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Alternating multi-stage maximum power point tracking controlled parallelled photovoltaic systems for "solar cooker"

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Abstract

In this paper we propose the control of a parallel multi-stage photovoltaic (PV) system using a reliable and precise Maximum Power Point Tracking (MPPT) control strategy. This technique is based on the acquisition of the electrical output quantities (voltage, current, and power), common to DC/DC converters, and the control of the power switches, in alternation. In the case of two stages, during the time t_i, converter 1 is regulated in real time by the MPPT control, and the second converter keeps the previous MPPT optimization parameters (t_{i-1}). During the following time t_{i+1}, converter 1 retains the previous MPPT optimization parameters (t_i) and converter 2 is regulated in real time by the MPPT controller. The proposed technique is experimented on a photovoltaic system that feeds a solar cooker. This system is formed by a thermal resistance, two types of PV panels (200 and 230 W) and two DC/DC converters. Compared to the classical technique (instantaneous control), the results obtained show a significant performance and improvements: Convergence speed towards the maximum power point PPM of 48%, variations the electrical quantities gaps (current, voltage, power) at the input and output of the DC/DC converters by a factor of 2.46, electrical energy production of 4%, plate heating temperature of 27.3%, and an efficiency of 5%. The temperatures of the thermal resistances are validated by the thermal models established during this work. The improvements in DC/DC converter performance and solar cooker heating temperature are attributed, on the one hand, to the nature of the proposed MPPT control, which reduces the dispersion of electrical quantities at the input and output of the DC/DC converters, and, on the other hand, to the rapid heating of the solar cooker by the electrical energy produced by the photovoltaic panels.

KEYWORDS

alternating MPPT control, alternating PWM signals, efficiency, heating temperature, maximum power point PPM, multi-stage photovoltaic system, photovoltaic cooker

1 | INTRODUCTION

Currently, in terms of reliability and cost, photovoltaic installations are the best alternatives for supplying electricity thanks to their increasingly cheaper costs, their increasingly high yields and their simplicity of installation. These installations are equipped with different MPPT control systems[1–8] in order to extract the maximum power, generated by the PV panels, based on the acquisition of the input electrical quantities (voltage, current and power). However, in an installation, the use of PV panels with different electrical parameters (open circuit voltages, short circuit currents and powers), the degradation and shading effect of the PV panels, considerably degrades the electrical functioning and optimal performance of the installation.

The majority of MPPT controls used so far adopt the perturb and observe (P&O) method, for single stage DC/DC converters. This method is based on acquiring the voltage and current at the input of the converter, calculating the electrical power and generating a PWM signal, following the sign of the power derivative.[1] This technique, known for its efficiency around 80%, and inaccuracy of converging to the point of maximum power PPM due to the significant dispersion of electrical quantities. In addition, due to climatic changes (shading, temperature…) the system is unstable and diverges to the conditions of open or closed circuit. The use of this MPPT control technique for multi-stage topologies requires the acquisition of the electrical quantities of each stage in order to independently control the switches of the DC/DC converters. This MPPP search procedure is incumbent from the point of view of the overall system structure, and consequently the complexity of the algorithm used and imprecision in terms of finding the PPM point. To overcome all these imperfections, we propose in this work an alternating MPPT control which is based on the acquisition of the output quantities to generate the PWM signals of each stage.

In applications, and particularly in PV energy cookers,[9–12] these techniques pose the problems of convergence towards the point of maximum power PPM,[1] of non-optimal operation of converters, of supply of thermal resistances by suitable electrical powers and therefore very low thermal and overall efficiency. In the literature, we find, practically, the absence of reliable results on the feasibility of these new generation cookers with PV energy. The main published works use solar batteries to power thermal resistors.[12–14] In Joshi and Jani,[13] the electrical power (around 75 W) and the cooking temperature (<120°C) provided are very low compared to those required by the users (>400 W, >200°C) and the cost is very excessive due to the use of batteries.

In this context, and to remedy the problems encountered in the literature, we propose a technique for optimizing the powers supplied by the PV panels by N stages of DC/DC converters, which supply the adequate energy to a common load (Resistors thermal). This technique is based on the use of electrical output quantities (voltage, current and power) and control of the switches of the converters by alternation. During the Δti time, the P converter ($1 < P < N$) is regulated in real time by the MPPT control and the other converters keep the previous MPPT optimization parameters during the Δt_{i-1}. During the following time Δt_{i+1}, the converter $P + 1$ is regulated in real time by the MPPT command and the other converters keep the previous MPPT optimization parameters (Δt_i).

In this paper we present the algorithm of the proposed technique for generating alternating PWM signals in the case of two converters ($N = 2$). Then, we apply this algorithm to a cooker (Hot plate) powered by a PV system, equipped with two types of PV panels (one 230 W panel and two 100 W panels each connected in parallel), two stages of DC/DC converters, supporting a power of 400 W each, and thermal resistance. The thermal resistance, connected to the outputs of the two converters, withstands currents of 10 A, voltage 100 V and temperature of 1,000°C. The choice of this system is part of the continuity of the patent awarded to our team by the Moroccan Office of Industrial and Commercial Property OMPIC in 2019.[15] The results obtained are compared to conventional methods, where the switches are controlled by two MPPT commands at the same time. Particular attention is paid to improving the duration of the heating of the water as well as the heating of the oil which shows the cooking temperature offered by the solar cooker, equipped with this MPPT control thus proposed.

2 | DOUBLE-STAGE PV SYSTEM STRUCTURE AND OPERATION

2.1 | Structure of the photovoltaic system

In Figure 1 is shown the structure of the two-stage system, with MPPT control by alternate proposed, in order to produce sufficient electrical energy that feeds a thermal resistance of a solar cooker (Hotplate). The different blocks of this system are the following:

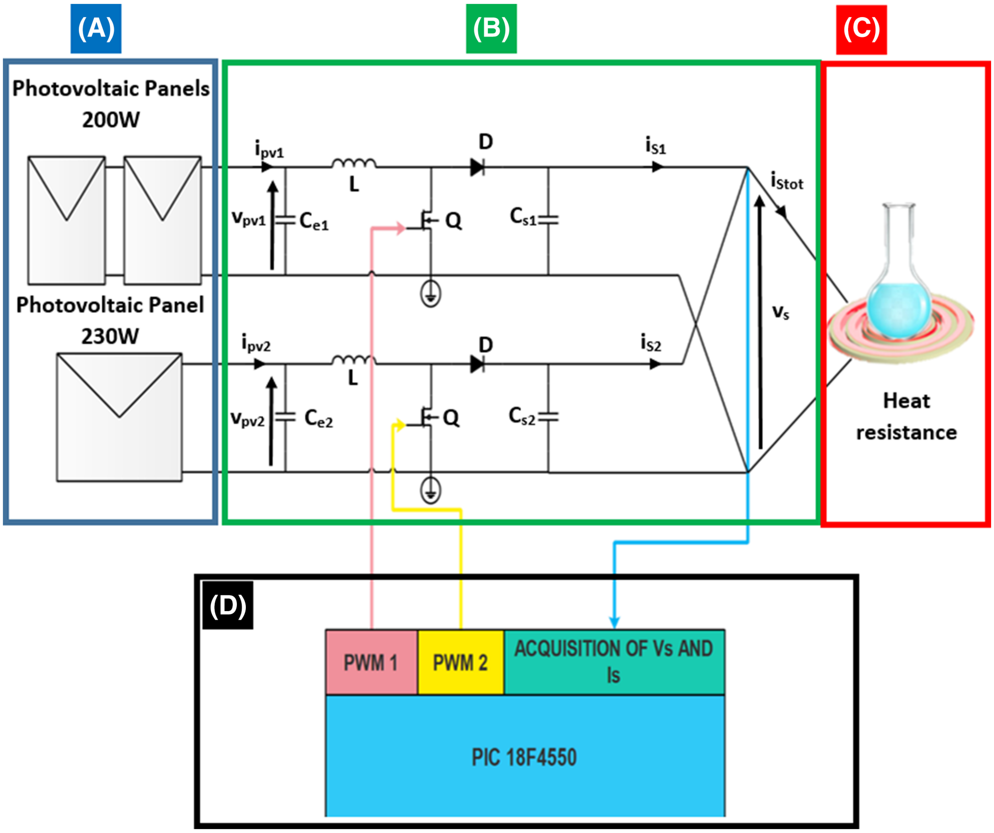

FIGURE 1 Block diagram of the double-stage photovoltaic system with MPPT control by alternate proposed

- **Block A:** Photovoltaic generator, formed by two types of PV panels, delivering an overall power of 430 W/peak. This power is calculated to provide sufficient energy to prepare all the cooking during a day at home (Heating water to 90°C, cooking at a temperature above 200°C).
- **Block B:** Two Boost-type DC/DC converters sized to operate at a frequency of 10 kHz and a power greater than 400 W each.[7] These converters are controlled by two PWM signals of frequency f = 10 kHz and of variable duty cycle α_1 and α_2. The choice of PV panels and the operating powers (400 W) require the use of the following:
- Inductors L = 100 μH,
- Capacitors Ce1 = Ce2 = 1,000 μF and Cs1 = Cs2 = 400 μF, supporting voltages of respectively 80 and 100 V,
- Low threshold voltage power diodes D,[7,16]
- MOSFET power switches, supporting currents of 33 `, voltage 100 V and low Ron voltage of 0.04 Ω.
- **Block C**: Load formed by a thermal resistance of 12 Ohm, supporting a current of 10 A, voltage of 100 V and temperature of 1,000°C.
- **Block D:** Digital circuit that manages the operation of the entire system, with MPPT control by alternate proposed. It is mainly formed by a microcontroller (PIC 18F4550) which ensures the acquisition of electrical quantities (voltage, current and power) at the input and output of converters, meteorological (lighting, ambient temperature) and thermal (temperature of the thermal resistance. and cooking). In addition, it generates the two PWM signals, of variable duty cycle α_1 and α_2, suitable from an algorithm set up during work (Figure 2).

2.2 | New MPPT and algorithm command by Alternate

To remedy the problems, drawbacks and malfunction of MPPT commands, discussed in the introduction, we propose a new method, requiring no change of electronic board, when adding a new stage, and characterized by its very fast

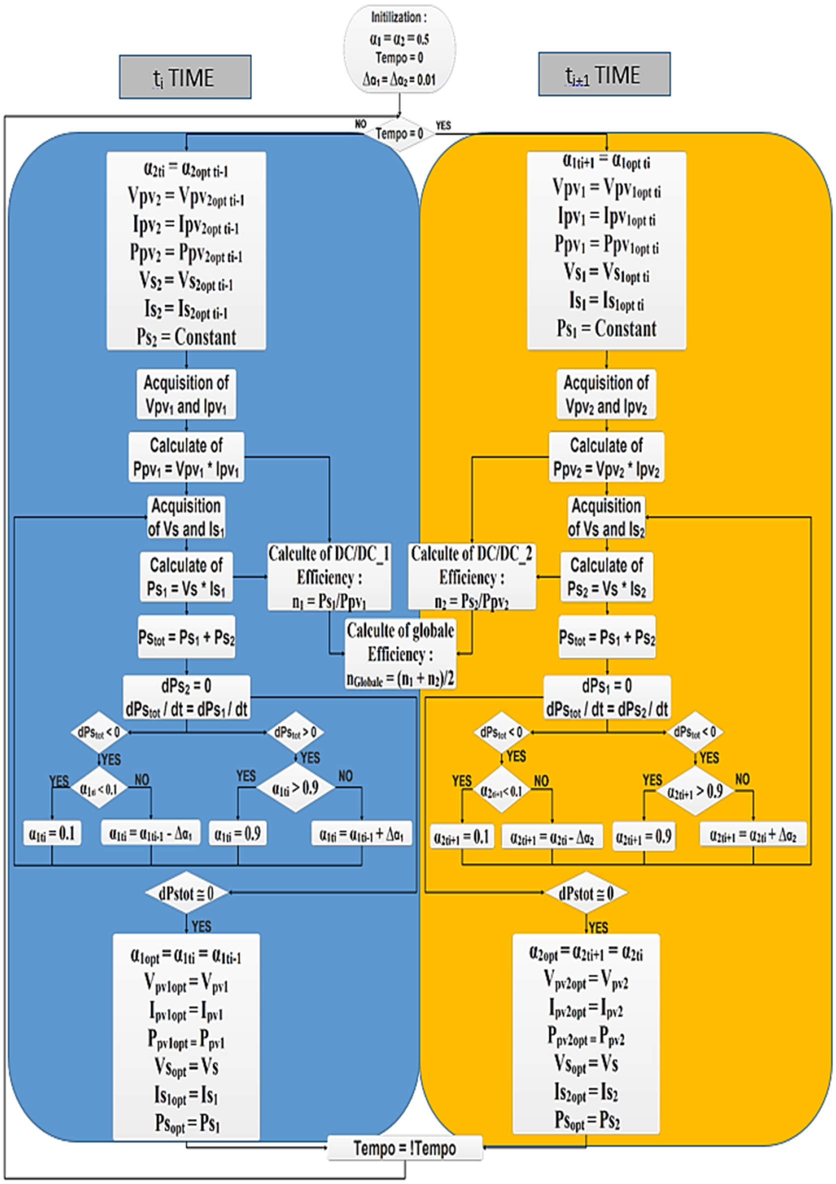

FIGURE 2 MPPT command algorithm by Alternate

execution speed ($\Delta t < 10$ ms). In our case, in an application using two stages of adaptations, the algorithm of Figure 2 shows the execution steps of the program, set up, to regulate, according to our concept, the operation of the converters around the MPP of PV panels. The main steps of this algorithm are the following:

- the acquisition of current and voltage at the common output of the two stages,
- The use of two PWM outputs of the microcontroller to control each stage,
- The two power switches of the two DC/DC converters are alternately controlled. To do this
- The duty cycles $\boldsymbol{\alpha_1}$ and $\boldsymbol{\alpha_2}$ of the two PWM signals, which control the two converters, are initialized, by default, to the value **0.5**,
- Control of converter 1 during the time $\Delta t_i = 10$ ms:
- The value of the variable **Tempo** = **1**,
- Converter 1 is regulated in real time by the MPPT command,
- Converter 2 keep the previous MPPT optimization parameters $\boldsymbol{\alpha_2} = \boldsymbol{\alpha_{2opt}}$ during the time $\Delta t_{i\text{-}1} = 10$ ms, and the power at its output is fixed (Ps2 = Constant).
- The total output power and its derivative are given by the following:

$$Ps\,tot = Ps1 + Ps2 \tag{1}$$

$$\frac{dPs\,tot}{dt} = \frac{dPs\,1}{dt} \tag{2}$$

From the sign of the derivative of relation 2, the MPPT command regulates the operation of converter 1, by converging the operating point of PV panel 1 towards the MPP. In this situation,

- If dPstot/dt > 0 and if the duty cycle $\boldsymbol{\alpha_1}$ does not reach the value **0.9**, the duty cycle $\boldsymbol{\alpha_1}$ of the first converter is incremented, by a step $\boldsymbol{\Delta\alpha_1 = 0.01}$, up to the PPM (i.e., $\boldsymbol{\alpha_1 = \alpha_{1opt}}$). If not $\boldsymbol{\alpha_1 = 0.9}$.
- If dPstot/dt < 0 and if the duty cycle $\boldsymbol{\alpha_1}$ does not reach the value **0.1**, the duty cycle $\boldsymbol{\alpha_1}$ of the first converter is decremented, by a step $\boldsymbol{\Delta\alpha_1 = 0.01}$, up to the PPM (i.e., $\boldsymbol{\alpha_1 = \alpha_{1opt}}$). If not $\boldsymbol{\alpha_1 = 0.1.}$
- If dPstot/dt ≅ 0 then the duty cycle $\alpha_1 = \alpha_{1opt}$, $Vpv_1 = Vpv_{1opt}$, $Ipv1 = Ipv_{1opt}$, $Pvp_1 = Ppv_{1opt}$

- Control of converter 2 during the time Δt_{i+1}:

- The value of the variable **Tempo** = 0,
- Converter 2 is regulated in real time by the MPPT command,
- Converter 1 keep the previous MPPT optimization parameters $\boldsymbol{\alpha_1 = \alpha_{1opt}}$ during the time $\Delta ti = 10$ ms, and the power at its output is fixed (Ps1 = Constant).
- The total output power and its derivative are given by

$$Ps\,tot = Ps1 + Ps2 \tag{3}$$

$$\frac{dPs\,tot}{dt} = \frac{dPs\,2}{dt} \tag{4}$$

From the sign of the derivative of relation 4, the MPPT command regulates the operation of converter 2, by converging the operating point of PV panel 2 towards the MPP. In this situation,

- If dPstot/dt > 0 and if the duty cycle $\boldsymbol{\alpha_2}$ does not reach the value **0.9**, the duty cycle $\boldsymbol{\alpha_2}$ of the first converter is incremented, by a step $\boldsymbol{\Delta\alpha_2 = 0.01}$, up to the MPP (i.e., $\boldsymbol{\alpha_2 = \alpha_{2opt}}$). If not $\boldsymbol{\alpha_2 = 0.9}$.
- If dPstot/dt < 0 and if the duty cycle $\boldsymbol{\alpha_2}$ does not reach the value **0.1**, the duty cycle $\boldsymbol{\alpha_2}$ of the first converter is decremented, by a step $\boldsymbol{\Delta\alpha_2 = 0.01}$, up to the PPM (i.e., $\boldsymbol{\alpha_2 = \alpha_{2opt}}$). If not $\boldsymbol{\alpha_2 = 0.1}$.
- If dPstot/dt ≅ 0 then the duty cycle $\alpha_2 = \alpha_{2opt}$, $Vpv_2 = Vp_{V2opt}$, $Ipv_2 = Ipv_{2opt}$, $Pvp_2 = Ppv_{2opt}$.

- The variable Tempo = 1.

It should be noted that the values of the duty cycles $\boldsymbol{\alpha_1}$ and $\boldsymbol{\alpha_2}$ are between **0.1** and **0.9** to avoid the cases of short circuit and open circuit. This preserves the proper functioning of the MOSFET and prevents its damage.[3]

2.3 | THERMAL MODELING: Application of heating the thermal resistance

We have chosen the application of the solar cooker with PV energy, because, in the literature, the proposed prototypes use only solar batteries[13] and the expected performances are not obtained (temperature < 120°C). Therefore, the heating of these cookers, without batteries, during the sunny day, requires the use of PV systems, DC/DC converters and the appropriate MPPT controls. We propose to use a multi-stage DC/DC converters in parallel, controlled by our new alternating MPPT control. Our goal is to heat up to a temperature above 200°C and rapid increases of this temperature during heating.

2.3.1 | Numerical model

In this paragraph, we have established the thermal model governing the heating of thermal resistance, with solar/photovoltaic energy (Figure 1), based on the principle of thermal energy balance includes the first law of thermodynamics

Equation 5.[17,18] The temperature variation of the thermal resistance T_r is written as a function of the absorbed electrical energy P_s, the energy exchanged in the form of heat flux by convection P_{cv} thermal energy emitted by radiation P_r by the following equation:

$$P_s = P_{store} - P_{cv} - P_r \tag{5}$$

with

Ps = electric energy absorbed by the heating resistor,

P_{store} = energy stored in the resistor due to the change in energy storage in the resistor, due to the increase in its internal energy during time. It is given by the following:

$$P_{store} = m_r \cdot Cp_r \frac{dT_r}{dt} \tag{6}$$

where

mr = mass of the heating resistor,Cprspecific heat of the heating resistor,

Tr = temperature of the heating resistor

P_{cv} = thermal energy exchanged by convection, it is calculated by the following relation[17,18]:

$$P_{cv} = h_{cv} S_r (T_r - T_{amb}) \tag{7}$$

where

h_{cv} = convective heat exchange coefficient between the heating resistor and the ambient environment,

S_r = exchange surface between the heating resistor and the external environment,

P_r = thermal energy emitted by radiation. It is calculated by the following relation[17,18]:

$$P_r = \sigma \varepsilon S_r \left(T_r^4 - T_c^4\right) \tag{8}$$

where

σ = Stefan–Boltzmann constant,

ε= emissivity of the heating resistor,

T_c = equivalent sky temperature. According to,[19] it is calculated as a function of the ambient temperature T_{amb} by the following relation.

$$T_c = 0.00552.(T_{amb})^{3/2} \tag{9}$$

Taking into account these Equations 5–8, the heat exchange balance model can be expressed by the following relation:

$$\begin{aligned} m_r \cdot Cp_r \frac{dT_r}{dt} &= P_s - P_{cv} - P_r \\ &= Ps - h_{cv} S_r (T_r - T_{amb}) - S_r \sigma \varepsilon \left(T_r^4 - T_c^4\right) \end{aligned} \tag{10}$$

2.3.2 | Thermal efficiency

We have subsequently determined the performance of the renewable energy cooker. This is done by estimating the power P_0 and the thermal efficiency η from the increase in water temperature (T_2-T_1), during time intervals [t_1,t_2] = 10 min, using the Funk model,[3] following the expressions

$$P0 = \frac{m \times Cp \times (T2 - T1)}{(\mathrm{t2} - \mathrm{t1})} \quad (11)$$

$$\eta = \frac{P0}{Ps} \quad (12)$$

with

m = mass of heated water (m = 1 L),

C_p = specific heat of the water (C_p = 4190 J/kg k),

P_s = ouput power delivered by the DC/DC converters.

3 | RESULTS AND DISCUSSIONS

3.1 | Experimental procedure

The application of the Cooker to PV energy, using the PV system, and which has been the subject of our experimental study is presented in Figure 3. This complete system is composed of the following:

- Block (**A**), which represents the source of solar photovoltaic energy. It is formed by the following:
  - Two types of monocrystalline PV panels. Type (1) is formed by two PV panels with an overall power of 200 W/peak, and type (2) by a single panel of 230 W/peak.
  - A meteorological station formed by a 10 W panel (3), a TCN type probe fitted with an adequate electronic circuit. It allows determining the intensity of lighting and the ambient temperature. The station is linked to the acquisition card (**B**).
- Power Block (**B**) formed by the following:
  - Two DC/DC boosters type.[16] Each converter is designed to operate at a chopping frequency of 10 kHz, a power of 500 W and a maximum current of 12 A.[20]
  - Two acquisition and control boards using a microcontroller (PIC 18F) which performs the following tasks:
    - The acquisition of electrical quantities at the input and output of converters, meteorological conditions (lighting and ambient temperature) and thermal quantities (temperature of the thermal resistance and of the cooking [C]).
    - The automatic generation of two PWM signals, of frequency of 10 kHz and of duty cycles α_1 and α_2, by executing the MPPT algorithm (Figure 2), to extract the maximum electrical power from the two types of PV panels. This allows the thermal resistances to be supplied under optimal conditions.

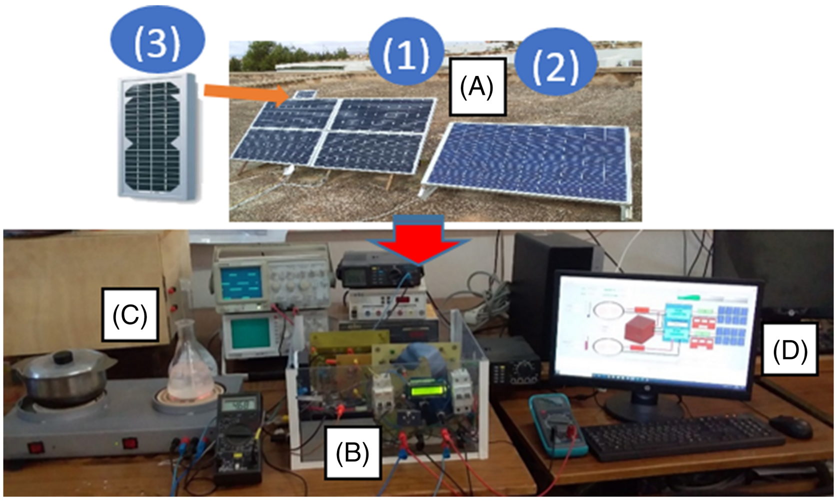

FIGURE 3 Application "photovoltaic cooker" with a photovoltaic system that executes the MPPT command by Alternate (Figure 2)

   - The manual generation of two PWM signals, with a frequency of 10 kHz and cyclic ratios α_1 and α_2. This mode makes it possible to extract the adjustable electrical powers of the two types of PV panels, to supply the thermal resistances.
   - Transfer of acquired data to the graphical interface (D).
- Two heating resistors (**C**) with a value of 12 Ω each. They are chosen to withstand currents of 10 A, at a voltage of 100 V, and a temperature of 1000°C.
- A computer (**D**) connected to the control and data acquisition card, via a USB link. It runs a LabVIEW language application for acquiring and storing data in an SQL database.[21]

3.2 | Photovoltaic generator

In order to validate the operation of our proposed MPPT controller, we used two types of PV panels in our double-stage system:

- Type 1: Two 100 W/peak panels in series for the first stage,
- Type 2: A single 230 W/peak panel for the second stage.

We noted the current–voltage and power-voltage characteristics of the two types of PV panels (1 and 2) used (Figure 3), during a sunny day. The typical electrical characteristics obtained on a panel, types 1 and 2, for illuminances varying from 250 and 800 W/m^2, are shown on Figure 4. From these characteristics, we have determined and represented on Table 1 the optimum electrical quantities. We can therefore deduce the following:

- The optimum electrical characteristics of both types of panels conform to those provided by the supplier.[22,23] For an illumination of 800 W/m^2, the power of type 1 is 70 W and type 2 is 180 W.

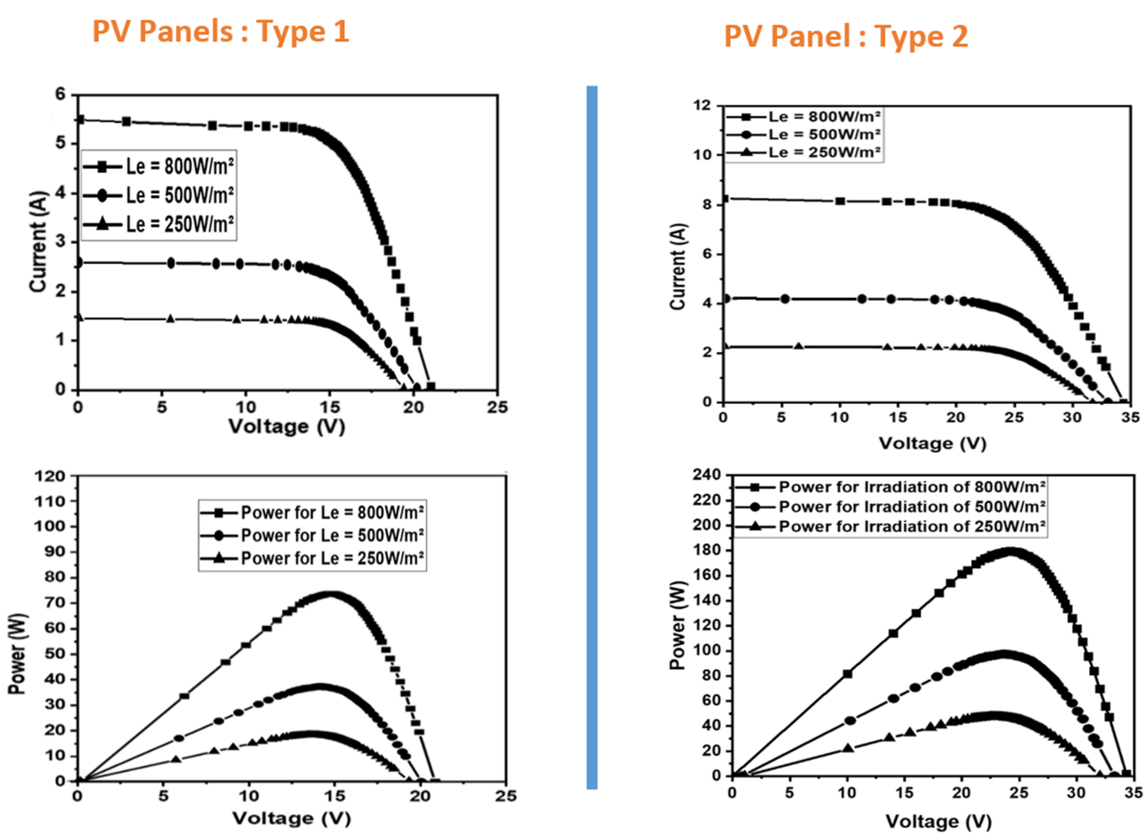

FIGURE 4 Current–voltage power-voltage characteristics of the two types 1 and 2 (Figure 3) of photovoltaic panels used, for three illuminations Le (250, 500, and 800 W/m^2). Ambient temperature = 25°C

TABLE 1 Optimal electrical quantities of a PV panel of Figure 3 (voltage: Vopt, current: Iopt, resistance: Ropt, power: Pot), types l and 2, in function of the irradiation Le

	Le (W/m^2)	Vopt (V)	Iopt (A)	Ropt (Ω)	Popt (W)
PV panel: type 1	250	14.8	1.3	11.38	19.24
	500	14.9	2.5	6	37.25
	800	15	4.5	3.4	70
PV panel: type 2	250	24	2	12	48
	500	24.5	3.9	6.3	95.5
	800	24.5	7.3	3.4	180

Note: Temperature = 25°C.

- Type 1 panels: when the illumination varies from 250 and 800 W/m^2, the power and optimum resistance of a single panel vary respectively from 19 to 70 W and from 11.38 to 3.4 Ω. In our case, by using a Boost converter, we connected the two panels in parallel. In this situation, the optimum power and resistance of our PV generator vary from 38 to 140 W and from 5.69 to 1.7 Ω, respectively.
- Type 2 panels: the power and the optimal resistance of the panel vary respectively from 48 to 180 W and from 3.4 to 12 Ω.

3.3 | Two-converter pv system operation

In order to show the validity of our proposed MPPT command, we experimented with the system of Figure 3 using the algorithm (Figure 2) of the new MPPT command, by exploiting the electrical quantities at the common output of the two DC/DC converters, and alternately controlling the two switches of the DC/DC converters. A comparative study is also carried out using the classic algorithm, by controlling the two switches independently and using the electrical quantities at the inputs of the converters. Also, to qualify each method, we determined the dispersion of each acquired electrical quantity. During a whole day, under an illumination of 700 W/m^2 and an ambient temperature of 25°C, for both methods, we have the following:

- Calculated the time of convergence towards the MPP,
- Record the variations of the cyclic ratios ($\boldsymbol{\alpha_1}$, $\boldsymbol{\alpha_2}$) controlling the DC/DC converters,
- Reading the voltages, currents and powers at the two inputs and common output of DC/DC converters,
- Calculated the overall efficiency of the system,
- Determine the maximum dispersion of each electrical quantity.

Typical electrical results obtained using the new Algorithm are shown in Figure 5, and the comparative study against the classical Algorithm is summarized in Tables 2 and 3. We can therefore conclude the following:

- In the case of the standard MPPT command the average convergence time is 700 ms, and in the case of the proposed MPPT command is 473 ms, that is, an improvement of 48%.
- For an illumination of 700 W/m^2 and an ambient temperature of 25°C (Figure 5), the maximum input voltage and current are respectively of the order of 35 V and 4 A for the first stage, and 27 V and 7 A for the second stage (Figure 5B,C).
- The common output voltage and current between the two converters are 52 V and 4.28 A (Figure 5D).
- The maximum input and output power are 263 and 226.5 W (Figure 5E).
- The efficiency of converters controlled by the proposed method is of the order of 86% (Figure 5G), that is, an improvement of 4.24% compared to the converter using standard algorithms.[1]
- The dispersions obtained using the proposed method are markedly improved compared to the standard method (Figure 5F). In the case of cyclic ratios, an improvement of 278% is observed. At around 2 p.m., where the illumination is at its peak, the new control delivers an output power that is 10 times more stable than the standard control. This therefore induces an improvement in the overall efficiency of 5%.

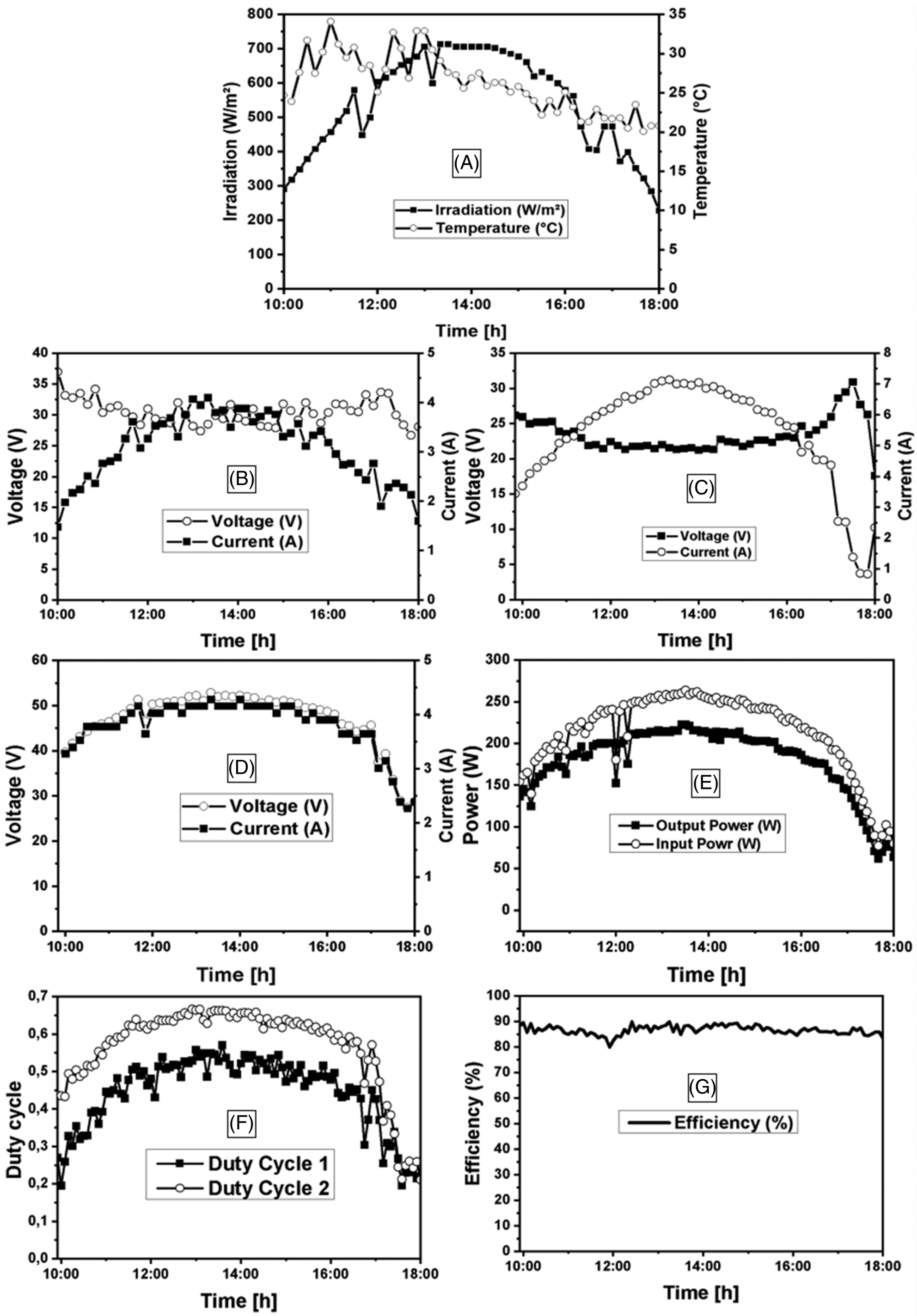

FIGURE 5 Typical irradiation and ambient temperature plots (A), input voltage and current of the first converter (B), input voltage and current of the second converter (C), output voltage and current of the two converters (D), total input and output power (E), duty cycles (α_1 and α_2) of the PWM signals (F), and efficiency of the two converters (G), using the MPPT command (Figure 3)

- The search for the maximum power point of one stage independently and alternately causes a slight variation in the output power of the other stage, but this variation is so minimal that it does not affect the operation of the system under optimal conditions.

The improved efficiency of DC/DC converters is attributed to the nature of the MPPT control, which is based on the common output power derivative of the parallel-connected stages. Each stage is alternately optimized independently.

TABLE 2 Maximum values and maximum dispersion of each electrical quantity using the proposed (command 1) and standard (command 2) MPPT command for the converter number 1

		Convertisseur 1						
		Tcon ms	α_1	Vpv1 (V)	Vs1 (V)	Pvp1 (W)	Ps1 (W)	η_1 (%)
Commande 1: New		473	0.56	35	52.9	117.8	102.5	87
	Dispersion (%)	-	4.6	15.7	0.7	2.03	0.7	2.8
Commande 2: Standard		700	0.57	35	51.6	116.5	95	81.4
	Dispersion (%)	-	17.4	17.8	3.7	7.42	11.2	11.2

TABLE 3 Maximum values and maximum dispersion of each electrical quantity using the proposed (command 1) and standard (command 2) MPPT command for the converter number 2

		Convertisseur 2						
		Tcon ms	α_2	Vpv2 (V)	Vs2 (V)	Pvp2 (V)	Ps2 (V)	η_2 (%)
Commande 1: New	Dispersion (%)	473	0.68	27	52.9	149.2	126.8	85
		-	2.7	2.1	0.7	2.2	0.7	2.7
Commande 2: Standard	Dispersion (%)	700	0.67	27	51.6	148.5	123.2	83
		-	8.4	3.7	8.5	7.01	11.1	11.2

This reduces the dispersion of electrical quantities, especially at the output, and consequently the efficiency of each DC/DC converter.

All the results obtained show a clear improvement in the operation of the system in Figure 3 using the proposed controller, regulating the operation of the two converters alternately. This is due to the stabilization of the output power of a converter (2 or 1), relative to the input power, by regulating the operation of a single converter (1 or 2). By comparing with the results of the literature, using the MPPT command, which is based on the generation of PWM signals from the input voltages and currents, we deduce remarkable performances in terms of speed (improvement of 48%), efficiency (improvement of 4.24%) and stability (factor of 4).

3.4 | Application: Solar cooker

To enhance the operation of the system of Figure 2, we heated around 2 pm, 1 L of water and 0.5 L of oil by regulating the operation of the system using the conventional method and our proposed MPPT control. Typical results obtained are shown in Figure 6. In the same Figure 6 we have represented the resistance temperature simulation results taking into account the specific, thermal and geometric characteristics of the resistance presented in Table 4. For an illuminance of 690 W/m^2, an ambient temperature of 30°C and an input power of the order of 200 W, the results obtained (Figure 6) show the following:

- The maximum output powers using the proposed control and the standard control are 226 and 202 W, respectively (Figure 6A,B), that is, an improvement of 12%,
- The temperature of the heating resistor reaches 730°C in the case of the new MPPT control, and 640°C in the case of the standard MPPT control (Figure 6C,D), that is, an improvement of 14%.
- Good agreement between simulation and experimental results concerning the heating of the thermal resistors. This clearly shows the validation of Equations 5–10 and the heating by photovoltaic energy.
- Water heating:
- After 10 min of heating, the water temperature drops from 23°C to 54°C using the standard control (i.e., 3.1°C/min) and from 23°C to 60°C for the proposed command (i.e., 3.7°C/min) (Figure 6C). This shows an improvement in the heating temperature speed of 19.35%.

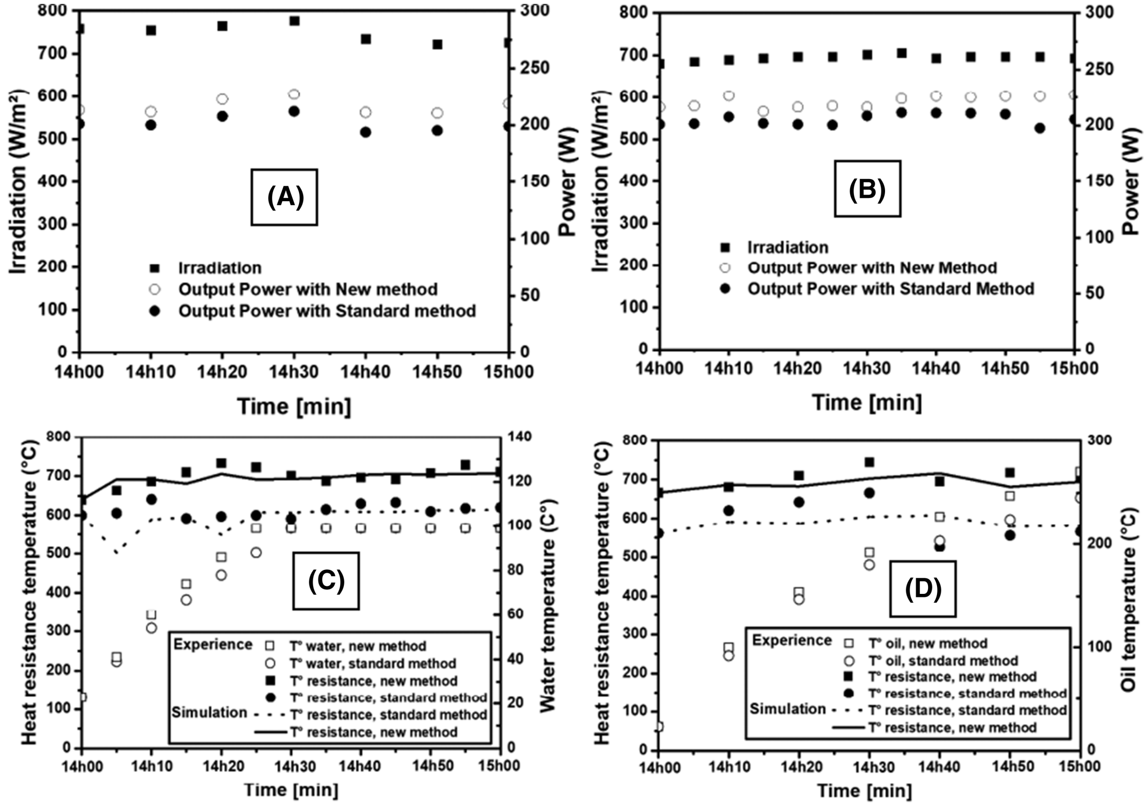

FIGURE 6 Typical plot of irradiation and output power used for water heating (A), typical plot of irradiation and output power used for oil heating (B), heating of the thermal resistor (simulation and experimentation, 1 L of water (C) and 0.5 L of oil (D) by the system in Figure 3 using the proposed and standard MPPT control

TABLE 4 Specific thermal and geometric characteristics of thermal resistance

Parameter	Value
Mass of the heating resistor	0.003634 kg
Specific heat of the resistance	445 J/kg k
Convective heat exchange coefficient	30–50 W/m^2 k
surface resistance	0.004 m^2
Stefan–Boltzmann constant	5.670*10^{-8} W/m^2 k^4
Emissivity of the heating resistor	0.9

- The average thermal efficiency achieved with the standard MPPT control is 69.12% compared to 74.1% with the proposed MPPT control,), that is, an improvement of 7.2%.
- The boiling time of a liter of water (90°C) is 26 min with the standard command and 21 min with the proposed command, that is, an improvement of 23.8%.
- The water reaches the maximum temperature (100°C) after 30 min of heating with the standard control and 25 min for the proposed control, that is, an improvement of 17%.
- Oil heating:
- The oil temperature varies from 23°C to 100°C in 10 min (i.e., 7.7°C/min) using the proposed method, and from 23°C to 92°C (i.e., 6.9°C/min) using the standard method (Figure 6D).
- In 30 min of heating, the oil temperature reaches 192°C (i.e., 5.9°C/min) using the proposed method and 180°C using the standard method.
- Using the proposed control (standard), the oil starts to vaporize after 40 min (53 min) of heating, to stabilize at a temperature of 273°C (245°C) after 1 h (1 h) of heating. This shows, an improvement of heating, of 11.4% compared to the standard method, and 126% compared to photovoltaic ovens using batteries.[13]

It should be noted that the results obtained during the period 14–15 h, are also obtained during the sunny day, since according to Figure 6, the supply of the load by a power of 400 W, can be realized practically from 11 to 17 h. In the case of a considerable decrease in the illumination intensity, and thus in the electrical power supplied by the PV panels, the correct operation of the DC/DC converters is always ensured by the proposed control. However, the decrease in heating temperature could be significant. To remedy this in a work in progress, we propose the use of solar batteries and the appropriate circuit to stabilize the performance of the application during the day.

All the results obtained in this paragraph show the good operation and the interesting performances of the PV energy cooker, equipped with a PV system using our proposed MPPT control strategy. Compared to the conventional MPPT control, a clear improvement is obtained on the time of convergence towards MPP and the stabilization of the electrical quantities (voltage, current and power).

In addition, in terms of heating time and temperature, by comparing with the best thermal yields of solar cookers in the literature of the box type[24] and of the cylindrical type,[19] the maximum yields achieved are of the order of 39%,[25–27] using our suggested control, the improvement can reach 89%.

The improvement in efficiency is attributed to the efficient production of electrical energy by the photovoltaic panels, for a given illuminance, and to the proper functioning of the DC/DC converters, under the proposed MPPT control. However, in the case of conventional thermal cookers, the efficiency of the cookers is very limited by the slow temperature rise in the cooker.[24]

4 | CONCLUSION

In this paper we presented a MPPT control method dedicated to parallel multi-stage photovoltaic systems, by following the electrical quantities (voltage, current, and power) at their common outputs. This method is based on the alternating control of the system's DC/DC converters. We have shown that the advantage of this technique is the stabilization of the output voltage of the converters, following the control of the DC/DC converters by their previous parameters, during a control alternation. In addition, we have experimented, with this proposed technique, the operation of a photovoltaic energy cooker, by heating water and oil. To validate this operation we have established the equations and models of heating of the thermal resistances allowing the heating of this cooker.

In the case of a two-stage system (200 and 230 W), by comparing the results obtained by this method with those of the standard method, which is based on the electrical input quantities, we have concluded the following:

- An improvement of DC/DC converters efficiency of 4.24%, and 48% in convergence time speed,
- Clear stabilization of the electrical quantities (duty cycles, voltages, currents and powers) at the input and output of converters. The variations of the electrical quantities gaps (current, voltage, power) at the input and output of the DC/DC converters is improved by average factor of 2.46.
- Good agreement between simulation and experimental results of the temperature of the thermal resistances,
- By comparison with classical box ovens (thermal), a photovoltaic energy cooker proposed in this work presents an improvement of 27.3% in the heating resistor temperature, 19.35% heating rate improvement, and 23.8% heating time.

The improvements obtained on the efficiency of the DC/DC converters and the proposed cooker are attributed, on the one hand, to the nature of the proposed MPPT control which reduces the dispersion of electrical quantities at the input and output of the converters and, on the other hand, to the rapid increase in the heating of the cooker by the electrical energy produced by the photovoltaic panels.

In perspective, this work is continued by proposing a MPPT control by alternation, whose role is to control the converters of the photovoltaic system, and to charge solar batteries during sunny days. These batteries are dimensioned to meet the needs of users in terms of electrical energy to operate the cookers during the lack of sun (rainy days and evenings).

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