Enhanced Converter Control of a Stand-Alone Multilevel Photovoltaic System Featuring a Protection and Supervision System

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***Abstract*—The focus of this paper is to optimize the control of a stand-alone discretized photovoltaic system and to reduce the power losses. High power installations require discretized photovoltaic systems. This architecture allows to avoid penalizing the entire system during a malfunction. However, its problems lie in the control of the converters of the adaptation stages and the monitoring of the global system in case of failure. The paper presents, on the one hand, an optimized control algorithm based on the Hill-Climbing method that takes into account the characteristics of the photovoltaic panels and the batteries used to improve the performance and reliability of the photovoltaic system, and, on the other hand, an automated energy management system and a remote supervision interface of the installation to ensure interaction with the site. The integration of the main blocks in our photovoltaic chain has guaranteed continuity of energy production, protection of equipment and reduction of intervention time in case of anomaly in the system. All the results obtained showed that the efficiency of the control of the adaptation stages is around 96%. The average relative error between the simulation and the experiment is 2.47%. After a daily measurement, the efficiency of the MPPT control (98.7%), the efficiency of the adaptation stages (88%) and the efficiency of the overall system (85%) are satisfactory and close to the optimal values of the overall system.**

***Index Terms*—Multi-level PV system, MPPT control, remote supervision, protection system, energy efficiency, PV management system**

I. Introduction

Current photovoltaic (PV) systems that use a single power stage can be exposed to several faults resulting in decreased system performance and reliability [1, 2]. Work [3, 4] has shown that a photovoltaic system consisting of multiple PV panels equipped with a single matching stage is at risk of not operating around its Maximum Power Point (MPP), if a portion of these panels is exposed to shading or one of the panels fails. Conventional systems also present a considerable decrease in efficiency [5, 6] when the PV chain malfunctions or when shading is present [7–9]. Shahrooz Hajighorbani *et al*. [10] have shown that if the PV system is partially shaded, it can result in an estimated power loss of 75%. In addition to the shading problems, a simple failure in the matching stage results in the shutdown of the overall PV system operation.

To overcome the problems considered in the literature, a multi-stage PV architecture [11, 12] is required to achieve a significant energy gain while isolating the failing stage in case of failures [13–15]. The advantage of discretizing a PV array into multiple stages, where each stage consists of a single PV panel with its own matching, is to make each stage independent of the others. On the one hand, this independence allows to avoid shading problems and failures in MPPT controls, and on the other hand, to improve the overall efficiency of the PV system. In these new discretized architectures, the problem that arises is the control of the power converter which includes floating voltages at the output of the DC-DC converter [16, 17]. The floating voltages at the converters disturb the waveform of the pulse width modulation (PWM) signal generated by the switch control and subsequently cause power losses in the PV system.

In this context, our research work aims to improve the Maximum Power Point Tracking (MPPT) control using new approaches to minimize the response time and increase the system stability. The improved MPPT control algorithm is based on the characteristics of the panels and batteries used. To improve the response time, most of the articles in the literature [18, 19] start the PPM search from zero or low value, which is not favorable for the response time of the MPPT control. However, our algorithm starts the PPM search from the lowest (large) value of the optimal operating range according to the PV panel parameters. To improve the stability of the system, the proposed algorithm changes the increment step according to the power of the PV panels ("big step" outside the optimal range; "small step" inside the range), which reduces the ripple rate of the search system.

Furthermore, in this work, we proposed a PV management system [20–22] to control and supervise the

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operation of the remote system used in stand-alone PV installations [23–25]. This system also protects the system equipment in case of malfunction to maintain the continuity of energy production. The control block proposed in this work has the objective of conditioning the PWM signal at the input of the power switches without distortion and correctly controlling the switching of the power switches of the stages. The basic structure of this block consists of two stages, formed by the power components and the Drivers: the first stage is intended to improve the shape of the PWM signal generated by the MPPT control and the second is intended to adapt the signal to the stage.

In case of false data acquisition by the system, the algorithm injected in the microcontroller compares the climate parameters (temperature; illumination) with the optimal values of the PV panels. Based on these parameters and if necessary, the system allows the interface to record the data, but the protection block takes care of the isolation of the stage with the anomaly.

The following table (Table I) summarizes the merits and demerits of the developed system compared to the literature:

TABLE I: COMPARATIVE BETWEEN THE LITERATURE AND THE SYSTEM DEVELOPED IN THIS ARTICLE

Characteristics	Literature	Developed system
Adaptation stage	Single	Multiple
Monitoring	Missing	Present
Protection	Missing	Present
MPPT control	Classic	Enhanced
Conditioning stage	Missing	Present
Response time	> 500ms	<260 ms
Stability	Unstable	Stable
Divergence	Probable	None
Operating mode	Grid-connected + Standalone	Standalone

In this study, we present the design, implementation, and experimentation of a discretized and optimized PV system that consists of two stages in series with a protection block, a control system, and a monitoring system.

The first part of the manuscript is devoted to the description of the operating principle of the digital MPPT control, the control of the switches and the protection and supervision blocks.

The second part will be reserved for the experimental validation of the multilevel architecture of our system. In this part we will focus on the optimal power production of the global system, the analysis of the main parameters of the discretized PV system extracted during half a day of operation and also the behavior of the system in front of the different anomalies caused during the experiment.

II. MATERIALS AND METHODS

A. Structure of the System

The photovoltaic chain discretized Fig. 1 adopted in this work is composed mainly of photovoltaic panels, static DC-DC converters type BOOST controlled by a digital MPPT control Fig. 2, a protection block and a remote monitoring system. The technical characteristics of these elements are listed as follows:

- PV generators (PVG) formed by two PV panels (PVG-1 and PVG-2) in monocrystalline silicon with an efficiency of 14.08%, oriented south of 42° with respect to the horizontal, characterized by (U_{MPP}=19.0V; I_{MPP}=7.90A; U_{OC}=22.9V; I_{SC}=8.31A).
- Tow Boost DC/DC converters, whose characteristics are: V_{IN}≈17V; V_{OUT}≈55V; f=10Khz.
- Digital MPPT control injected in an ARDUINO microcontroller.
- Switch control unit that allows proper control of the state of power switches at each stage.
- Protection block to protect PV equipment in case of failure detection.
- Monitoring system developed with the Node-RED platform linked to the Firebase database, allowing real-time monitoring of system operation.
- Load that can be batteries of 12 V with a capacity of 150 Ah or a variable power resistor of 50 Ω / 500 W.

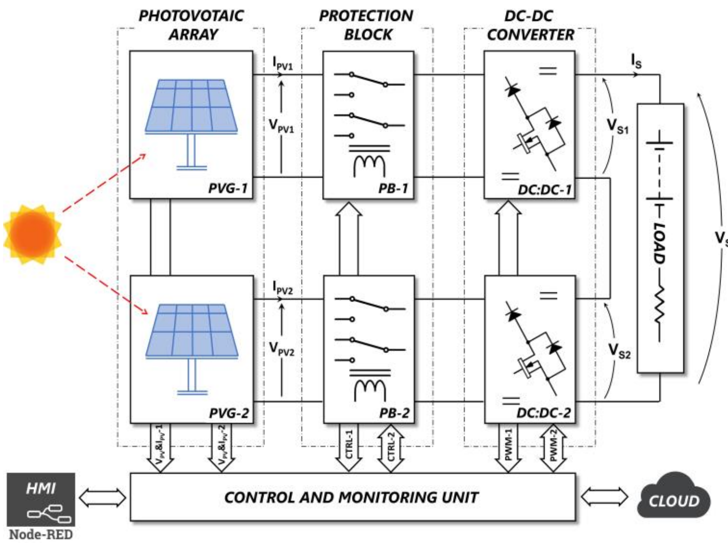

Fig. 1. Synoptic diagram of the discretized photovoltaic chain.

B. MPPT Control Unit

MPPT control unit used in this work, is implemented in an Arduino-UNO kit allowing the acquisition and conversion of the different electrical parameters of the PV modules Fig. 2. The MPPT algorithm [26–28] injected in the microcontroller is based on the Hill Climbing method [29–31], including a specific voltage range of the PV panels. This range represents the optimal operation of the PV modules for any climatic conditions. The latter allows to generate, simultaneously, two PWM signals to control the DC-DC converters Fig. 3 of each stage of the system to make it converge towards the optimal operation.

The operating principal of the MPPT algorithm is based on the calculation of the power derivative of the PV panels, and the study of the voltage variations outside and inside the optimal operating range of the PV panels. For our case, we forced a Maximum Power Point (MPP) search in the voltage range (12V−15.5V) considering the characteristics of the PV panels used as a function of temperature and illumination intensity Fig. 4 [32]. This allows us to vary the duty cycle of the PWM-1 and PWM-2 signals that control the power switches and converge the PV array operating point to the MPP with good response time and accuracy, while avoiding system divergence.

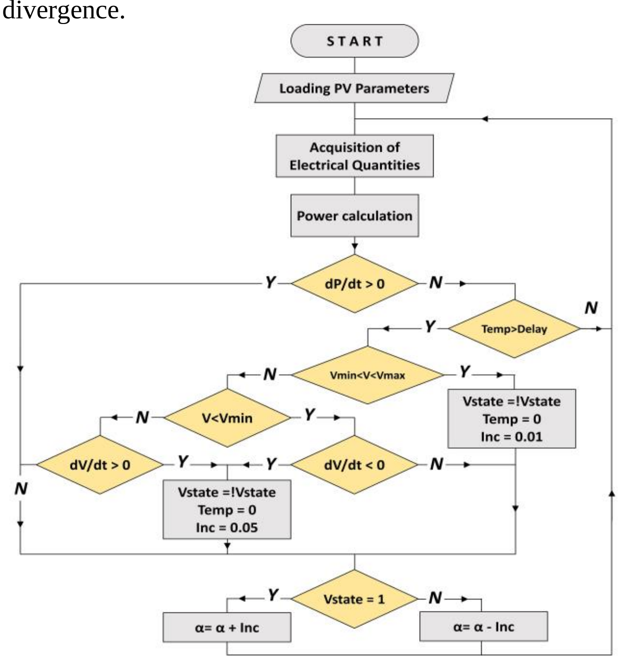

Fig. 2. MPPT algorithm implemented in the microcontroller to drive the PV system.

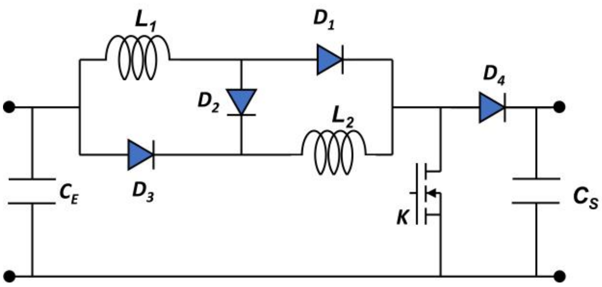

Fig. 3. Electrical diagram of the Boost DC-DC converter.

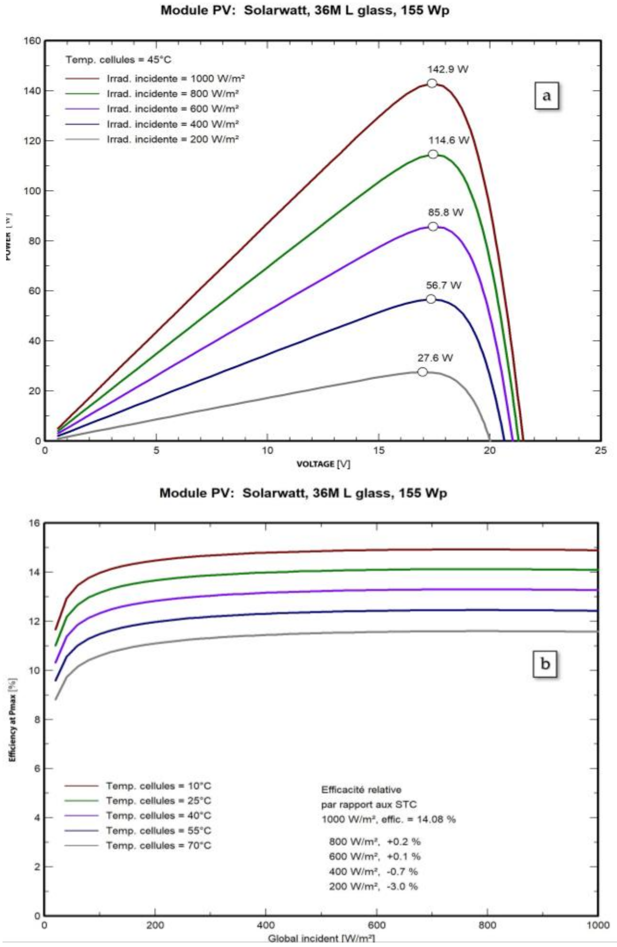

Fig. 4. (a) Experimental characteristics of the electrical power and voltage of the Module 36M L-glass 155 [32]. (b) PV panel efficiency as a function of temperature and illumination.

C. Control Block

The MPPT control implemented in this work based on an Arduino microcontroller can generate a PWM signal with an amplitude of only 5V. However, our PV installation, formed by two stages of DC-DC converters in series, controlled by power switches, requires PWM signals (PWM1 and PWM2) of the order of 12V and 35V. The use of a driver-based power circuit (IR2110) [33] Fig. 5 is necessary to provide the desired PWM signals.

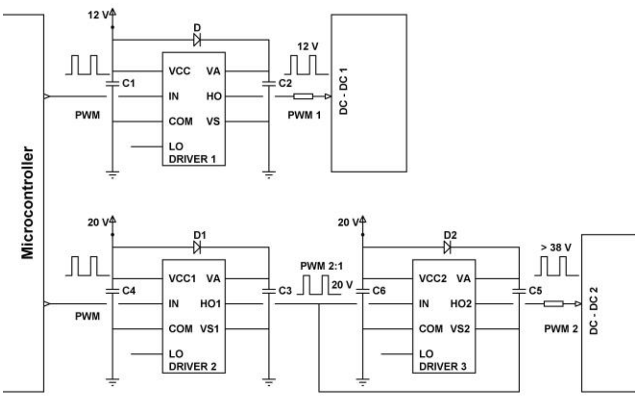

Fig. 5. Electrical diagram of the driver-based control block.

The Fig. 5 represents the structure of the power circuit proposed in this work, the description of which follows:

The lower stage needs only one driver to provide the PWM1 signal:

$$HO = VCC + VS \tag{1}$$

where VCC is the low side fixed supply voltage, HO is the high side output voltage, and VS is the high side floating supply offset voltage, all of the first stage.

With VCC=12V which corresponds to the power supply of the Driver.

The PWM1 signal is variable in amplitude of the order of VCC because the PWM signal is also variable, and Vs is grounded:

$$HO = VCC \approx 12\ V \tag{2}$$

The upper stage, on the other hand, needs the association of two identical drivers as shown in Fig. 5. With this structure we can obtain two signals PWM2_1 and PWM2 with the desired amplitudes:

$$HO1 = VCC1 + VS1 \tag{3}$$

where VCC1 is the low side fixed supply voltage, HO1 is the high side output voltage, and VS1 is the high side floating supply offset voltage, all of the first driver, second stage.

With VCC1=20V which corresponds to the power supply of the Drivers.

VS1 is grounded, so

$$HO1 = VCC1 \tag{4}$$
$$HO2 = VCC2 + VS2 \tag{5}$$

where VCC2 is the low side fixed supply voltage, HO2 is the high side output voltage, and VS2 is the high side floating supply offset voltage, all of the second driver, second stage.

$$= VCC2 + HO1 \tag{6}$$

The PWM and HO1 signals are variable and VS2 is connected to HO1 so the PWM2_1 and PWM2 signals are variable and of amplitude about 20 V and 40 V respectively.

From this analysis we can conclude that our power circuit in Fig. 5 can generate the necessary signals to drive the DC-DC converters:

- PWM 1 signal, rectangular with 12V amplitude,
- PWM 2_1 signal, rectangular, amplitude 20V,
- PWM 2 signal, rectangular, amplitude 40V.

D. Protection Block

The protection system integrated in our PV installation allows to protect the equipment's and to manage the operation of the two stages through a series of voltage/current measurements of each stage, so it corrects the state of the system according to the nature of the anomaly. In fact, after acquiring the different electrical values, the supervision system analyses these data and generates adequate control signals to manage the operation of the installation.

Fig. 6 shows the synoptic diagram of the protection system. The operation of this system is based on the flowchart in Fig. 7 and can be summarized in 4 cases:

- Case 1: Problem or bad connection of the PVG1 generator; in this case the supervision system disconnects stage 1 (upper stage) from the rest of the installation.
- Case 2: Problem or bad connection of the PVG2 generator; in this case the supervision system disconnects stage 2 (lower stage) from the rest of the installation.
- Case 3: The PVG1 and PVG2 generators are in good condition and well connected, and if there is a problem with the load (not/incorrectly connected) the supervision system stops the operation of the installation completely.
- Case 4: The PVG1 and PVG2 generators and the load are in good condition and well connected, and the supervision system allows normal operation of the installation.

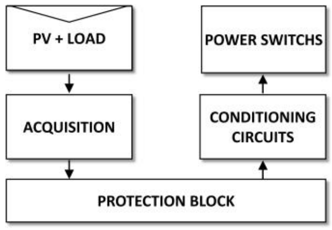

Fig. 6. The functional structure of the protection block.

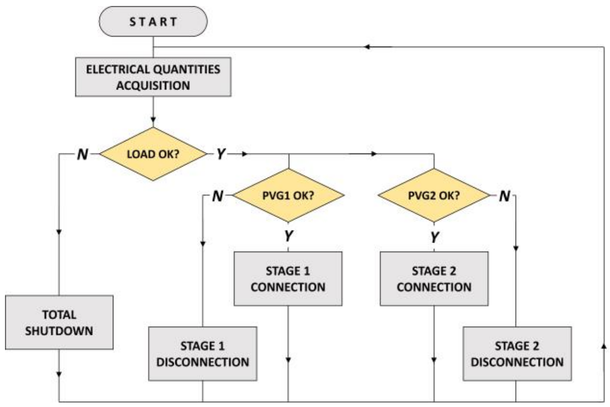

Fig. 7. The functional flowchart of the protection block.

E. Monitoring Block

In order to reduce the intervention time in case of failure and to detect instantly the anomalies of the PV chain, the implementation of a real-time monitoring block is necessary. The monitoring block developed during this work ensures the visualization of the different electrical values of the production line, the archiving of these values and the detection of anomalies at the main stages of the PV system.

The hardware aspect of the supervision block is composed of an Arduino-UNO kit for information processing and the NRF24L01 transmission module to establish a wireless communication.

The Dashboard of visualization (Fig. 8) was developed with the platform Node Red to assure the numerical display with precision of the electric quantity and also the graphic display to have an idea on the evolution of the parameter to be analyzed. This Dashboard is mainly composed of three parts, the first one is reserved for the PV modules, the second one for the DC-DC converters and the third one for the load.

Fig. 8. An overview on the main Dashboard of the monitoring block.

The archiving is provided by the Firebase hosting service which has the particularity to automatically connect and continue the communication in case of power loss or system reset. In addition, this service allows a simple, fast, and secure notification in case of failure or malfunction.

III. Results and Discussion

A. Operation of the Control Block

In order to ensure the two signals necessary for the control of the converters of the two stages of our PV installation a control block is essential.

The control block receives the basic PWM signal generated by the microcontroller and through the two drivers (Fig. 5) The control block ensures the amplification and the improvement of the shape of the signal supplied by the amplifier in order to have a practically rectangular PWM signal.

The two signals PWM1 and PWM2 generated at the output of the control block will respectively drive the switches of the DC-DC1 and DC-DC2 converters.

The readings of the PWM1, PWM2:1 and PWM2 signals obtained experimentally for an illuminance of 833 W/m2 Fig. 9 show that:

- They are perfectly rectangular with a duty cycle of 52.5% and a frequency of 10.0017 kHz.
- They reached respectively the amplitudes 11.5 V, 18.5 V and 36.5 V.
- They coincide with the signals obtained in numerical simulation.

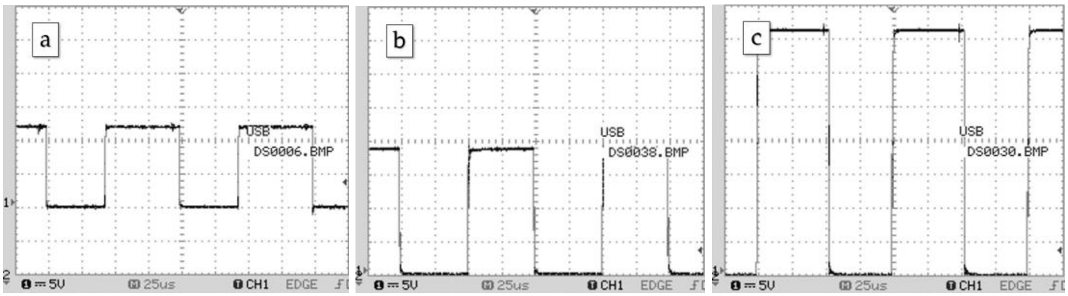

Fig. 9. The experimental readings of the signals: (a) PWM1, (b) PWM2:1 and (c) PWM2.

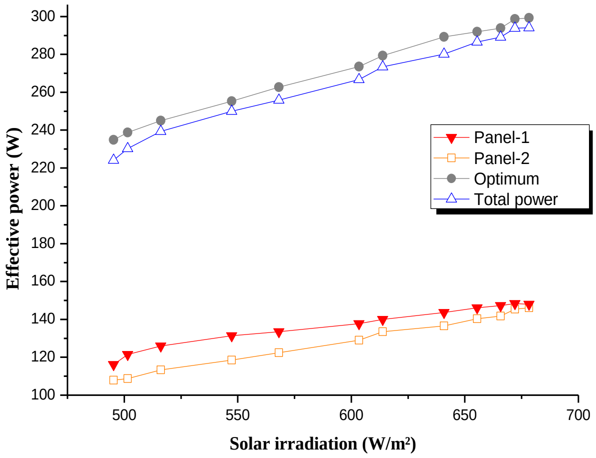

Fig. 10. The experimental and optimal power production of the PV system.

B. Optimal Functioning between Simulation and Experimental Results

The results of the optimal simulation are performed with PSPICE software using PV modeling.

Measurements are taken between 10:00 am and 1:00 pm where the illuminance starts with 480W/m² and then increases to 680W/m² with a temperature that varies from 37°C to 43°C during the same period.

Fig. 10 shows the optimal power generation of the PV system, the experimental results, the PV power generated by the two panels PVG-1 and PVG-2 of the two-level discretized system. These results show that:

- The illumination levels received by the PV panels in the system are slightly different, which explains the difference between the power output of PVG-1 and PVG-2 panels.
- The use of the multilevel architecture (Fig. 1) E has proven to be essential to operate in an optimal way. It prevents the system from malfunctioning due to shading conditions or PV panel malfunction.
- The smooth control of the MPPT control ensured optimal operation throughout the experimental period regardless of illumination and temperature variation.
- The MPPT control efficiency of the multilevel PV system used is about 96% during the system operation.
- We can clearly see a correspondence between the energy produced by the experimental PV system and that of the optimal system.

All the results obtained show a good performance of the multilevel PV system as well as the MPPT control designed for this work. Also, the multilevel architecture of a PV system can significantly increase the PV energy production compared to the conventional architecture. As for the MPPT control used in this work, it can ensure the optimal operation of the PV system regardless of the load or weather variations.

C. The Operation of the Protection Block Installation

To test the efficiency and reliability of the protection block during normal operation of the PV system: we have created 3 component defaults and for each case we have taken the electrical values at the input and output of the system (at the level of the input/output of the converters). The various tests are carried out at an irradiation of approximately 600w/m² and a temperature of approximately 38°C.

Concerning the DC load: we disconnected abruptly the DC load from the rest of the installation at the time *t* = 20s, at this moment; the monitoring system detects the nature of the anomaly (the electrical output values are cancelled) and disconnects the two generators PVG-1 and PVG-2 by generating two signals Control (Ctrl1 and Ctrl2) in the state 0 controlling simultaneously the protection blocks (PB1 and PB2). Fig. 11 shows the variations of the different electrical quantities of the output and the input during this operation.

For the DC/DC1 converter: we have created an open circuit at the DC/DC1 at the time *t* = 20s, after detection of this problem and in order to protect the plant, the monitoring system disconnects the PVG-1 generator through the control signal Ctrl1 and connects the lower stage of the plant directly to the DC load by short-circuiting the output of the DC/DC1. The results in Fig. 12 show that before *t* = 20s, the system operates under optimal conditions (on both stages of the system), and the output power Ps is equal to the sum of the powers supplied by the two stages. However, after *t* = 20s, the upper stage is disconnected, and the power Ps is equal to the power produced by the lower stage.

At the PVG-2 level, we disconnected it from the rest of the plant at the time *t* = 20s, after detecting this problem and to protect the plant; the supervision system disconnects the PVG-2 generator through the control signal Ctrl2 and connects the upper stage of the system directly to the DC load by short-circuiting the output of DC / DC2. The results in Fig. 13 show that before *t* = 20s the system operates under optimal conditions (through both stages of the system), and the output power Ps is equal to the sum of the powers supplied by the two stages. However, after *t* = 20s, the lower stage is disconnected, and the power Ps is equal to the power produced by the upper stage.

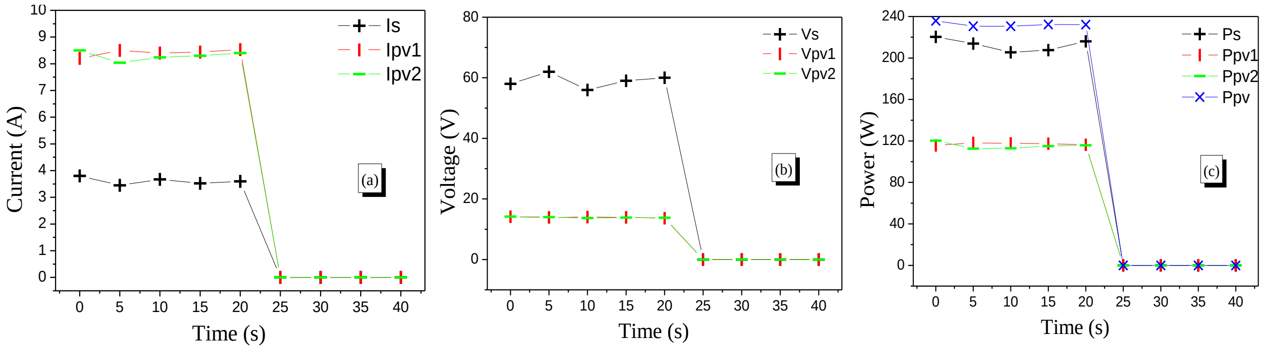

Fig. 11. Electrical values of the PV system in the presence of a load default: (a) current, (b) voltage and (c) power.

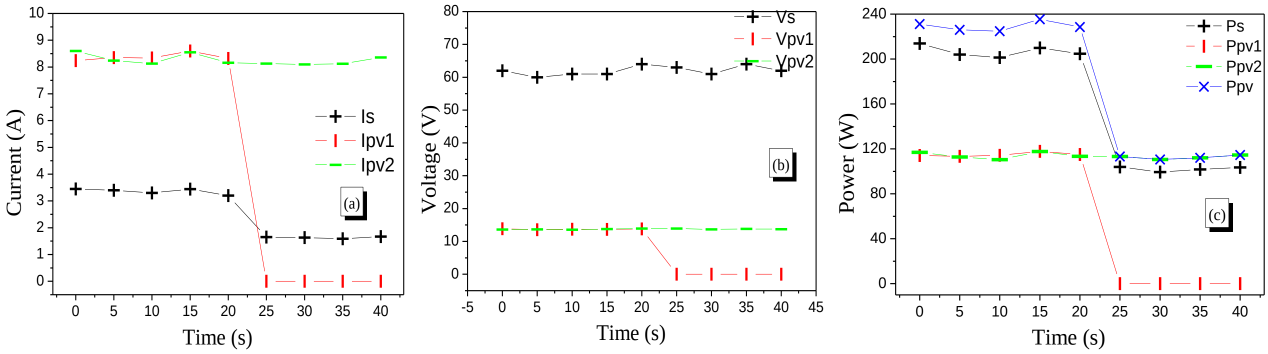

Fig. 12. Electrical values of the PV system in the presence of a default at the DC/DC1 converter: (a) current, (b) voltage and (c) power.

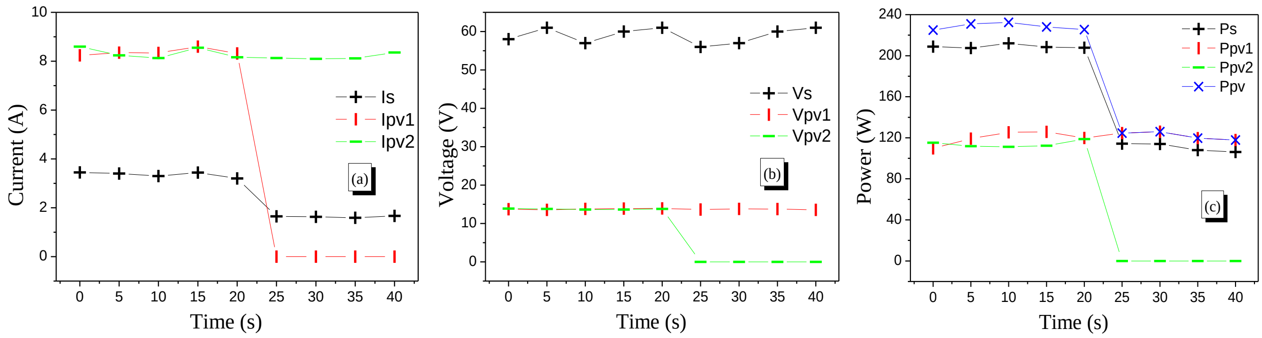

Fig. 13. Electrical values of the PV system in the presence of a fault at PVG-2: (a) current, (b) voltage and (c) power.

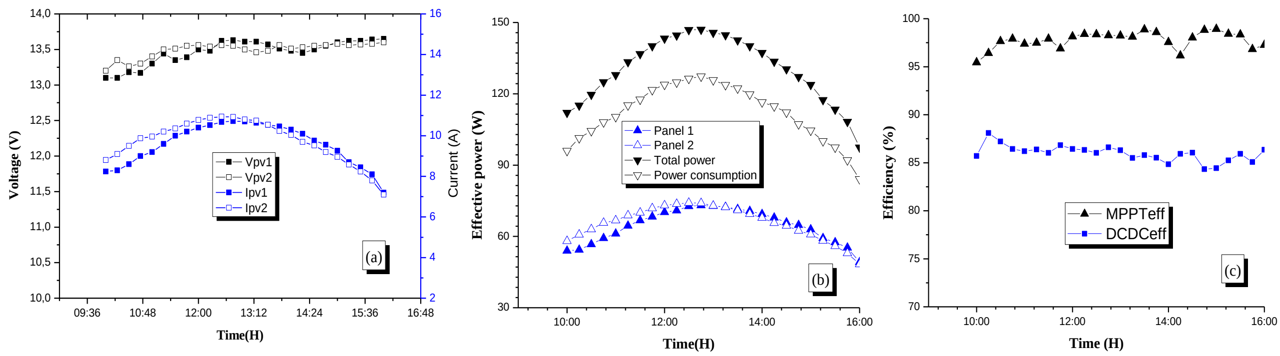

Fig. 14. Typical experimental results of the PV system operation: (a) Voltage and current (b) power production and consumption (c) Efficiency of MPPT control and DC/DC converters.

D. Operation of the Global System

Fig. 14 shows the typical experimental results of the PV system operation, obtained during half a day: the electrical quantities of the discretized system (voltage, current and power) and the MPPT control efficiencies as well as the DC/DC converters.

In Fig. 14, we have also plotted the results of the optimal simulation. All the obtained results show that:

- Illuminance and temperature vary from 480W/m² to 700W/m² and from 37°C to 43°C, respectively.
- For each DC/DC converter, the input and output voltages (14.2 V and 31 V), the input current (2 A - 2.6 A) and the output current (1 A) are identical and very similar to the simulation.
- The output voltage Vs is very close to the simulated voltage and equal to the sum of the output voltages

of each DC/DC boost converter (61 V).
- The output current of the overall system is identical to that at the output of each converter.
- The total power of the PV system (45 W - 65 W) is equal to the sum of the powers of each stage.
- The efficiency of the MPPT control (98.7%), the efficiency of the whole DC/DC converter (88%) and the efficiency of the global system (85%) are satisfactory and close to the optimal values of the global system.

The results obtained during the experimentation of the PV system designed and realized during this work show, on the one hand, the good functioning of each block of the system and, on the other hand, the validation of the control block which controls the power switches of the two DC/DC converters connected in series.

Therefore, the control block proposed in this work can be used in multilevel PV systems to control the power switches of DC/DC converters with floating voltages.

IV. Conclusion

The solution implemented in this work was developed with the aim of ensuring the control of the power converters in a robust manner, regardless of the operating state of the stage, shading level, lighting, temperature or load.

The optimized algorithm for power converter control has significantly improved the response time and stability of the system by using the optimal operating range of the photovoltaic panels.

The validation of the prototype operation is proved by the obtained experimental results which showed the following: The total power produced by the system (125.13W) is indeed the sum of the powers of all the stages (64.45W; 65.67W). The experimental and simulated values of the total power produced coincide perfectly with a relative error of 2.4%. The experimental control signals have duty cycles of 52.5% with a perfectly rectangular shape. The amplitude of the control signals (11.5V, 18.5V and 36.5V) is sufficient to control the converters. The efficiency (P_S×100/P_{PV}) of each stage is about 88.5%.

The protection block has ensured that the system is completely isolated from a faulty load. In the event that a stage fails, the energy flow is maintained by the protection block. The human-machine interface ensures a comprehensive and precise view of the system's operating state. All events are recorded and archived for future analysis.

Finally, the results of this work show that an optimized and supervised control of a discretized photovoltaic system significantly increases the energy production that can be applied on a stand-alone installation.

Conflict of Interest

The authors declare no conflict of interest.

Author Contributions

Mohammed Faysal Yaden carried out the conceptualization, programming, data analysis, experimentation, writing and editing of the original version. Mustapha Melhaoui contributed to programming and verification of the analysis methods. El Hadi Baghaz performed simulations, measurements, and revision of the manuscript. Prof. Kamal Hirech was responsible of supervision and results validations. All authors had approved the final version.

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