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Design and Simulation of a Photovoltaic Water Heater

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Abstract: - In this article, we present the results of simulating a photovoltaic water heating system that utilizes a solar battery to store electrical energy. Through the use of a DC/DC Boost converter, the 300 Wp photovoltaic panel and a 24 V, 200 Ah solar battery provide the power for the 15 Ω thermal resistance. We have considered the electrical power of both energy sources and simulated the temperature of the resistor based on the lighting intensity using thermal models. Using the Orcad-Pspice circuit simulator, we have designed the power system (DC/DC converter) and simulated its operation, taking into account the duty cycle of the PWM signal, the lighting intensity when the photovoltaic panels are supplying power and the battery discharge when it is being used. The results show that the resistances can heat up to 703°C with a power of 300 W. Also, the voltage, current, and efficiency of the DC/DC converter for 1000 W/m2 of radiation are 37.29 V, 7.85 A, and 292.73 W at the input and 72.5 Volt, 4 Am, and 290 Watt at the output. In this case, the DC/DC converter is about 99% efficient. The results demonstrate that the DC/DC converter is operating correctly and that the thermal resistance is heated according to the requirements of the photovoltaic water heater to be implemented in this study.

Keywords: Photovoltaic Water Heater, Photovoltaic energy, DC / DC converter, Power Electronics, Battery powered solar, PWM control.

I. INTRODUCTION

The photovoltaic water heater, utilizing solar energy to heat water, offers an innovative, environmentally friendly, and cost-effective alternative for environmentally conscious consumers. This technology helps reduce dependence on fossil fuels, which are responsible for depleting reserves and environmental pollution, as well as global warming caused by greenhouse gas emissions.

The works already published in the literature show that the use of photovoltaic water heaters can significantly reduce the carbon footprint associated with hot water production. By using solar panels to generate electricity, these systems directly convert solar energy into heat, thereby avoiding the greenhouse gas emissions associated with traditional water heating methods [1]. Furthermore, photovoltaic water heaters can lead to significant savings on energy bills. By harnessing free solar energy, consumers can reduce their reliance on fossil fuels and conventional electricity sources, resulting in long-term financial savings [2,3].

The use of a gas water heater has several drawbacks compared to using a photovoltaic water heater. For example, greenhouse gas emissions resulting from the combustion of natural gas contribute to climate change and air pollution; gas water heaters are responsible for a significant portion of CO_2 emissions in residential households [4].

Moreover, using natural gas as a fuel for water heating is a non-renewable resource, raising concerns about gas reserve depletion. In contrast, a photovoltaic water heater utilizes solar energy, an abundant renewable energy source. According to research conducted by Zhou et al. (2023), the use of photovoltaic water heaters can significantly contribute to reducing dependence on fossil fuels [5].Par conséquence, le chauffe-eau à gaz présente des inconvénients majeurs en termes d'impact environnemental et de dépendance aux combustibles fossiles.

The importance of solar energy has increased in current global discussions on energy and the environment. As the world becomes increasingly concerned about the environment, deforestation and the search for renewable energy alternatives to fossil fuels are raising significant concerns. Due to the scarcity of fossil fuels, the concentration of

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fuel reserves, and the constant rise in electricity prices, the world is confronted with energy security challenges. In recent years, researchers have gradually turned their attention to solar energy [6,7]. It is crucial to conduct studies to address energy-related issues as life is directly impacted by energy and its consumption. Solar energy is currently in high demand for various applications such as water heating, cooking, electricity generation, and refrigeration. One solution to tackle this situation is to utilize an abundant and environmentally friendly energy source like solar energy. [8,11-14].

In this article, we present the structure of a photovoltaic water heater powered by a 300 W solar panel and a 24 V/200 Ah solar battery, as proposed in this study. The results of the thermal simulation of the heating resistors based on electrical power are then discussed, along with those of the DC/DC converter, which serves to power this resistor using a photovoltaic panel and a solar battery. The temperature of the heating resistor and the electrical quantities, namely voltage, current, and power, at the input and output of the DC/DC converter, are considered to evaluate the feasibility of this water heater in users' homes throughout the year (day and night), regardless of weather conditions.

II. Design of a Photovoltaic Water Heater System

A. Specifications

The aim of this study is to simulate and implement a hybrid water heater powered either by photovoltaic energy or by energy accumulated in solar batteries, while complying with the required specifications:

- **Energy source** responsible for generating electrical energy to power the water heater. In the context of our work, two sources are utilized:
  - ✓ A 300 Wp photovoltaic panel, characterized by:
    - The maximum power output is 300 W,
    - The optimal voltage is 31.5 volts,
    - The Optimal current is 9.50 A,
    - The open circuit voltage is 39.5 volts,
    - The short circuit current measured is 9.98 A.
  - ✓ A solar battery with a voltage of 24V and a capacity of 200 Ah is capable of storing between 8 and 10 kWh of electrical energy supplied by photovoltaic panels.
- **Power block** consisting of a converter for DC and DC power. The technical specifications of this converter adhere to our requirements and the sizing of each electrical component:
  - Power: 800 W ,
  - Input Voltage: 0 - 60 V ,
  - Input Current: 0 - 5 A ,
  - Input Voltage Ripple: 1 V ,
  - Output Voltage Ripple: 0.5 V ,
  - Active Component (Power Switch): MOSFET IRF540 ,
  - Passive Components: Inductance = 400µH, Input Capacitance = 1000 µF, Output Capacitance = 220 µF, Schottky Diode type MU8100.
- **Water heater,** consisting of a thermal resistor of 15 Ω, used for heating water is characterized by the following specifications:
  - Material: copper,
  - Voltage: 12 Volts,

- Brand: AMAPT,
- Power: 300 Watts.

B. Synoptic and electrical diagram

The electrical diagram and synoptic diagram of the photovoltaic water heater proposed in this work are shown in Fig. 1. The overall structure of the blocks that make up this system are :

- **Energy source** whose purpose is to generate electricity to heat water. For our work, and in accordance with the specifications (paragraph II.1), we are using two sources:
  - A photovoltaic panel of 300 Wc is used to provide the electrical energy to the photovoltaic water heating system.
  - A 24V/200Ah solar battery storing 8-10 kWh of electrical energy generated by the PV panel.
- **Power block** formed by a DC/DC converter (100 V, 5 A, 800 W) of the Boost type. Its purpose is to control and adapt the power source to the load (thermal resistance), by modulating the PWM signal shapes generated by the analog circuit, to correctly control the power switch (MOSFET) on opening and closing.
- **Water heater**, formed by a thermal resistance of 15 Ω.

The thermal models of the heating resistor are presented below, along with the simulation of the heating temperature based on the electrical energy PS that powers it. According to the expression, this energy depends on the resistance R and the current I flowing through it.

In the following, we present the thermal models for heating the warming resistor and simulating the heating temperature as a function of the electrical energy PS that supplies it. This energy is a function of the resistance value R and the current I flowing through it.

$$P_S = R.I^2 \qquad (1)$$

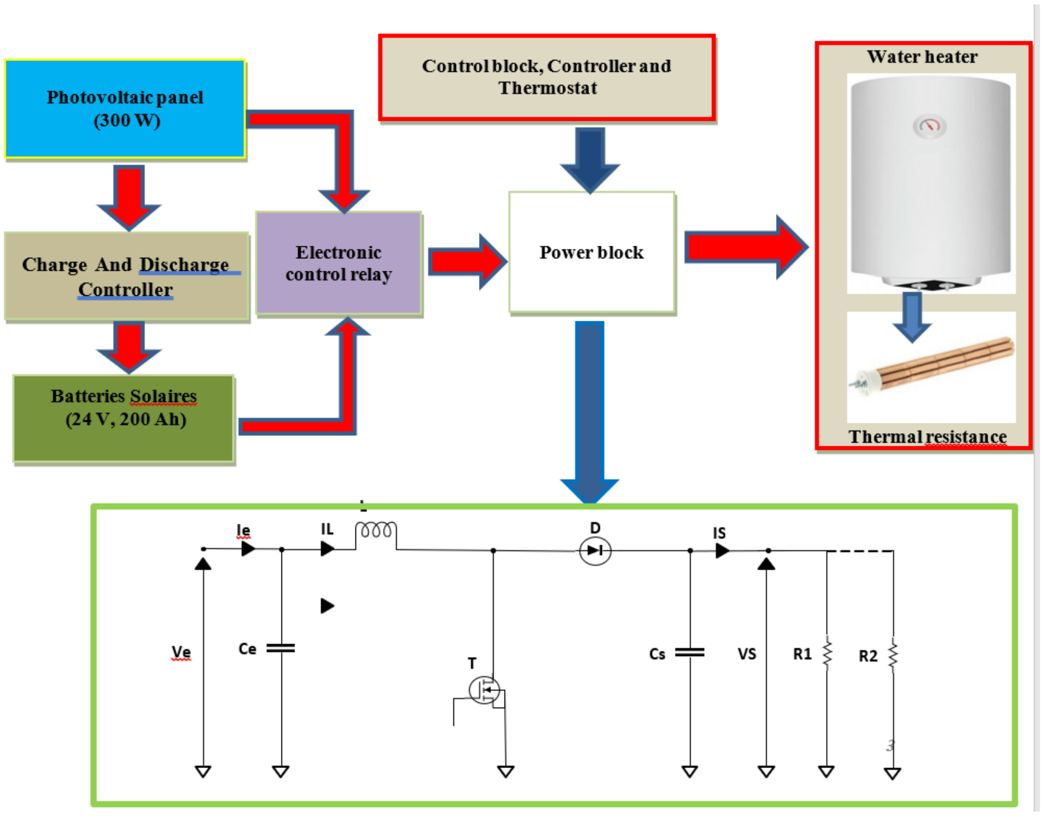


Fig. 1: Synoptic and electrical diagram of a photovoltaic water heater.

III. Modelling and thermal simulation of thermal resistance.

A. Energy balance.

The resistor powered by photovoltaic panels or solar batteries receives a heating power Ps (Fig. 2). Subsequently, during a relatively short transient period, a portion of energy Pstore is stored in this resistor while another part is lost in the form of thermal flux through convection (Pcv) and radiation (Pr). This results in an increase in the internal energy of the thermal resistor and consequently its temperature. The energy balance equation can be written in terms of the mass mr and temperature Tr of the heating resistor, the heat transfer coefficients by convection and radiation (hcv, hr), and the exchange surface (Sr) by the following expressions:

$$\mathbf{P_s = P_{store} + P_{cv} + P_r} \qquad \textbf{(2)}$$

More, $$\mathbf{R\,I^2 = m_r\,.\,Cp_r \frac{dT_r}{dt} + h_{cv} S_r (T_r - T_{amb}) + \sigma\varepsilon\, S_r\, (T_r^4 - T_c^4)} \qquad \textbf{(3)}$$

With: $\mathbf{Cp_r}$: Mass specific heat of the heating resistor,

$\mathbf{T_{amb}}$: Ambient temperature,

$\mathbf{T_C}$: Sky temperature, expressed as a function of the temperatures of the resistance $\mathbf{T_r}$ and the ambient temperature in the form [15-17] : $\mathbf{T_C = 0.00552.(T_{amb})^{3/2}}$ **(4)**

σ : Stefan-Boltzmann constant,

Ɛ: Emissivity of the heating resistor.

From equation 2, we derive the thermal model [18,19,20] that enables simulating the temperature (Tr) of the thermal resistor heating, based on the electrical power Ps and the electrical current supplied by the PV arrays or solar battery. Following the first law of thermodynamics [20], the thermal energy balance associated with the heating of the thermal resistor is expressed in the form:

$$\mathbf{m_r\,.\,Cp_r \frac{dT_r}{dt} = RI^2 - h_{cv} S_r (T_r - T_{amb}) - S_r \sigma\varepsilon\, (T_r^4 - T_c^4)} \qquad \textbf{(5)}$$

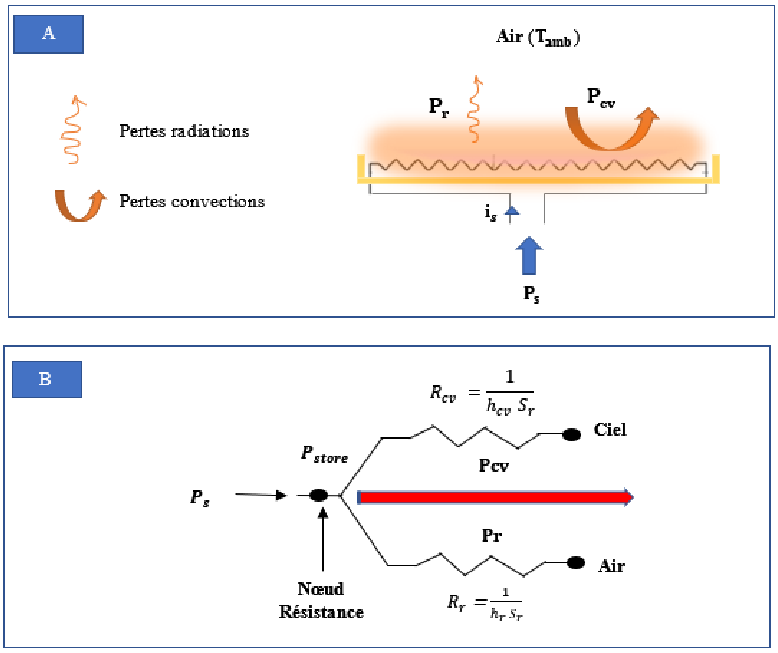


Fig. 2: Energy flows exchanged by the resistor with the outside world.

A- Heat exchange phenomena of the thermal resistor,

B- Digram of exchanged flows.

B. Thermal simulation results

The numerical resolution of the models (Equations 1 to 5) of the water heater (Fig. 1) is performed using the 4th-order Runge-Kutta method in Matlab. We used this method because of its exceptional accuracy and stability.

The program, developed in Matlab, solves the first-order differential equation model (equation 5) numerically, and deducing the temperatures T_r and T_{amb}, following the steps in Fig. 3.

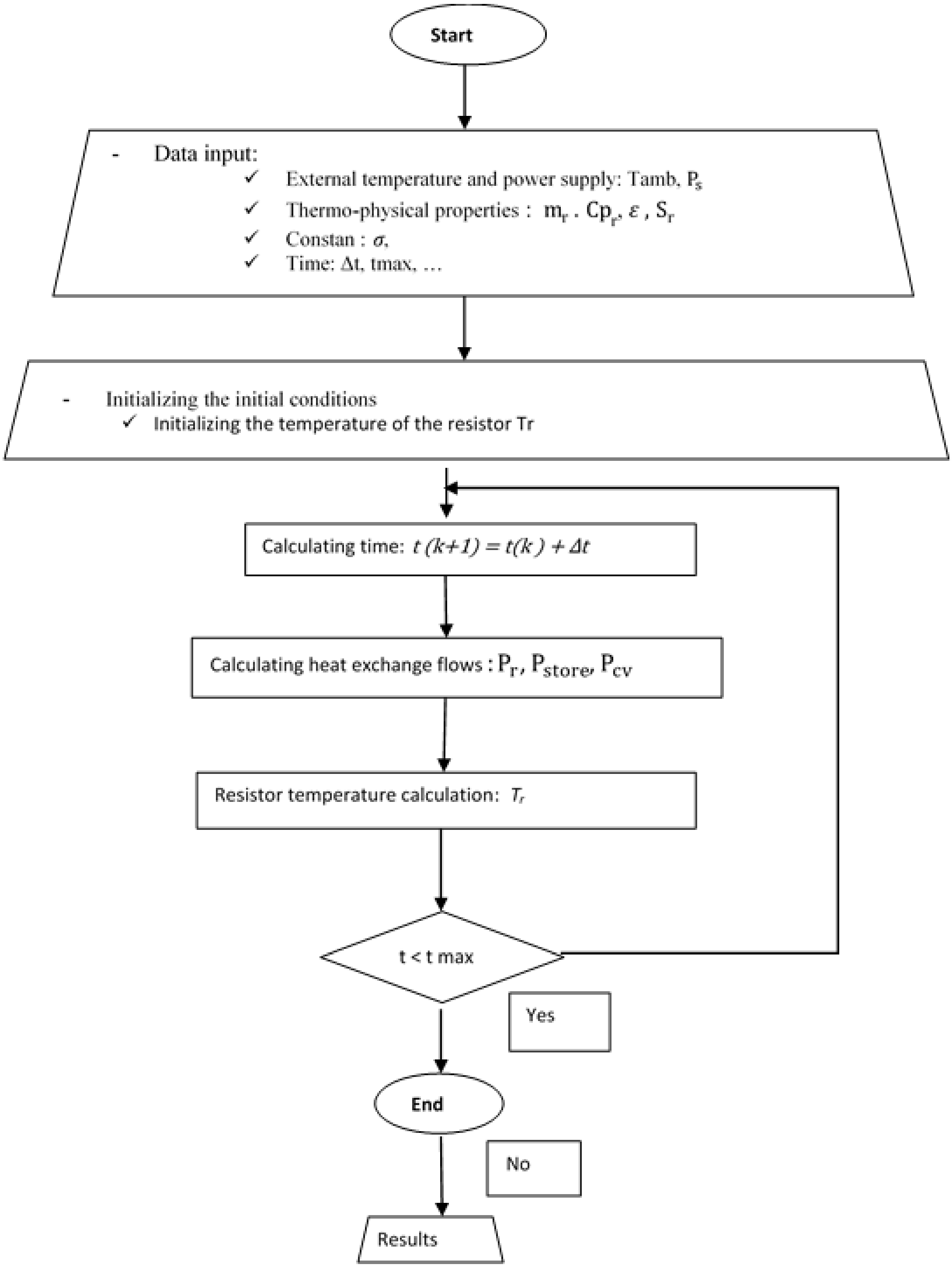


Fig. 3: Algorithm of the developed calculation code

From the established numerical code, we simulated the resistance's temperature (Tr) based on the electrical powers (current I flowing through it) for two resistance values (15 and 25 and 7.5 Ω) and specific parameters of the resistor. The results obtained (Fig. 4) show:

- The maximum temperature of the resistor increases from 703 to 1300 C when the power varies from 300 to 1200 W;
- The thermal resistor's heating temperature increases by 6% when the power increases by 200 W;
- A power ranging from 1000 to 1200 W has a heating temperature of 1228 to 1310 C.;
- The heating power varies from 375 to 625 W (an increase of 66.66%) for a current of 5 A when the resistance value changes from 15 to 25 (an increase of 66%);

The obtained results demonstrate the correct functioning of the simulation code developed during this work, based on the Runge-Kutta resolution method. Furthermore, the temperatures of the resistor increase significantly depending on the power supply; these temperature values could reach 1310°C.

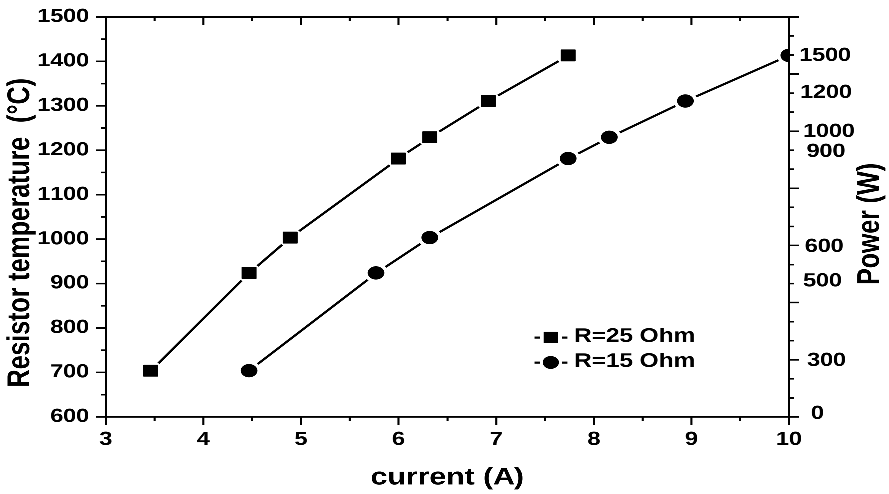


Fig. 4 : Variation of temperatures based on power and current.

IV. ELECTRICAL SIMULATION

A. Power supply from PV panels

1) Functioning of the PV panels

To power the heating resistor of the Photovoltaic water heater using PV panels, we used a JAM 60S02-300/PR type PV panel, rated at 300Wp, consisting of 80 identical cells connected in series. The simulation of their electrical operation is carried out by implementing them in the Orcad-Pspice simulator. To achieve this, we implemented a PV cell on Fig. 5 with its electrical circuit and hierarchical block (Cell, Vm, Vp). In our study, a cell comprises a diode D, a current source (ICC), a series contact resistance (RS), and a parallel resistance (Rsh) (cell leakage current). Taking into account the electrical characteristics provided by the manufacturer, the current ICC is expressed as a function of the illumination intensity (Le) according to the expression:

$$\mathbf{I_{CC} = 0.00932 \times Le + 0.0055} \qquad \textbf{(6)}$$

Taking into account this cell model, we implemented and simulated the electrical operation of a PV panel and an array of panels formed by two branches of two PV panels in series based on the illumination intensity. The results obtained (Fig. 6) show:

- Standard test conditions (STC: 1000 W/m^2, Tamb: 25°C) permit the PV panel to deliver:
- Optimal voltage of 36.5 V ;
- Optimal current of 8.35 A ;
- Optimal power of 305 W .

The current-voltage and power-voltage electrical characteristics of a photovoltaic cell and a photovoltaic panel, when the illumination intensity varies from 200 to 1000 W/m2 at a temperature of 25°C (Fig. 6), show that proper functioning of the power system.

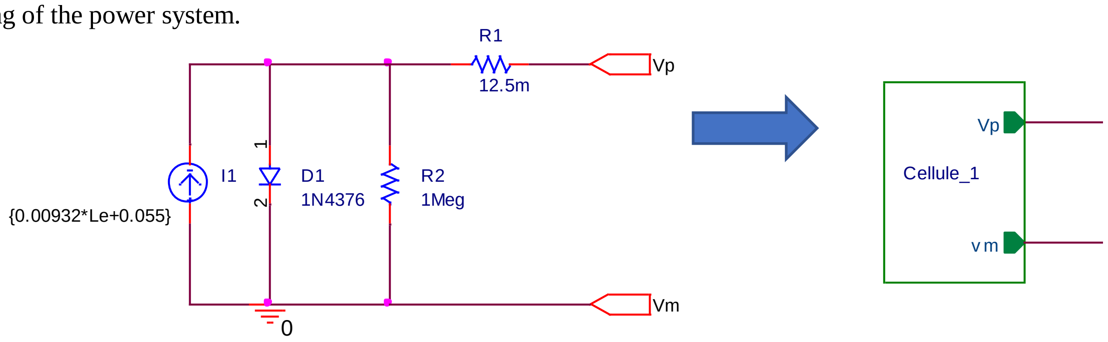


Fig. 5 : Implementation of a PV cell through its electrical circuit and hierarchical block

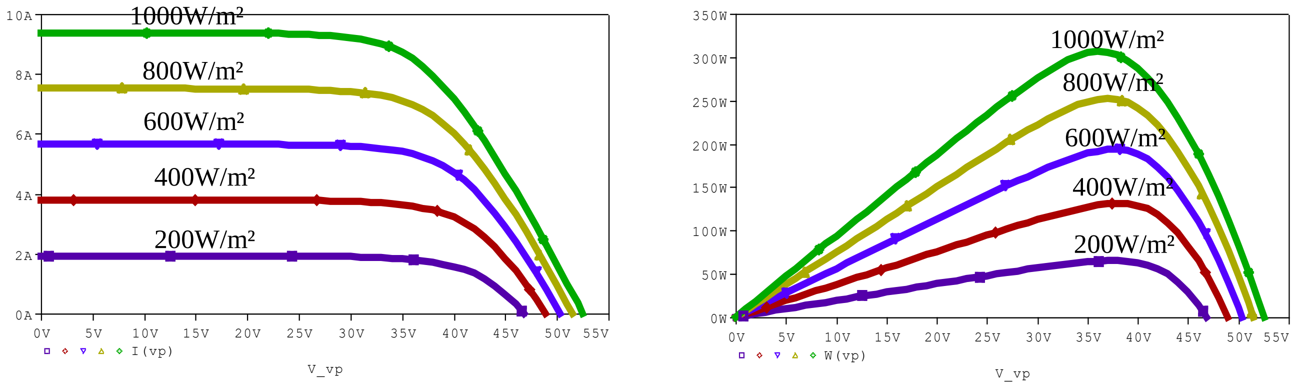


Fig. 6. Electrical current-voltage and power-voltage characteristics of a photovoltaic panel.

2) *Waveform*

We simulated the functioning of the system in Fig. 1 for an illuminance of 1000 W/m², a temperature of 25°C, a heating resistor of 15 Ω and a duty cycle α=0.5. In Fig. 7, we have plotted the different waveforms of the PV system during two periods of the PWM signal controlling the power switch. These results show:

We simulated the functioning of the system in Fig. 1 for an illuminance of 1000 W/m², a temperature of 25°C, a heating resistor of 15 Ω and a duty cycle α=0.5. In Fig. 7, we have plotted the different waveforms of the PV system during two periods of the PWM signal controlling the power switch. These results show:

- ✓ The input and output voltages of the Boost converter are approximately 37.29 V and 72.5 V, respectively,
- ✓ When the switch is closed (open), the potential difference across the inductor is VL = Vpv = 37.29 V V (VL = Vpv - VS = -35.21 V),
- ✓ The inductor's current ranges from 6 A to 10.14 A, with an average value of 78.07 A and a ripple of 4.14 A,
- ✓ The converter has an average input current of 7.85 A and an average output current of 4 A.

Good functioning of the system proposed in this work is shown by the waveforms (Fig. 7) of the photovoltaic water heater power block (300W).

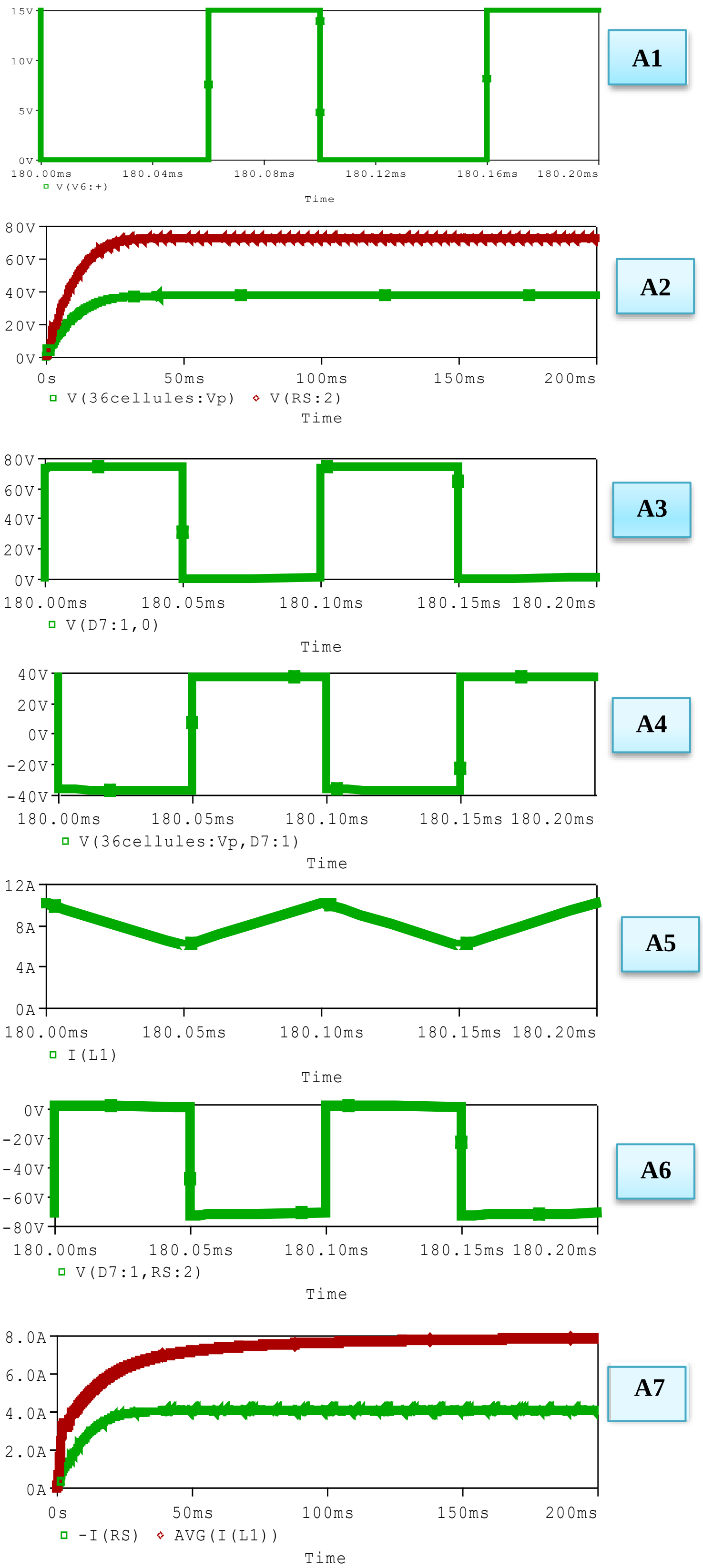


Fig. 7. Waveforms of the water heater power block, powered by a PV panel (300 Wp) in the case of Le=1000W/m2, duty cycle α=0.5 of the PWM control signal.

A1 : PWM control signal ;

A2: Voltage at converter input and output;

A3: MOSFET output voltage;

A4: Terminal voltage of inductor ;

A5: Inductance current IL ;

A6: Diode terminal voltage;

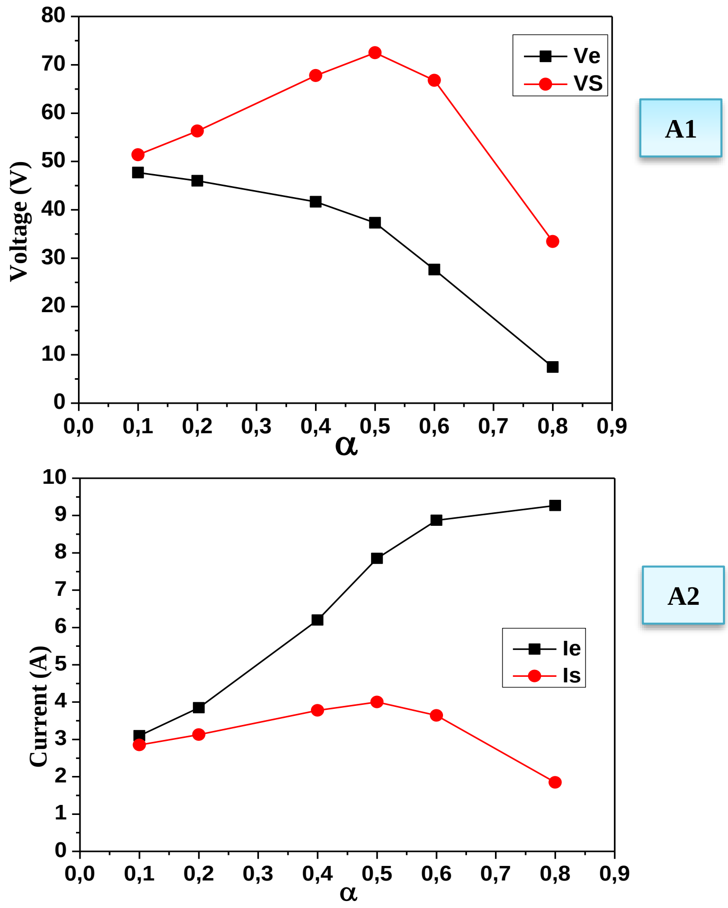
A7: Input and output currents.

3) Functioning of the system as a function of the duty cycle

The operation of the PV system shown in Fig.1 has been analyzed in Fig. 8 as a function of the duty cycle of the PWM signals for a 1000 W/m2 illumination. The maximum power point is obtained for a duty cycle of the order of 0.5, according to the typical results. These conditions affect the electrical values at the system's input and output:

- ✓ The voltages at the Boost converter's input and output are between 37.29V and 72.5V, respectively,
- ✓ The current at the input and output of the Boost converter is around 7.85 A and 4 A, respectively,
- ✓ The power at the converter's input and output is between 292.73 and 290 Watts,
- ✓ The panels have an optimal resistance of around 4.75,
- ✓ The converter has an efficiency of 99%.

After analyzing these simulation results, we have concluded that the system we have designed is capable of heating the photovoltaic water heater using a 15 Ω heating resistor, at a warming power of 300 W.



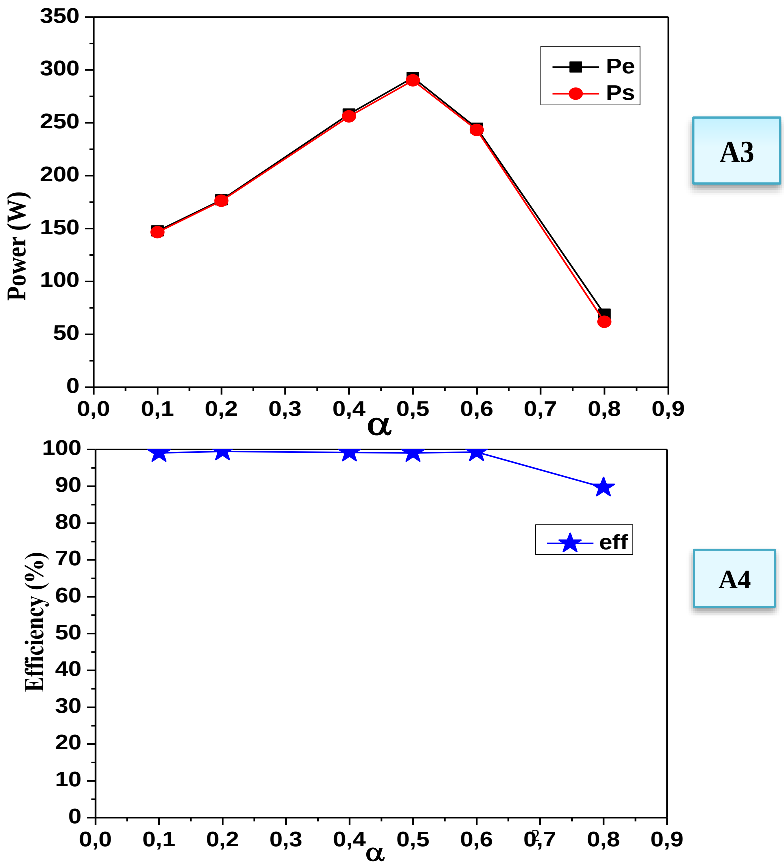


Fig. 8 . Electrical values of the water heater (300 W), as a function of the duty cycle of the PWM signal controlling the Mosfet transistor for 1000 W/m illuminance.

A1: Input and output voltages of the converter.

A2: Input and output currents of the converter.

A3: Input and output powers of a converter.

A4: Efficiency of the converter

B. Powering by solar batteries

This part proposes to power a photovoltaic water heater from a battery (24V, 200 Ah) on sunny days and at night, employing the DC/DC converter and PWM control blocks shown in Fig. 1. The typical simulation results obtained have been presented to monitor the operation of the DC/DC converter and record the electrical parameters at its input and output.

1) DC/DC converter waveform

We simulated in Fig. 9 the operation of the system in Fig. 1,during two periods of the PWM control signal with a duty cycle of α=0.4, while heating a heating resistor of 15 Ω. These results show that:

- ✓ There are approximately 24 V and 38.6 V at the input and output of the Boost converter,
- ✓ When the switch is closed (open), the potential difference across the inductance is: VL = Vpv= 24 V (VL = Vpv-VS= -14.6 V),
- ✓ The current in the inductance varies between 3.23 A and 5.36 A, with an average value of 4.28 A and a ripple of 2.13 A,
- ✓ The converter's average input and output currents are approximately 4.28 A and 2.58 A, respectively.

The waveforms of the power block of the water heater, powered by a 24V solar battery with a duty cycle of α=0.4 of the PWM control signal and supplying a 15 Ω resistor, illustrate the proper functioning of the system proposed in this work (Fig. 9).

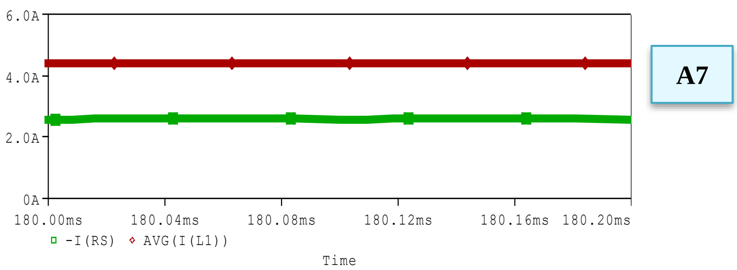


Fig. 9. Waveforms of the power block of the water heater, powered by a 24V solar battery with a duty cycle of α=0.4.

A1: PWM control signal ;

A2: Voltage at converter input and output;

A3: MOSFET output voltage;

A4: Terminal voltage of inductor ;

A5: Inductance current IL ;

A6: Diode terminal voltage;

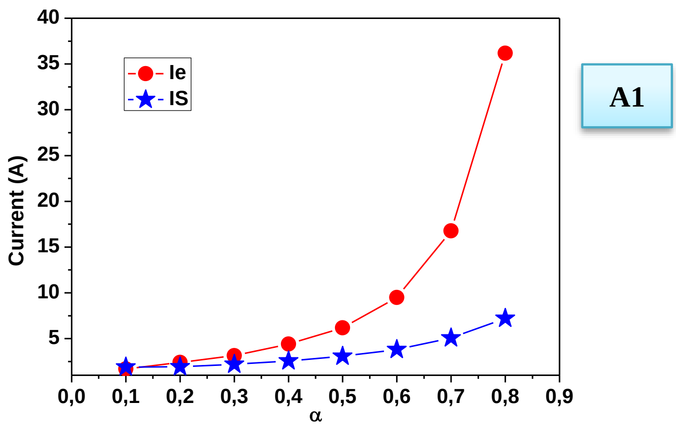
A7: Input and output current.

2) Functioning of the system as a function of the duty cycle α

On Fig. 10, we have depicted the various electrical quantities at the input and output of the DC/DC Boost converters for the water heater, based on the duty cycle α in the case of supplying a 15 Ω resistor. The results obtained show that:

- ✓ When the duty cycle is 0.8, the current and power from the battery exceed 36.17 A and 868 W, respectively. The voltage, current, and power across the resistor exceed 108 V, 7.22 A, and 779.76 W, respectively,
- ✓ When the duty cycle is 0.65, the current and power from the battery are 13.1 A and 316 W, respectively. The voltage, current, and power across the resistor are 66.48 V, 4.5 A, and 300 W, respectively.

The results shown in this paragraph are similar to those obtained when powering the PV panel (paragraph IV.1.3) We can say that the water heater is powered by solar batteries through a power system with a control electrical circuit.



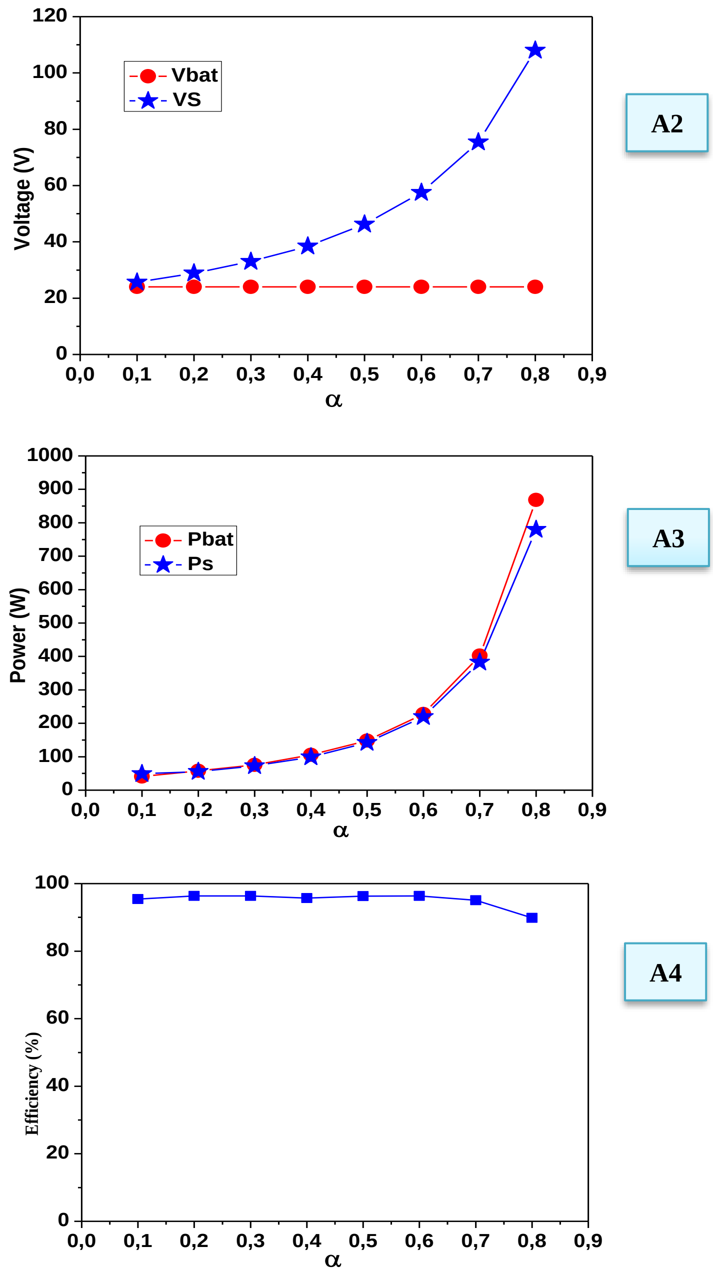


Fig.10. Electrical values of the water heater, as a function of the PWW signal duty cycle, powered by a 24V battery.

A1: Input current Ie and output current Is of the Boost converter,

A2: Input voltage VBat and output voltage Vs of the Boost converter,

A3: Input power Pe and output power Ps of the Boost converter,

A4: Efficiency of the converter.

3) Analyse d Analysis of the results

This article analyzes the operation of a water heater powered by photovoltaic panels (300 W) and stored in 24V/200Ah batteries. The resistance of the photovoltaic water heater is 15 Ω. Water heating is achieved using a Boost chopper controlled by a 10 kHz PWM signal. Our study extended the thermal and electrical simulation of the heating resistor based on the electrical power supplied to it.

The simulation results obtained show :

- **Thermal simulation**: Using a developed code, We showed that when the power changes from 300 to 1200 W, the resistor gets hotter from 703°C to 1300°C. Under these conditions, the current flowing through it is between 5.5 A and 8 A. When the power is at 300 W, the temperature of the resistor is around 703°C.

- **Electrical simulation:**

  - The implementation and simulation of the operation of the photovoltaic panel demonstrate their performance based on the light intensity (200-1200 W/m2) at an room temperature of 25°C. Special attention has been given to their maximum power points (voltage, current, power). For 300 W power, when the irradiance varies from 200 to 1000 W/m2, this maximum power point is: current = 2 - 9.6 A, power = 60 - 300 W.

  - For a 300 W solar water heater without storage, with an illumination intensity of 1000 W/m² and a temperature of 25 °C: The analysis of the heating resistor reveals that the maximum power point is reached when αopt = 0.5. The input and output electrical values of the system are respectively:

✓ The voltages of the Boost converter are 37.29 V for the input and 72.5 V for the output,
✓ The Boost converter's input and output currents are 7.85 A and 4 A, respectively,
✓ The converter has a power of 292.73 W at the input and 290 W at the output,
✓ The optimal resistance of the PV panels is 4.75 Ω,
✓ The converter efficiency is 99%.

When using solar batteries to power the heating resistor, the simulation results of the system indicate that the electrical values at the input and output of the converter are as follows:

✓ When the duty cycle is 0.8, the current and power from the battery exceed 36.17 A and 868 W, respectively. The voltage, current, and power across the resistor exceed 108 V, 7.22 A, and 779.76 W, respectively.
✓ When the duty cycle is 0.65, the current and power from the battery are 12.9 A and 309 W, respectively. The voltage, current, and power across the resistor are 66.48 V, 4.5 A, and 300 W, respectively.

All the simulation results obtained in this work show that the block (DC/DC converter) works well, and that it is possible to heat water using photovoltaic panels or solar batteries. Controlling the DC/DC converter operation by varying the PWM signal's duty cycle makes it possible to regulate the power of the energy sources (photovoltaic panels or batteries) and therefore the heating temperature of the heating elements.

V. CONCLUSION

In this paper, we designed and simulated the operation of a water heating system powered by a photovoltaic panel (300 W) with storage in a 24V/200Ah battery. The heating system consists of a 15 Ω resistor, powered by a Boost chopper controlled by a PWM signal.

The results of the system simulation when powered by a PV panel show that the maximum power point is obtained for α_{opt}=0.5. Under these conditions, the input voltage is V_e=37.29 V and at the converter output V_s=72.5 V, the input current is I_e=7.85 A and at the converter output I_s=4 A. Furthermore, the power at input P_e=292.73 W and at converter output P_s=290 W, with an optimum PV panel resistance of around 4.75 Ω and converter efficiency of around 99%.

When supplied by a solar battery: simulation of the system in this case shows, for a duty cycle of α=0.65, the voltage at input V_e=24V and at converter output V_s=66.48V, as well as the current at input I_e=12.9A and at converter output I_s=4.5A. Furthermore, the power at input P_e=309W and at converter output P_s=300W, with a converter efficiency of around 97%.

All the simulation results obtained in this work show that the block (DC/DC converter) works well, and that it is possible to heat water using photovoltaic panels or solar batteries. Controlling the DC/DC converter function by varying the duty cycle of the PWM signal enables us to regulate the power of the energy sources (photovoltaic panels or batteries) and therefore the heating temperature of the heating elements.

This work is considered a fundamental tool for validating the experimental operation of the water heater specifications based on the light intensity throughout a day and the power of the batteries during non-sunny days and nights. To achieve this, we propose the following perspectives :

- Installation of a meteorological station to measure light intensity and ambient temperature.
- Assembly and in-depth electrical characterization of the photovoltaic panels.
- Layout and development of control and power block boards.
- Water heater experimentation in the laboratory: photovoltaic panels, solar batteries, control and power units, heating resistors.

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