

Design and Implementation of an Efficient Single-Phase Five-Level Multilevel Inverter for Solar PV Applications

Ayoub Nouaiti^{1*}, Abdallah Saad², Abdelouahed Mesbahi³, Mohamed Khafallah⁴

^{1,2,3,4}Laboratory of Energy and Electrical Systems, Superior National School of Electricity and Mechanical,
Hassan II University of Casablanca, B.P 8118, Oasis, Casablanca, Morocco

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Abstract

This paper presents the design, simulation, and implementation of a new single-phase five-level inverter, for photovoltaic systems, with a reduced number of power switches and fewer gate-drivers power supply. This multilevel inverter consists of a high step-up DC-DC converter, a switched-capacitor converter, and a full bridge converter. The proposed topology is used to deliver optimal AC voltage and current with fewer harmonics to the loads by controlling the high step-up DC-DC converter with a small duty cycle. A prototype of a 200W rated power feeding an inductive load from solar panels is tested by simulation and experiment. A maximum power point tracking method and a pulse width modulation technique are presented and evaluated under normalized criteria for voltage, frequency, and total harmonics distortion (THD). The experimental results show that the proposed multi-level inverter is an efficient converter to supply power energy from solar panels to industrial machines such as single phase induction motors.

Keywords: photovoltaic system, switched capacitor converter, multilevel inverter, boost converter

1. Introduction

Wind and solar energy are currently being used to reduce the consumption of fossil fuels and decrease greenhouse gas emissions. Power electronics techniques and converters play a crucial role in this energy transition. Researchers and industrialists continue to improve these fields by developing new solutions that minimize both component count and manufacturing costs [1].

In photovoltaic (PV) systems, in which electricity is generated by converting the energy produced by solar panels from DC to AC, the use of high-efficiency inverters is necessary. Classical inverters pose certain problems such as high switching losses, bulky output filters, and considerable harmonics.

Multilevel inverters can overcome these problems. They provide sinusoidal AC waveforms with fewer harmonics and output filters that are of reduced size and sometimes eliminated. They can be used in high-power applications with low switching losses across the power switches, thus increasing the efficiency of the PV chain conversion [2]. Standard multilevel inverters are classified into three categories: cascade H-bridge inverter, flying capacitor inverter, and neutral point clamped inverter [3]. From these categories, several topologies of multilevel inverters are derived by utilizing symmetric, asymmetric, and hybrid arrangements [4]. The switched capacitor converter (SCC) is one of the derived topologies. It is used as a step-up converter, delivers multilevel DC voltage, and can be tied with classical inverters to obtain multilevel AC waveforms. Many SCC circuits have been discussed in the literature [5-7]; however, they are used for systems operating at high frequency and cannot supply power energy for systems operating at low frequencies such as 50 Hz and 60 Hz.

* Corresponding author. E-mail address: nouayoub@gmail.com

Tel.: +212522230789; Fax: +212522231299

This paper presents the design, simulation, and experimental testing of a new single-phase five-level inverter for photovoltaic system applications. This photovoltaic inverter is novel because it combines the new high step-up DC-DC converter (HSUC), proposed in [8], with the SCC [9-11] and conventional full bridge converter (FBC). By utilizing the proposed combination, the HSUC is controlled with a small duty cycle thus reducing the switching losses across its power switches. The output AC voltage is sinusoidal in shape with five levels, and the total number of power switches and gate driver power supply are reduced compared to conventional multilevel inverters. This multilevel inverter presents many advantages over a classical inverter composed of a conventional boost converter and a full bridge converter used in a PV chain conversion, where the duty cycle is very high and the output AC voltage has two or three levels [12].

The proposed topology is tested using the maximum power point tracking method (MPPT) to verify the ability of the system to extract maximum power energy from solar panels. In addition, an efficient pulse width modulation (PWM) control method is applied, that enables the system to deliver good output AC waveforms with fewer harmonics without using output filters. An experimental prototype of a 200 W rated power is fabricated at the laboratory and tested by supplying power energy from solar panels to a single-phase induction motor, in order to validate the simulation results and to confirm the high efficiency of the proposed multilevel inverter.

This paper is organized as follows: Section 2 describes the proposed single-phase five-level inverter, Section 3 presents the control strategies used, Section 4 presents the simulation results, Section 5 presents the experimental results, and Section 6 presents the conclusion.

2. Description of the proposed Phase Five-Level Inverter

The topology of the proposed single phase five-level inverter is shown in Fig. 1. It consists of a single input DC voltage (V_{in}) from solar panels (PV), the HSUC, and the DC-AC five-level converter (FLC).

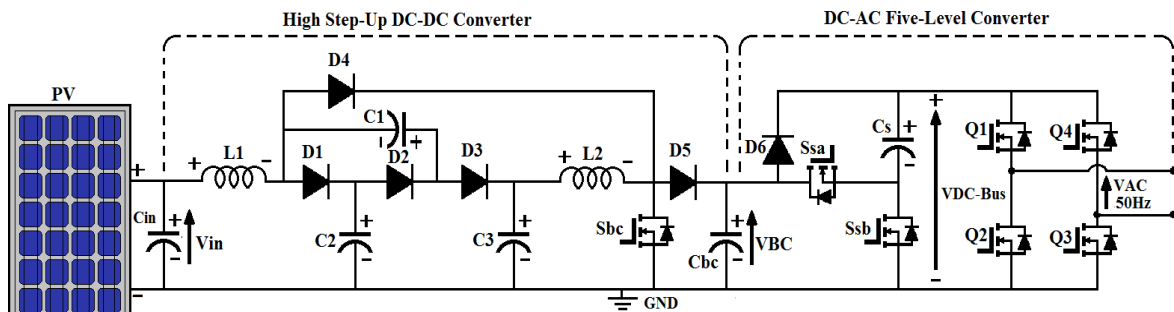


Fig. 1 Topology of the proposed photovoltaic multilevel inverter

2.1. Solar panels

Solar panels are made of an electrical assemblage of small solar cells which produce DC current through the photovoltaic effect by absorbing photons from sunlight. A simple model of a solar cell is shown in Fig. 2; it's based on a current source, single diode, parallel resistance and a series resistance.

The expression of the generated current from this model is shown in Eq. (1) [1, 11-13]:

$$I = I_{ph} - I_s \left(\exp \frac{q(V + R_s I)}{NKT} - 1 \right) - \frac{(V + R_s I)}{R_p} \quad (1)$$

where I is the output current, I_s is the reverse saturation current of the diode, I_{ph} is the photocurrent, N is the ideality factor of the diode, V is the output voltage, q is the electron charge ($1.60217662 \times 10^{-19}$ coulombs), K is the Boltzmann constant ($1.38064852 \times 10^{-23} \text{ m}^2 \text{ kg s}^{-2} \text{ K}^{-1}$), and T is the junction temperature.

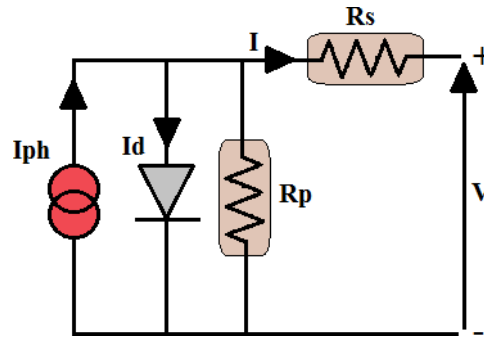


Fig. 2 Simple model of a solar cell

2.2. High Step-Up DC-DC converter

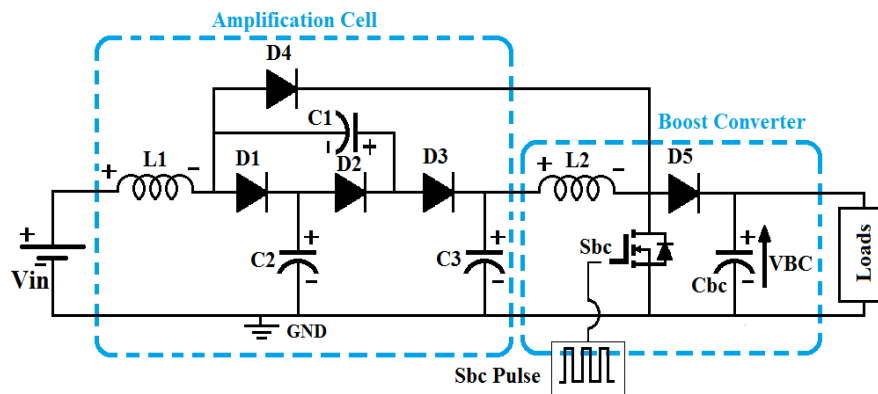


Fig. 3 The used high step-up DC-DC converter

The used HSUC is shown in Fig. 3. It's composed of an amplification cell tied with a simple boost converter. The amplification cell consists of one inductor (L1), four diodes (D1, D2, D3, and D4), and three capacitors (C1, C2 and C3), while the boost converter consists of one inductor (L2), one diode (D5), one power switch (Sbc), and one capacitor (Cbc).

This DC-DC converter is used to deliver high output voltage (V_{bc}) from a lower voltage (V_{in}). V_{bc} and V_{in} are related to one equation expressed in Eq. (2) [8]:

$$\frac{V_{bc}}{V_{in}} = \frac{2}{(1-D)^2} \quad (2)$$

where D is the duty cycle of the control signal of this DC-DC converter ($0 \leq D \leq 1$).

The operation of the HSUC and the sizing of the important used elements are presented in detail as follows, which is not the case of [8]: By considering that Sbc is controlled with a pulse signal having a duty cycle (D), and a chosen frequency (F_s); two important modes are discussed.

- (1) Mode I: When Sbc is ON, the diodes D4 and D2 are forward biased; the remaining diodes (D1, D3, and D5) are reversely biased, as shown in Fig. 4 (a).

In this mode; the inductor L1 is charged by current from V_{in} through D4 and Sbc; the capacitors C1 and C2 are charged and discharged in order to get balanced state through D2, D4, and Sbc; the inductor L2 is charged by current from VC3 through Sbc; the capacitor Cbc supply power energy to the load.

The derived equations from mode (I) are presented as follow:

$$VL1 = Vin \quad (3)$$

$$VC1 = VC2 \quad (4)$$

$$VL2 = VC3 \quad (5)$$

(2) Mode II: When Sbc is OFF, the diodes D1, D3, and D5 are forward biased; the remaining diodes (D2 and D4) are reversely biased, as shown in Fig. 4 (b).

In this mode; the capacitor C2 is charged by voltage from V_{in} and $VL1$ through D1; the capacitor C3 is charged by $VC1$ through D3; the inductor $L2$ supply power energy to the load and the capacitor Cbc.

The derived equations from mode (II) are presented as follow:

$$VL1 = Vin - VC2 \quad (6)$$

$$VC3 = VC1 + VC2 \quad (7)$$

The inductor $L1$ is charged and discharged with current during the period T_s ; for this:

$$VL1 \times D + VL1 \times (1 - D) = 0 \quad (8)$$

From Eq. (3), Eq. (6), and Eq. (8):

$$Vin \times D + (Vin - VC2) \times (1 - D) = 0 \quad (9)$$

From Eq. (4), Eq. (7), and Eq. (9):

$$VC3 = \frac{2Vin}{(1 - D)} \quad (10)$$

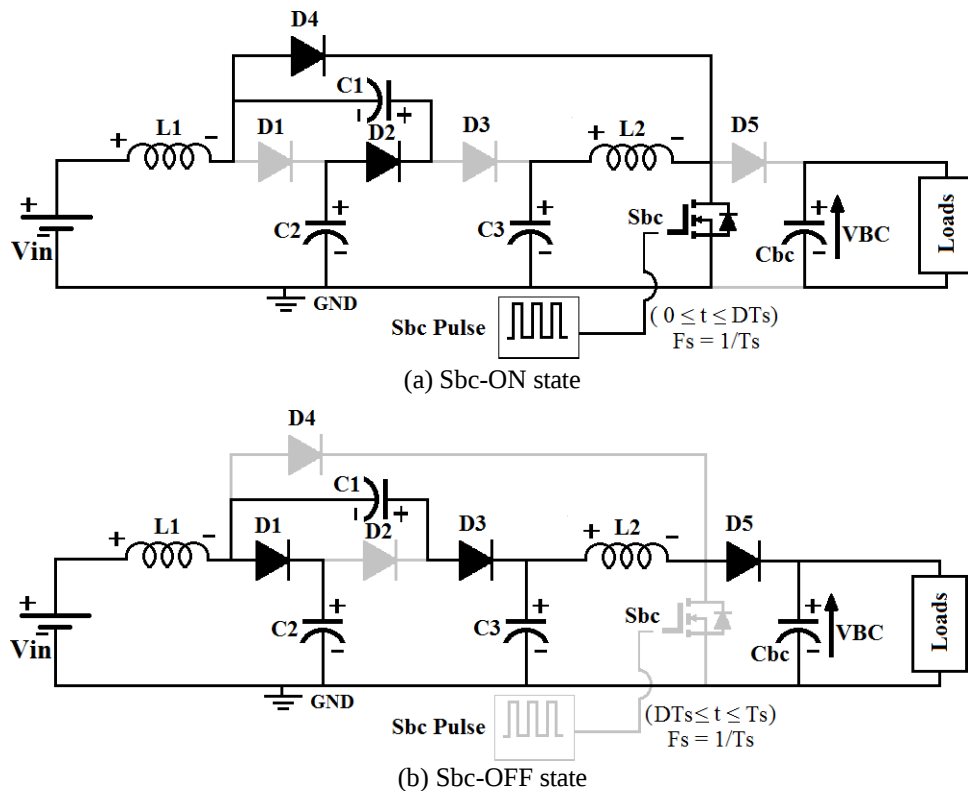


Fig. 4 The operating states of the power switch Sbc

As indicated previously, the used HSUC contains an amplification cell tied with a conventional boost converter; for this, by considering the related equation between the input voltage and the output voltage of a boost converter [14]:

$$VBC = \frac{VC3}{(1-D)} \quad (11)$$

From Eqs. (10)-(11), the related equation between VBC and V_{in} is demonstrated in Eq. (12):

$$\frac{VBC}{V_{in}} = \frac{2}{(1-D)^2} \quad (12)$$

Fig. 5 shows the obtained waveforms during mode I and mode II.

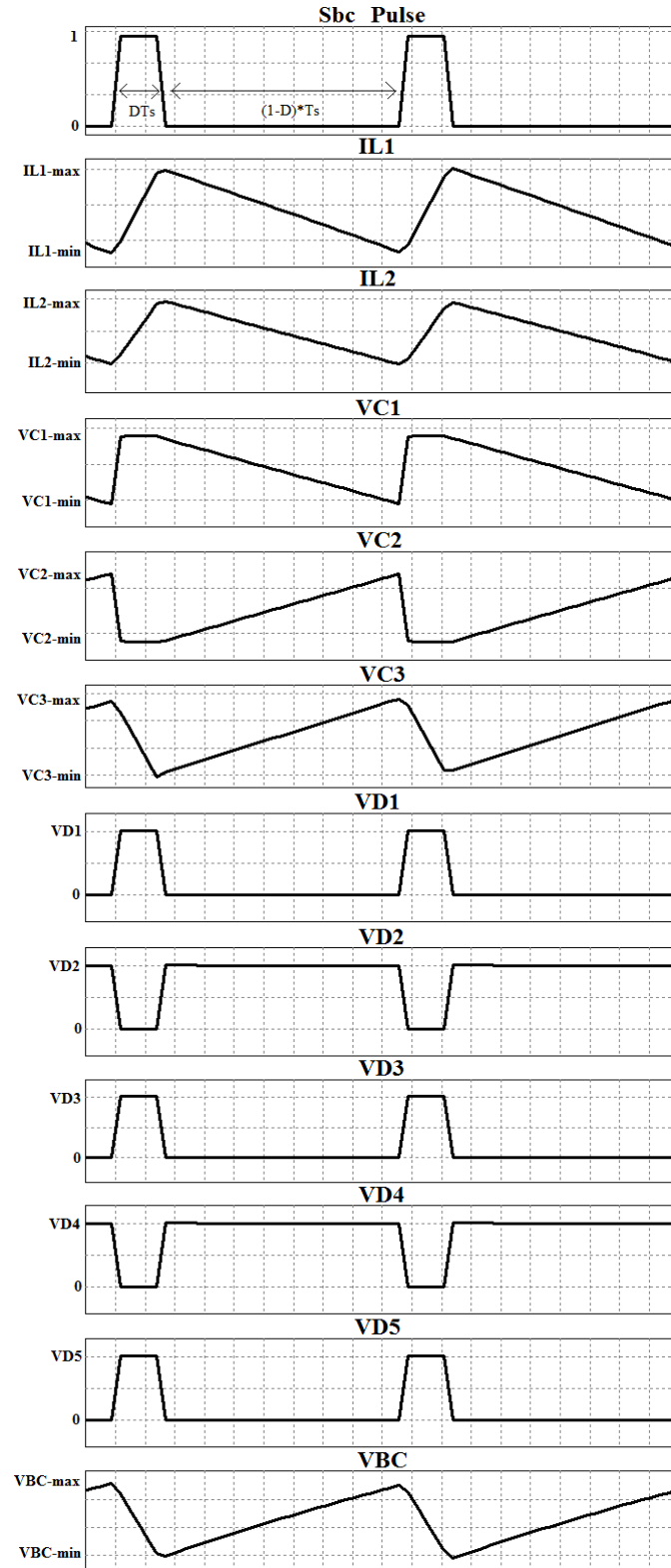


Fig. 5 Waveforms of the used DC-DC converter during continuous modes (Mode I and Mode II)

In order to use the DC-DC converter in the correct form, the values of the different used elements have to be calculated. For a conventional boost converter, the values of its input inductor (L_{in}) and its output capacitor (C_{out}) can be determined using Eq. (13) and Eq. (14) [14].

$$L_{in} = \frac{V_e \times D}{\Delta I_L \times F_s} \quad (13)$$

$$C_{out} = \frac{I_s \times D}{\Delta V_C \times F_s} \quad (14)$$

where D and F_s are respectively the duty cycle and the frequency of the control signal; V_e and I_s are respectively the input voltage and output current; ΔI_L and ΔV_C are respectively the ripples of the input current and the output voltage.

By similarity from Eq. (13) and Eq. (14), the values of the inductor L_2 and the capacitor C_{bc} can be determined using Eq. (15) and Eq. (16).

$$L_2 = \frac{V_{C3} \times D}{\Delta I_{L2} \times F_s} \quad (15)$$

$$C_{bc} = \frac{I_s \times D}{\Delta V_{BC} \times F_s} \quad (16)$$

The studied HSUC is used to step-up voltage (Step-down current); for this, by similarity from Eq. (10), the current across the inductor L_2 can be determined using Eq. (17).

$$I_{L2} = \frac{(1-D) \times I_{L1}}{2} \quad (17)$$

From Eq. (10), Eq. (15), and Eq. (17), the expression of L_2 can be simplified.

$$L_2 = \frac{4 \times D \times V_{in}}{(1-D)^2 \times \Delta I_{L1} \times F_s} \quad (18)$$

The inductor L_1 is charged with current when S_{bc} is ON, and discharged when S_{bc} is OFF; for this, by similarity from Eq. (13), the inductor L_1 can be determined using Eq. (19).

$$L_1 = \frac{V_{in} \times D}{\Delta I_{L1} \times F_s} \quad (19)$$

The capacitor C_3 is discharged when S_{bc} is ON, and charged when S_{bc} is OFF; for this, by similarity from Eq. (14), the capacitor C_3 can be determined using Eq. (20).

$$C_3 = \frac{I_{C3} \times D}{\Delta V_{C3} \times F_s} = \frac{I_{L2} \times D}{\Delta V_{C3} \times F_s} \quad (20)$$

From Eq. (17) and Eq. (20), the expression of C_3 can be simplified.

$$C_3 = \frac{I_{L1} \times D \times (1-D)}{2 \times \Delta V_{C3} \times F_s} \quad (21)$$

From Eq. (4), Eq. (7), and Eq. (21), the capacitors C_1 and C_2 can be determined using Eq. (22).

$$C1 = C2 = \frac{C3}{2} = \frac{IL1 \times D \times (1 - D)}{4 \times \Delta VC3 \times Fs} \quad (22)$$

2.3. DC-AC five-level converter

The used DC-AC FLC is shown in Fig. 6. It's composed of a switched-capacitor converter (SCC), and a full bridge converter (FBC). The SCC consists of two power switches (Ssa and Ssb) and one capacitor (Cs), while the FBC consists of four power switches (Q1, Q2, Q3, and Q4).

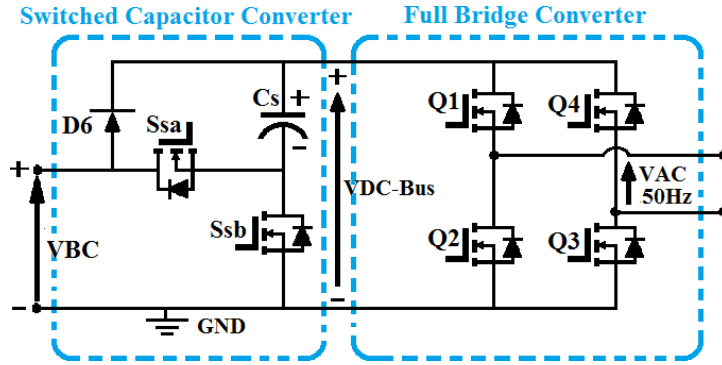


Fig. 6 The used DC-AC five-level converter

The SCC delivers an output DC voltage (VDC-Bus) greater than VBC by switching the capacitor Cs in series and in parallel. The operation of this converter is described as follows:

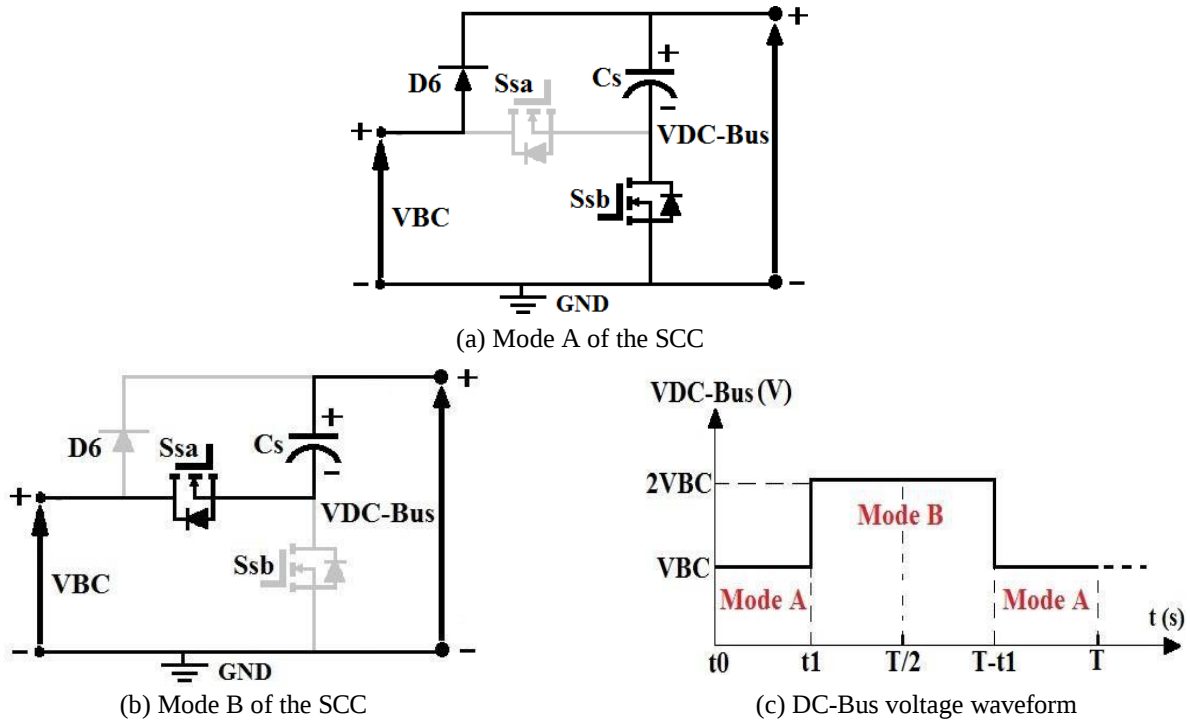


Fig. 7 The two operating modes of the SCC with the generated DC-Bus voltage waveform

- (1) Mode A: When the switch Ssb is ON (Ssa is OFF); the diode D6 is forward biased. In this case, the capacitor Cs is charged by VBC, as shown in Fig. 7 (a). The expression of the DC-Bus voltage is developed in Eq. (23):

$$VDC - Bus = VC_s = VBC \quad (23)$$

- (2) Mode B: When Ssa is ON (Ssb is OFF); the diode D6 is reversely biased. In this case, the capacitor Cs is discharged, as shown in Fig. 7 (b). The expression of the DC-Bus voltage is developed in Eq. (24):

$$VDC - Bus = VC_s + VBC = 2 \times VBC \quad (24)$$

From Eq. (23) and Eq. (24), the SCC generates a positive staircase waveform which begins from VBC and ends at 2VBC, repeated at each period (T), as shown in Fig. 7 (c), where [t₀, t₁] and [t₁, T-t₁] are the times' intervals for mode A, mode B respectively.

To calculate the value of the used capacitor C_s, it's necessary to know [15-16]:

- (1) The value of the output AC current supplied to the AC load and the difference phase (ϕ) between this current and the output AC voltage.
- (2) The length of time of each step of DC Bus staircase waveform.

By using the two conditions described above, the amount charge Q_{Cs} of the capacitance C_s is firstly calculated using Eq. (25):

$$Q_{Cs} = \int_{t_1}^{T-t_1} I_{out} \times \sin(2\pi ft - \phi) \times dt \quad (25)$$

where f and I_{out} are respectively the frequency of the output AC voltage and the amplitude of the AC current supplied to the load, [t₁; T-t₁] is the time interval which is corresponded to longest discharging cycle (LDC) of C_s, as shown in Fig. 7 (c) and detailed in mode B.

By considering that ΔV_{Cs} is the chosen voltage ripple across the capacitor C_s, the value of its capacitance can be calculated using Eq. (26):

$$C_s \geq \frac{Q_{Cs}}{\Delta V_{Cs}} \quad (26)$$

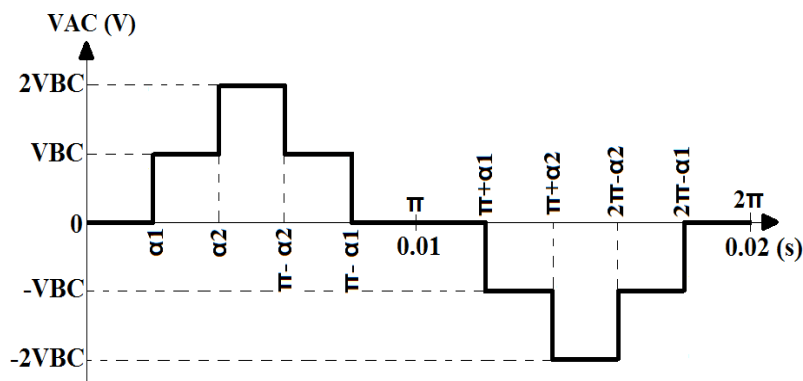


Fig. 8 Output AC voltage waveform

The FBC is used to convert VDC-Bus to an AC voltage (VAC) with a specified frequency (50Hz in this study). Table 1 summarizes the switching states of all used power switches in the DC-AC FLC, and Fig. 8 shows the obtained VAC voltage waveform.

Table 1 Switching states of the power switches

Switching states						VAC
Q1	Q2	Q3	Q4	Ssb	Ssa	
ON	OFF	ON	OFF	OFF	ON	+2VBC
ON	OFF	ON	OFF	ON	OFF	+VBC
OFF	ON	ON	OFF	OFF	OFF	0
ON	OFF	OFF	ON	OFF	OFF	0
OFF	ON	OFF	ON	ON	OFF	-VBC
OFF	ON	OFF	ON	OFF	ON	-2VBC

3. Control Strategies of The Studied Multilevel Inverter

3.1. Control method of the used HSUC with maximum power point tracking

The MPPT methods are used in photovoltaic systems to extract maximum power energy from solar panels under different climatic conditions. Several methods of MPPT are presented in the literature [17]. The algorithm Perturb and Observe (P&O) still the easy way to implement the MPPT; This method is based on measuring input voltage (V_{in}) and input current (I_{in}) from solar panels, and operates by perturbing V_{in} to extract maximum power energy, as shown in Fig. 9. Although some problems can appear with this method, such as oscillations around the maximum power point (MPP); the P&O was used to test the robustness of the studied DC-DC converter in critical conditions. Fig. 10 shows the implementation of the chosen MPPT method with the HSUC.

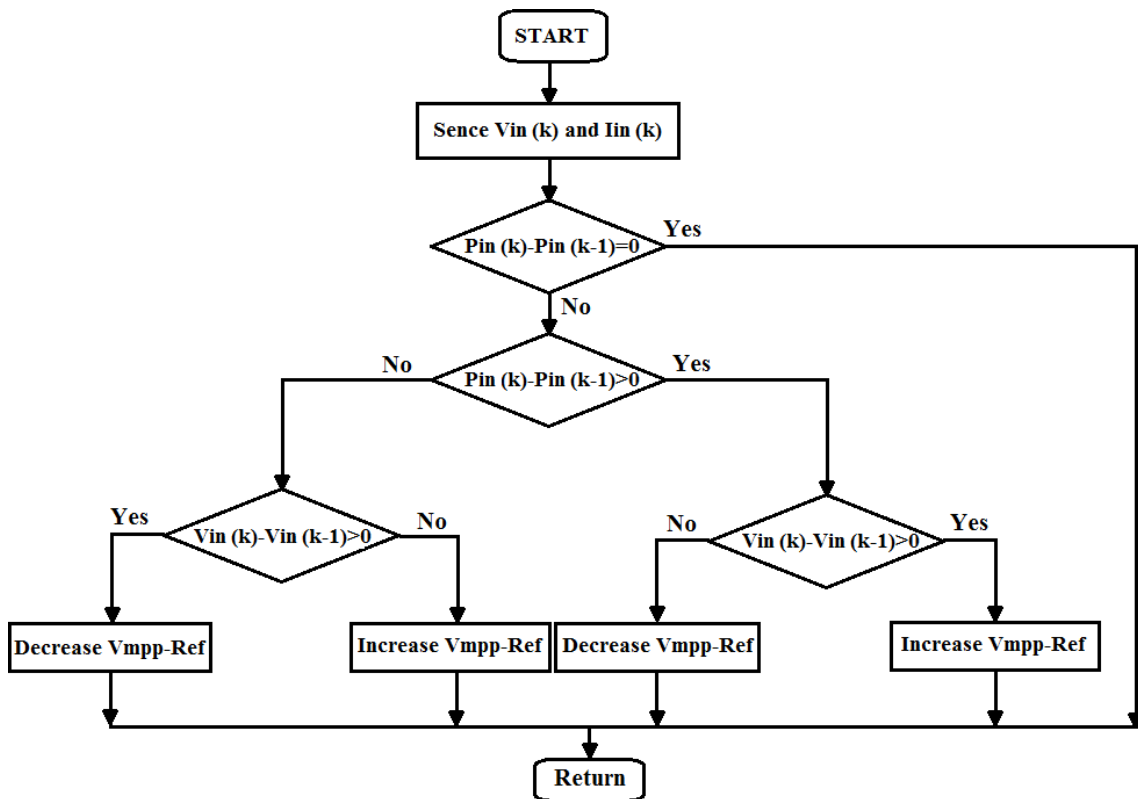


Fig. 9 Flowchart of the P&O method

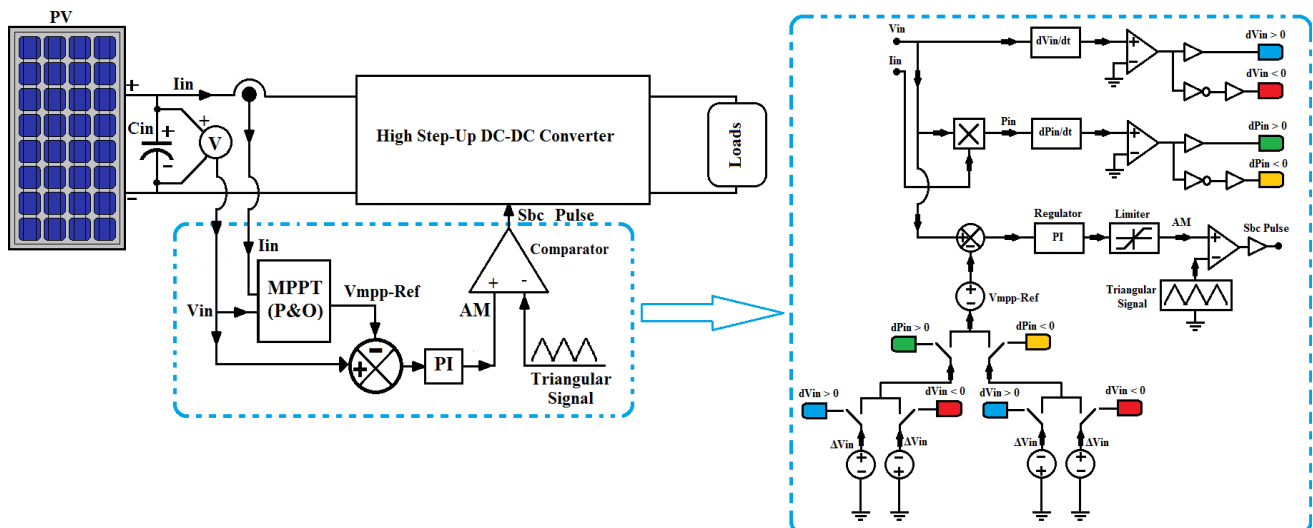


Fig. 10 P&O method with the studied DC-DC converter

The used MPPT is equipped with a PI regulator to minimize the difference error between the sensed voltage V_{in} and $V_{mpp-Ref}$, and also to faster the response of the MPPT method to any sudden variation in climatic conditions [14-18]. The generated signal (AM) from the PI regulator is compared with a high-frequency triangular signal to generate the control signal with the appropriate duty cycle for the HSUC.

3.2. Control method of the used DC-AC FLC with PWM method

In order to control the studied DC-AC FLC with high-frequency modulation technique, an efficient and simple pulse width modulation (PWM) method is applied [19-20]. It's based on comparing two identical high-frequency triangular carrier signals (Carr1 and Carr2) with a rectified low-frequency (50Hz) sinusoidal signal (Ref), as shown in Fig. 11.

The RMS value of the output AC voltage (VAC) is controlled with the proposed PWM method by varying the modulation index MI which is expressed in Eq. (27).

$$MI = \frac{AR}{2AC} \quad (27)$$

where AR and AC are respectively the amplitudes of the rectified signal (Ref) and the carrier signals.

In order to control the power switches used in the DC-AC FLC, and to respect the charge and discharge cycle of the capacitor C_s , as shown previously in Mode A and Mode B with the proposed PWM method, logic gates are used for comparing the carrier signals (Carr1 and Carr2) with the reference signal (Ref), as described in Table 2. Q3 and Q4 are controlled with two opposite square wave pulses (with a frequency of 50Hz). The generated waveforms of VDC-Bus and VAC with the PWM method are shown in Fig. 11.

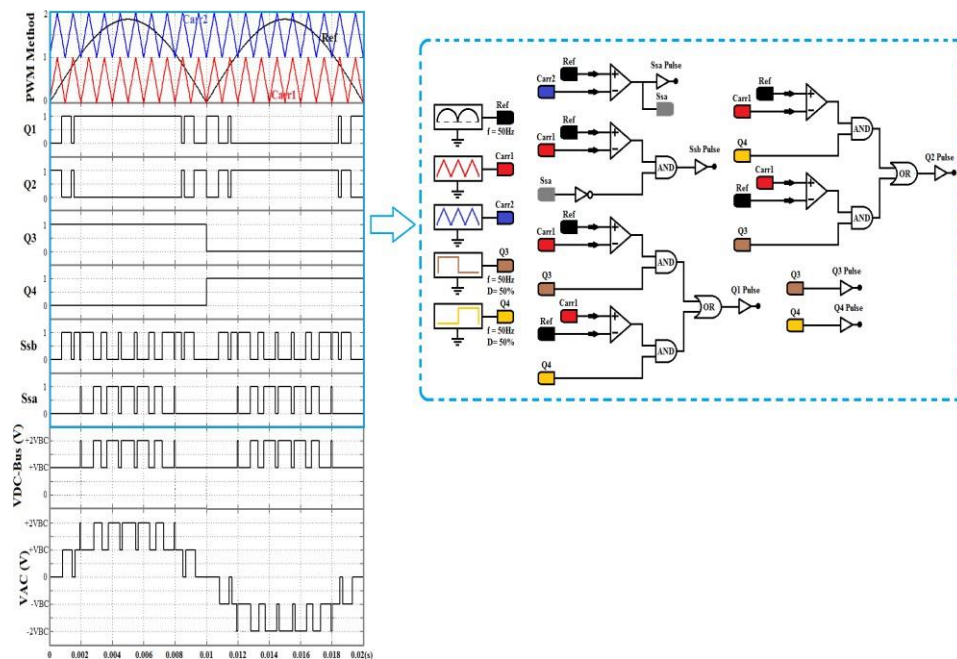


Fig. 11 The used PWM method with the obtained gate pulses and the generated waveforms

Table 2 Switching conditions of the power switches with logic gates

Conditions	ON switches
{(Ref >= Carr1) AND (Q3 pulse)} OR{(Ref <= Carr1) AND (Q4 pulse)}	Q1
{(Ref >= Carr1) AND (Q4 pulse)} OR{(Ref <= Carr1) AND (Q3 pulse)}	Q2
(Ref >= Carr2)	Ssa
{(Ref >= Carr1) AND (NOT Ssa pulse)}	Ssb

4. Simulation results

A prototype of a 200W rated power of the proposed photovoltaic multilevel inverter is designed with ideal components and tested on PSIM Software [21]. Two identical solar panels coupled in series are used as a DC source. Table 3 resumes the values of the main elements used in the proposed multilevel inverter, and Table 4 resumes the electrical parameters of the used solar panels.

Table 3 Values of the used elements in the multilevel inverter

Elements	Values
Inductors L1 and L2	2mH; 12mH
Capacitors Cin, C1, C2, C3, Cbc, and Cs	240 μ F; 120 μ F; 120 μ F; 240 μ F; 750 μ F; 750 μ F

Table 4 Parameters of one solar panel under 1000W/m² and 25°C

Parameters	Values
Maximum power (P _{max})	240W
Voltage at P _{max} (V _{mp})	29.9V
Current at P _{max} (I _{mp})	8.03A
Short-circuit current (I _{sc})	8.60A
Open-circuit voltage (V _{oc})	37.0V

Fig. 12 shows the obtained I-V characteristics (a) and P-V characteristics (b) of the model of the two solar panels coupled in series, with different irradiation levels, and constant temperature level (25°C).

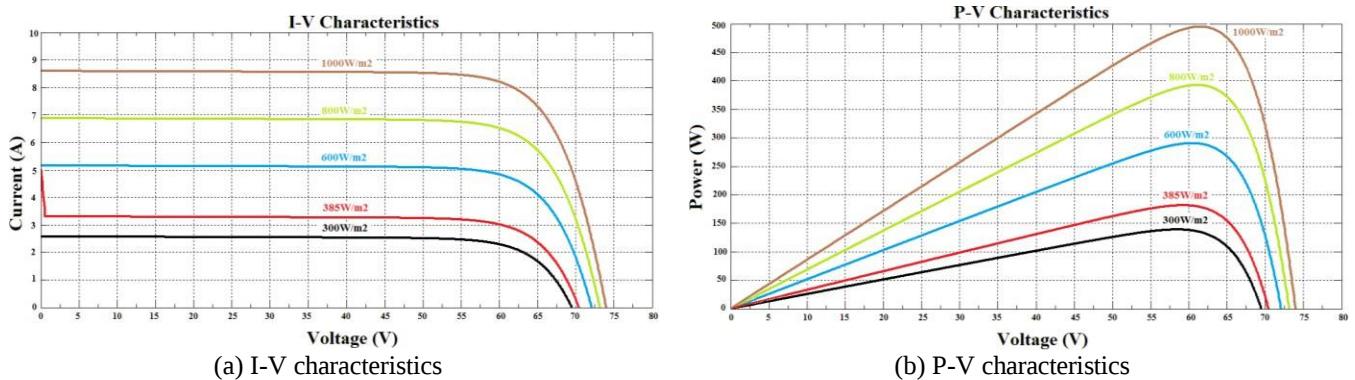


Fig. 12 I-V characteristics and P-V characteristics of the two solar panels coupled in series

4.1. Simulation results of the used HSUC with MPPT

The HSUC was tested with the proposed MPPT method shown in Fig. 10. In accordance with its rated power (200 W); the variable irradiation levels between 300 W/m² and 385 W/m² were selected. In this case, the maximum power energy available across the two solar panels varied between 140 and 180 W, as shown in Fig. 12 (b). The important used parameters in this simulation test are listed below:

- (1) V_{mpp-Ref} of the MPPT is 59V.
- (2) The frequency of the triangular signal (F_s) used in the comparison as shown in Fig. 10 is 31 kHz.
- (3) The output load is constant with a rated power of 200W.
- (4) From 0 to 0.5 second and 1 to 1.5 second, the solar irradiation level is 385W/m² and the temperature level is 25°C.
- (5) From 0.5 to 1 second and 1.5 to 2 second, the solar irradiation level is 300W/m² and the temperature level is 25°C.

Fig. 13 shows the obtained voltage (V_{in}) and current (I_{in}) from the two solar panels under this test. From the obtained results, the voltage V_{in} is fixed at 58.8V with the MPPT method, the average value of current I_{in} is variable between 2.37A and 3.06A; as a result, the maximum power energy is variable between 139.35W(58.8V×2.37A) and 180W(58.8V×3.06A).

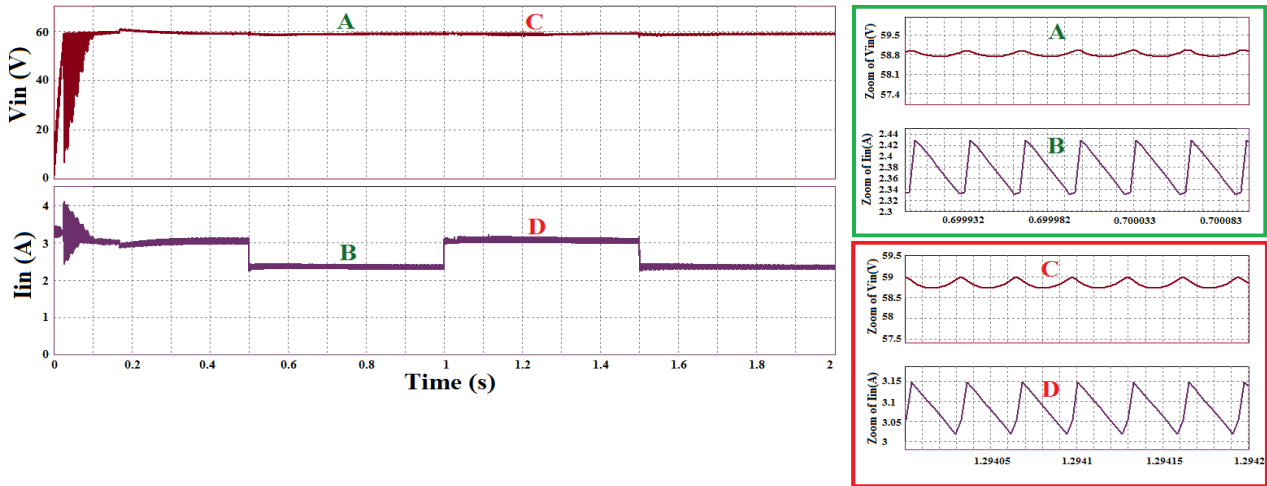


Fig. 13 The voltage V_{in} (V) and current I_{in} (A) supplied to the HSUC with the MPPT method

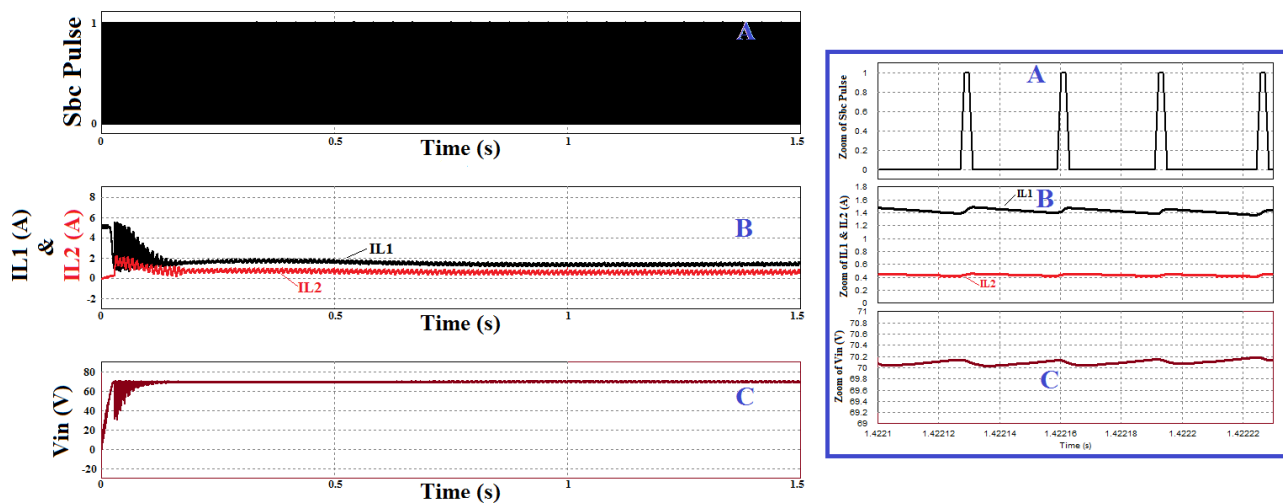
It's clear from the presented results that the used HSUC is apt to work with the MPPT method to extract maximum power energy from solar panels.

4.2. Simulation results of the studied photovoltaic multilevel inverter with PWM method ($MI=0.92$)

In order to test the influence of the PWM control method (Fig. 11) on the charging and discharging cycles of the used capacitors, the HSUC is controlled in open loop with a fixed pulse signal, and the DC-AC FLC is controlled with the PWM method with a fixed modulation index. The important used parameters in this simulation test are listed below:

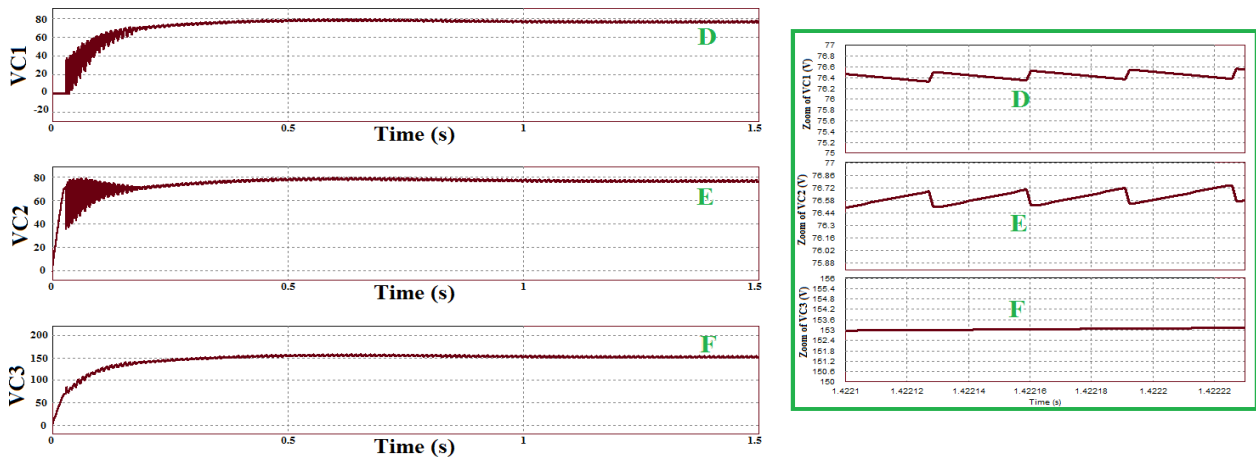
- (1) The MI of the PWM method is 0.92.
- (2) The value of D is 0.09.
- (3) The frequency of the fixed pulse signal F_s is 31 kHz.
- (4) The AC load is inductive: $R=64.81\Omega$; $L=0.488H$; $\cos(\varphi)=0.38$.
- (5) The irradiation level is $600W/m^2$ and the temperature level is $25^\circ C$.
- (6) The frequency of the two identical carrier signals used in the PWM method is $F_{carr}=2\text{ kHz}$.

Fig. 14 presents an overview of the used pulse control signal, the charging and discharging currents of the inductors L_1 and L_2 , the input voltage V_{in} from solar panels, the voltages across the capacitors C_1 , C_2 , C_3 , and C_{bc} , the voltage V_{DC-Bus} , the obtained AC voltage and current, and the FFT spectrum.

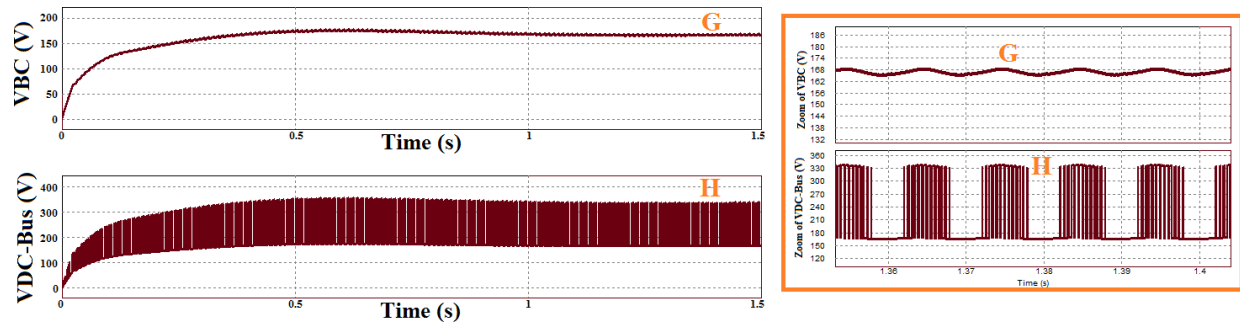


(a) A: Sbc Pulse; B: currents IL_1 and IL_2 ; C: voltage V_{in}

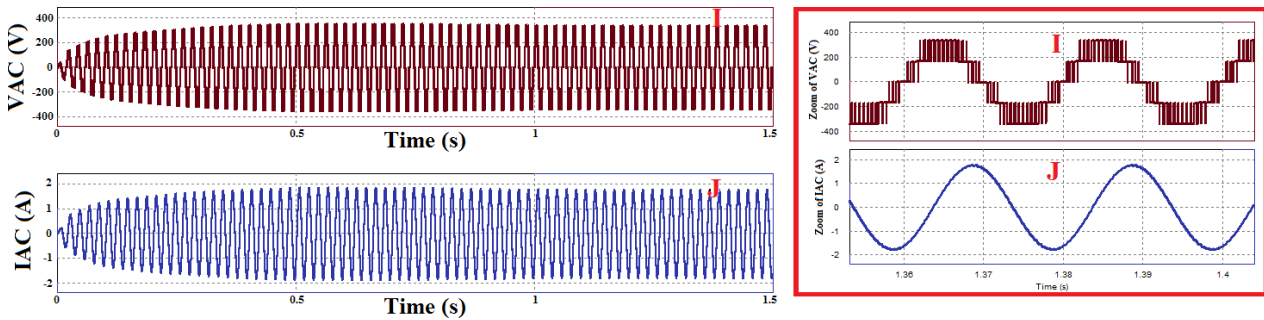
Fig. 14 Simulation results of the studied photovoltaic multilevel inverter with PWM method



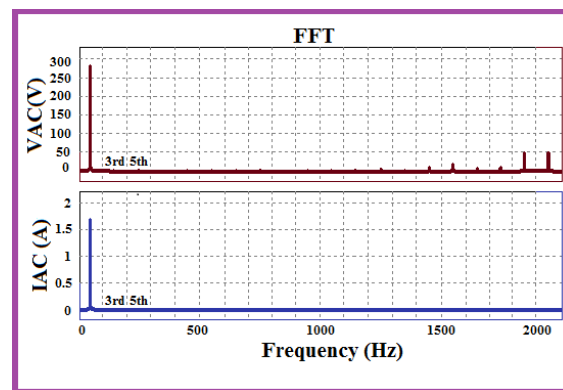
(b) D: voltage VC1; E: voltage VC2; F: voltage VC3



(c) G: voltage VBC; H: voltage VDC-Bus



(d) I: voltage VAC; J: current IAC



(e) K: FFT spectrum of VAC and IAC

Fig. 14 Simulation results of the studied photovoltaic multilevel inverter with PWM method (continued)

The two solar panels deliver an input DC voltage V_{in} of 70V (Fig. 14 (a)) to the PV system. The ripple of the current $IL1$ across the inductor $L1$ (2mH) is very small and the average value of this current is 1.45A (Fig. 14 (a)). The ripple of the current $IL2$ across the inductor $L2$ (12mH) is also very small and the average value of this current is 0.67A (Fig. 14 (a)). The ripple of the voltage $VC1$ across the capacitor $C1$ is very small and the average value of this voltage is 76V (Fig. 14 (b)). The ripple of the voltage $VC2$ across the capacitor $C2$ is very small and the average value of this voltage is 76V (Fig. 14 (b)). The ripple of

the voltage V_{C3} across the capacitor $C3$ is very small and the average value of this voltage is 153V (Fig. 14 (b)). The HSUC delivers an output voltage V_{BC} of 167V (Fig. 14 (c)) by using the small duty cycle (0.09). The VDC-Bus voltage from the SCC (Fig. 14 (c)) starts from 167V and ends at 334V repeated at each half period (0.01s). The FBC delivers an output AC voltage (Fig. 14 (d)) with five levels and an RMS value of 219V. The output AC current (Fig. 14 (d)) is sinusoidal in shape with an RMS value of 1.26A. The FFT analysis of V_{AC} and I_{AC} (Fig. 14 (e)) shows that the even harmonics are absent and the first important odd harmonics (3rd, 5th) are absent.

It's clear from the obtained results that the proposed multilevel inverter converter is able to be controlled with the PWM method without any problem of voltage balancing across the used capacitors. Also with the proposed PWM method, this multilevel inverter delivers optimal AC voltage and current with fewer harmonics without using filters.

5. Experimental Results

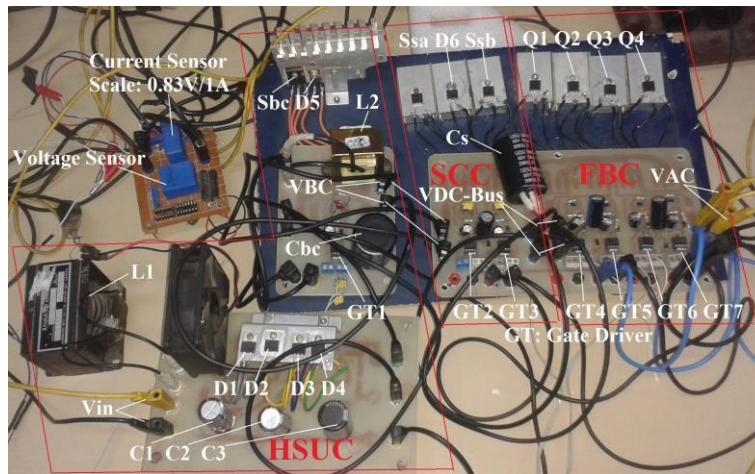


Fig. 15 The experimental prototype of the proposed multilevel inverter

An experimental prototype (200W rated power) of the proposed multilevel inverter is fabricated at the laboratory as shown in Fig. 15. The values of the main elements used experimentally are the same as indicated in Table 3. In order to record the experimental results a digital oscilloscope (DO) is used, it contains two channel for measuring (ch1 and ch4).

5.1. Experimental results of the used HSUC with MPPT

The MPPT method shown in Fig. 10 is implemented on a microcontroller and tested with the HSUC. Fig. 16 shows the synoptic of the experimental test bench. In order to respect the rated power (200W) of the fabricated HSUC, a variable DC source (0-63V/0-3A) is used as an input voltage for the experimental setup. The objective of this test is to adjust automatically the input voltage from the variable DC source at a chosen $V_{mpp-Ref}$ and extract the maximum current (3A).

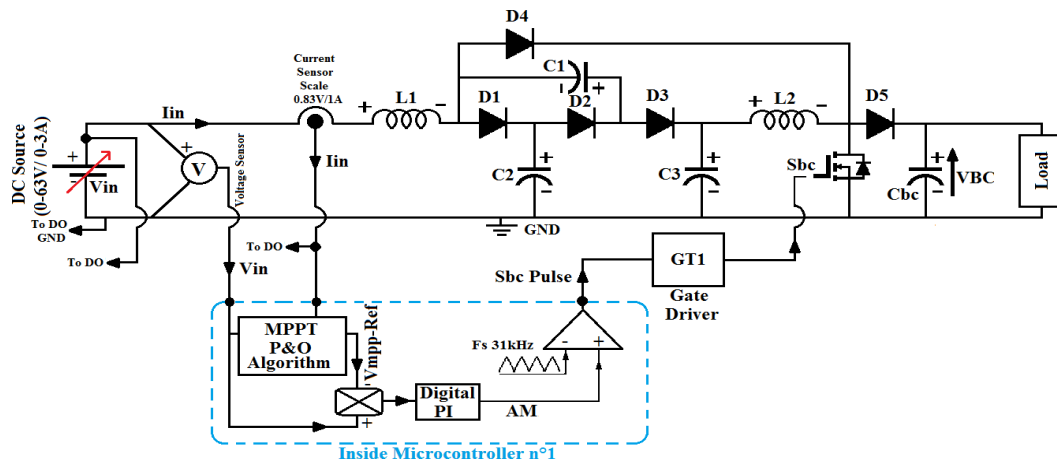


Fig. 16 Synoptic of the experimental test bench of the HSUC with the MPPT method

The important used parameters in this test are listed below:

- (1) $V_{mpp-Ref}$ of the MPPT is 59V.
- (2) The value of F_s is 31 kHz.
- (3) The output load is constant with a rated power of 200W.
- (4) The used current sensor delivers 0.83V for each 1A.

Fig. 17 shows the regulated input voltage V_{in} with the delivered maximum current I_{in} from the variable DC source under MPPT test.

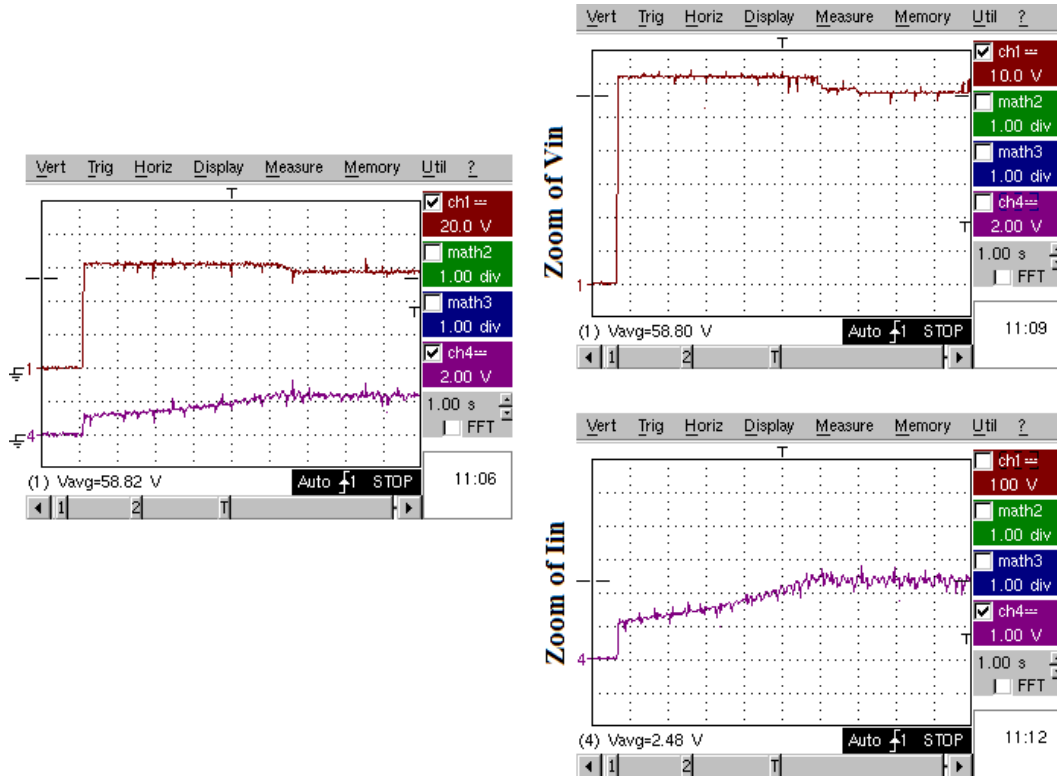


Fig. 17 The input voltage V_{in} (ch1) and input current I_{in} (ch4) under MPPT test

From Fig. 17, the input voltage V_{in} from variable DC source is regulated automatically at 58.8V (ch1), and the generated current I_{in} for the HSUC oscillates around 3A (ch4) ($P_{max}=176.4W$); this proves the robustness of the implemented MPPT program, and also the ability of the HSUC to be used with critical MPPT methods.

5.2. Experimental results of the studied photovoltaic multilevel inverter with PWM method ($MI=0.92$)

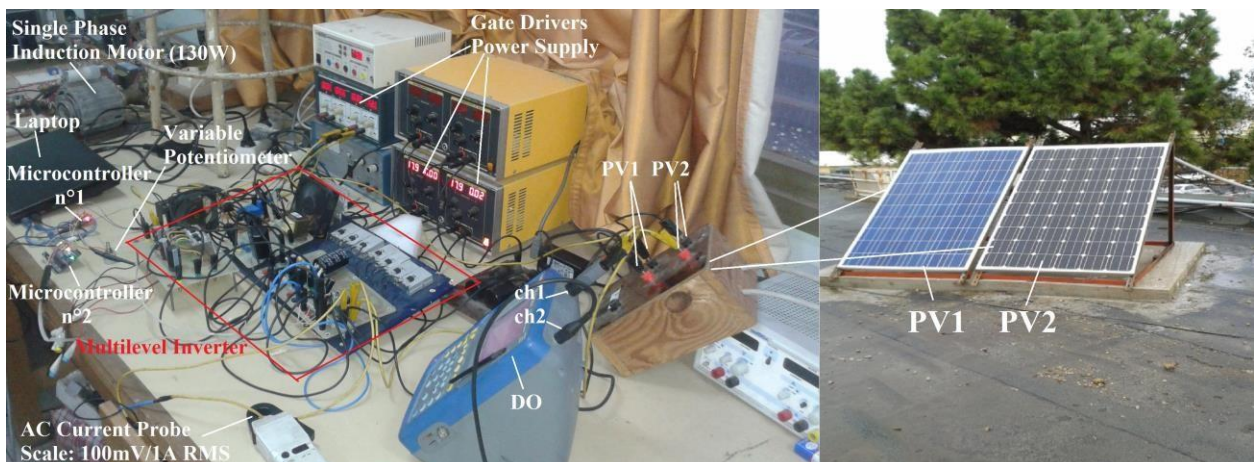


Fig. 18 the two solar panels installed at the laboratory roof with the experimental test bench

In this test, the HSUC is controlled in open loop with a variable pulse signal from a potentiometer, and the DC-AC FLC is controlled with the PWM method with a fixed modulation index (Fig. 11). Two solar panels coupled in series installed at the laboratory roof are used as a DC source for the experimental setup as shown in Fig. 18, which its characteristics are the same as indicated in Table 4. Fig. 19 shows the synoptic of the experimental test bench. Two microcontrollers are used as a digital control system. The switches Q2, Q3, Ssb, and Sbc have a common source with the GND for this; a common power supply for the gate drivers is used.

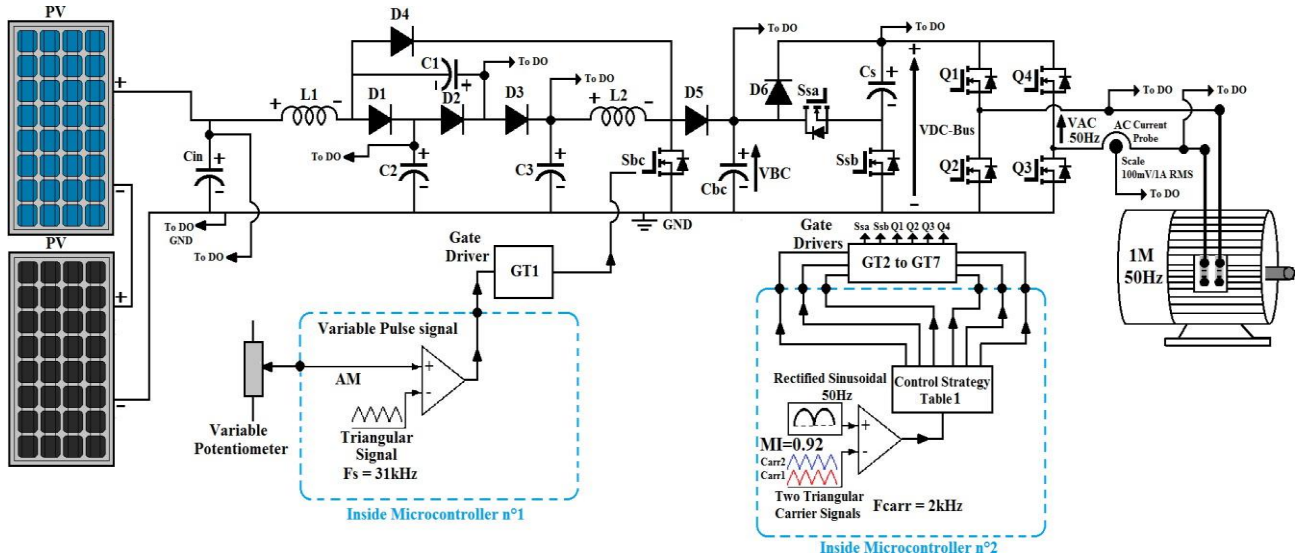


Fig. 19 Synoptic of the experimental test bench of the proposed multilevel inverter with PWM method

The important used parameters are:

- (1) The MI of the PWM method applied on the DC-AC FLC is 0.92.
- (2) The value of F_s is 31 kHz.
- (3) The frequency of the two identical carrier signals used in the PWM method is $F_{carr} = 2$ kHz.
- (4) The AC load is a 130W single phase induction motor.
- (5) The used AC current probe delivers 100mV for each 1A RMS.

Fig. 20 presents an overview of the used pulse control signal, the input voltage V_{in} from solar panels, the voltages across the capacitors C1, C2, C3, and Cbc, the voltage VDC-Bus, the obtained AC voltage and current, and the FFT spectrum.

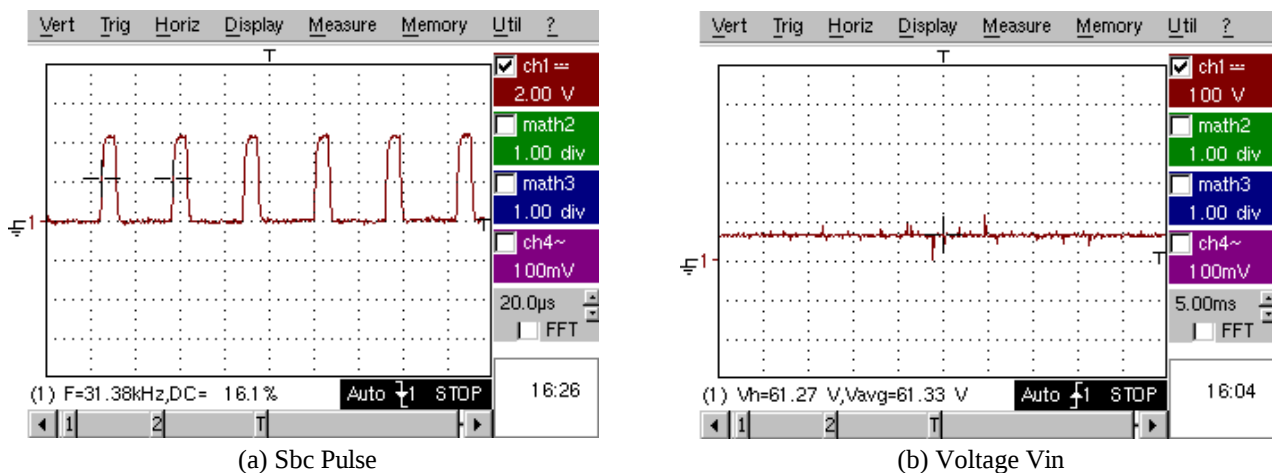


Fig. 20 Experimental results of the studied photovoltaic multilevel inverter with PWM method

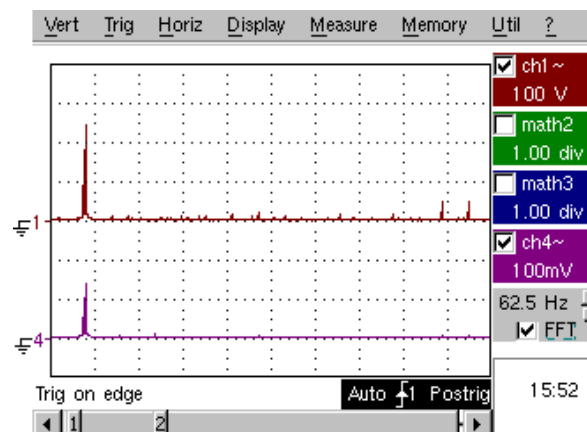
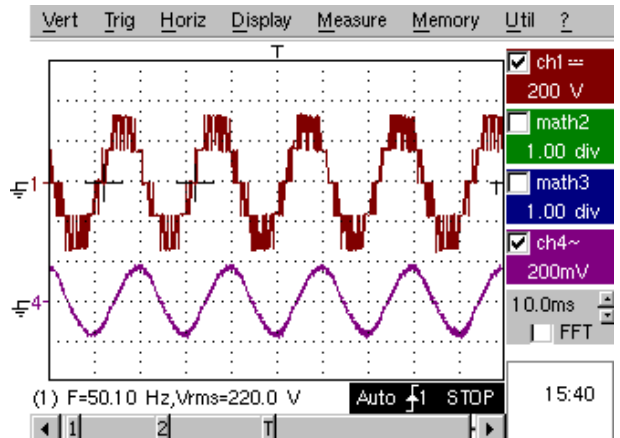
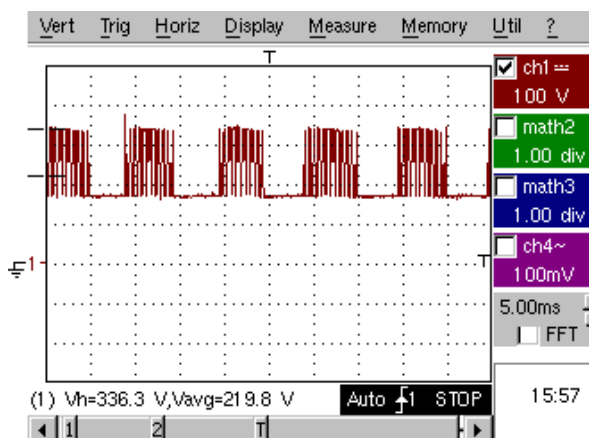
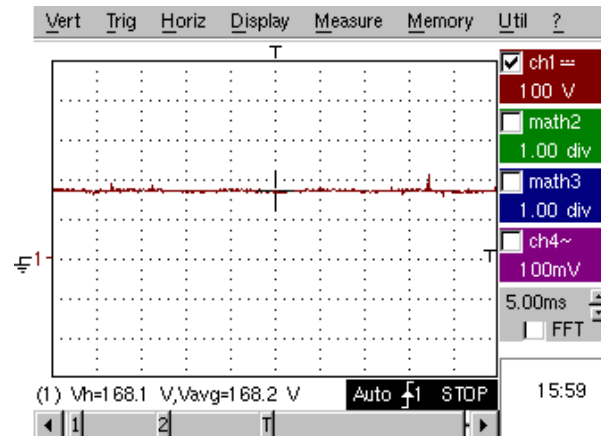
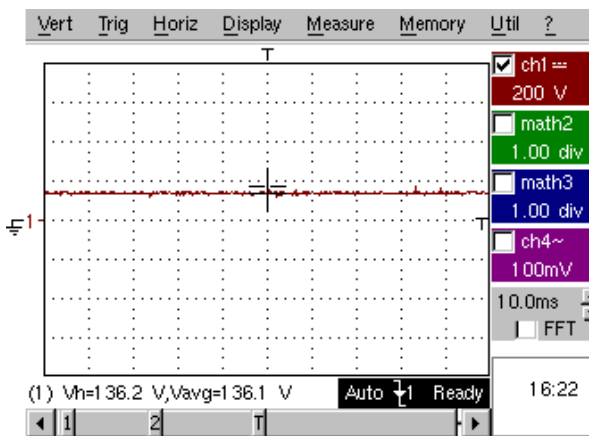
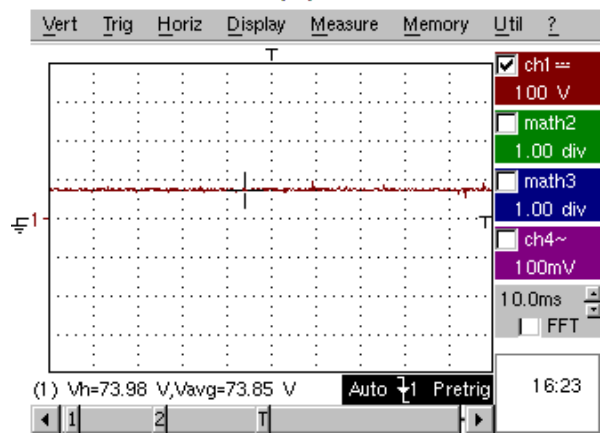
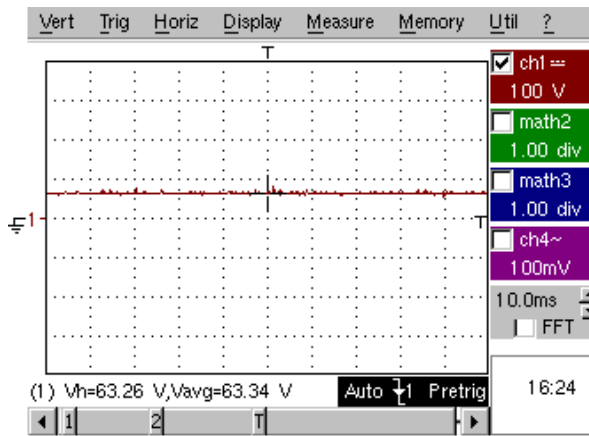


Fig. 20 Experimental results of the studied photovoltaic multilevel inverter with PWM method (continued)

The two solar panels deliver an input DC voltage V_{in} of 61.33V (Fig. 20 (b)) to the experimental setup. The voltage $VC1$ across the capacitor $C1$ is constant with an average value of 63.34V (Fig. 20 (c)). The voltage $VC2$ across the capacitor $C2$ is constant with an average value of 73.85V (Fig. 20 (d)). The voltage $VC3$ across the capacitor $C3$ is constant with an average value of 136.1V (Fig. 20 (e)). The HSUC delivers an output voltage V_{BC} of 168.2V (Fig. 20 (f)) by using a small duty cycle D of 0.16 (Fig. 20 (a)). The VDC-Bus voltage from the SCC (Fig. 20 (g)) starts from 168V and ends at 336.3V repeated at each half period (0.01s). The FBC delivers an output AC voltage (ch1) (Fig. 20 (h)) with five levels and an RMS value of 220.4V. The output AC current (ch4) (Fig. 20 (h)) is sinusoidal in shape with an RMS value of 1.22A. The FFT analysis of VAC and IAC (Fig. 20 (i)) shows that the even harmonics are absent and the first important odd harmonics (3rd, 5th) are absent.

The experimental results confirm that the photovoltaic multilevel inverter with the PWM method is apt to supply power energy from solar panels to industrial machines such as induction motors with no voltage balancing problem across capacitors. In addition, this inverter delivers good output AC waveforms with fewer harmonics without using output filter.

5.3. The voltage conversion ratio of the fabricated HSUC, and the efficiency of the proposed multilevel inverter:

(1) Voltage conversion ratio (G):

The voltage conversion ratio (G) of the fabricated HSUC has been compared experimentally to a conventional boost converter for different values of the duty cycle (D). Fig. 21 shows the obtained results.

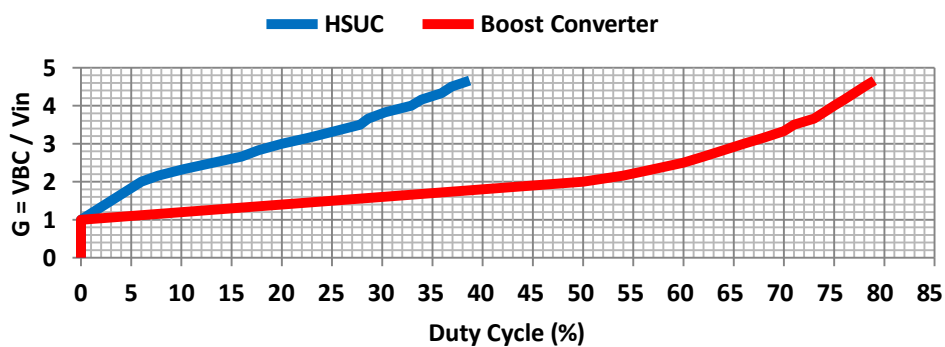


Fig. 21 The voltage conversion ratio of the HSUC and the conventional Boost Converter

From Fig. 21, the HSUC offers the possibility to transfer more energy with high voltage using just a small duty cycle compared to the classical Boost Converter.

(2) The efficiency of the proposed inverter:

The efficiency of the HSUC and the DC-AC FLC circuits has been analyzed experimentally for different levels of power energy. Fig. 22 shows the obtained results.

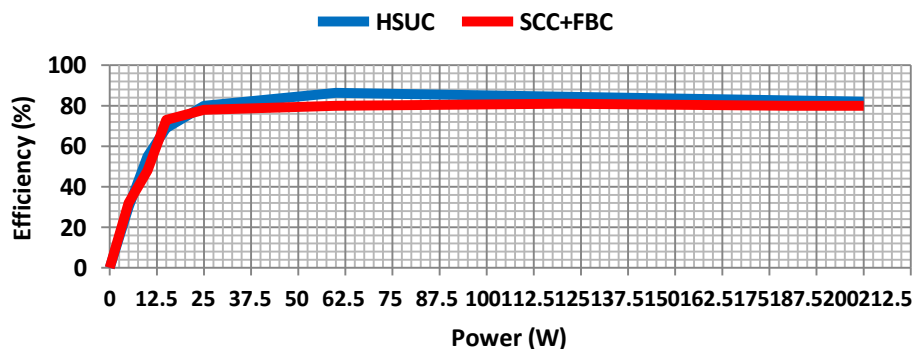


Fig. 22 The efficiency of the HSUC and the DC-AC FLC circuits

From Fig. 22, the efficiency of the HSUC circuit and the DC-AC FLC circuit is around 80%. This percentage has been obtained from the first experimental test at the laboratory, but it will be increased using other optimal power switches.

6. Conclusions

In this paper, a new single-phase five-level inverter for PV system applications has been proposed. This multilevel inverter was novel, because it combined an HSUC converter recently presented in the literature with an efficient DC-DC SCC and a simple H-bridge DC-AC converter. To generate five-level output AC voltage, the proposed topology requires only a single input DC voltage source from solar panels in contrast to conventional multilevel inverters. The maximum power point method and PWM technique were used for testing in simulations and experiments with a 200 W prototype. The transfer of power energy from solar panels to the AC load with this inverter was performed using a small duty cycle (< 0.2) of the control signal for the DC-DC converter.

This multilevel inverter presents many advantages, such as reduced number of power switches (seven) and gate driver power supply, good output AC waveforms, fewer harmonics, no voltage balancing problem across capacitors, low switching losses, high efficiency, the ability to extract maximum power energy from solar panels, the ability to supply power energy from a low-voltage DC source to industrial machines meeting industrial criteria for voltage and frequency (220 V; 50 Hz), simplicity, and easy implementation. For all these reasons, the proposed system can be used as an alternative type of inverter in PV system applications.

In future work, the performance of the proposed PV multilevel inverter will be ameliorated by increasing its rated power (1 KW) and using a closed loop control system.

Author Contribution Statement

Ayoub Nouaiti: Conceptualization, Methodology, Investigation, Writing – original draft, Project administration. **Abdallah Saad:** Investigation, Data curation, Writing – review and editing. **Abdelouahed Mesbahi:** Formal analysis, Software, Visualization, Writing – review and editing. **Mohamed Khafallah:** Supervision, Validation, Resources, Writing – review and editing.

Declaration of Competing Interest

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

Data Availability

Data will be made available on request.

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Ethics Approval and Consent

This study does not involve human participants, animals, or sensitive personal data. Ethical approval was therefore not required.

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