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Multilevel DC/DC converter architectures for high performance PV system

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This paper proposes a robust multilevel DC/DC converter for photovoltaic installation using a specific MPPT control that ensures the optimal operation of the system. The multilevel PV architecture consists of using a DC/DC converter with each level in the PV system, controlled by their owns MPPT controller to provide independently the maximum of energy in all weather conditions. The experimental results present a comparative study between the classical and the two-level PV architecture, using the MPPT algorithm implemented on a microcontroller that provides PWM signals to control the power switches of the PV system. The proposed system shows an enhancement of the energy efficiency, and good functioning of control system during the whole PV system operation.

Keywords: PV system, Multilevel DC/DC topology, MPPT, Energy control

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1. Introduction

The cost of photovoltaic energy is directly related to the cells cost and the quality of the energy which PV panels are able to provide during their operating. It is mainly influenced by the price of the raw material for the photovoltaic industry and the improvement of manufacturing technology [1-4], and by the efficiency of the energy conversion system. To remedy this problem, MPPT algorithms are used to maximize the energy power produced by the photovoltaic panels [5-10]. Therefore, it guarantees an optimal operation of photovoltaic systems regardless of the weather conditions.

Currently, PV installations have some problems during their operations causing a heavy loss of energy if some components are not working properly, especially when the PV system uses several panels causing a system dysfunction. Having one or more panels poorly enlightened or having anomalies, make the operation of the PV system away from the optimal operation, that's why we have been interested into a multilevel DC/DC topology [10-14]. In this context, to understand the multilevel PV system, we developed and analyzed two PV systems under the same conditions (Multilevel and classical topologies), to show the energy efficiency and the good operation of the multilevel topology.

In this work, we will present the experimental results of a two-level PV system, and we will analyze the operation of each power level (PV generators, MPPT control…).

2. Structure of Multilevel DC/DC topology

2.1 Block diagram

The use of DC/DC converters in PV systems is highly recommended for an optimal operation. It allows transferring the maximum of the energy from PV panels to the DC load.

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However, when PV installations are using several PV panels, a classical topology of DC/DC converter could decrease drastically the energy production if the PV panels are shaded. Besides, this topology could stop the PV production following a malfunction in PV generator or in the DC/DC converters, as a result, the use of multilevel DC/DC topology is highly recommended.

For example, a multilevel converter topology using series connection (Fig. 1), each PV panel is coupled to DC/DC converter so that each power stage is entirely decoupled from the remaining stages. If a PV panel fails, the system ensures PV energy to the load via the remaining stages. Besides, when using a classical topology, one single MPPT control cannot track the maximum power point of all the PV panels because they do not may have the same irradiation level (shading, inclination of the solar modules …), or the same behavior. On the other hand, the multilevel topology can afford the maximum of energy of the whole system using different MPPT control for each PV generator, which make this topology more efficient, and more productive.

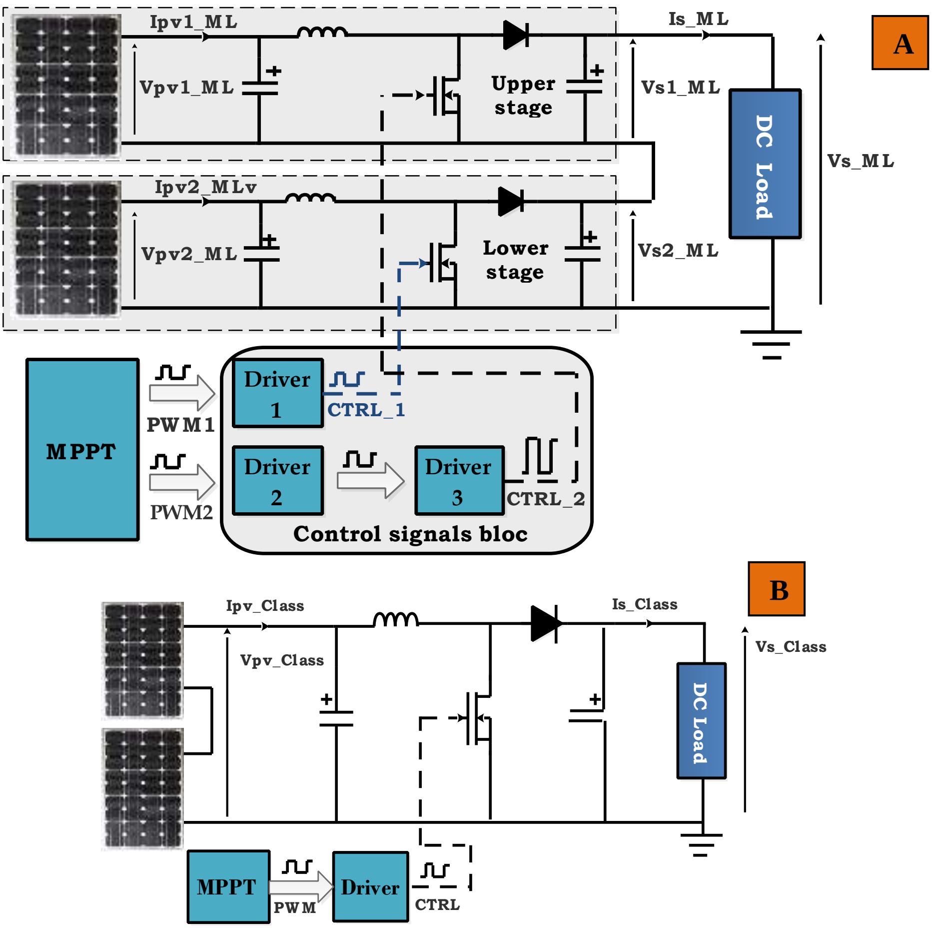


Fig. 1: System synoptic diagram of two-level PV system. **A:** Multilevel topology of photovoltaic system. **B:** Classical photovoltaic system.

2.2 MPPT Control

The MPPT algorithm implemented on the microcontroller ensures that the PV panel works around its maximum power point. The algorithm is based on Hill Climbing method that includes an optimal voltage range. This, represents the range where the photovoltaic panels work under the optimal conditions under any circumstances [4].

In this context, various studies and analyzes on PV panels have been carried out in previous studies in our laboratory [4] :

- On Fig. 2A, we represented the typical experimental and simulated power-voltage characteristics according to different Irradiance. These results show that the PV panel can provide under standard test conditions (STC) a power of 55 W, a current of 4.2 A at a voltage of 13V.
- On Fig 2.B, we represented the optimal PV voltage according to different Irradiance and temperature. From the experimental characteristics of the SP75 PV panels used for this work [15], we noticed an optimal operating range of the PV panels in all weather conditions. Therefore, we used this optimal voltage range (Vopt) which is between Vmin = 12 V and Vmax = 16 V, as an additional parameter when executing the MPPT algorithm, in order to increase the speed and accuracy of the MPPT.

The operating principle of the algorithm is based on power evolution of PV panel and of the study of their optimal voltage range to set the appropriate duty cycles of each PWM signals controlling the PV system. We set an important variation of the duty cycle outside the operating range (Inc=0.05) and a slight variation inside the operating range (Inc = 0.01) (Fig. 3). This procedure will not only increase the accuracy but also the speed search of the Maximum Power Point, avoiding the divergence of the system and ensuring the optimal operation of the whole PV system.

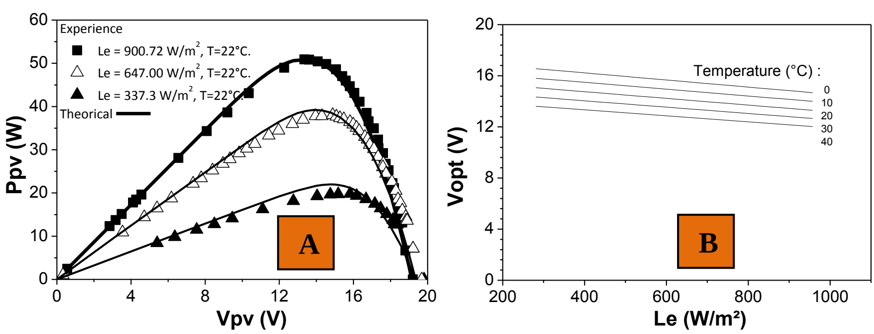


Fig. 2: **A:** Experimental electrical power-voltage characteristics of SP75 PV panel (■,Δ,□) and the simulated ones using Pspice simulator (——). T: 22-25°C. **B:** Simulated electrical characteristics of The PV panels according to the temperature and the irradiation.

3. System PV behavior

In order to study the reliability and optimization provided by the multilevel PV structure, we have simulated, analyzed and compared the operation of four-level PV structure in series with the classical PV structure, which are equipped with the MPPT control developed within this work. The two PV systems are simulated under the same weather conditions, within an ambient temperature of 25 ° C.

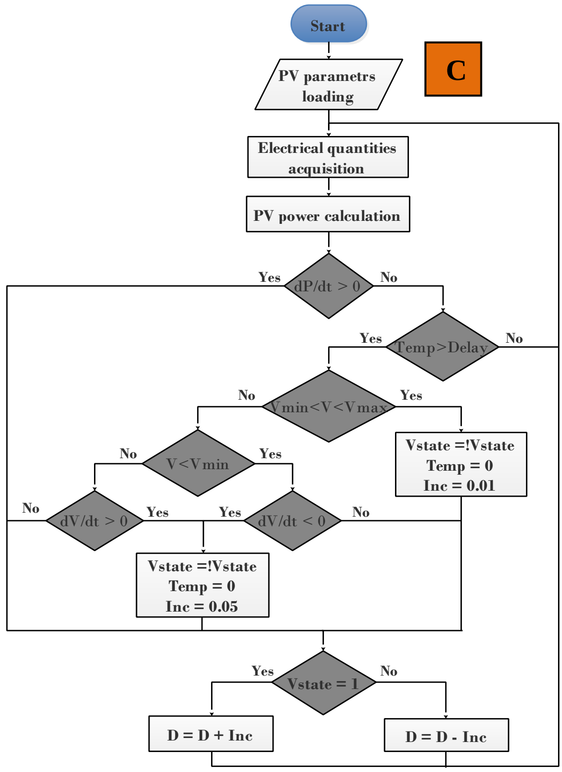


Fig. 3: **A:** New approach of the MPPT algorithm

We simulated two PV systems (Four-level and classical topologies) which supplying a resistive load of 50Ω (Fig. 4) according to two scenarios:

- First Scenario: The two PV systems operate under optimal weather conditions. Almost the same illumination is received by all the PV panels (Le1 = 1000W/m², Le2 = 1000W/m², Le3 = 950W/m², Le4 = 9500 W/m²).
- Second Scenario: The two PV systems experience a sudden change in irradiance due to the partial shading of the PV panels.

Fig. 5 shows the obtained simulation results of the two PV systems during their operation representing the electrical quantities of the PV panels, and those of the load (voltage, current and power). The results show:

- From 0 to 0.12s: We simulated the classical and the multilevel PV system under the optimal conditions. The PV panels receive almost the same irradiance: Le1 = 900 W/m², Le2 = 950 W/m², Le3 = 960 W/m² and Le4 = 960 W/m²:
  - The PV power is slightly different from one panel to another, hence the need to use an matching stage for each level of the PV system;
  - The electrical quantities of the multilevel PV system remain stable. The input voltage which is the sum of PV panels voltage has reached 54.2V (V_{PV_ML} = V_{PV1_ML} + V_{PV2_ML} + V_{PV3_ML} + V_{PV4_ML}), and the generated input current is approximately I_{PV_ML} = 4.1A (Fig 5A and Fig 5C). The output voltage is around V_{S_ML} = 98V, and the current absorbed by the load is stabilized around I_{S_ML} = 1.97A (Fig 5B and Fig 5.D).

- The electrical quantities of the classical architecture also remain stable. The PV voltage is of the order of V_{PV_Class} = 54.4 V, and the PV current is around I_{PV_Class} = 3.97 A. On the other hand, the voltage across the load and the current absorbed by the load are respectively of the order of 97 V and 1.92 A (Fig 5A to Fig 5D);
- The PV power generated by the multilevel PV structure is around P_{PV_ML} = 222 W, while the energy production of the classical PV system is around P_{PV_Class} = 216 W. On the other hand, the absorbed power by the load by the multilevel PV structure is P_{S_ML} = 193 W against P_{S_Class} = 187 W using the classical architecture (Fig 5E and Fig 5F).
- The energy gain resulting from multilevel PV structure reach 5%.

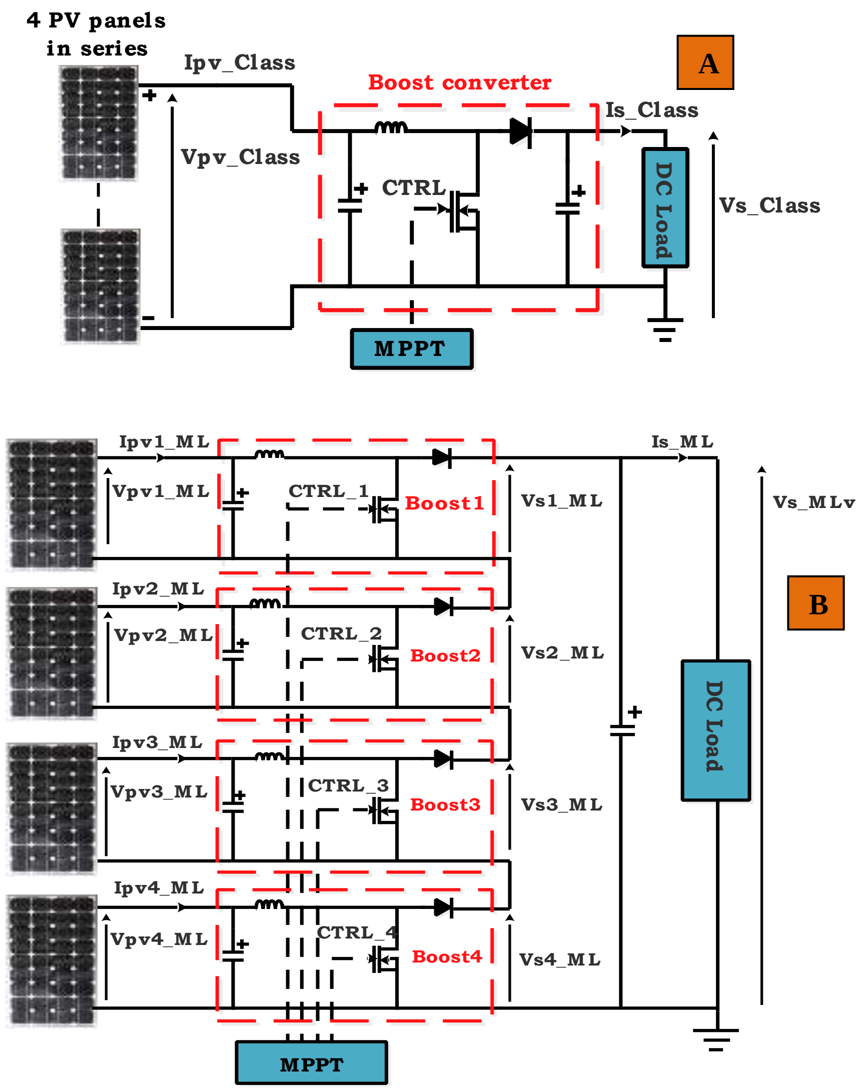


Fig. 4: System synoptic diagram of PV system. A: Classical photovoltaic system. B: Four-level topology of photovoltaic system

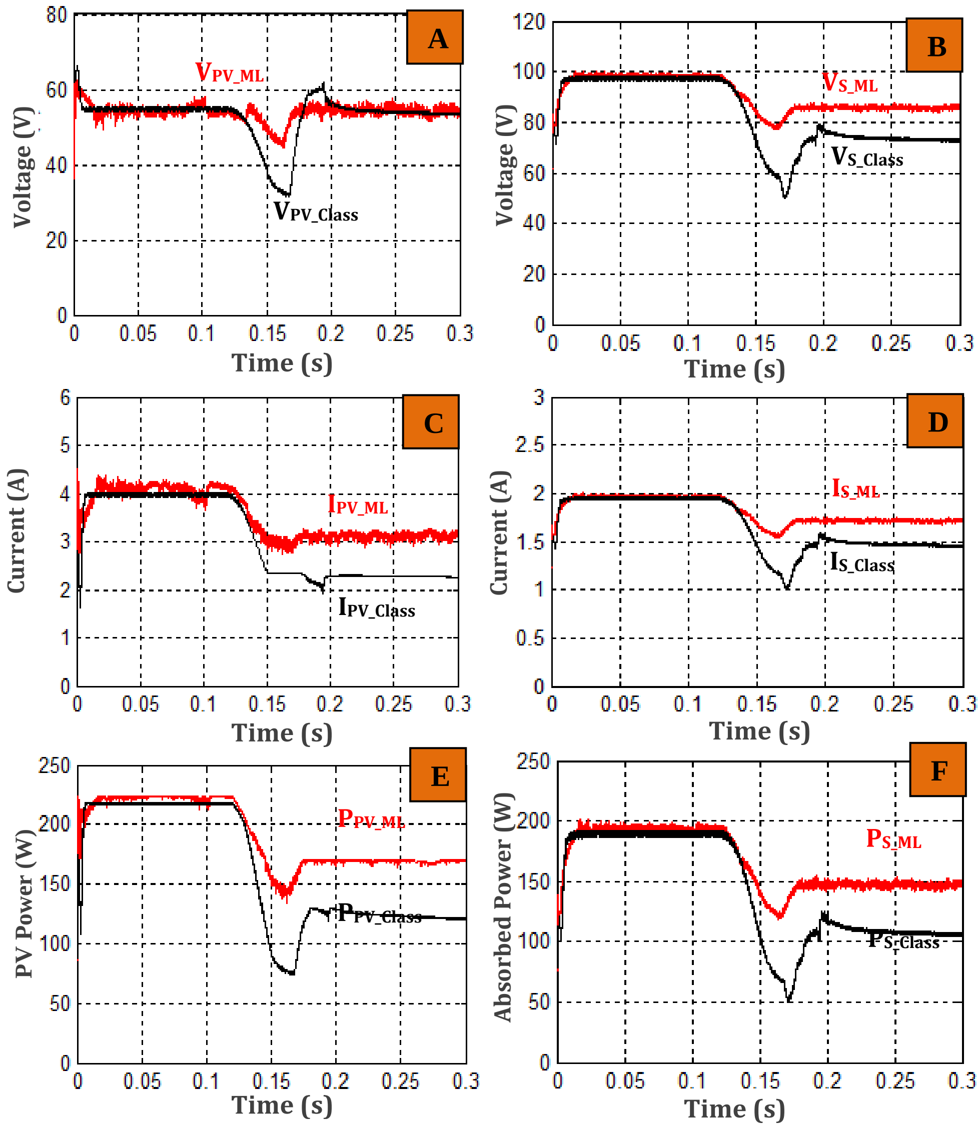


Fig. 5: Simulation results of two different PV systems behavior face to PV generator shading (Four-level PV topology and classical PV topology in series)

- From 0.12s to 0.3s: We maintained the irradiation level received by panels N°1 and 2 (Le1 = 900 W/m², Le2 = 950 W/m²), and we suddenly changed the irradiation level received by panels N°3 and 4 (Le3 = Le4 = 500W/m²):
  - The PV panel electrical quantities of the multilevel and classical structures remain practically stable: V_{PV_ML} = 54.2 V, I_{PV_ML} = 3.05 A, V_{PV_Class} = 55 V and I_{PV_Class} = 2.31 A (Fig 5A and Fig 5C).
  - The output voltage of the multilevel and classical PV systems are respectively of the order of V_{S_ML} = 85 V and V_{S_Class} = 75 V, and the currents absorbed by the load are respectively of the order of I_{S_ML} = 1.74 A and I_{S_Class} = 1.49 A (Fig 5B and Fig 5D);

- The PV power of the multilevel PV system is of the order of P_{PV_ML} = 165 W, and the PV power generated by the classical PV system does not exceed P_{PV_Class} = 125 W. The load consumption using the multilevel and classical PV system are respectively of the order of P_{S_ML} = 149 W and P_{S_Class} = 112 W (Fig 5E and Fig 5F);
- We note in this case, that the energy gain can reach 23% by using the multilevel PV structure compared to the classical PV structure. We also obtained a 25% energy consumption gain by using the multilevel structure compared to classical one.

The simulation results obtained when the PV panels are exposed to the same irradiation level show the good functioning and the reliability of both PV systems, as well as the MPPT control realized during this work. However, the use of the multilevel PV structure is much more efficient in presence of shading phenomena, as we have demonstrated in the extreme case that we simulated. The multilevel structure can afford an energy gain up to 25% compared to the classical structure thanks to its characteristic, which make possible to provide the maximum of the energy from every PV panel.

4. Experimental results and discussions

4.1 Experimental procedure

To study the reliability and optimization provided by the multilevel PV structure, we analyzed and compared the functioning of two different PV systems using two PV panels in series as presented in Fig 1. The PV system, which is the subject of our study, and the fully automated test bench are displayed on Fig.6. This system is composed by:

- Two monocrystalline PV panels for each PV system, delivering under optimal conditions, energy power of 62 W, a voltage of 14.2 V and a current of 4.4A each [15];
- Two DC/DC boost converter used for the multilevel topology and one DC/DC boost used for the classical PV system. The converters are designed to operate at a frequency of 10 kHz with a maximum power of 200 W and a current of 12A [4];
- A resistive load of 50 Ω of each PV system;
- The control circuit, based on the use of the microcontroller, performing the MPPT algorithm to control power switches of DC/DC converters;
- A weather station equipped with a Pyranometer and temperature sensor to measure the irradiation level and the ambient temperature using digital multimeter (KEITLY 2700).

4.2 Control signals

To drive N-type Mosfets (IRF540), it must be applied to their gates an amplitude signal such that $V_{GS} \geqslant 12$ V. The microcontroller generates PWM signals with a maximum amplitude voltage of 5V. To amplify these signals, we used a transistor amplifier followed by a driver circuit (IR2111).

In the case of the PV system with the classical topology (Fig. 1B), the use of a circuit similar to the circuit of Fig. 7A that can provide a 12V control signal (CTRL), is largely sufficient to drive the Mosfet, since its source pin (Vs) is connected to the ground.

However, on the two-level DC/DC topology (Fig. 1A), the Mosfet source of the lower power stage is connected to the ground. Therefore, the use of a single driver circuit to generate a control signal of 12V is sufficient to control the power switch (Fig. 7B).

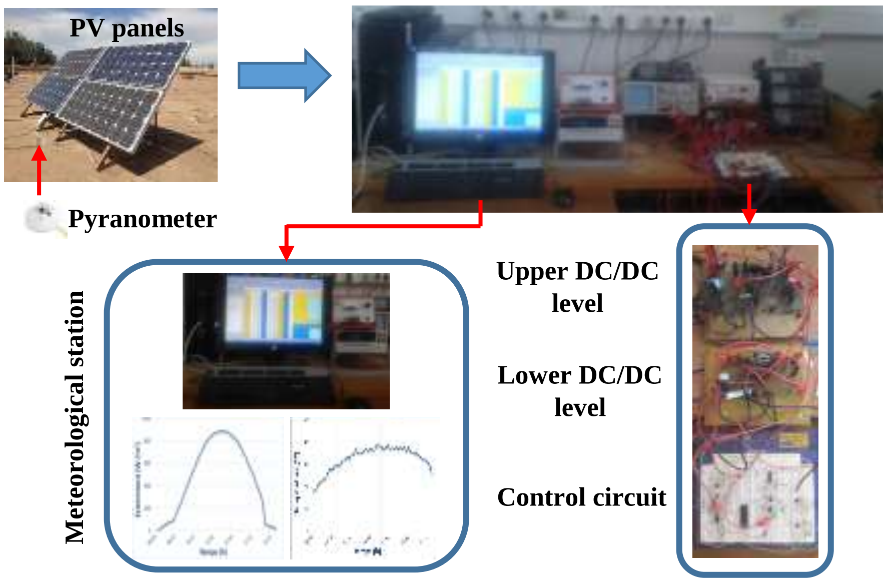


Fig. 6: Photovoltaic system designed and the automated test bench installed at the Laboratory

On the other hand, the Mosfet source of the upper stage is connected to the output of the lower stage (Fig. 1A). In order to control the Mosfet, knowing that Mosfet source is a non-zero voltage (can reach 25 V in our case), it is therefore essential to amplify the gate signal in order to ensure that V_{GS} is greater than or equal to 12V. Thus, an amplitude signal of 38V to drive the Mosfet gate is sufficient to control the power switch. Therefore, we designed the circuit of Fig 7B, using the characteristics of the driver circuit, in order to amplify the PWM signal (PWM2), and to drive the power switch of the upper stage (CTRL_2).

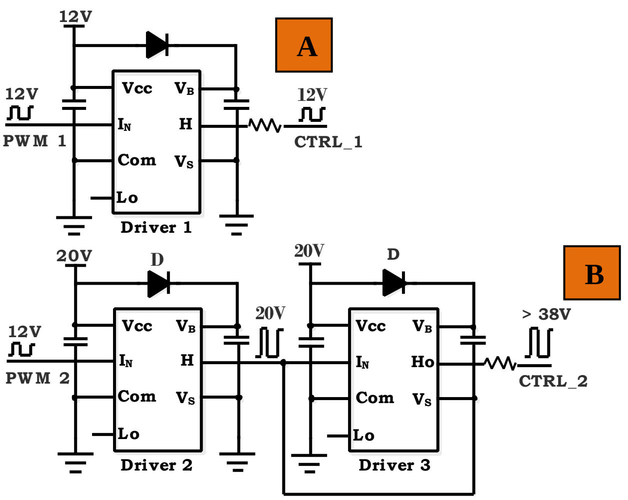


Fig. 7: Bloc diagram of two-level topology driver circuit. A: Driver control of lower stage. B: Driver circuit of upper stage

4.3 Multilevel PV system operation

In order to evaluate the reliability and the performances of multilevel PV structure compared to a classical architecture, we designed and realized two-level PV systems (classical structure and multilevel structure) as presented in figure 1, operating during a whole day in the same meteorological conditions.

A control circuit performing the MPPT algorithm for an optimal PV operation controls each PV system. For the multilevel topology, the microcontroller generates two PWM signals (PWM1 and PWM2). The driver circuit (Fig. 7) allows the amplification of the PWM signals to control the two Mosfets of the PV system (CTRL1 and CTRL2).

- Fig. 8A shows the 12V PWM signal, which controls the lower stage of the multilevel topology PV system.
- The upper stage, whose Mosfet source is a non-zero, is driven by the PWM signal shown in Fig. 8B (Amplitude of 38V and a frequency of 10 KHz),

On Fig. 9, we noted the electrical quantities of both PV systems during their operation (Voltage, Current, Power, DC/DC converter efficiency and the MPPT efficiency). During the PV systems operation, irradiance and temperature vary respectively from 450 W/m² to 750 W/m² and from 37 °C to 41 °C. On the same figure, we presented optimal electrical quantities simulated by PSpice simulator. All the results show:

- The Irradiance received by the two panels are slightly different, hence the need to work with a multilevel topology (Fig. 9A and is 9.B);
- The effectiveness and reliability of the MPPT control. Indeed, it ensures the stability and the smooth of both PV systems during the whole operation (Fig. 9C to Fig. 9H).
- The energy power produced by the multilevel PV system is close to the optimal result simulated by PSpice simulator. For an irradiance of 700W/m² and a temperature of 42°C, the multilevel PV system delivered 74 W, while the conventional PV system has delivered 71 W and the simulated maximum PV power indicates 75 W (Fig. 9G).
- The energy absorbed by the load is important in the case of a multilevel PV system than with a classical PV system. For an irradiance of 700W/m², the load absorbed 63 W using the multilevel PV system, and 58 W using the classical PV system (Fig. 9H).
- The MPPT efficiency of the multilevel PV system is around 97% throughout the PV system operating, and around 92.2% using the classical PV system (Fig. 9I). This, is because the two PV panels do not receive the same illumination, and therefore we will have two different maximum power point.
- The energy efficiency of the matching power stage of the multilevel topology varies between 84% and 86% throughout the PV operation. On the other hand, the DC/DC efficiency of the classical PV system does not exceed 83% (Fig. 9J).
- The energy produced during the PV system operation by the multilevel PV system is 272 Wh, and 257 Wh by the classical PV system. The energy delivered to the load is 231 Wh when using the multilevel PV system, and 211 Wh while with the classical PV system.

All these results, shows the smooth operation of the multilevel PV system and the MPPT control designed for this work. The use this topology allows a significant energy savings compared to the classical PV system, which is of the order of 5% for a two-level PV system. The energy saving can quickly increase when we use a significant number of PV panels. Besides the energy savings, the PV multilevel topology can operate under optimal conditions and the PV panel failure do not affect the operation of the PV system.

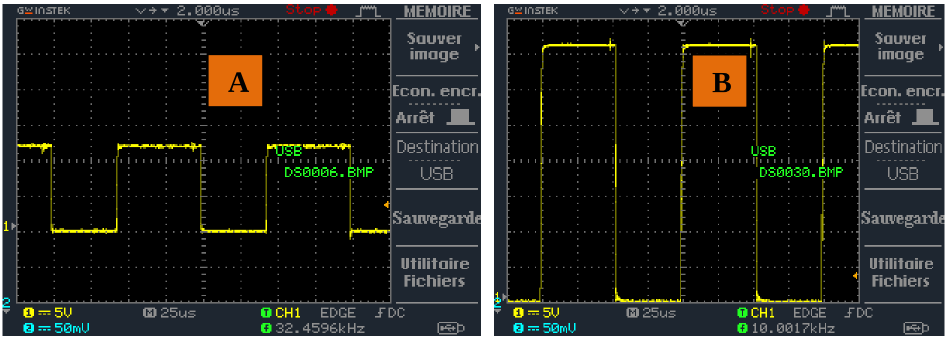
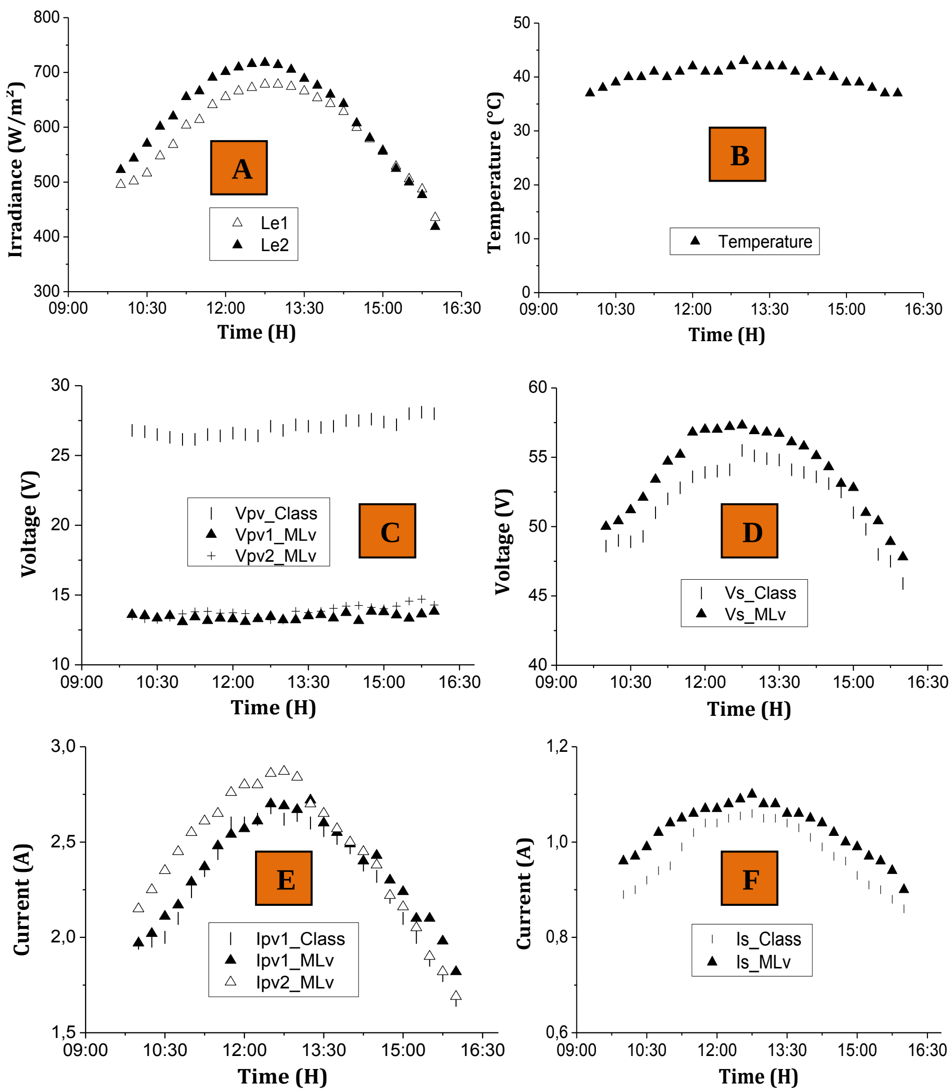


Fig. 8: Control signals of the multilevel PV system. A: control signal of the lower stage. B: Control signal of the floating stage



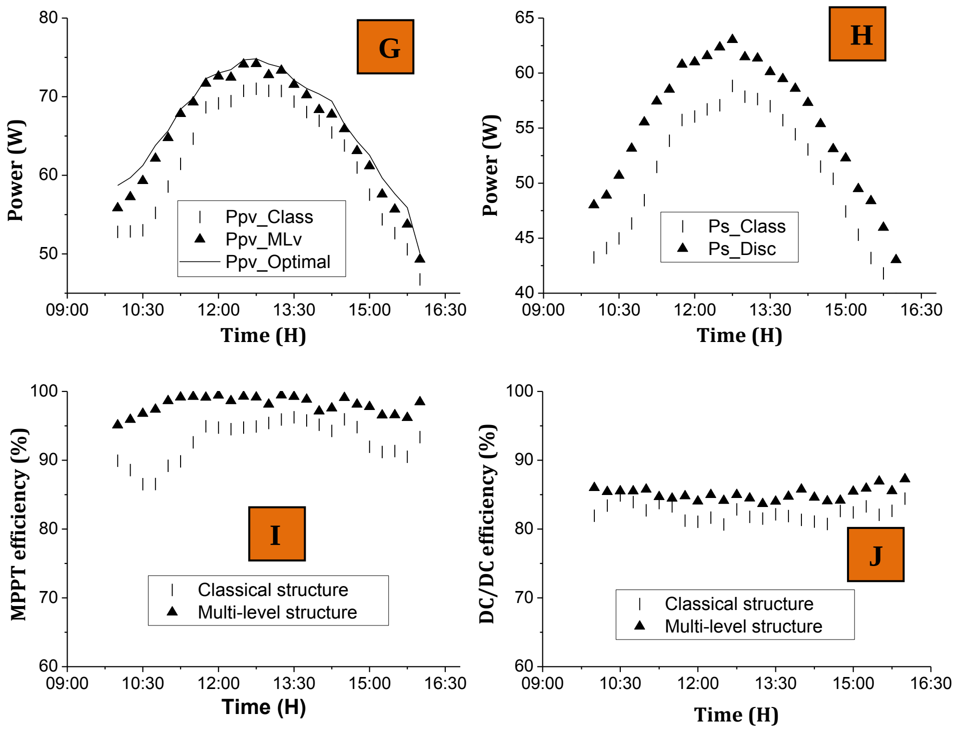


Fig. 9: Experimental and optimal electrical quantities (currents, voltages, powers and PV system efficiencies) of the multilevel PV system and the classical PV system during a whole day of PV system operation

5. Conclusion

In this work, we analysed the conception and the validation of multilevel DC/DC topology. The power levels that ensure the matching power of our PV system are controlled by a single microcontroller performing the MPPT algorithm to ensure the optimal operation of the PV system under the optimal conditions regardless of the weather conditions. Thus, the simulation results of the four-level PV system in series between the two DC/DC topologies (Multilevel and classical topologies) reveals an interesting energy saving when using the multilevel structure, which can provide more than 22% of the energy compared by the classical structure.

On the other hand, from the experimental data obtained during the operation of the two-level DC/DC topologies in series during a whole day of operation, we have shown:

- A good agreement between the optimal and the experimental results during a full day of PV system operation.
- The good operation of each DC/DC power level and the complete PV system under the optimal conditions regardless of the weather conditions.
- Good performance using our MPPT control performed by using a single microcontroller and that controls the two power converters simultaneously. The MPPT efficiency is about 98% regardless of the weather conditions.
- The entire system efficiency is the order of 87%, including two DC/DC converters.

- We obtained 5% of energy gain using two-level converter topology compared to the classical PV system. The energy gain may increase by increasing the number of PV panels used.
- The multilevel PV system ensure a better operation than the classical PV system, especially if one or more PV panels fails.

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