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Published Online 28 August 2015 **Research Article**

An Efficient Grid Connected Photovoltaic System Based on the Seven-Level PUC converter

[1]Youssef Ounejjar, [2]Adil Tannouche, [1]Lahcen Bejjit, [2]Khalid Sbai

[1]Université Moulay Ismail, Ecole Supérieure de Technologie, Meknès, Maroc
[2]Laboratoire Etude des Matériaux et Modélisation des Systèmes (LEM2A), Equipe Matériaux Avancés et Systèmes Energétique (MASEN), Université Moulay Ismail, Faculté des Sciences de Meknès, Maroc

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ABSTRACT

In this paper, authors propose an advanced grid connected photovoltaic system based on the seven-level PUC converter. The latter has the advantage to operate with a single DC source while generating fifteen voltage levels. Even it is constituted only from eight switches and two capacitors; it can nevertheless offer a seven-level output voltage. In order to extract the maximum power from the PV array, authors makes use of the incremental conduction MPPT technique. Associated to the proposed multiband hysteresis control technique, the grid voltage and current are nearly sinusoidal. With such waveforms, there is no need of additional investment in any filters which increases the system energetic efficiency. Authors' choice has been focused on the Canadian Solar 220W CS5P-220P Panel due to its highest PVUSA Test Conditions (PTC) ratings established by the California Energy Commission. The proposed concept was verified by simulations performed in the Matlab Simulink and SimPowerSystem environments.

Key words: PUC topology, multilevel converters, renewable energy, Photovoltaic (PV), MPPT, hysteresis controller

INTRODUCTION

Nowadays, renewable energy resources are deeply studied. The main design objective of photovoltaic (PV) systems has been for long time to extract the maximum power from the PV array. Therefore, the maximum power point tracking (MPPT) of a uniformly irradiated PV array and the maximization of the conversion efficiency have been the main design issues [1]. Energetic efficiency depends also on the yield of the electric power conversion. This is achieved through multilevel converters which insure good power quality. The Packed U Cells (PUC) topology [2-4] is one of the very competitive multilevel converters. A Comparison toward concurrent multilevel converters is given in table 1.

In the latter, NPC [5], FC [6] and CHB [7] refer to Neutral Point Clamped diode, Flying Capacitors and Cascaded Half Bridges converters respectively. Recently, many other topologies, like Conergy-NPC [8], H5 [9] and ANPC [10] were utilized in order to deliver green electricity with good power quality. Nevertheless, the power devices count increases hugely when the number of output voltage levels becomes higher than three. Moreover, some converters, like CHB, require independent and isolated DC sources, which swell up the installation cost. The maximum power point tracking (MPPT) technique was introduced in order to extract the maximum power of the PV panel for a profitable use of the photovoltaic energy.

Recently, many propositions were developed to insure a high efficiency of the PV systems. The well known are the constant voltage tracking (CVT) [11], the perturb-and-observe (P&O) [12] and the incremental conductance (INCOND) technique [13-14]. The former ones have a poor dynamic response which limits their utilization in a changing illumination condition.

Corresponding Author: Youssef Ounejjar, Ecole de Technologie, University Moulay Ismail EST, B.P: 3103-Toulal, 50040 Meknès, Maroc
Tel: +212615030347; E-mail: youssef.ounejjar.1@ens.etsmtl.ca

Table 1: Comparison of seven level topologies toward PUC converter

	NPC	FC	CHB	PUC
Capacitors	6	6	3	2
Clamping diodes	10	0	0	0
Switches	12	12	12	6

In this paper, authors propose a photovoltaic system based on the seven-level PUC inverter for grid connected applications. Combined with the INCOND MPPT technique, the proposed system allows a good power quality in the grid side with a good energetic conversion yield. Even the PUC inverter is constituted only from eight switches and two capacitors; it can nevertheless offer a seven-level output voltage. A multiband hysteresis control technique is also performed to draw a nearly sinusoidal grid current.

This technique has been proven to be the most suitable solution for all the applications of current controlled voltage source inverters where performance requirements are more demanding, albeit at the expense of variable switching frequency.

Proposed Photovoltaic System:

The proposed system makes use of only one PV panel while generating seven level output voltage as shown in fig.1. The attainable output voltage levels depend merely on the ratios between these sources. Table 2 depicts them with their according switches pulses in case of $\frac{V_a}{V_{dc}} = \frac{1}{3}$. Herein, Vdc and Va refer to the DC link and auxiliary DC bus voltages respectively. Switches Ti and $\overline{Ti}$ operate complimentarily, thus, only Ti switches are considered in this table 2.

Table 2: Switching table of the 7-level PUC converter

V_{an}	T1	T2	T3
Vdc	1	0	0
Vdc-Va	1	0	1
Va	1	1	0
0	0	0	0
-Va	0	0	1
Va-Vdc	0	1	0
-Vdc	0	1	1

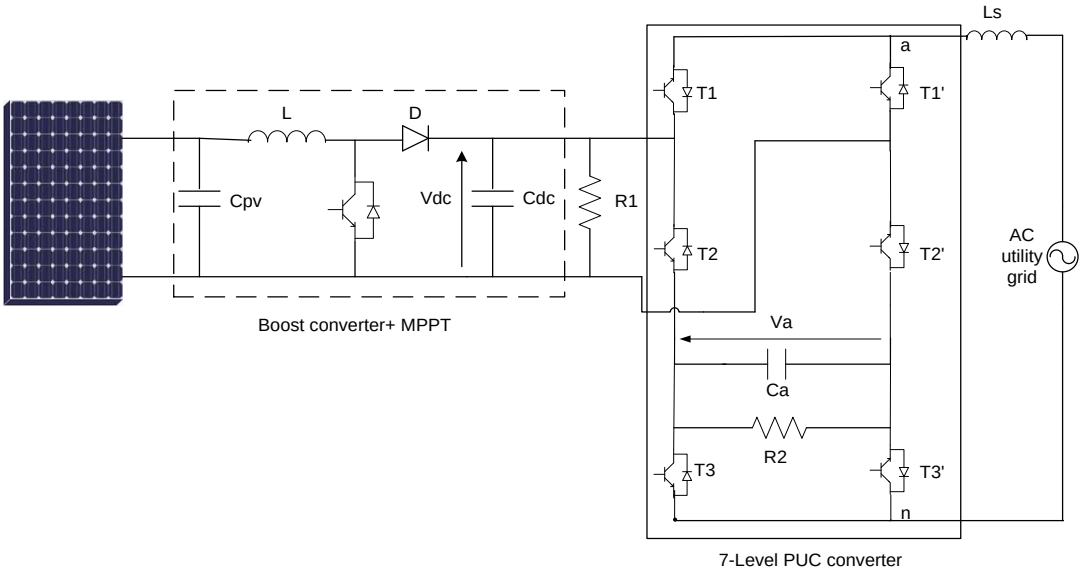

Fig. 1: Proposed PV system

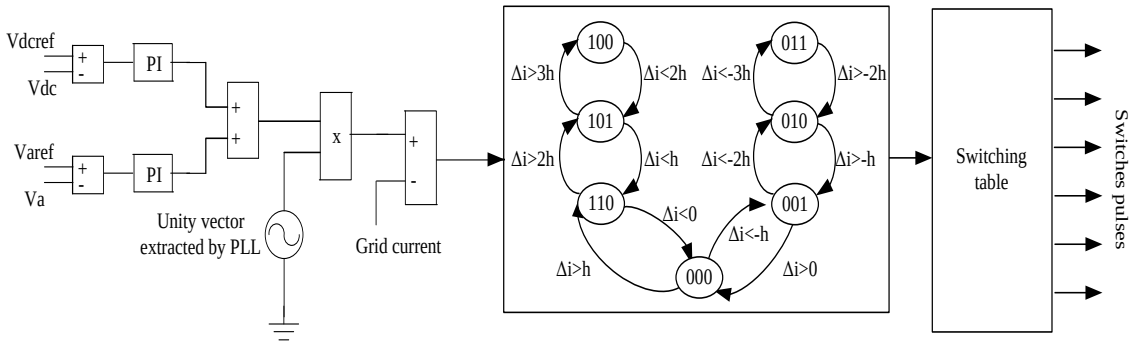

Fig. 2: Multiband hyteresis control strategy

The proposed seven-level PUC converter is very competitive and highly efficient, it also allows multi-loads operation. In fact, two optional DC loads are available. A six-band hysteresis control technique is proposed to perform this balancing objective and to draw a nearly sinusoidal grid current. The capacitors voltages Vdc and Va are controlled to follow their references using a PI regulator. Then, the peak current reference can be generated by the following equation:

$$i_s^* = \left(k_{p2}\tilde{v}_{dc} + k_{i2}\int \tilde{v}_{dc}dt\right) + \left(k_{p3}\tilde{v}_a + k_{i3}\int \tilde{v}_a dt\right) \quad (1)$$

Where: $\tilde{v}_{dc} = V_{dc}^* - V_{dc}$, $\tilde{v}_a = V_a^* - V_a$, V_{dc}^* and V_a^* are the capacitors voltages references.

Grid current is then brought to follow its reference by the proposed six-band hyteresis technique which is depicted in fig.2.

The PV cell current can be written as the following equation:

$$I_v = I_{ph} - I_d = I_{ph} - I_s\left(\exp\left(\frac{qV_v}{akT}\right) - 1\right) \quad (2)$$

For N_s and N_p series and parallel connected cells respectively, the equation becomes:

$$I = N_p I_{ph} - N_p I_s\left(\exp\left(\frac{q\left(V + R_s I\right)}{aN_s kT}\right) - 1\right) - \frac{V + R_s I}{R_p} \quad (3)$$

Where I_{ph} is photocurrent which depends on the incident irradiation, I_s is the diode reverse saturation current. R_s and R_p are the array equivalent series and parallel resistance respectively. According to fig.3 and noticing that the maximum power point corresponds to the point defined by $\frac{dP_{pv}}{dv} = 0$ and that the slope is positive (negative) on the left (right) of this point, then knowing that:

$$\frac{dP_{pv}}{dv} \cong I + V\frac{\Delta I}{\Delta V} \quad (4)$$

A comparison between the instantaneous conductance $\frac{I}{V}$ and the incremental conductance $\frac{\Delta I}{\Delta V}$ can be then deduced as in equation (5).

$$\begin{cases} \frac{\Delta I}{\Delta V} = \frac{-I}{V} & \text{at MPP point} \\ \frac{\Delta I}{\Delta V} > \frac{-I}{V} & \text{at left of MPP point} \\ \frac{\Delta I}{\Delta V} < \frac{-I}{V} & \text{at right of MPP point} \end{cases} \quad (5)$$

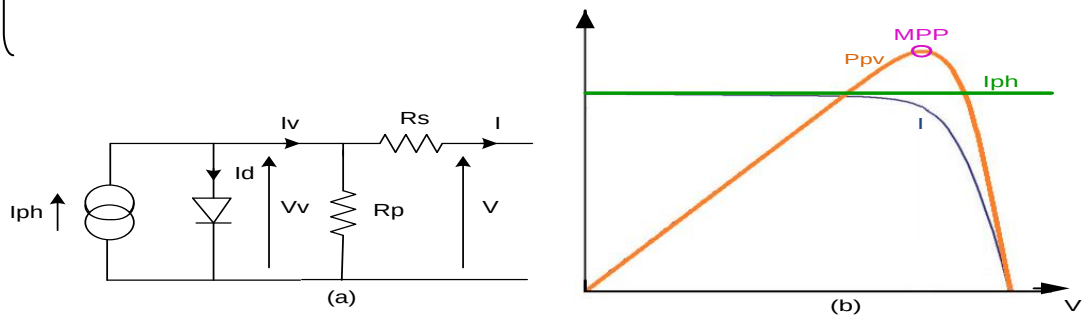

Fig. 3: (a) Single PV cell model (b) I_{ph}-V, I-V and P_{pv}-V characteristics

Thus, a tracking of the MPP can be performed using this technique well known as the incremental conduction. However, the error between the two conductances must be brought to zero to enhance the tracking dynamic. Consequently, a PI regulator must be introduced.

Our interest has been focused on the Canadian Solar 220W CS5P-220P Panel due to its top ranking PV which was established by the California Energy Commission in "California for higher energy production". Its I-V and P_{pv}-V characteristics are depicted fig.4.

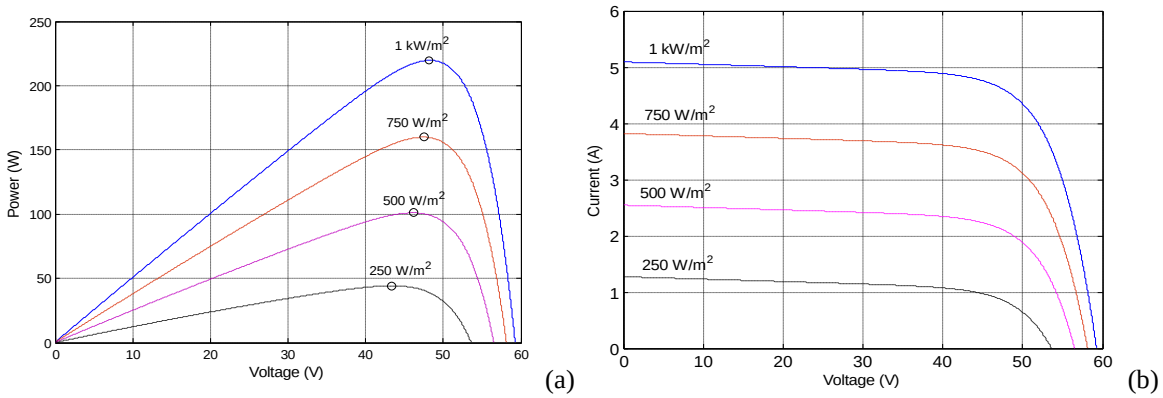

Fig. 4: P_{pv}-V (a) and I-V (b) characteristics of the Canadian Solar CS5P-220P PV array

Simulation Results:

The grid parameters are: 120Vrms, 60 Hz and 3mH as line inductance. The The DC-link voltage reference is 240V, thus the auxiliary DC bus voltage reference is 80V. The values of DC loads resistances are R1=120Ω and R2=220 Ω. The PV array is constituted from one series and one parallel connected cells. Simulation was performed in Matlab Simulink and SimPowerSystems environment. The system was simulated without and with the MPPT technique in case of 1 kW/m^2 irradiation. Fig.5 shows the evolution of the PV array power. At t=0.6s, the MPPT is activated which allows the operating point to reach the MPP permitting, therefore, the extraction of the maximum power from the PV array as confirmed in the same figure where the maximum power is 220W. The voltage is around its MPP value (around 48V) as shown in fig.6.

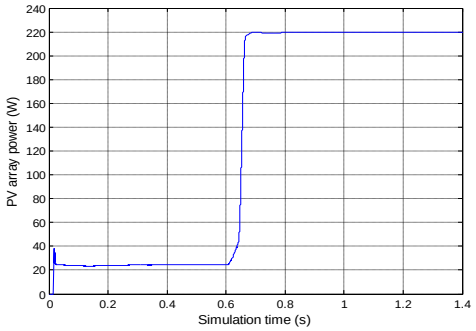

Fig. 5: PV power evolution without and with MPPT

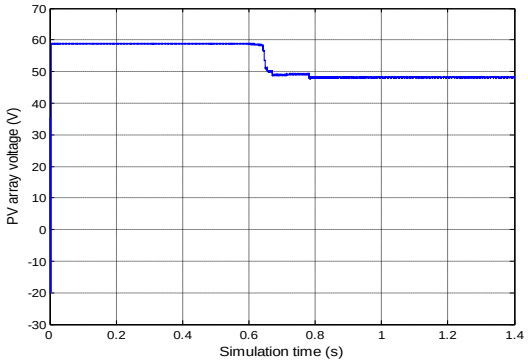

Fig. 6: PV voltage evolution without and with MPPT

The proposed system was verified against drastic atmospheric variation. Thus, a stepped irradiation from 1 kW/m^2 to $250W/m^2$ happens at t=1s.

Simulation results prove that the PV array power is at its maximum point both before and after irradiation step. In fact, fig.7 shows that the system operates at its MPP condition which is characterized by a PV power of 220W and 45W in case of $1kW/m^2$ and $250W/m^2$ irradiation respectively.

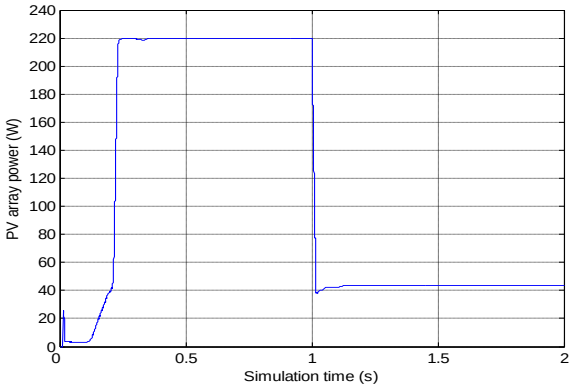

Fig. 7: PV power evolution before and after irradiation step

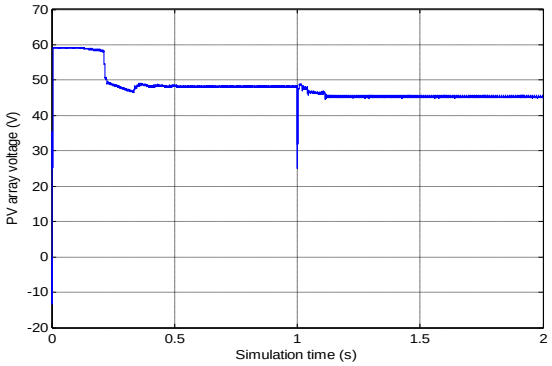

Fig. 8: PV voltage evolution before and after irradiation step

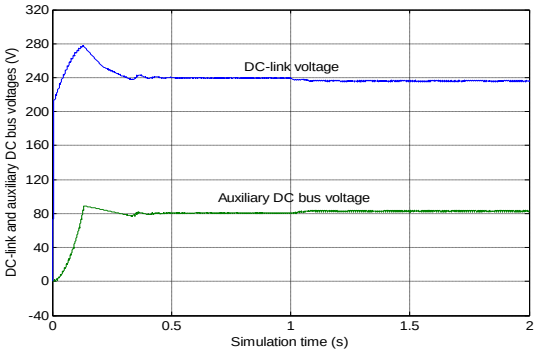

Fig. 9: DC-Link and auxiliary DC bus voltages evolution

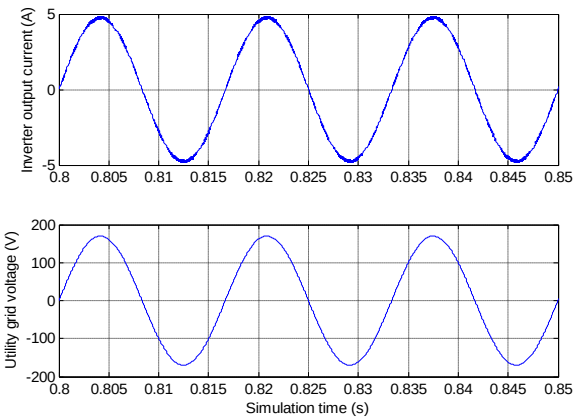

Fig. 10: Grid current and voltage waveforms

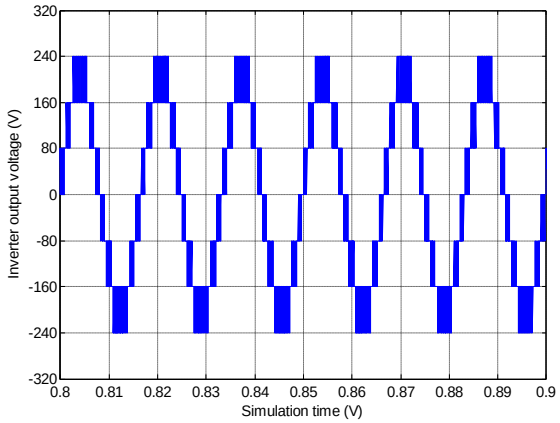

Fig. 11: Inverter output voltage waveform

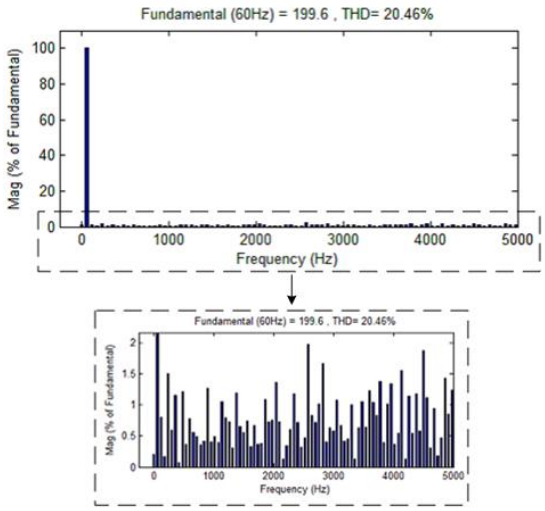

Fig. 12: Harmonics spectrum of the inverter output voltage

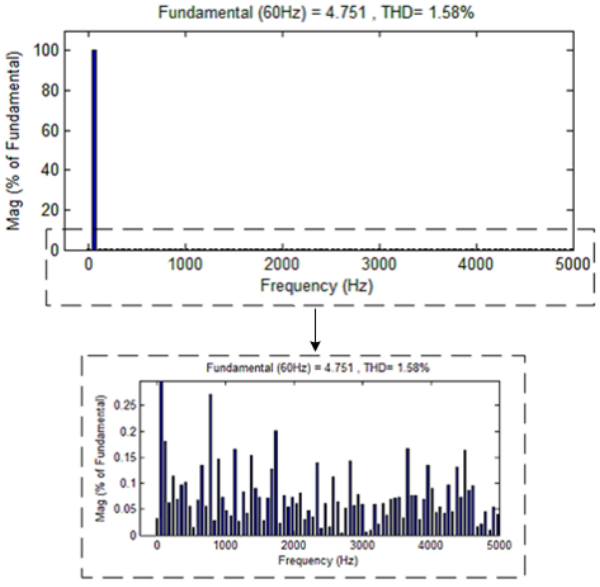

Fig. 13: Harmonics spectrum of grid current

The PV voltage goes around its MPP values after a transient time as depicted in fig.8. The good dynamics of the proposed multiband hysteresis control is proven by fig.9. In fact, the DC-link and auxiliary DC bus voltages are well regulated and maintained around their references even after a drastic irradiation step.

The grid voltage and current, which is the inverter output current, are depicted in fig.10. With such waveforms, there is no need of additional investment in any filters. The harmonics spectrum of the inverter output voltage is illustrated in fig.12. The total harmonics distortion of grid current is around 1.58% as depicted in fig.13. This permits to avoid bulky filters which results on a very high energetic efficiency and a reduced installation cost.

Conclusion:

An advanced grid connected photovoltaic system based on seven-level PUC inverter is presented in this paper. The proposed converter is very competitive and highly efficient, it also allows multi-loads operation. The proposed controller allows a good regulation of the inverter capacitors voltages which results on a nearly sinusoidal grid current. With such waveforms, filters can then be reduced or even avoided leading to a very high energetic efficiency and a reduced installation cost. For a profitable use of PV array, an MPPT technique is used to insure extracting the maximum power. The proposed concept dynamics were verified by simulations during severe illumination changes.

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