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Power system of DC/DC applications: Case of cooking

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ABSTRACT

In this paper, we present the structure, the sizing and the experimentation of a power system that allows to feed, through solar batteries, the DC (direct current) equipment with photovoltaic renewable energies (Cookers, distillers, refrigerators, drying, ...). The proposed system is based on the use of a multi-branch Boost type DC/DC converter, controlled by a Microcontroller, which generates PWM signals of frequency 20 kHz and variable α duty cycle. The electrical energy, produced by the photovoltaic panels (600 W), is stored in the solar batteries (24 V, 520 Ah) and then transferred to the application through the proposed DC/DC converter. The experimentation of the proposed system to supply a solar cooker (Box Oven) of 500–600 W, heated by thermal resistances, shows efficiencies of the DC/DC converter of 86 %, heating temperature of the thermal resistance and water that reach 640 °C and 99 °C after 20 s and 25 min, energy supplied by the batteries and that of heating are respectively of the order of 491 Wh and 421 Wh (That is to say 3.93 % and 3.37 % of the total energy supplied by the battery).

The comparison of all the results obtained with those simulated and the economic analysis of the use of renewable energies stored in the batteries, show the good functioning and the validity of the power system, proposed in this work.

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1. Introduction

Cooking is one of the most basic functions of human life [1,2], cooking remains the main activity of every household in developed and developing countries [2], this sector being one of the largest energy consumers, accounts for 36 % of total primary energy consumption [3,4]. Due to the continuous increase in demand, annually, energy consumption increases by an average of 1 % in developed countries and 5 % in developing countries [5–7]. However, the world's conventional energy resources used for cooking are rapidly depleting and their use can create environmental problems such as pollution [8], greenhouse effect [9], global warming [10], etc. [2,11,12], therefore, the need to use renewable energy sources has grown rapidly over the past two decades. According to the International Energy Agency showed that in 2050, solar energy can provide about 45 % of global energy demand [6].

The depletion of conventional energy sources and their adverse effects on the environment have drawn the attention of global researchers to renewable energy sources, the replacement of fossil fuels with these sources has become an urgent need for the clean and sustainable development of the energy sector, globally [8]. Solar energy is freely and abundantly available all year round and can be effectively used with various types of domestic/industrial applications of other energy systems [4,11,13,14].

Solar cooking attracts many researchers in various theoretical and experimental studies, many configurations of solar cookers have been developed and tested in the literature, all these configurations can be broadly divided into three categories [1]: box-type solar cooker, parabolic solar cooker, reflective type solar cooker, However, most of the previously developed solar cooker designs are not fully consumer friendly, complicated or expensive are unaffordable for poor or small households, most people prefer fossil fuels and biomass due to their faster cooking and lower cost [15,16].

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The intermittence in the availability of solar energy has been a challenging task for various studies conducted in this field to solve the problem of lack of sunlight and ensure operation during these low sunlight periods. Researchers have tried various modifications to improve the performance and increase the utility of these systems [4]. However, some of these designs still require design and cost optimization for global acceptability [15]. While these applications also face problems in adapting loads to solar batteries for low power and energy supply installations. [17–21]. To address the problem of lack of adaptation of loads to solar batteries using DC/DC converters, in order to minimize power losses.

In this work, we propose the design and realization of a cooker (box oven), autonomous power of 300 W. After describing the structure of the power system (Boost type DC/DC converter with three branches), equipped with an electronic block of regulation and controls heated by solar batteries (24 V, 520 Ah), we present the results of simulation and experimentation of the proposed system. Particular attention is paid to the electrical quantities (voltage, current and power) of the proposed DC/DC converter, according to the duty cycles of the PWM controls of the power switches, the branches of the DC/DC converter and the transfers of the maximum power supplied by the batteries to the thermal resistance of two types of cookers (box ovens), and the validation of the proposed technique for heating applications.

2. Structure and operation of the system

The synoptic diagram of the system powered by electrical energy stored in the solar batteries to heat the cookers (Box Oven), via a DC/DC converter with several branches, is shown in Fig. 1. The different blocks of this system are made up of the following equipment:

- A field of photovoltaic panels with a total power of 400 W, whose role is to supply electrical energy and store it in the solar batteries, via a charge/discharge regulator.
- Solar batteries are mounted to have a voltage/capacity of 24 V/520 Ah which supplies electrical energy to the DC/DC converter. It provides stored electrical energy to power thermal resistors via power blocks and digital electronics
- The power block is formed by a three-branch interleaved Boost-type DC/DC converter, for which the power switches are controlled by three identical PWM signals, with a frequency of 20 kHz and a duty cycle α. The role of this BOOST converter is to raise the 24 V DC voltage of the battery to a DC voltage of 67 V, under a power of 300 W.
- The PWM control block is formed by the Raspberry Pi Pico type microcontroller and analog, digital, passive, and active components. All active components are biased by 5 V and 12 V voltages, from the solar battery. This command block generates 3 PWM signals to operate the 3 power switches (T1, T2, T3) of the interleaved Boost converter in a non-linear mode.
- Application: Box oven heated by thermal resistors supporting a temperature of 1400 °C, a power of 600 W, this resistor is characterized by: longer life and better technical properties, higher surface load, and high resistivity. It is widely used to make hot plate heating equipment industrial ovens and domestic heaters. . ..

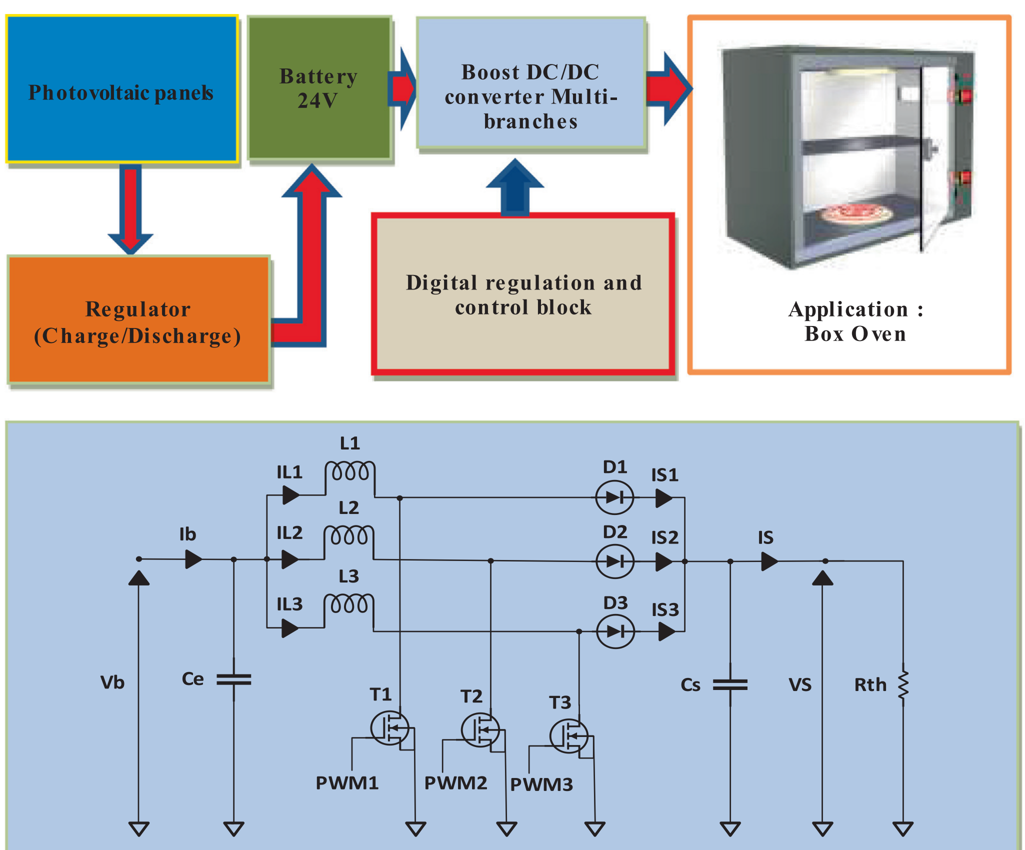

Fig. 1. Global synoptic diagram and electrical diagrams of the autonomous system of the multistage Boost DC/DC converter. allowing to supply a DC load by the solar batteries.

3. Experimental results and discussions

3.1. Experimental procedure

Fig. 2, represents the power system, allowing the supply of a DC load by a solar battery through a multistage DC/DC converter, and the measurement bench set up to characterize this system. As shown in Fig. 2, we used the following equipment:

- Photovoltaic panels of 600 W, whose role is to provide electrical energy and store it in the solar batteries, via a charge/discharge controller,
- A 24 V/520 Ah solar battery, whose role is to supply the multistage Boost DC/DC converter, with a DC voltage of 24 V and variable currents of less than 30 A, depending on the value of the thermal resistance RTherm of the application (box oven),
- A DC/DC Boost converter, with three identical branches and input and output capacitors (Ce = 1000 μF and Cs = 1000 μF). Each branch is formed by an inductor (L = 100 μH), switches (MOSFET IRF540N) and fast diode (Schottky). This structure makes it possible to limit the strong currents which circulate in the inductances following the strong current delivered by the battery. This converter is dimensioned so that this one functions with a power of 300 W, in continuous mode, with a frequency of 20 kHz, input voltage of 24 V, output voltage vs of 70 V, output current Is = 5 A, undulations of the currents of the inductances ΔiL = 1,5A
- A digital control of the DC/DC converter, which provides three identical PWM signals to control the three switches (T1, T2 and T3) in nonlinear regime, by a PWM signal of frequency 20 KHz of duty cycle α = 0.7. This control is based on the use of the Microcontroller 'Raspberry Pi Pico' and a block of three drivers IR2111, to adapt the PWM signals and the input of the power switches.
- Load formed by a cooker (oven box, size: 64 cm:43 cm:36 cm), heated by two thermal resistances, supporting a temperature of 1400 °C, a power of 600 W.
- Power switches (ON/OFF) for the supply of the realized system.

3.2. Experimental validation of system operation

The proposed system of the DC/DC converter and these control blocks of Fig. 2 is implemented in the Pspice simulator in order to follow the operation of the DC/DC converter and to record the electrical quantities (voltage, current, and power) at the input and at the output of this converter. In the following, we present the typical simulation results obtained. In Fig. 3 we have represented the typical waveforms of the PWM signal, voltage V_{DS} of the output of the switch, voltage V_L at the terminals of the inductance, and voltage V_D at the terminals of the diode, of each branch of the DC/DC converter, also the battery voltage V_{Bat} and output vS for a duty cycle α = 0.7. In Table 1. we have represented the comparison of different electrical quantities simulated and experienced at the input (Ib, Pb) and at and at the output (v_S I_S, P_S) and the efficiency of the DC/DC converter for a duty cycle α = 0.7, for a load (15 Ω) where the battery voltage is constant and around 24 V. In the case of a duty cycle of 0.7 and a resistance of 15 Ω the results obtained show:(See Fig. 4.).

- The currents in the branches and output of the DC/DC converter are respectively of the order of 5.06 A and 4.8 A.
- The output voltage and current of the DC/DC converter are around 73 V and 4.8 A.
- The input and output powers are of the order of 364.5 W and 350.4 W, i.e. efficiency of the order of 96 %.
- A very good agreement between simulation and experiment

The analysis of these simulation results allows us to conclude that for our power application, which provides heating a cooker (box oven of 15 Ω thermal resistance) at a heating power of 350 W, the duty cycle of the PWM signals of the DC converter /DC is of the order of α = 0.7. Under these conditions, the input and output currents and voltage, and efficiency of the DC/DC converter are respectively of the order of 15.19 A, 24 V, 4.8 A, 73 V, and 96 %.

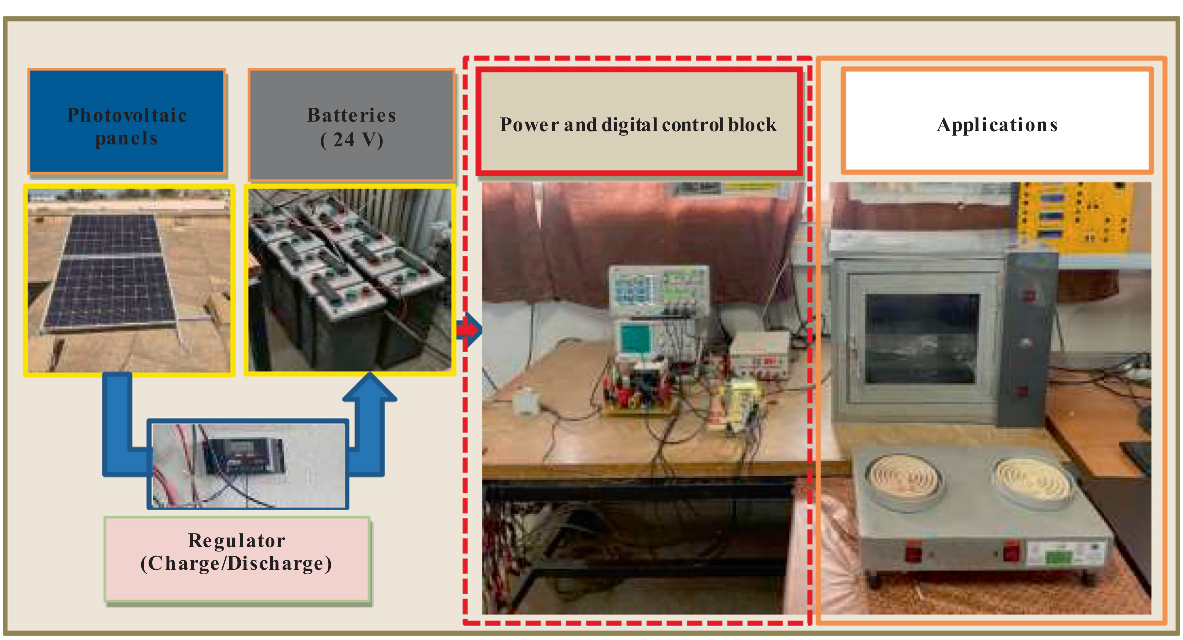

Fig. 2. Synoptic diagram of the autonomous system, allowing to feed a DC load by the solar batteries and a DC/DC converter of Boost type multistage.

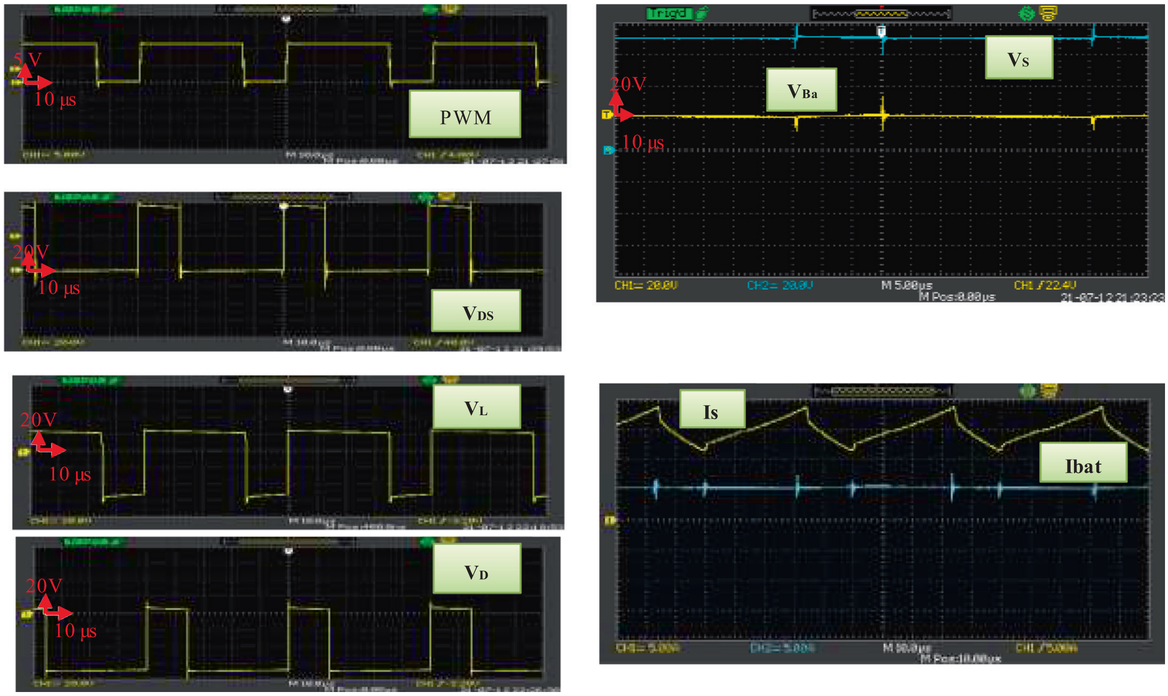

Fig. 3. Typical waveforms of the PWM signal, switch output voltage V_{DS}, voltage V_L at the terminals of the inductor and voltage V_D at the terminals of the diode, battery voltage V_{Bat} and output voltage v_S of each branch of the converter DC/DC, for a duty cycle α = 0.7.

Table 1
Comparison between simulation results and experimental results.

Electrical quantities	Simulation	Experience
Ibat (A)	**15.19**	**15**
Vbat (V)	**24**	**20.6**
$I_{L1} = I_{L2} = I_{L3}$ (A)	**5.06**	**5**
I_S (A)	**4.8**	**4,1**
v_S (V)	**73**	**65.6**
P_S (W)	**350.4**	**266.5**
P_{Bat} (W)	**364.56**	**309**
Converter efficiency (%)	**0,96**	**0,86**

3.3. Operation of the box oven cooker by solar batteries

In order to show the efficiency of the 'Box Oven' cooker (Fig. 1), developed during this work, we tested the prototype of Fig. 2, by heating one liter of water until boiling, during the experiment, we recorded the electrical quantities (voltage, current, power) at the input and output of the DC/DC converter, electrical heating energy, electrical energy supplied by the batteries, yields of the DC/DC converter, resistance temperature and water heating temperature.

It should be noted that from the heating of the water, we deduced the efficiency η of the heating of the cooker by photovoltaic energy, from the expression [22,23]:

$$\eta = \frac{m_w.c_p.\Delta T}{Ps} \quad (1)$$

Where,

m (w): Mass of heated water (mw = 1Kg),

ΔT: Variation in the temperature of the water,

c_p: Specific heat capacity of water at constant pressure (4,18 Kj/Kg.°C).

P_S: output power of the converter.

3.3.1. Water heating

We have experimented with the box oevn, heating 1 L of water, recorded the variations of the various electrical quantities at the inlet and outlet of the converter, the temperature of the thermal resistance and inside the oven. All the results obtained show that:

- The power at the input and output of the converter are respectively of the order of 331.8 W and 287.24 W, or an efficiency of 86 %,
- The voltages and currents at the input of the converter are respectively of the order of 21 V, 15.8 A, and at the output of the order 66.8 V and 4.3A.
- The temperature of the middle of the oven reaches 100 °C after 30 min of heating, that is to say 3.33 °C/min,
- The maximum temperature of the heating resistor is about 620 °C.
- The capacity of the battery consumed during the firing is about 20.55 Ah (i.e. a 3.9 % decrease of the battery charge level),
- During 5 min of heating, the water temperature varies from 20 °C to 37 °C, i.e. 3.4 °C/min. This heating shows a thermal efficiency of about 78 %,
- Energy supplied by the batteries and that of heating are respectively of the order of 491 Wh and 421 Wh (i.e. 3.93 % and 3.37 % of the total energy supplied by the battery).

All the results obtained in this paragraph show performances comparable to the results obtained in the case of the heating plate, and better performances compared to those obtained in the case of the traditional box ovens [19,2024–26]. We can thus conclude the validation of the operation of the box ovens by the electric energy supplied by the solar batteries and the power system, provided with the electric control circuit, designed in this work.

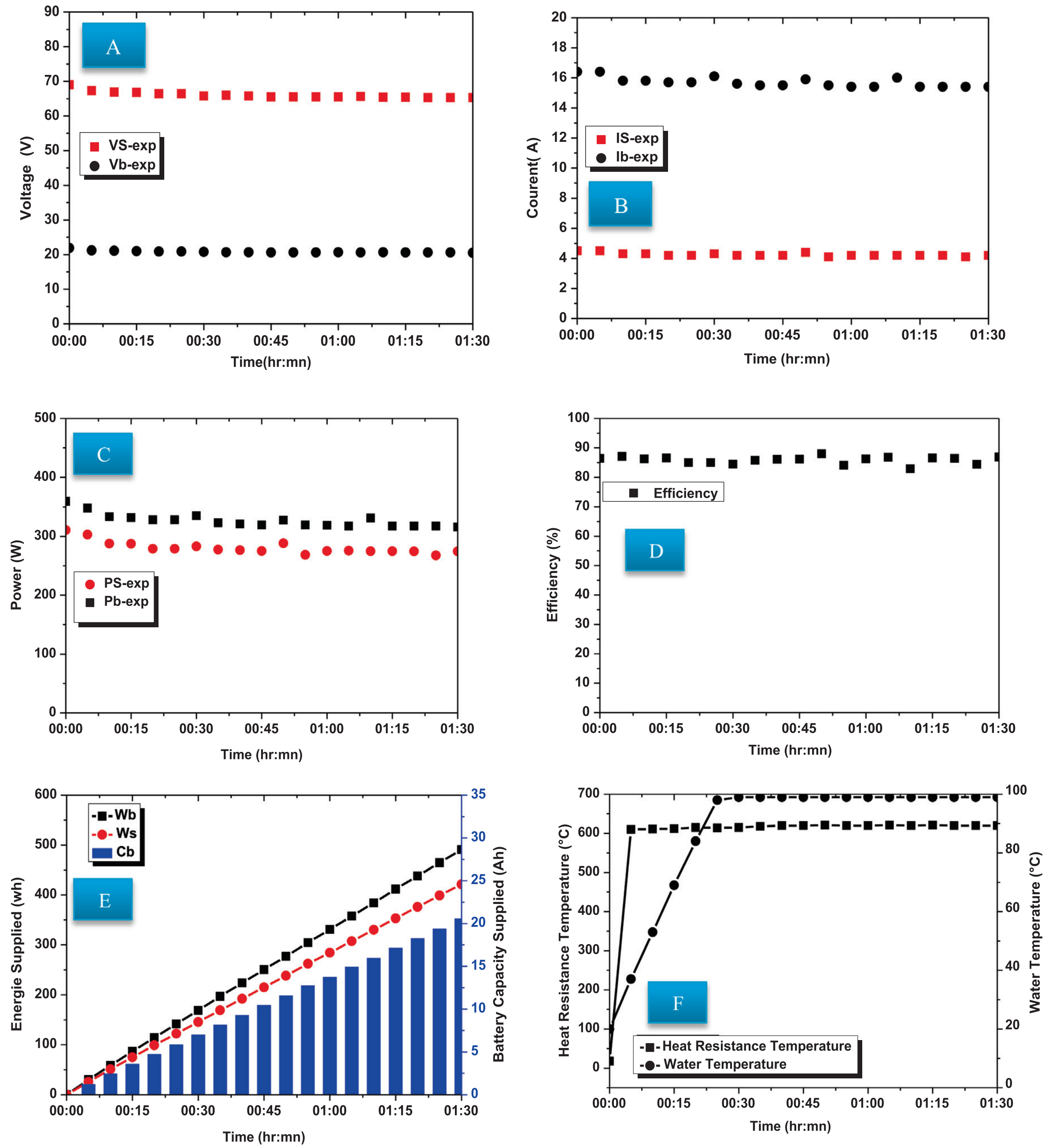

Fig. 4. Experimental electrical quantities, at the input and at the output of the complete system, in the case of the heating of 1 kg of water.a Input and output voltages;b Input and output currents;c Converter input and output power;d Efficiency of the converter;e Energy supplied by the batteries, energy consumed by the thermal resistance during heating and Capacity supplied by the batteries;f Temperature of thermal resistors and water.

4. Conclusion

In this paper, we presented the results of the simulation and experimentation of a new technique for powering solar cookers using batteries (24 V DC, 520Ah), through an adaptation stage at the base of the three-branches BOOST DC/DC converter, controlled by three PWM signals with a frequency of 20 kHz and a duty cycle of 0.7. The results obtained show:

- Simulation of system operation, depending on the duty cycle and the load, heating power of 350 W at the output of the DC/DC Boost converter, is obtained for a duty cycle α = 0.7 and a load of 15 Ω. Under these conditions, the output power is 350.4 W and therefore efficiency of 96 %. Experimental validation of these simulation results shows good agreement
- The experimentation of the system proposed to supply a solar cooker (box oven) of 500–600 W, heated by thermal resistors, shows yields of the DC/DC converter of 86 %, heating temperature of the thermal resistor and the water which reaches 640 °C and 99 °C after 20 s and 25 min, the energy supplied by the batteries and that of the heating are respectively of the order of 491 Wh and 421 Wh (i.e. 3.93 % and 3.37 %% of the energy supplied by the battery).

All the results obtained show a good agreement between the simulation and the experiment, remarkable performance for a duty cycle of 0.7, where the efficiency of the proposed DC/DC converter is 86 %, the heating temperature at the interior of the oven, and the electrical energy consumed during the heating of 3.93 % of batteries. These performances demonstrate both the proper functioning of the power system and the DC application of heating by solar batteries.

Data availability

No data was used for the research described in the article.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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- National Initiative for Human Development INDH, Berkane Province, Morocco, project 2017//29.

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