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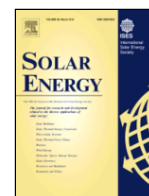
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Enhanced auto-scaling incremental conductance MPPT method, implemented on low-cost microcontroller and SEPIC converter

Salah Necaibia^a, Mounia Samira Kelaiaia^a, Hocine Labar^a, Ammar Necaibia^b, Edgardo D. Castronuovo^{c,*}

^a *Electrotechnique Laboratory, Electrical Engineering Department, Faculty of Engineering, Badji Mokhtar University, BP 12 Sidi Amar, Annaba 23000, Algeria*

^b *Unité de Recherche en Energies Renouvelables en Milieu Saharien, URERMS, Centre de Développement des Energies Renouvelables CDER 01000, Adrar, Algeria*

^c *Department of Electrical Engineering, University Carlos III of Madrid, Spain. Avda. de la Universidad 30, 28911 Leganés (Madrid), Spain*

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ABSTRACT

This paper proposes a new maximum power point tracking (MPPT) algorithm for photovoltaic (PV) systems, which is tested in simulations and practical implementations. In the proposed PV-MPPT system, a new control strategy is applied to create two operating areas. In each area, the step-size is different in the function of the closeness to the MPP. Because of this strategy, some drawbacks of the conventional incremental conductance (IncCond) methods are eliminated. A single-ended primary-inductor converter (SEPIC) DC-DC converter is controlled with the proposed MPPT technique. The modified IncCond method is validated under simulation with test data, real data and real scenarios of solar irradiation. The results of the proposed approach show higher MPPT efficiencies and shorter convergence times than the conventional IncCond method even in rapidly changing conditions of solar radiation.

Nomenclature

E_g	band-gap energy of the semiconductor of the cell
I_{mpp}	current at maximum power point (A)
I_{out}	SEPIC output current (A)
I_{ph}	photocurrent (A)
I_{pv}	PV current (A)
I_s	saturation current (A)
I_{sc}	short-circuit current (A)
I_{so}	reverse saturation at T_r (A)
N_p	numbers of cells connected in parallel
N_s	numbers of cells connected in series
P_{out}	SEPIC output power (W)
P_{mpp}	power at maximum power point (W)
P_{pv}	PV power (W)
$P_{MPPT}(t)$	instantaneous extracted power using the MPPT approach
$P_{MPPT}^*(t)$	exact instantaneous output PV power
R_p	parallel resistance (Ω)
R_s	series resistance (Ω)

T_r	cell reference temperature ($^{\circ}\text{C}$)
V_{mpp}	voltage at maximum power point (V)
V_{oc}	open-circuit voltage (V)
V_{out}	SEPIC output voltage (V)
V_{pv}	PV voltage (V)
V_D	forward voltage drop of the diode
dD	change in duty cycle
dI_{pv}	change in PV current (A)
dP_{pv}	change in PV power (W)
dV_{pv}	change in PV voltage (V)
k_i	short-circuit current temperature coefficient
A	ideality factor
D	duty cycle
K	Boltzmann constant (J/K)
S	irradiance W/m^2 .
T	cell temperature ($^{\circ}\text{C}$)
q	electron charge (C)
η_{MPPT}	MPPT efficiency
$\eta_{MPPT(avg)}$	average MPPT efficiency

* Corresponding author.

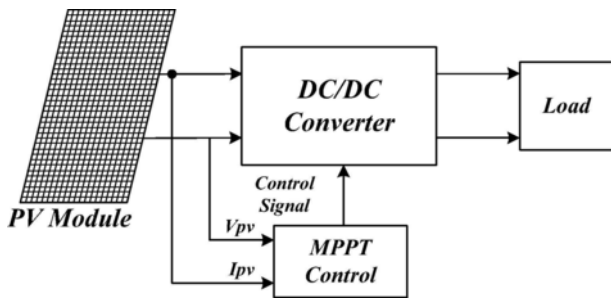


Fig. 1. Block diagram of the PV system.

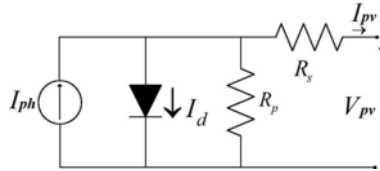


Fig. 2. Equivalent representation of a PV cell.

Table 1
Parameters of the PV panel (ISOFOTON IS-75/12) (Necaibia et al., 2015).

Parameters	Variable	Value
Maximum power	P_{mpp}	75 [W]
Maximum voltage	V_{mpp}	17.3 [V]
Current at max power	I_{mpp}	4.34 [A]
Open circuit voltage	V_{oc}	21.6 [V]
Short circuit current	I_{sc}	4.67 [A]
Series resistance	R_s	0.221 [Ω]
Parallel resistance	R_p	866.923 [Ω]
Number of series cells	N_s	36

1. Introduction

In recent years, PV energy has shown significant progress as an alternative to solve energy problems, particularly in desert areas, because of growing environmental concerns and the price decline of PV modules (Fathabadi, 2017). Nevertheless, the low conversion efficiency of transforming solar energy into electric energy is one of the main obstacles against the widespread diffusion of this type of energy source. Therefore, the maximum power extraction of each panel is currently one of the main technological challenges (Necaibia et al., 2017; Tobón et al., 2017).

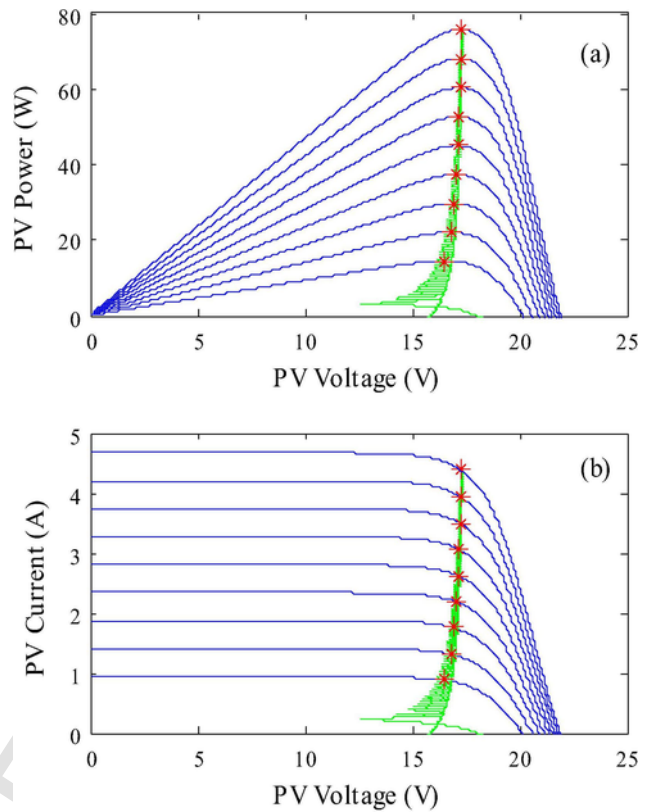


Fig. 3. Effect of irradiation in V_{mpp} and I_{mpp} with different irradiation levels in (a) $P - V$ curve and (b) $I - V$ curve.

Cost-effectiveness and efficiency are the most important criteria for the PV system design, since a PV system must be designed with high efficiency at minimum cost (Amir et al., 2017; Murtaza et al., 2017). However, PV panels have nonlinear output characteristics, and the main factors that affect the PV output power are the solar irradiation, temperature and load impedance (Bradai et al., 2017; Li et al., 2017). Because of the nonlinear output characteristics of PV systems, an MPPT control is required to track the optimal operation. Several researchers studied MPPT methods for PV modules. The indirect MPPT approaches such as fractional short-circuit current (Ahmed Sher et al., 2015; Diego et al., 2018) and open circuit voltage (Ahmad, 2010; Surya Kumari et al., 2011) offer a simple way to acquire the MPP, they based on mathematical concepts, which cannot accurately track the MPP at any weather conditions. However, they need periodical disconnection or short-circuit of the PV panel to measure the short-circuit current or

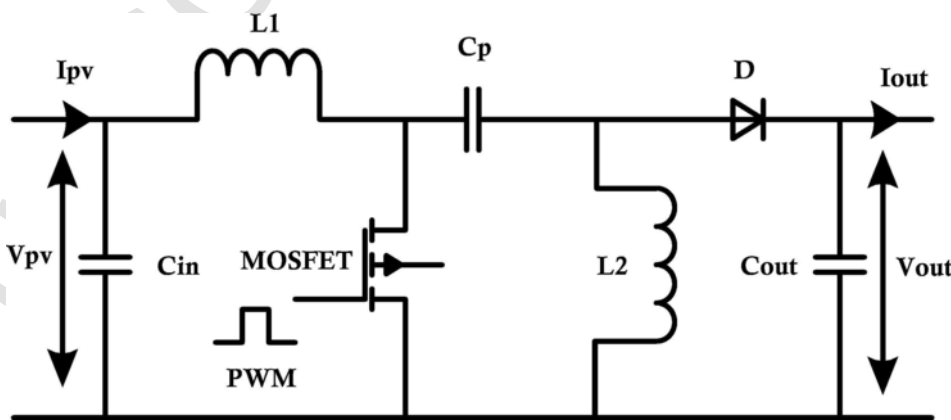


Fig. 4. SEPIC Converter.

Table 2
SEPIC converter components.

Parameters	Variable	Value
Capacitor	$C_{in} = C_{out}$	2200 μF
Inductor	$L_1 = L_2$	274 μH
Coupling capacitor	C_p	1000 μF
Switching frequency	f_{sw}	10 kHz

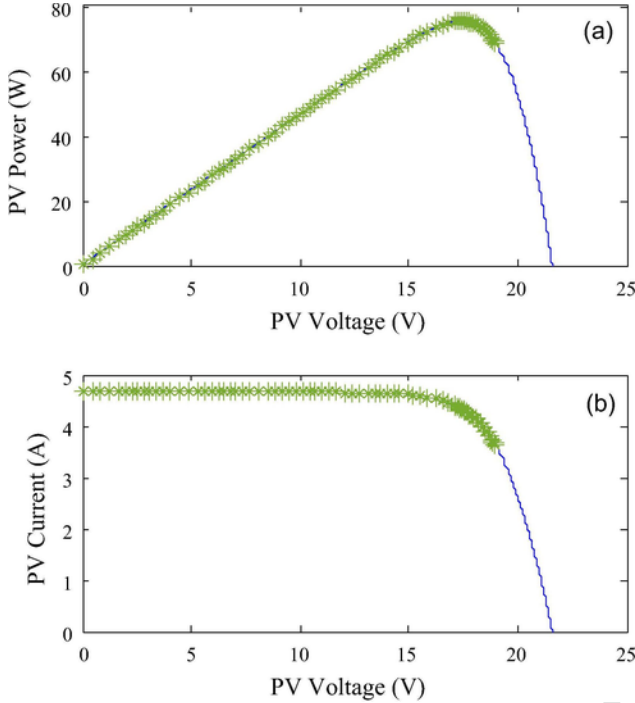


Fig. 5. Tracking the MPP through a SEPIC converter for the (a) $P - V$ curve and (b) $I - V$ curve.

open-circuit voltage for reference, resulting in more power loss (Fangrui et al., 2008). The most common direct MPPT approaches are perturbation and observation (P&O) and IncCond. The main advantages of these two methods are that they are compatible with any PV module, require no information about the configuration of the PV module, and are easily implemented. In this paper, an MPPT approach is followed. MPPT methods are simple, have low cost, can quickly track rapidly changing conditions and have small output power fluctuations (Jin et al., 2017; Kotti and Shireen, 2015). Some variants, as the hill climbing method (Mousavi, 2016), can be used to track the main peak of the array power curve in the presence of a shadow.

In general, the main drawback of conventional MPPT methods is the selection of the perturbation step-size, which is a trade-off between the magnitude of the steady-state fluctuation and the tracking velocity (Peng et al., 2018a; 2018b; Tang et al., 2017; Thangavelu et al., 2017). To overcome this problem, researchers developed auto scaling step-size MPPT methods to search for a good speed convergence and reduce the steady-state errors (Wang et al., 2016). A scaling factor is generally required to achieve the optimal MPPT performance (Kolesnik and Kuperman, 2016). The most used methods to implement the adaptive step-size are the derivatives in voltage (dP_{pv}/dV_{pv}) (Liu et al., 2008), duty cycle (dP_{pv}/dD) (Tan et al., 2015) and current (dP_{pv}/dI_{pv}) (Mei et al., 2011). All of these adaptive step-size methods involve relatively high time to reach the MPP because of the required calculations for the step-size. Therefore, they are efficient under constant solar irradiation,

but under rapidly irradiance changes, the performances of these adaptive methods are degraded. Overshooting problems, setbacks because of the slow convergence times, constant scaling factor and expensive implementations are issues generally associated with the conventional derivative MPPT methods (Al-Dhaifallah et al., 2018; Amir et al., 2017; Murtaza et al., 2017).

To address these problems, the present study proposes a new auto scaling IncCond MPPT method. The new control strategy creates two operating areas in the function of the nearness to the searched MPP, whose step-size changes between two fixed values. The suggested technique is advantageous over other methods because it is independent from population optimization and does not require scaling factors like this methods (Abdelsalam et al., 2011; Kollimalla and Mishra, 2014a; 2014b; Loukriz et al., 2016; Talbi et al., 2018), resulting in a highly adaptable approach and requiring a simple algorithm with few design parameters, which can be programmed in low-cost microcontrollers. An experimental comparative study of the conventional and proposed MPPT methods is presented here. The effectiveness of the proposed method in terms of tracking performance and improved stability is validated using detailed simulation and experimental results.

2. Components modelling of PV system

The PV system consists of several components, including PV panels, a DC-DC converter, an MPPT control and the load. The block diagram of the entire PV system is shown in Fig. 1.

2.1. PV modelling

The main elements of a PV system are the PV cells. These cells are connected in series and parallel to conform modules. Many modules are added in the function of the power requirement. The current-voltage characteristic of a PV module is a nonlinear function of the solar radiation intensity and ambient temperature, as described in Eq. (1) (Boukenoui et al., 2017; Bounechba et al., 2016; Seyedmahmoudian et al., 2014; Li et al., 2017; Zhao et al., 2017). The equivalent scheme of a PV cell is shown in Fig. 2.

$$I_{pv} = N_p I_{ph} - N_p I_s \left\{ e^{\left[\frac{q(V_{pv} + R_s I_{pv})}{N_s A K T} \right]} - 1 \right\} - N_p \frac{q(V_{pv} + R_s I_{pv})}{R_p N_s} \quad (1)$$

The photocurrent of the PV module depends on the ambient temperature and irradiance, as given by (2).

$$I_{ph} = [I_s + k_i (T - T_r)] \frac{S}{100} \quad (2)$$

where

$$I_s = I_{so} * \left(\frac{T}{T_r} \right)^3 * e^{\left[\left(-\frac{q.E_g}{A.K} \right) * \left(\frac{1}{T_r} - \frac{1}{T} \right) \right]} \quad (3)$$

$$\text{and } A = \frac{q(V_{pv} + R_s I_{pv})}{N_s}$$

PV characteristics are specified by manufacturers as shown in Table 1 under defined standard test conditions (temperature = 25 °C; irradiance = 1000 W/m²). However, the PV output changes with the solar irradiance variation (Dounis et al., 2015). Fig. 3 shows the increase in delivered PV power and current for different irradiance levels. In the operational area, the current output of a PV module is almost constant for a constant solar radiation intensity (Fig. 3b). Thus, the output power is proportional to the radiation intensity (Fig. 3a).

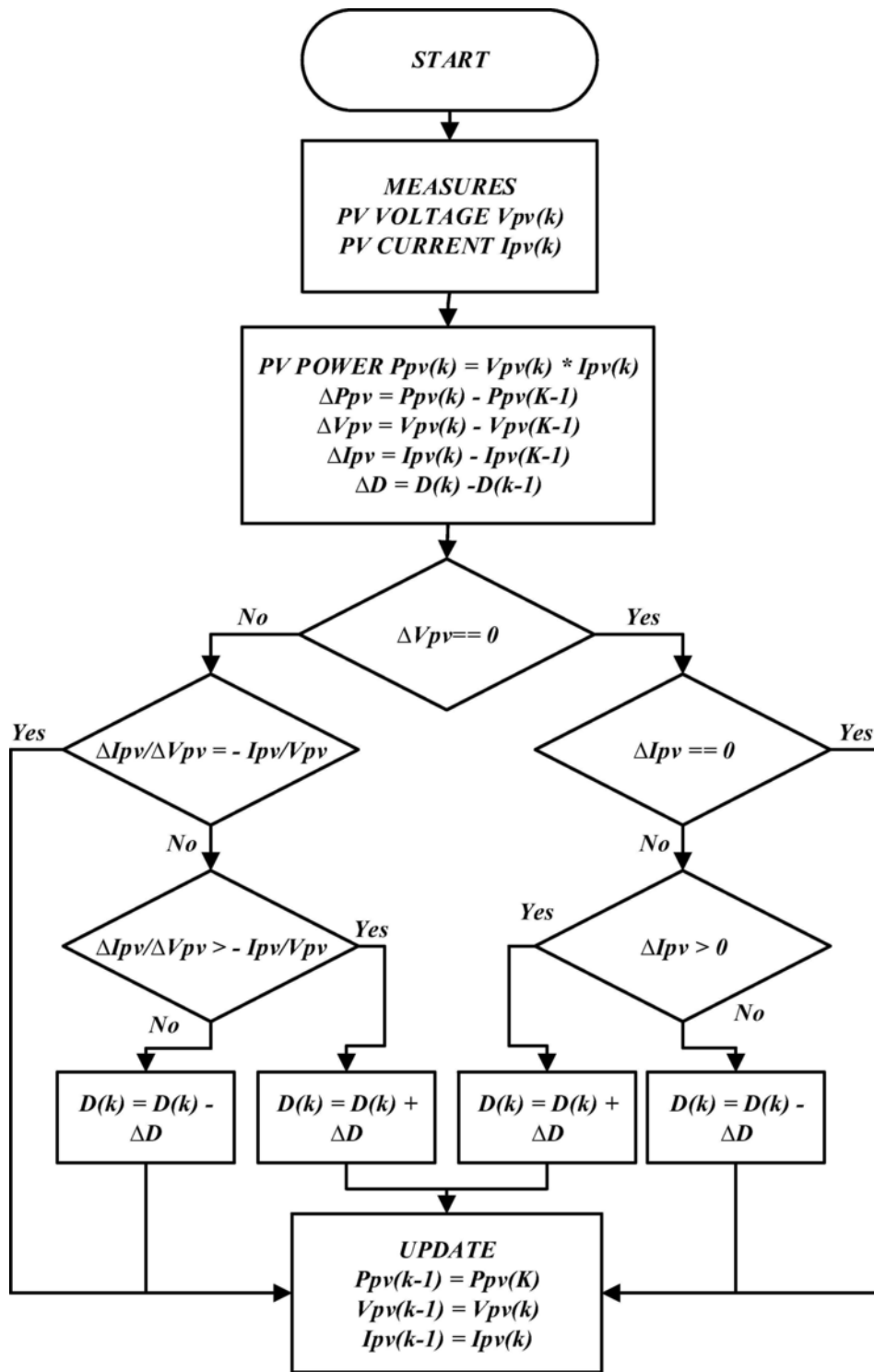


Fig. 6. Flowchart of the traditional IncCond technique.

2.2. Switching converter analysis

Switching converters are always required in the connection of a PV array. Even in the direct association between a battery and a PV panel, a non-return diode is necessary. Switching converters are mostly required to adjust the output voltage to the planned use. DC-DC choppers are the most used systems in PV schemes (Chiang et al., 2009). In the

present case, the SEPIC converter of Fig. 4 is used as an interface between the PV panel and the load. The SEPIC topology is advantageous because of its low current ripples and high MPPT efficiency (Choi, 2016). It can control the PV voltage and transfer energy from the PV plant to the load at different solar irradiance levels (Saravanan and Babu, 2017).

The SEPIC switching power supply uses two inductors allowing a wider choice of inductors while a single inductor coupled will be measured (customized). Its advantage is to allow a lower current ripple.

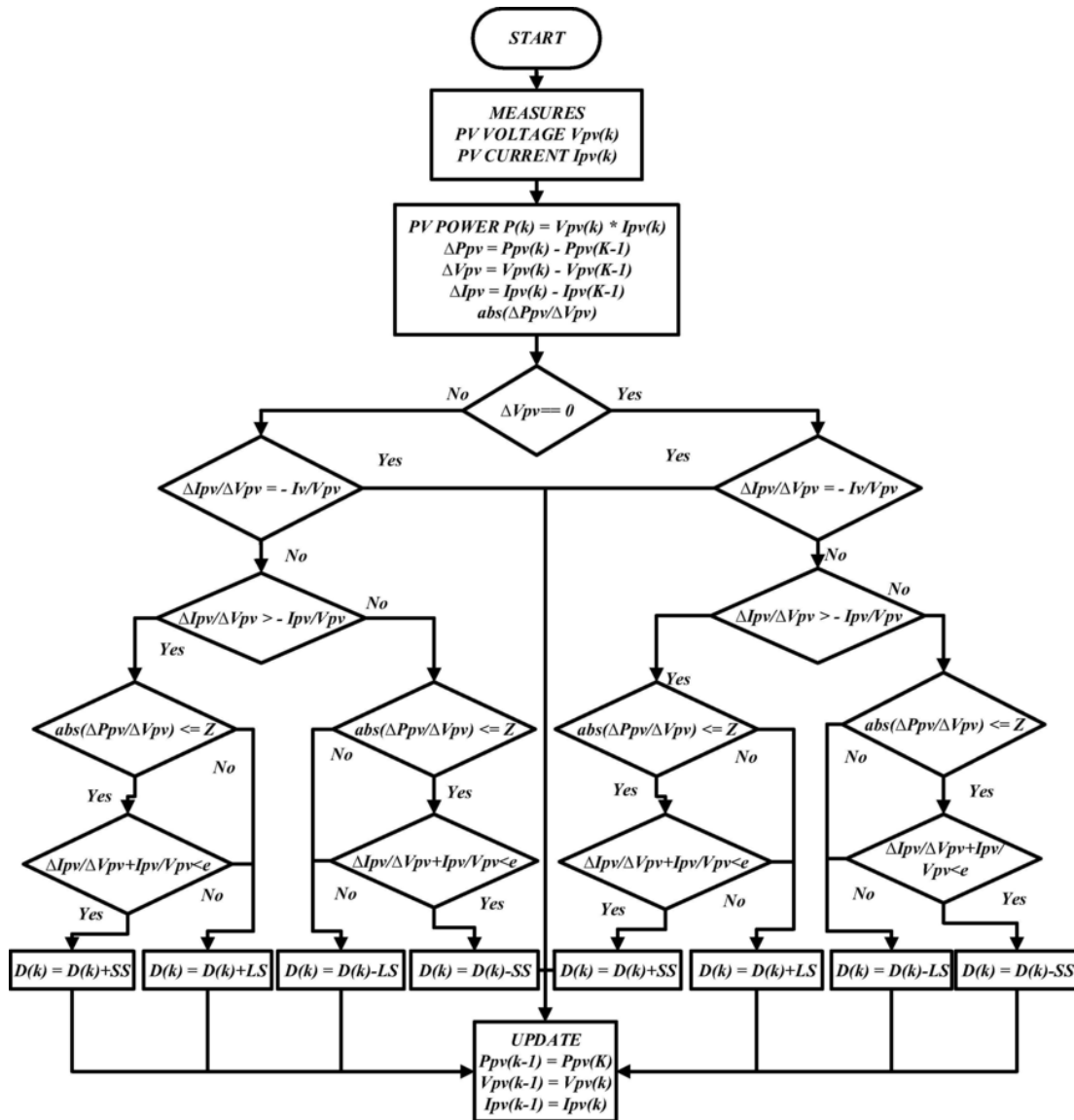


Fig. 7. Flowchart of the proposed IncCond technique.

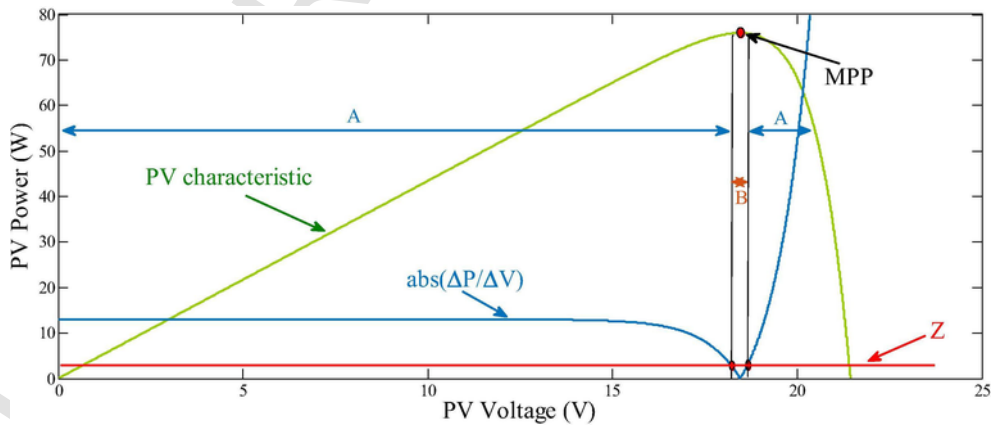


Fig. 8. PV characteristic with the operating areas.

The inductor $L1$ at the input of the circuit makes the SEPIC converter assembly look like a boost converter. The advantage of this converter is the isolation between the input and the output by the capacitor C_p . The

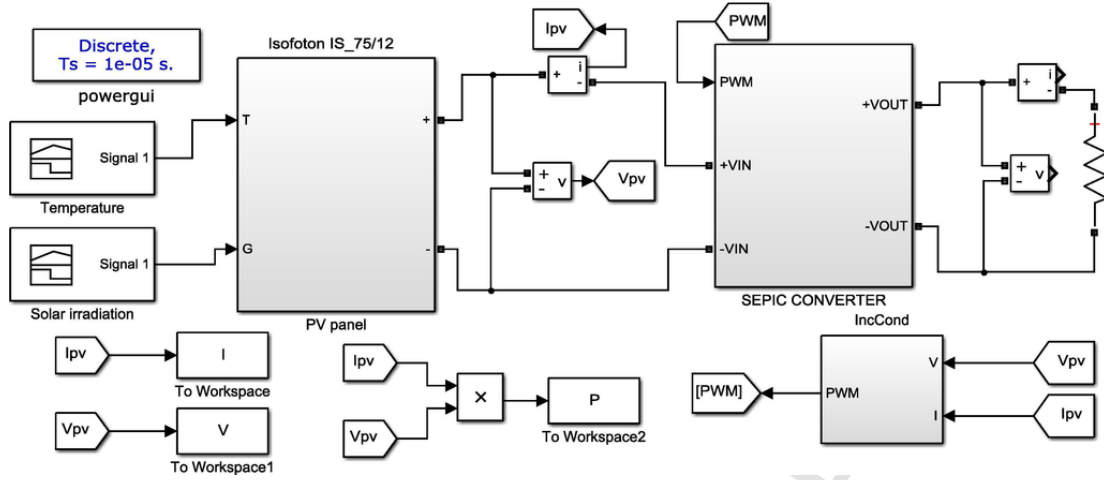


Fig. 9. Block diagram of the MPPT system.

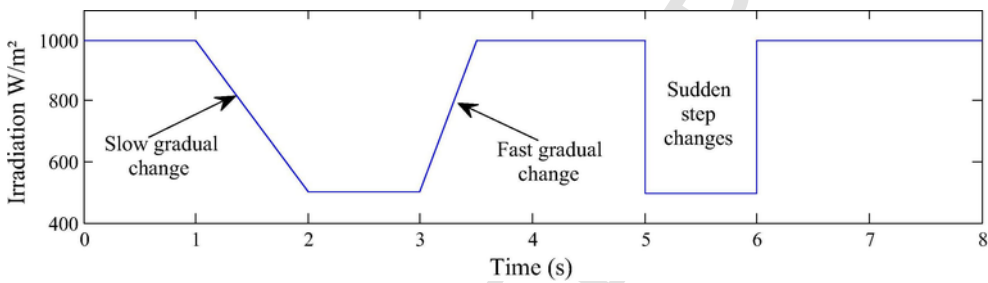


Fig. 10. Test types of different solar irradianations.

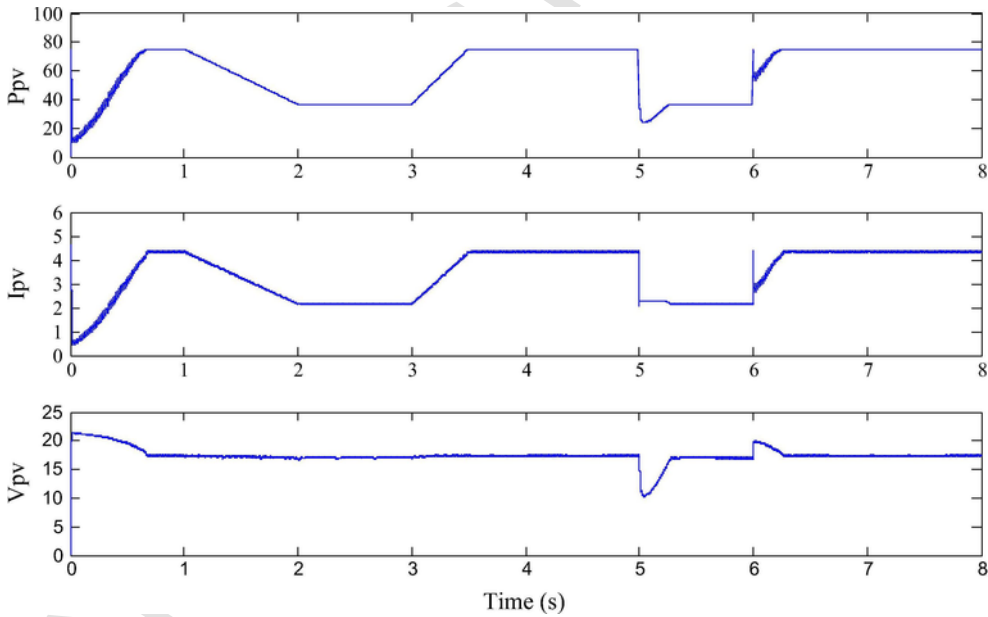


Fig. 11. Tracking waveforms for the PV power, current and voltage of the traditional IncCond approach.

capacitor C_p protects against a short circuit or an output overload. Indeed, the switching power supply SEPIC has the advantage of being able to cut its output voltage up to 0V unlike a boost power supply where the smallest output voltage is equal to the input voltage.

The relation between output and input voltages is given in the (4):

$$V_{out} = V_{pv} \frac{D}{1-D} \quad (4)$$

If the power conversion is considered perfect and losses are not considered, then (5).

$$P_{pv} = P_{out} \quad (5)$$

$$V_{pv} I_{pv} = V_{out} I_{out} \quad (6)$$

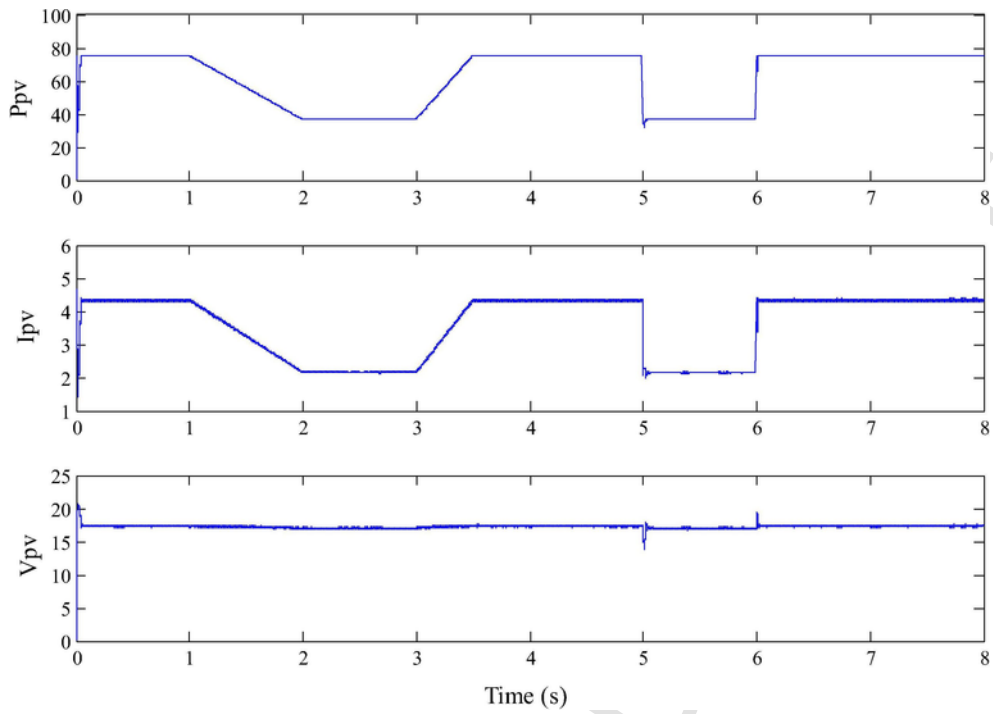


Fig. 12. Tracking waveforms for the PV power, current and voltage of the proposed IncCond approach.

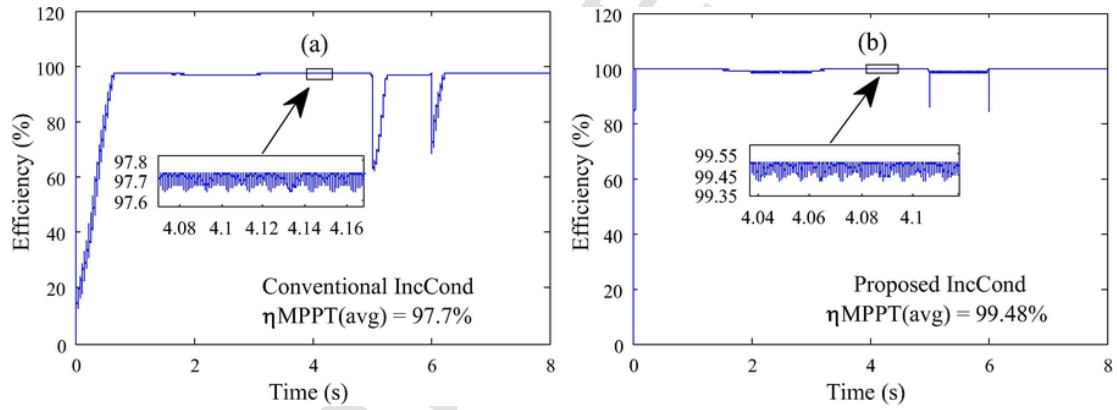


Fig. 13. Tracking efficiency: (a) Conventional IncCond algorithm; (b) proposed IncCond approach.

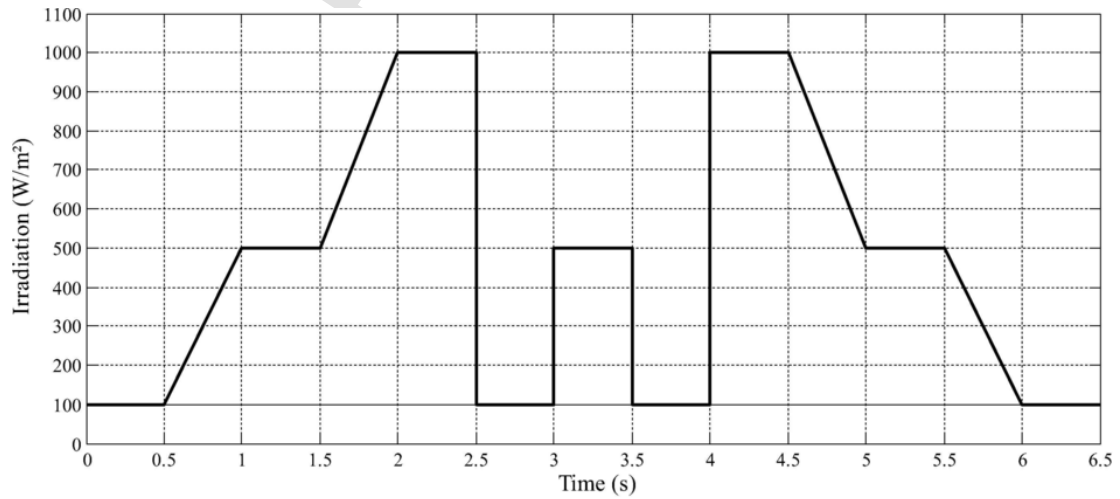


Fig. 14. Fast multi-changing irradiance profile.

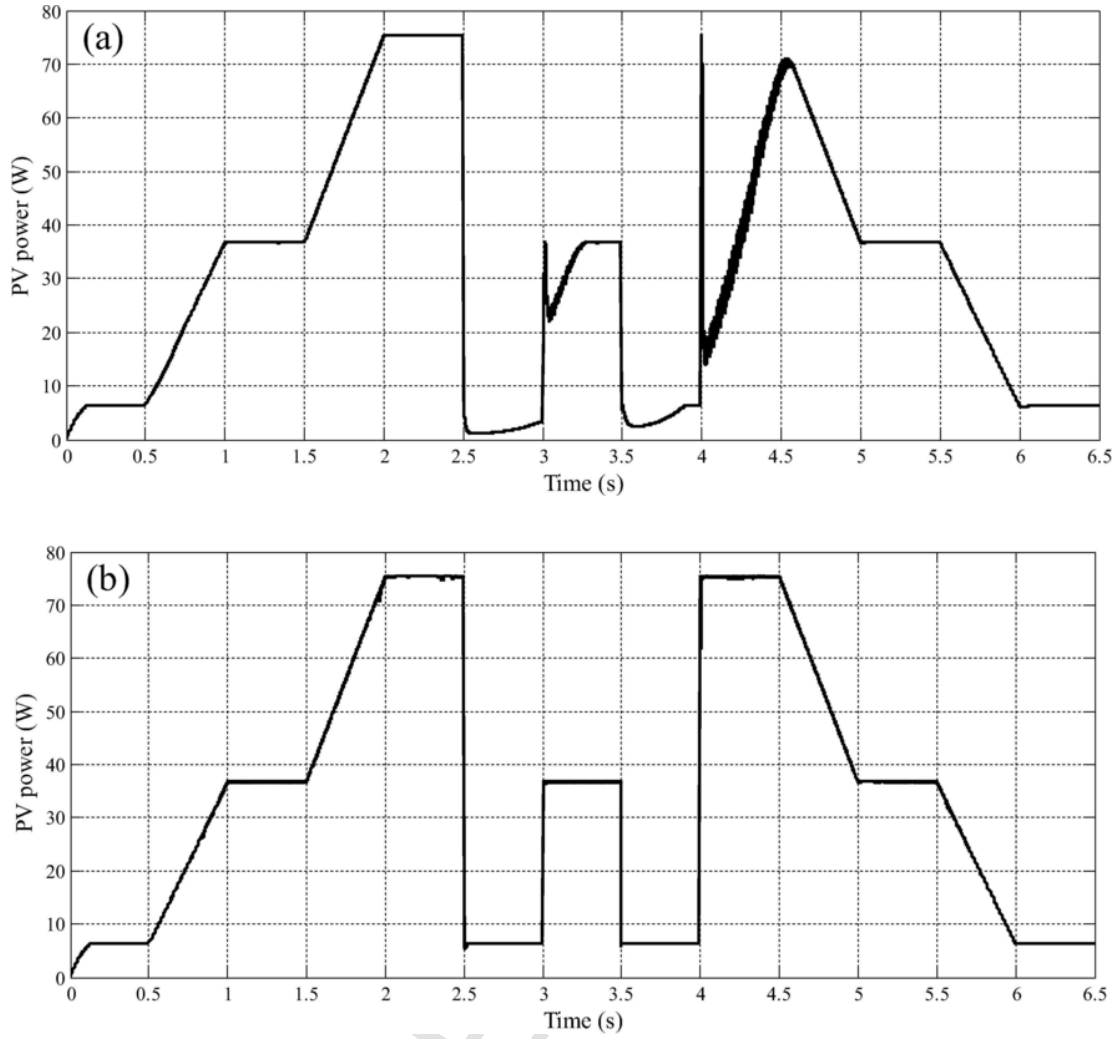


Fig. 15. PV power waveforms for: (a) Conventional IncCond approach, (b) Proposed IncCond approach.

Substituting (4) into (6), we obtain (7).

$$I_{out} = I_{pv} \frac{1-D}{D} \quad (7)$$

Only Continuous Conduction Mode (CCM) of the converter is studied, namely the current in the inductor never equal to zero.

A duty cycle close to 50%, the PV voltage is equal to the output voltage. The duty cycle is given by (Leema Rose and Sankaragomathi, 2016):

$$D = \frac{V_{out} + V_D}{V_{pv} + V_{out} + V_D} \quad (8)$$

The duty cycle varies depending on the applied PV voltage. So, its maximum is (Leema Rose and Sankaragomathi, 2016):

$$D_{max} = \frac{V_{out} + V_D}{V_{pv(min)} + V_{out} + V_D} \quad (9)$$

The inductance values are calculated mainly by the accepted current ripple. Generally, a maximum ripple allowed is 40% of the maximum PV current (Leema Rose and Sankaragomathi, 2016). The current ripple is defined by the following equation (Leema Rose and

Sankaragomathi, 2016):

$$\Delta I_l = I_{pv} \times 40\% = V_{out} \times \frac{V_{out}}{V_{pv(min)}} \times 40\% \quad (10)$$

The value of the L_1 et L_2 must choose is given by (Leema Rose and Sankaragomathi, 2016):

$$L_1 = L_2 = \frac{V_{pv(min)}}{\Delta I_l \times f_{sw}} \times D_{max} \quad (11)$$

The capacitor C_p must be calculated from the desired voltage ripple defined by the following expression (Leema Rose and Sankaragomathi, 2016):

$$\Delta V_C = \frac{I_{out} + D_{max}}{C_p \times f_{sw}} \quad (12)$$

Filtering capacitors C_{in} et C_{out} are given by (Leema Rose and Sankaragomathi, 2016): (After equation 13) Results of calculations are provided in Table 2.

$$C_{in} = C_{out} \geq \frac{I_{out} \times D_{max}}{V_{ripple} \times f_{sw}} \quad (13)$$



Fig. 16. Meteorological station of the Research Unit in Renewable Energies, Saharan Medium, Adrar, Algeria.

3. Description of MPPT methods

The MPPT control is implemented to extract the maximum energy produced from the PV-module and transfer it to the load (Ghasemi et al., 2018; Jeyaprabha and Selvakumar, 2017). This control is considered the most important method to improve the efficiency of the PV system. The MPPT efficiency control requirements are fast dynamics, good steady-state performance, high efficiency and low design cost. Some MPPT approaches have been examined to improve the performance of PV systems, such as (Kofinas et al., 2017; Lasheen et al., 2017; Nabipour et al., 2017). In the following sections, the behaviour of a traditional IncCond method under fast changing irradiation conditions is evaluated. The results show that the efficiency under fast changing conditions can be improved. In this paper, a new IncCond method is proposed, implemented, tested and compared with this conventional algorithm under different irradiation conditions.

3.1. Conventional incremental conductance method

The IncCond approach is used extensively in practice because of its ease of implementation. IncCond technique has some difficulties in adjusting the step. The size of the step will determine the tracking speed, when the step-size is large, the system response rapidly, but the PV system may not work at the real MPP, and the oscillations around the MPP will be significant. On the other hand, its tracking time is relatively long since the step-size is tuned to be small enough to reach the desired MPPT. Also, its behaviour can be erratic when irradiation levels change rapidly. This method uses current and voltage sensors to measure the output current and voltage of the PV module (Rezk and Eltamaly, 2015). This technique computes the peak power point by comparing the incremental conductance $\frac{dI_{pv}}{dV_{pv}}$ to the conductance

$\frac{I_{pv}}{V_{pv}}$. When the gradient $\frac{dI_{pv}}{dV_{pv}} = 0$, the PV panel operates at the MPP

(Houssamo et al., 2013; Ma et al., 2016). Eqs. (14)–(17) are used in this method to identify the optimal operating point of the PV panel (Kok Soon et al., 2013). The flowchart of the traditional IncCond technique (Kok Soon et al., 2013; Williams et al., 2016) is shown in Fig. 6.

$$\frac{\Delta P_{pv}}{\Delta V_{pv}} = 0 \quad (14)$$

This equation can be rewritten as:

$$\frac{\Delta P_{pv}}{\Delta V_{pv}} = \frac{\Delta(I_{pv} \cdot V_{pv})}{\Delta V_{pv}} = \frac{V_{pv} \cdot \Delta I_{pv}}{\Delta V_{pv}} + \frac{I_{pv} \cdot \Delta V_{pv}}{\Delta V_{pv}} \quad (15)$$

$$\frac{\Delta P_{pv}}{\Delta V_{pv}} = \Delta V_{pv} \frac{\Delta I_{pv}}{\Delta V_{pv}} + I_{pv} \quad (16)$$

which implies that

$$\frac{\Delta I_{pv}}{\Delta V_{pv}} + \frac{I_{pv}}{V_{pv}} = 0 \quad (17)$$

In Fig. 5, the tracking process of a conventional MPPT control with a fixed step-size in a SEPIC converter is plotted for both power and current versus voltage. The MPPT method tracks the optimal operating point and stabilizes around it with good efficiency in steady-state conditions.

3.2. Proposed MPPT method

The conventional IncCond method depends on the step-size perturbation; therefore, when it is not correctly adjusted, it cannot accurately track the maximum energy and causes energy losses (Chao and Wu, 2016). A large step-size results in quick convergence but also large energy losses. A small step-size can reach the MPP in a steady-state operation but cannot follow quick radiation variations. To improve the IncCond method, the proposed approach is designed to increase the tracking accuracy by eliminating the steady-state perturbation and preventing the loss of direction towards the MPP. The flow chart of the proposed IncCond algorithm is shown in Fig. 7. Eq. (18) is used to create two operating areas (as shown in Fig. 8), where Z is a small value (0.001 in this implementation). Operating areas A and B have large step (LS) and small step (SS) for the step-size, respectively.

$$\left| \frac{\Delta P_{pv}}{\Delta V_{pv}} \right| \leq Z \quad (18)$$

$$\frac{\Delta I_{pv}}{\Delta V_{pv}} + \frac{I_{pv}}{V_{pv}} < e = 0.04 \quad (19)$$

In area A (condition (18) cannot be reached), the step-size is settled as LS to quickly track the MPP. In area B, the MPP lays, and condition (17) can be satisfied. Therefore, in this area, the step-size is settled as SS for a more precise search of the MPP. In short, the algorithm uses a large step-size (LS) when the system operates far from the MPP and a small step-size (SS) when the system operates near the MPP (area B). Another important test was added (19) to detect whether there are large variations in either irradiation or load. The program continuously checks this test. If this condition is not verified, large changes occur in either the load or the solar irradiation. Thus, the algorithm sets up the step-size as LS. If condition (19) is satisfied, no variations occur in the load and solar irradiation, and the system continues to search the MPP with the defined step-sizes in the function of the areas determined by (18). Because (19) rarely achieves zero, a small tolerance is used: $e = 0.04$.

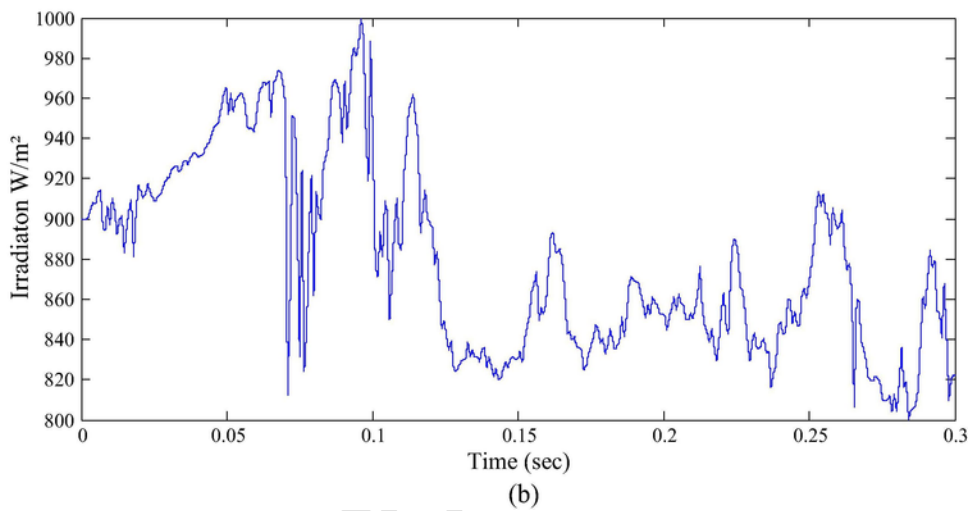
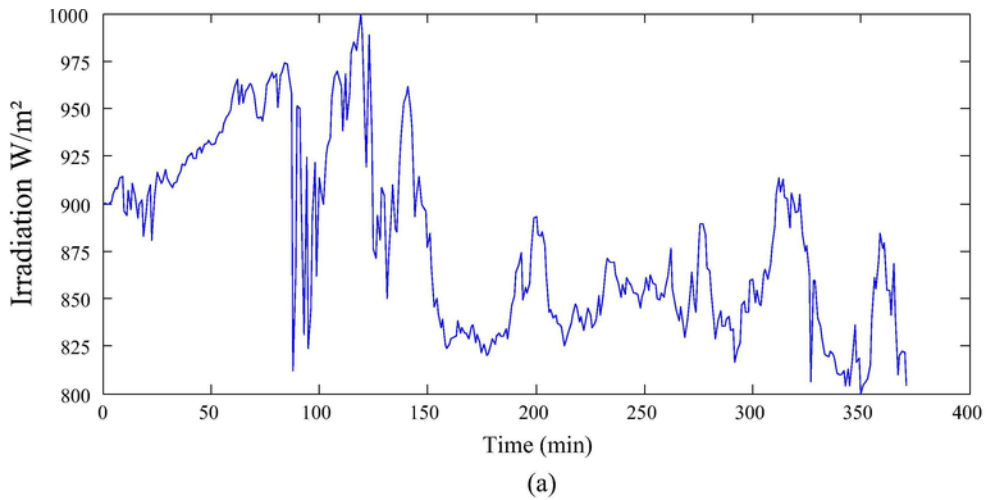


Fig. 17. Real scenario of solar irradiation: (a) Full recollected data; (b) evaluation period.

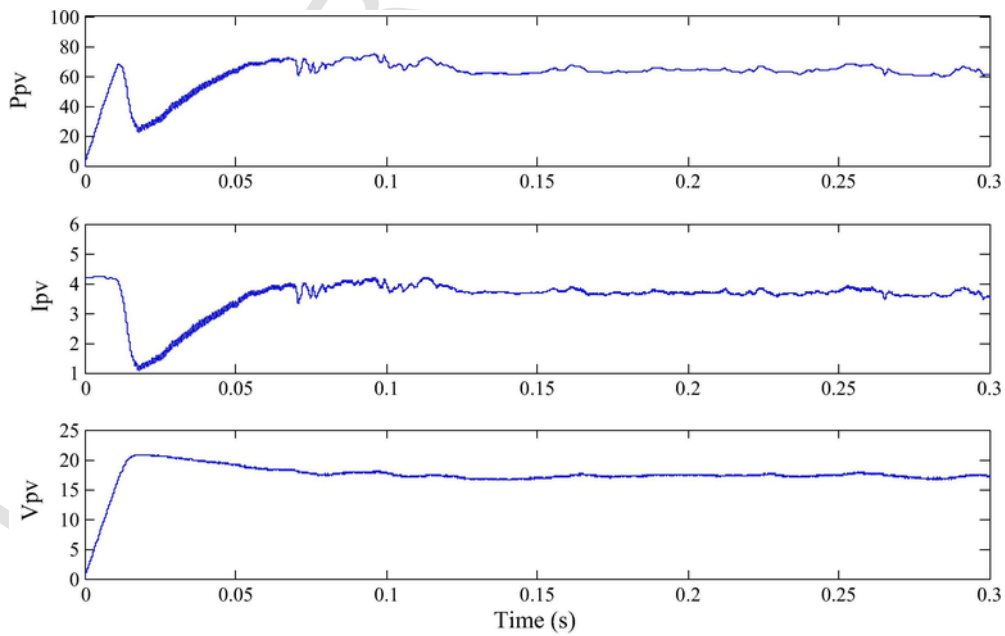


Fig. 18. Tracking waveforms for the PV power, current and voltage, which were obtained using the traditional IncCond approach.

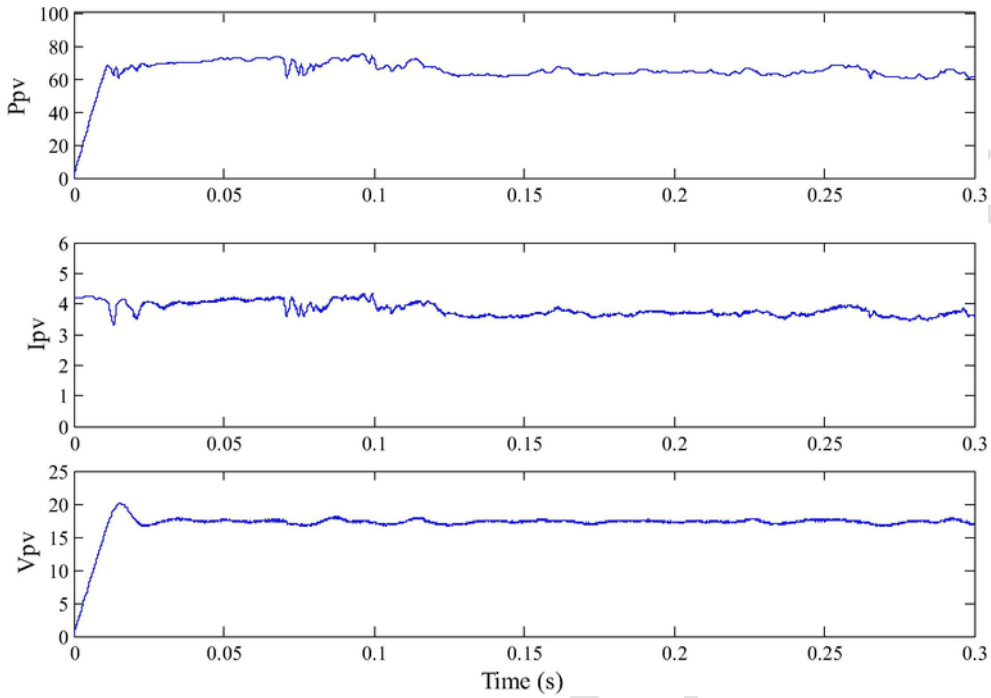


Fig. 19. Tracking waveforms for the PV power, current and voltage, which were obtained using the proposed IncCond approach.

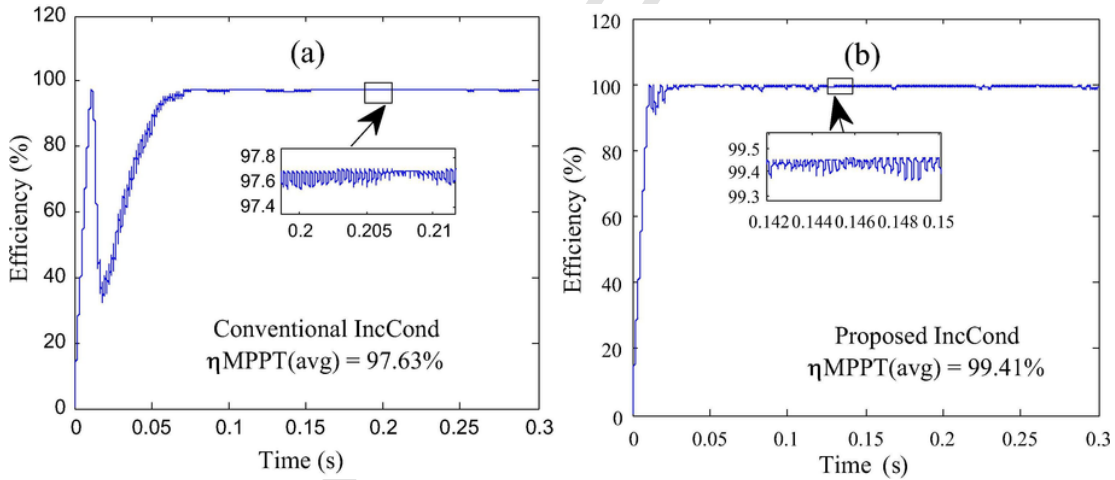


Fig. 20. Tracking efficiency: (a) traditional IncCond technique; (b) proposed IncCond technique.

4. Simulation results

The proposed system has been verified using the MATLAB/Simulink environment. The block diagram of the overall MPPT system is shown in Fig. 9. The PV module is ISOFOTON IS-75/12 (Table 1) (Necaibia et al., 2015). The conventional and proposed IncCond approaches are simulated in various operating conditions to compare these MPPT methods under identical operating conditions.

In this section, the MPP-tracking efficiency of the two techniques is first evaluated under the test conditions (various types of irradiance as shown in Fig. 10) and a real solar irradiation scenario (Fig. 15). In the next section, an actual implementation is performed. The efficiency is calculated using (20).

$$\eta_{MPPT} = \frac{P_{MPP}(t)}{P_{MPP^*}(t)} \times 100 \tag{20}$$

The average MPP-tracking efficiency is obtained from (21) by integrating the instantaneous available output PV power (P_{MPP^*}) and instantaneous extracted power using the MPPT approach (P_{MPP}).

$$\eta_{MPPT} = \frac{\int P_{MPP}(t) dt}{\int P_{MPP^*}(t) dt} \times 100 \tag{21}$$

4.1. Test case evaluation

This test aims to assess both tracking velocity and tracking accuracy under different types of irradiance through simulations. The irradiance level is changed from 500 W/m² to 1000 W/m² with fast, slow and sudden step changes, as shown in Fig. 10. The tracking waveforms of the power, current and voltage by the conventional and proposed methods are presented in Figs. 11 and 12, respectively. The conven-

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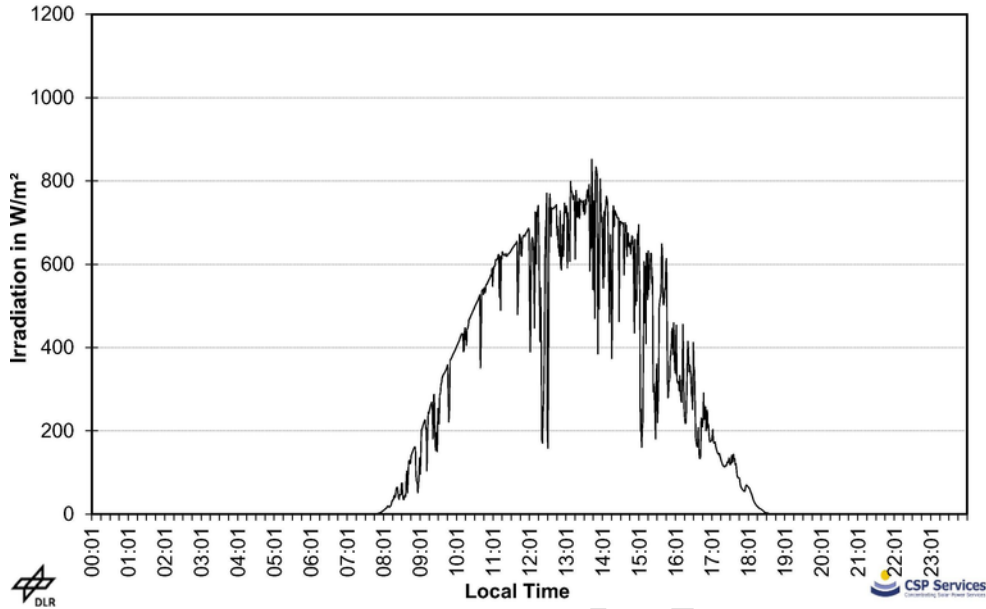


Fig. 21. Irradiance, Meteorological Station of Adrar, Algeria.

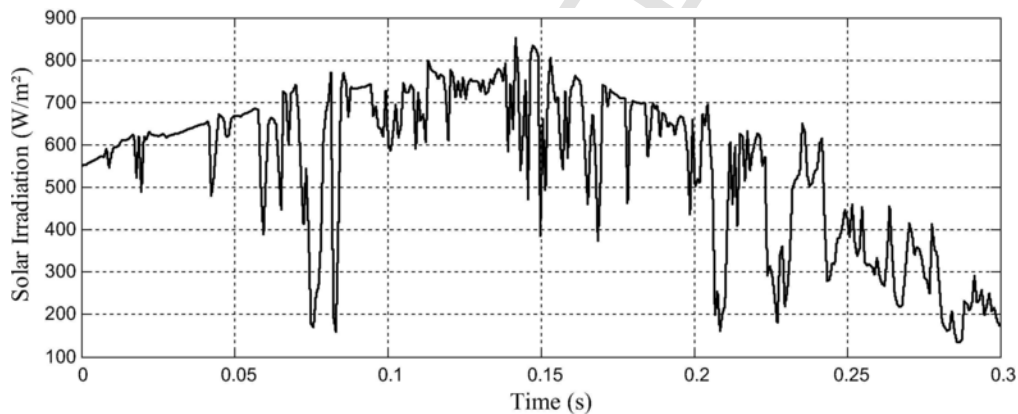


Fig. 22. Real scenario of solar irradiation, cloudy conditions.

tional IncCond technique measures the current and voltage step by step, which requires 0.65 s to finish the tracking process, for a step-size of 0.003. The proposed method accelerates the transient tracking time and requires 0.05 s to reach the MPP for $LS = 0.01$ and $SS = 0.001$. Therefore, the tracking velocity of the proposed algorithm is 7.7% of that of the conventional algorithm.

Fast decreases and increases in solar irradiation (sudden step changes) make the conventional algorithm drift away from the MPP and cause a decrease in tracking efficiency and energy losses. However, the proposed algorithm can almost perfectly follow the variations. The results clearly show that the proposed technique has better performance than the conventional technique (faster settling time and no loss of direction), which results in an increase in energy harvested by the PV module under rapidly changing conditions in solar insolation profiles.

Regarding the tracking efficiency, $\eta_{MPPT(ave)}$ of conventional technique is 97.7% (Fig. 13(a)). The efficiency is affected by the tracking error of the maximum energy point and loss of direction at sudden changes in solar irradiation. For the proposed method, $\eta_{MPPT(ave)}$ is 99.48% (Fig. 13(b)), which is an increase of 1.78%. In photovoltaic applications, this improvement can be notably important in terms of rev-

enue because the PV systems have a lifetime of more than twenty years, and the irradiance values continuously change.

To provide a complete assessment under changing solar irradiation, the response for a cloudy day is tested for both conventional and proposed MPPT approach. Simulations are carried out for a period of 6.5 s at 25 °C temperature, using the profile (Fig. 14) proposed by (Peng et al., 2018b).

From Fig. 15, the suggested IncCond approach performs better than the traditional one and has faster convergence speed and efficiency under rapidly changing solar irradiances. The proposal is able to find the new maximum PV power after each change in solar irradiation of the figure, without significant fluctuation in power.

4.2. Real scenario of solar irradiation

The simulations presented below were performed using the measurements collected from a weather database in the city of Adrar (Algeria) at the weather acquisition station in Fig. 16. The converter is supposed to supply a load near Adrar. In Fig. 17(a), the evolution of the irradiation data for 371 min of a typical day is presented. In Fig. 17(b), a portion of recollected data in Fig. 17(a) is extracted to evaluate the be-

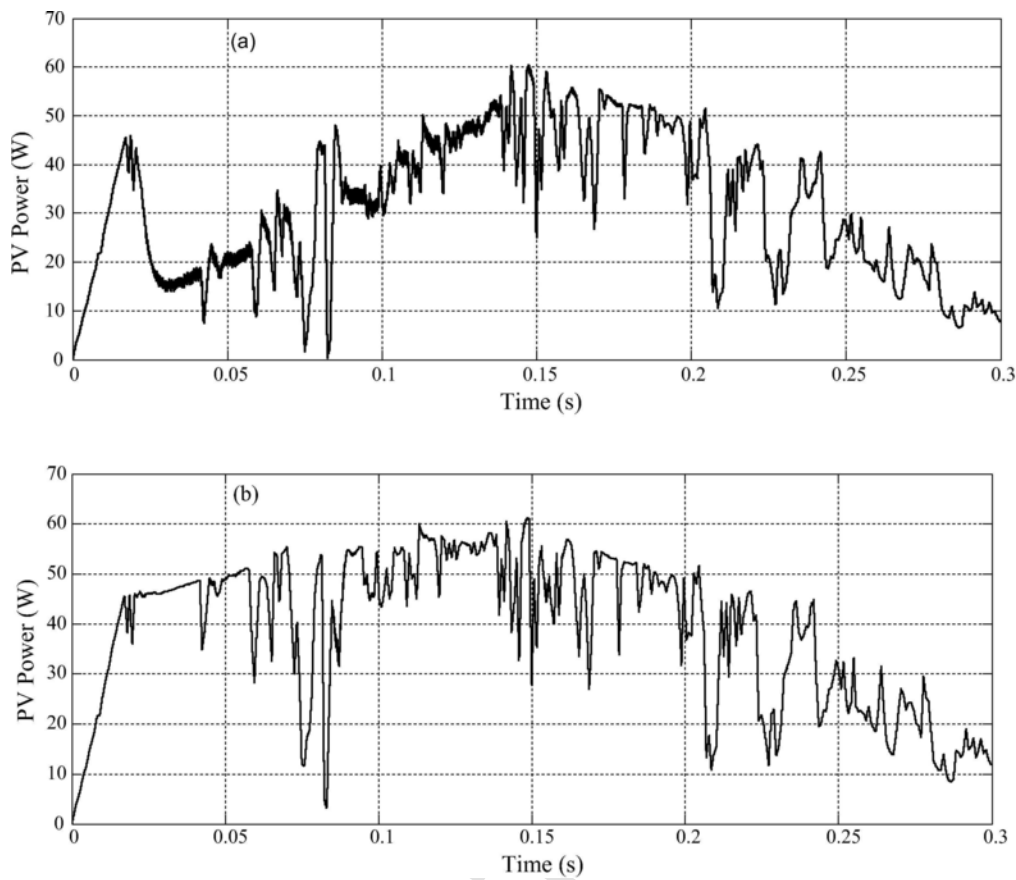


Fig. 23. PV power waveforms under cloudy conditions for: (a) Conventional IncCond approach, (b) Proposed IncCond approach.

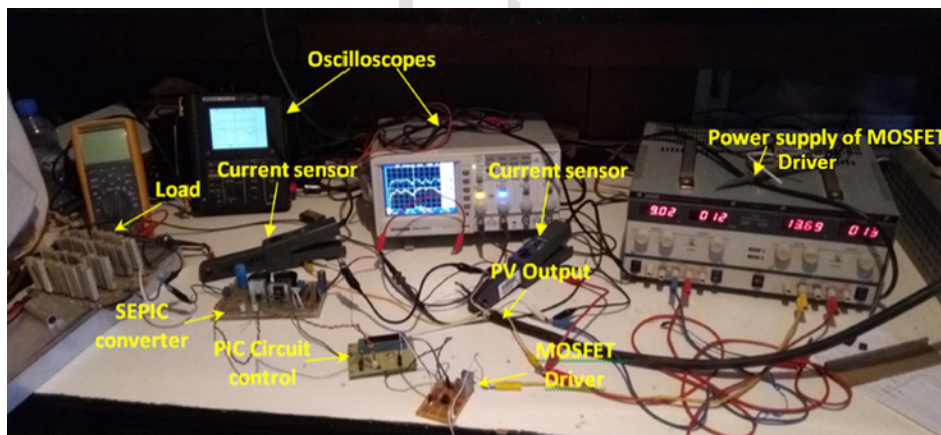


Fig. 24. Components of the PV system under test.

behaviour of the conventional and proposed MPPT approaches. Continuous variations in solar irradiance are observed in the real data. The tracking waveforms of the power, current and voltage of the conventional and proposed methods are shown in Figs. 18 and 19, respectively. The Conventional IncCond method is notably slow to reach the optimal operation: it takes 0.07 s to reach the transitory regime. The proposed method accelerates the tracking time and takes 0.01 s to reach the optimal operation. Thus, the proposed technique performs better in terms of tracking speed to the PPM.

$\eta_{MPPT(ave)}$ of the conventional and proposed methods is 97.63% and 99.41%, respectively (Fig. 20). Therefore, with real data, the efficiency

of MPPT increases by approximately 1.80% compared with the conventional approach, which confirms the high-precision tracking quality of the proposed approach.

The simulation results show that the modified algorithm offers more speed convergence to reach the desired MPP with less error for maximizing the delivered PV panel power. In the next section, practical results are presented by implementing the proposed method in a low-expensive microprocessor.

Real conditions from the same meteorological station are used to test the behaviour of proposed algorithm in a cloudy day. The evolution of the irradiation data for the cloudy day is presented in Fig. 21.



Fig. 25. PV panel under test.

An extract of 0.3s of irradiance at this localization is presented in Fig. 22.

In Fig. 23, the simulations for conventional and proposed IncCond approaches are shown, for the irradiation of Fig. 22. Traditional IncCond technique cannot track the MPP correctly under fast varying solar irradiance conditions, mainly in the interval between 0.05 and 0.1 sec. Lower tracking control results in significant losses and reductions in the power to be delivered to the load. On the other hand, with the proposed approach, a very close MPP tracking is observed.

5. Experimental results

The overall experimental system consists of several components: a DC-DC converter, a gate-drive, a microcontroller, a load (Fig. 24) and the PV panel (Fig. 25). The experiments were performed to test the performance of the proposed method in a difficult atmospheric condition in the Saharan desert near the city of Adrar, Algeria.

The presented results of two typical tests were obtained at 10h:53min (proposed algorithm) and 11h:24min (conventional method) of a standard day, December 22, 2016. In Figs. 26 and 27, the irradiance and temperature at this localization are shown, as obtained from the meteorological station of Adrar. The irradiance and cell temperature are 437.64 W/m² and 11.82 °C at 10h:53min and 498.98 W/m² and 12.93 °C at 11h:24min. The effectiveness of the proposed MPPT approach was evaluated using a commercially available microcontroller PIC16F877A and the PV module ISOFOTON IS-75/12. The results of these two tests are shown in the oscilloscope screens of Figs. 28 and 29.

In Figs. 28a and 29a, the traditional MPPT technique produces sharp fluctuations in the steady state because of the size of the perturbation step and irradiation profile, which causes power losses in the PV production. The proposed variable-step-size MPPT technique limits the amplitude perturbation around the MPP to a notably low value with a high tracking velocity and good dynamic response (Fig. 29b).

6. Conclusion

In this paper, a new IncCond MPPT technique has been developed and implemented to eliminate some tracking drawbacks of the conventional method. The obtained results confirm the enhanced performance of the proposed MPPT approach and demonstrate that with various types of irradiance, the PV system can perform better under changing irradiation conditions. The suggested method provides good dynamic performance in simulations and real scenarios of solar irradiation in Saharan desert, Algeria. The MPP is quickly attained (the tracking velocity of the proposed algorithm is 7.7% of the conventional approach), the convergence time in the transient states is short (in the order of 0.01 s), and the oscillation in the steady state is considerably dimin-

enerMENA High-Precision Meteorological Station in Adrar, Algeria - 1 min, December 22 2016

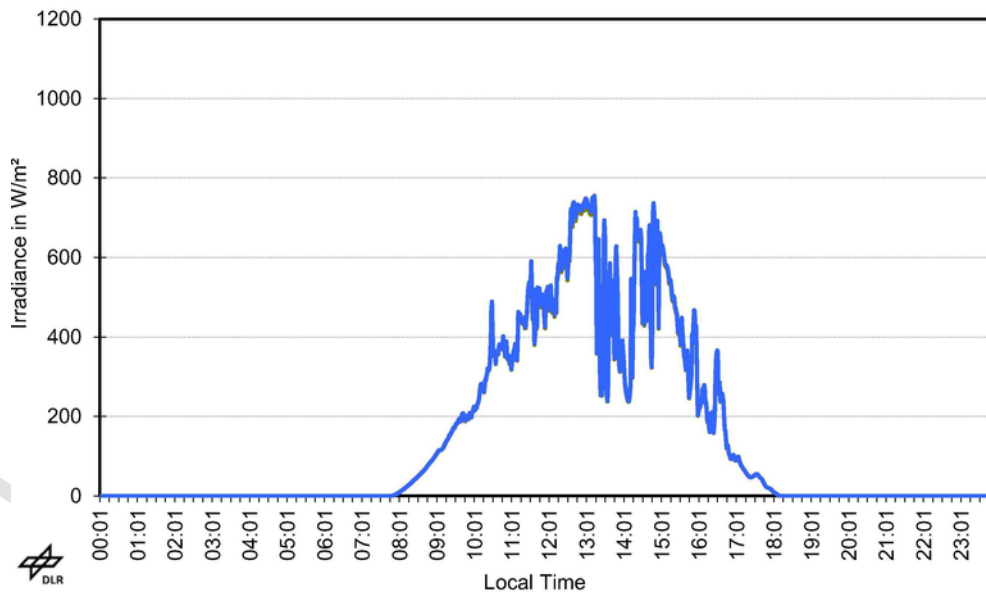


Fig. 26. Irradiance, Meteorological Station of Adrar, Algeria.

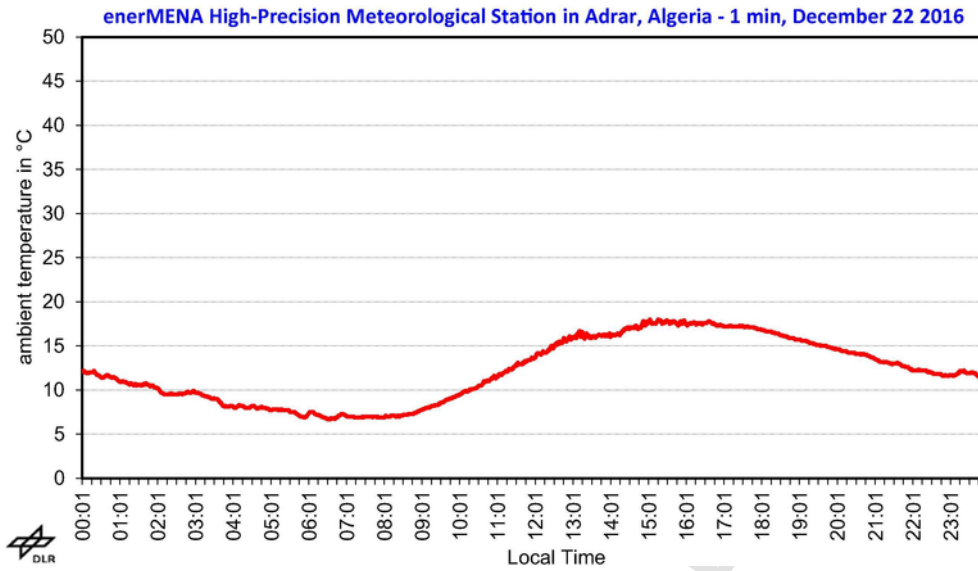


Fig. 27. Ambient temperature, Meteorological Station of Adrar, Algeria.

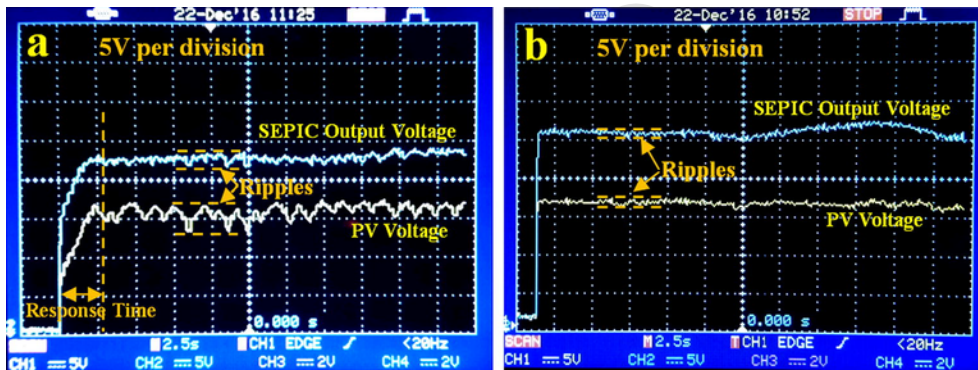


Fig. 28. Output voltage of the PV-module and SEPIC Converter: (a) traditional IncCond approach; (b) proposed IncCond approach.

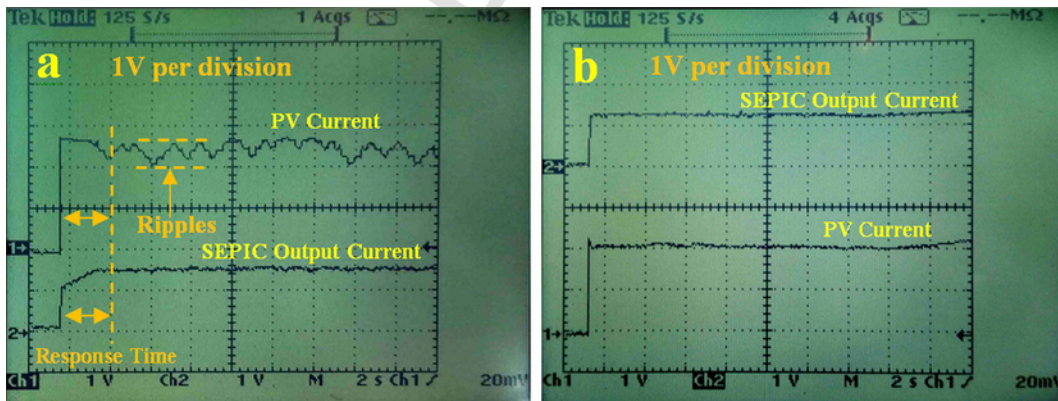


Fig. 29. Output current of the PV-module and SEPIC converter: (a) traditional IncCond approach; (b) proposed IncCond approach.

ished (as shown in the oscilloscope pictures). In addition, the proposed method can be easily implemented in low-cost and low-power conception microcontrollers.

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