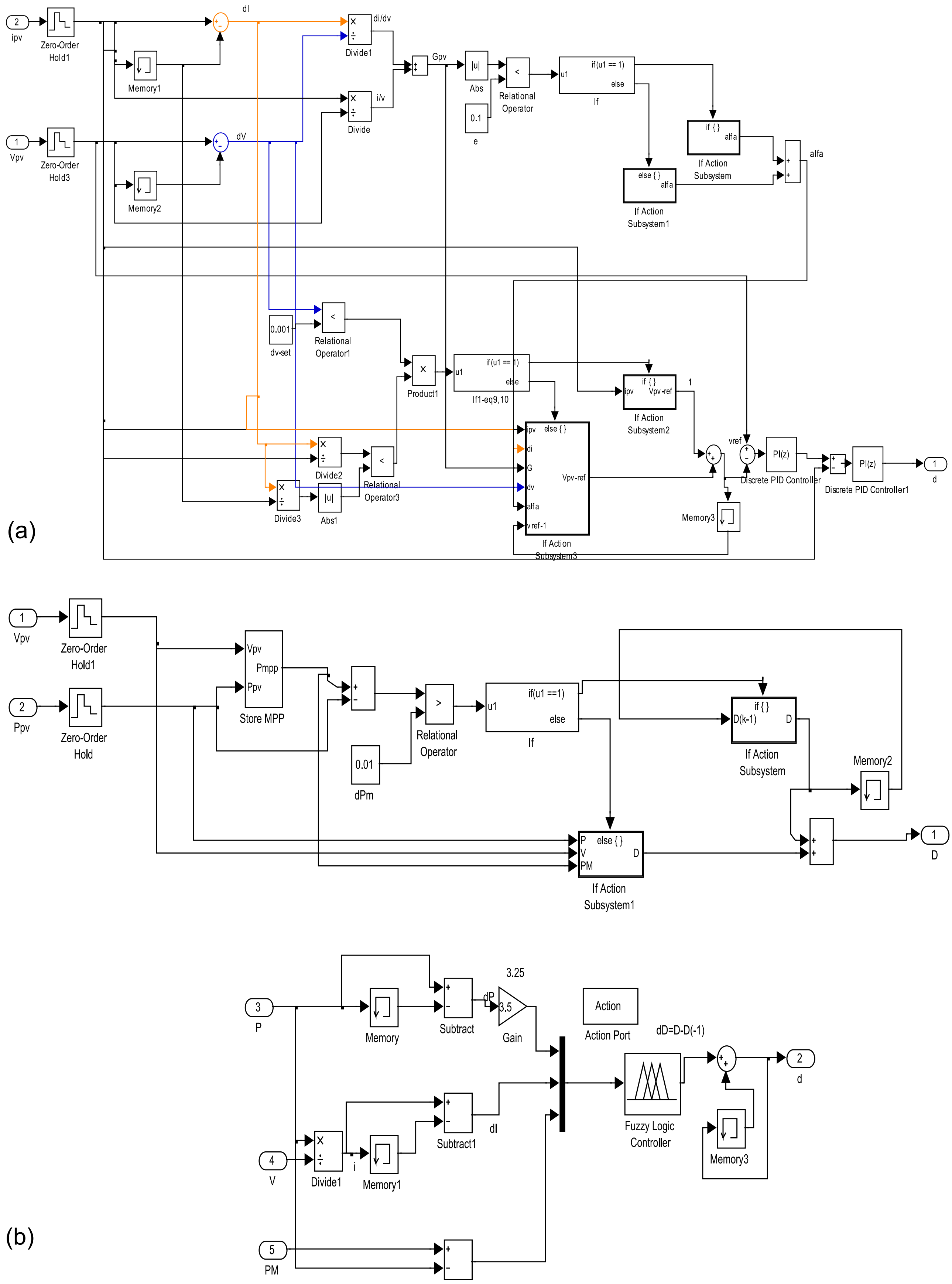

Fig. 15. (a) The developed Matlab/Simulink block of Ji et al. algorithm [8]. (b) The developed Matlab/Simulink block of Alajmi et al. algorithm [19].

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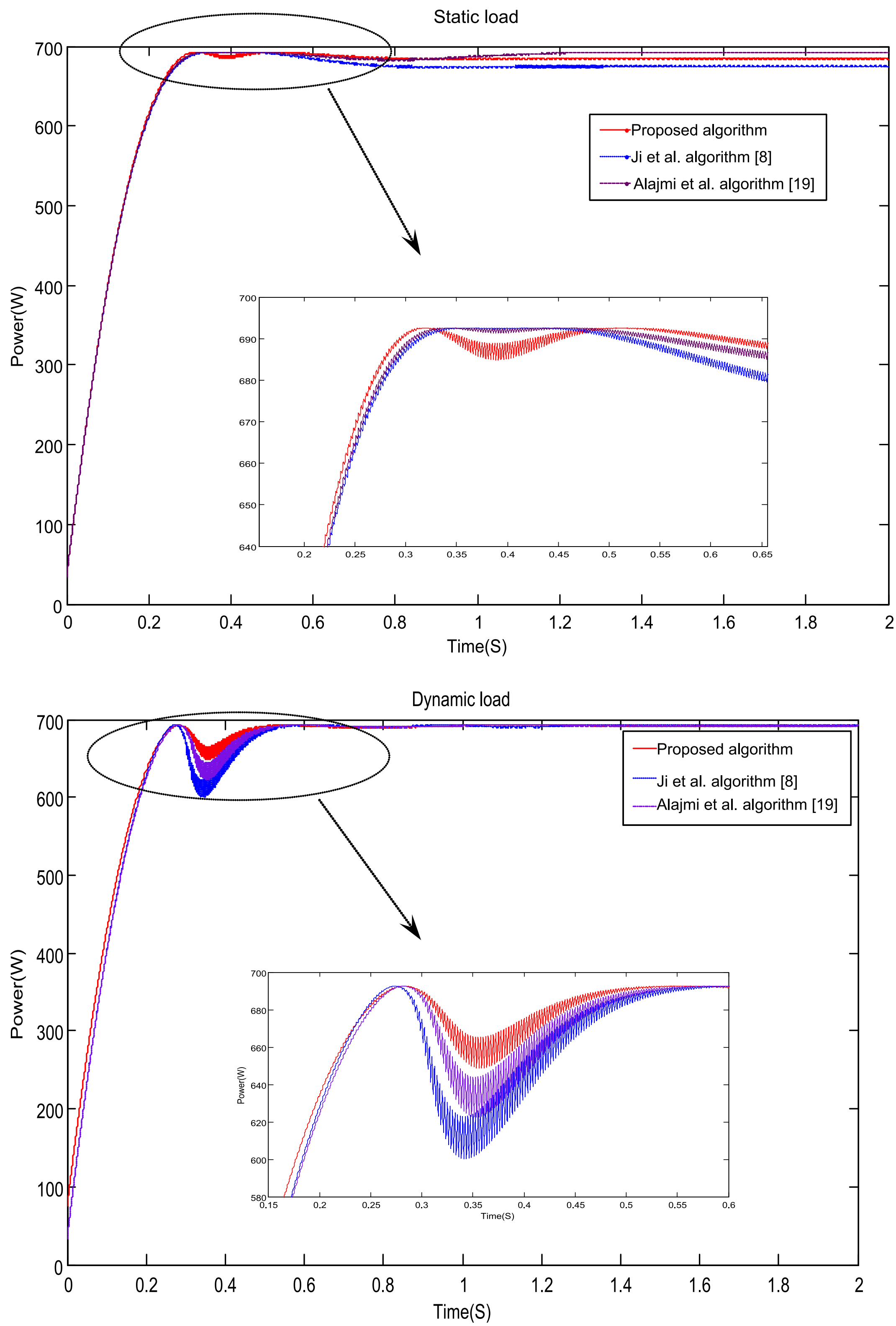

Fig. 16. PV-array output power of the proposed algorithm, Ji et al. algorithm [8] and Alajmi et al. algorithm [19] for both resistive and dynamic loads.

Table 4
The performances of the three compared algorithms under PSCs (case c).

	Proposed algorithm	Ji et al. algorithm [8]	Alajmi et al. algorithm [19]
Static load (resistor)			
Response time	0.245 s	0.240 s	0.258 s
Static error	8.5 W	18 W	2.1 W
Efficiency	95.80%	94.85%	95.02%
Dynamic load (DC motor)			
Response time	0.220 s	0.221 s	0.255 s
Static error	2.00 W	2.70 W	1.90 W
Efficiency	95.00%	94.70%	94.90%

stores the maximum power during the perturbation and observation stages. Our method consists to use a new simplified MPPT search algorithm and a predictive controller as described above.

Fig. 15(a) and (b) shows the block diagrams of Ji et al. [8] and Alajmi et al. [19] algorithms developed under Matlab/simulink software respectively.

The algorithms developed in Refs. [8,19] are tested only for a resistive load, connected to a DC–DC converter, however, here we try to test these algorithms as well as our method in both resistive and DC motor loads in order to show their performance. Fig. 16 shows the output power of the three algorithms under partial shaded conditions (e.g. case c). It is clearly shown that all algorithms are able to track the global MPP with different time responses for both loads.

Table 4 reports the performances of the different MPPT algorithms under PSCs (e.g. case c). With respect to the results presented in Table 4, by comparing the response time, static error and efficiency, it is noted that the algorithm introduced here performs better than the other two algorithms, as the drawbacks of calculation complexity reported in Ref. [19] and the negative influence of the step size variation on the system performance given in Ref. [8] are successfully reduced by the present method.

Particularly, Ji et al. [8] algorithm presents more oscillations when the MPP is achieved and its performance depends on the speed changing circumstances whereas Alajmi et al. [19] algorithm has less oscillation around the GMPP however, it provides more power (resistive load) than expected and its implementation is relatively difficult due to the fuzzy logic used, which comprises 30 rules, which increases the implementation cost of the control system.

4. Conclusions and perspective

In this paper, a new method to track the global MPP under PSCs was developed and tested. A Matlab/Simulink based simulation of a partially shaded stand-alone PV system with two types of load was carried out to validate the proposed method. The results demonstrate that the proposed method avoids local MPPs and track very fast the global MPP with negligible oscillations. It has been observed that the efficiency of the proposed method is not influenced by the type of the load connected to the DC–DC boost converter, however, a slight variation is observed when the system is connected with DC motor, but after a small amount of time the system stabilizes to the GMPP. Comparative study shows that the examined algorithms have some advantages and disadvantages; they can guarantee the convergence to real MPP with short time, however, the designed algorithm outperforms the examined MPPT algorithms. The main advantages of the developed algorithm are fast convergence to the GMPP, higher efficiency, robustness and its possibility to implement easily. Further work is being conducted on the overall system design and experimental implementation.

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Appendix

```
%MPPT
Input Vk and Ik
%Initial conditions
If vk==0
      PM=0
      VM=0
End
%Calculate Power Pk
pk=vk*Ik
% Calculate I* and V*
If (pk>PM)
      PM=pk
      VM=vk
%Output VM and PM
  If (VM>Vk)
        Vk* =Vk-step
        Ik* =Ik-step
     Else

        Vk* =Vk+step
        Ik* =Ik+step
  End
Else
     PM=PM
      VM=VM
%Output VM and PM
If (VM>Vk)
        Vk*=Vk+step
        Ik*=Ik+step
     Else

        Vk*=Vk-step
        Ik*=Ik-step
  End
End
Output I* and V*

% MPC
Input Vk, Ik, I*, V*and Vck
%Calculate I and Vc at the next sampling instant k+8
Ik1s0=Ik-(Ts/L)*Vc+(Ts/L)*Vk
Vck1s0=(Ts/C)*Ik+(1-(Ts/R*C))*Vck
Ik1s1=Ik+(Ts/L)*Vk
Vck1s1=(1-(Ts/R*C))*Vck
Js0=WA*abs(Vck1s0-V*)+ WA*abs(Ik1s0-I*)
Js1=WA*abs(Vck1s1-V*)+ WA*abs(Ik1s1-I*)
If (Js0<Js1)
        S=0
     Else
        S=1
End
Output S
```

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