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# Performances of Photovoltaic Generator Multi-Level Cascade

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## Abstract

In this paper, we study the performances of the cascade of the solar cell panels with the multilevel inverter. In the first part, we develop a knowledge model of the inverter by using connection functions of this converter. A PWM strategy which uses four bipolar carriers is developed to control this converter. In this part, the inverter is fed by constant input DC voltages. The performance of the algorithm is studied on the base of the harmonic rate. Then, we present the solar cell model. In the last part, we study the stability problem of the input DC voltages of the inverter. Thus, we study a cascade constituted by two photovoltaic cell panels – five-level NPC VSI - permanent magnet synchronous machine (PMSM). This studied lets to find a solution to solve this problem. The performances obtained with this cascade are full of promise to be using this inverter in renewable energy

Keywords: Multilevel inverter; Generator Cells; Renewable; PMSM.

## Nomenclature

$I$ : Current delivered by photovoltaic cell,
$V$ : Voltage delivered by photovoltaic cell,
$I_{ph}$ : Photo-current,
$I_s$ : Saturation current of diode dependants of temperature,
$R_s$ : Series resistance,
$R_{sh}$ : Shunt resistance,
$q$ : Charge of electron = $1.602.10^{-19}$C,
$K$ : Boltzmann Constant = $1.381.10^{-23}$J/K,
A : Quality factor of diode,
$T$ : Cell Temperature in °K.
g : gap.

## 1.Introduction

During last century, the consumption of electrical energy has greatly increased because the industry growth. The energy demand predictions for next years confirm the growth of the energy consumption. Consequently, the traditional energy sources (fossil) will last few more decades. And this will produce an outage of the energy in the word. On the other hand the consumption of the traditional sources contributes greatly to the greenhouse effect, for this reason, it is necessary to use the renewable energy sources no polluting such as solar cell. The industrial consumers need to be fed by sinusoidal voltage generators. In the last decade the power electronic technology has made a very important advance their development. On the one hand, the power switches used in the structures of converters are able to switch more quickly, On the other hand, new structures have emerged converters. Some of them promote high switching frequencies. And instead to transfer significant levels of power (multi-level structures,…).

In this paper, we are interested to study the cascade of a multilevel inverter and solar cell generator.

The performances obtained with this cascade are full of promise to be used in renewable energy production systems.

## 2.Modelling of Five Level NPC Voltage Source Inverter

The three-phase five-level NPC VSI is a new conversion structure used to feed, with variable frequency and voltage, power alternating current machines. Several structures are possible for five-level inverters [1]. In this paper, we study the Neutral Point Clamping (NPC) structure (Figure1). This converter is constituted by three arms and four DC voltages sources. Every arm has eight bi-directional switches, six in series and two in parallel, and two diodes $DD_{k0}$ and $DD_{k1}$ which let to have zero voltage for $V_{kM}$. Every switch is composed by a transistor and a diode in anti-parallel. For an arm k of the three-phase five-level NPC VSI, several complementary laws controls are possible. The control law which lets an optimal working of this inverter is [1]:

$$\begin{cases} B_{K4} = \overline{B}_{K2} \\ B_{K5} = \overline{B}_{K1} \\ B_{K6} = \overline{B}_{K3} \end{cases}$$

Where $B_{ks}$ represents the gate control of the switch $T_{ks}$

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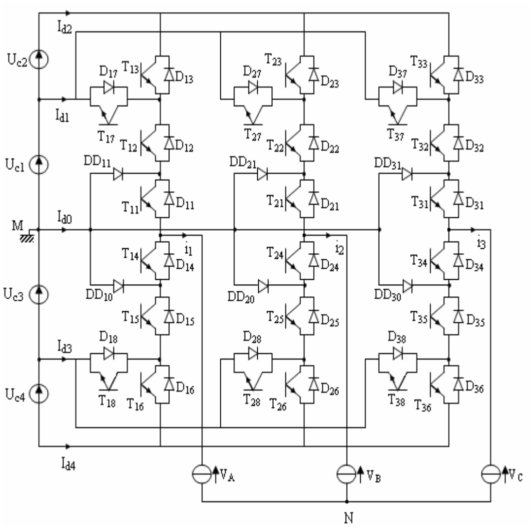


Figure 1. A Five-level NPC voltage source inverter

The switch connection function $F_{ks}$ indicates the opened or closed state of the switch $TD_{ks}$. We define two a half arm connection function $F^b_{km}$ with:
k : arm number

$$m = \begin{cases} 0 \text{ for the lower half arm} \\ 1 \text{ for the upper half arm} \end{cases}$$

and:

$$\begin{cases} F^b_{K1} = F_{K1} F_{K2} F_{K3} \\ F^b_{K0} = F_{K4} F_{K5} F_{K6} \end{cases}$$

The output voltages of the inverter relatively to the middle point M are defined as follows:

$$\begin{bmatrix} V_{AM} \\ V_{BM} \\ V_{CM} \end{bmatrix} = \begin{bmatrix} F_{17}+F^b_{11} \\ F_{27}+F^b_{21} \\ F_{37}+F^b_{31} \end{bmatrix} U_{c1} + \begin{bmatrix} F^b_{11} \\ F^b_{21} \\ F^b_{31} \end{bmatrix} U_{c2} - \begin{bmatrix} F_{18}+F^b_{10} \\ F_{28}+F^b_{20} \\ F_{38}+F^b_{30} \end{bmatrix} U_{c3} - \begin{bmatrix} F^b_{10} \\ F^b_{20} \\ F^b_{30} \end{bmatrix} U_{c4}$$

The system (3) shows that a five-level NPC VSI can be considered as four two-level voltage source inverters in series. This characteristic lets us to extrapolate the strategies used for the two-level inverter to the five-level NPC inverter.
The input currents of the inverter are given as follows:

$$\begin{cases} i_{d1} = F_{17} i_1 + F_{27} i_2 + F_{37} i_3 \\ i_{d2} = F^b_{11} i_1 + F^b_{21} i_2 + F^b_{31} i_3 \\ i_{d3} = F_{18} i_1 + F_{28} i_2 + F_{38} i_3 \\ i_{d4} = F^b_{10} i_1 + F^b_{20} i_2 + F^b_{30} i_3 \end{cases}$$

The current $i_{d0}$ is given as follows:

$$i_{d0} = (i_1 + i_2 + i_3 + i_4) - (i_{d1} + i_{d2} + i_3)$$

## 3. PWM Strategy of the Five Level NPC VSI

In this part, we present a PWM algorithm of the five-level NPC VSI: the space vector modulation strategy with four bipolar carriers. This strategy is characterized by two parameters [1], [2]:
- The modulation index m is defined as a ratio between the carrier frequency $f_p$ and the reference voltage frequency f:

$$m = \frac{f_p}{f}$$

The modulation rate r is the ratio between the magnitude $V_m$ of the reference voltage and three times of the carrier's magnitude $U_{pm}$: .

$$r = \frac{V_m}{U_{pm}}$$

Figure2 shows the signals of this strategy

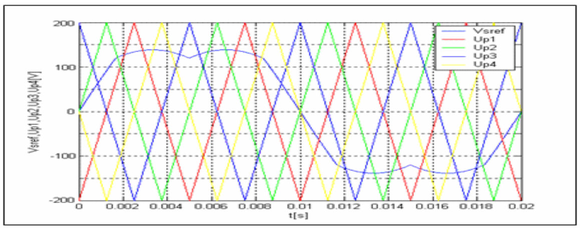
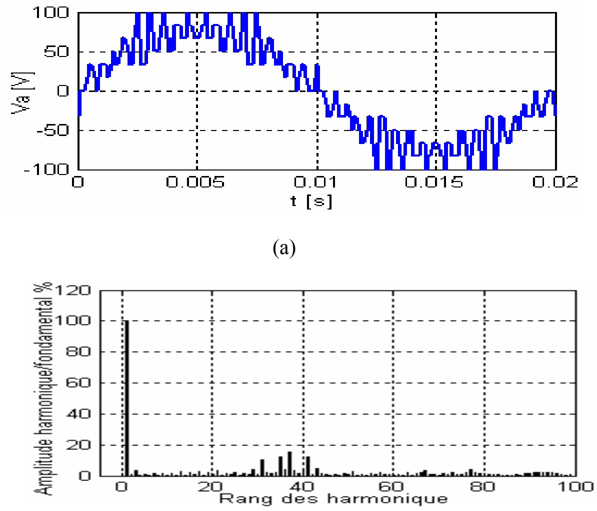


Figure 2. Space vector modulation strategy associated to four bipolar carriers



(a)

(b)

Figure 3.(a,b) The simple voltage of the inverter and its spectrum (m=10)

For even values of m, the output voltages present symmetry relatively to the quarter of the period. Then, only odd harmonics exist. These harmonics gather by families centred around frequencies multiple of 4mf. The first family centred around frequency 4mf is the most important in view of its magnitude.

## 4. Modelling of Photovoltaic Generator

Since the invention of solar cells in en 1954, several models have been proposed to describe its function and behavior under different weather conditions (light and temperature) [3]. In this paper, we present the model with one exponential (diode) [4], [5]. The electrical scheme is given in figure 4.

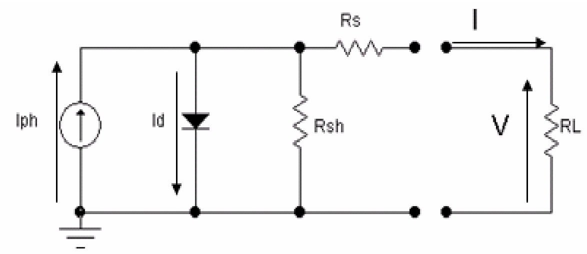


Figure 4. Electrical Scheme of a photovoltaic cell with one diode

The expression of the current-voltage characteristic is given as follows:

$$I = I_{ph} - I_S \times [\exp(\frac{q \times (V + R_s \times I)}{A \times k \times T}) - 1] - \frac{V + R_s \times I}{R_{sh}}$$

Thus, the equivalent scheme of a photovoltaic generator (PG) is given in figure5.

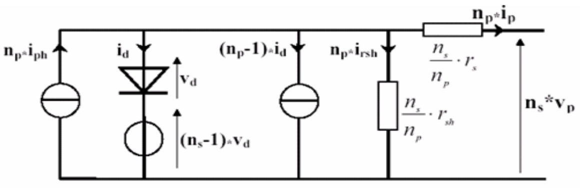


Figure 5. Equivalent scheme of photovoltaic generator

The expression of the current-voltage characteristic of photovoltaic generator is given as follows:

$$I_g = I_{ph,g} - I_{s,g}[\exp\left(q\frac{V_g + R_{s,g} I_g}{AkN_{ms}T}\right) - 1] - \frac{V_g + R_{s,g} I_g}{R_{sh,g}}$$

The functional scheme of photovoltaic generator uses Matlab/Simulink is given in figure6.
In this paper, we have used photovoltaic generator MSX-83 composed by 36 cells in en series

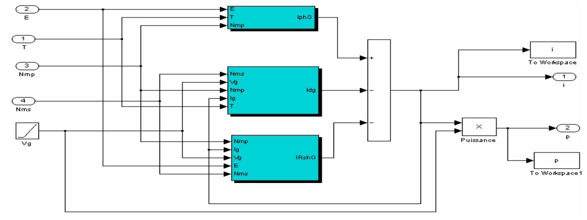


Figure 6. Functional Scheme of photovoltaic generator

The figures 6, 7 and 8 represents respectively current–voltage characteristics, power–voltage and current–voltage (reel case) of panel MSX-83, for a temperature T=25° and light E=1000W/m$^2$.

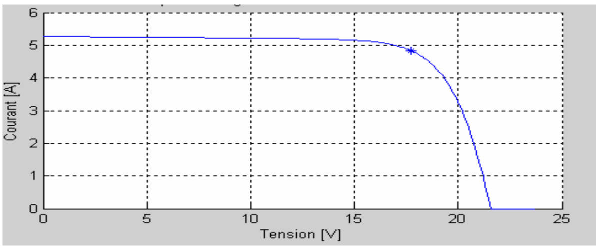


Figure 7. Current–voltage Characteristic PG

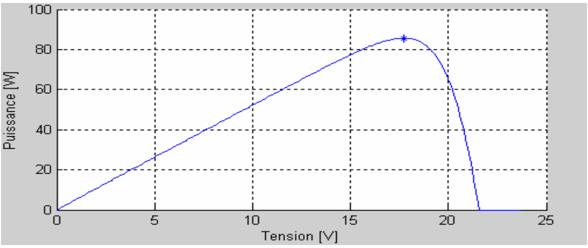


Figure 8. Power–voltage Characteristic PG

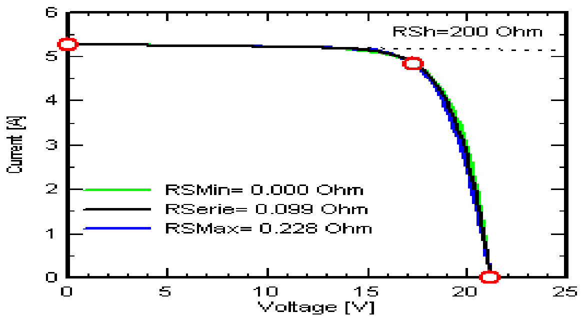


Figure 9. Real Characteristic current–voltage of PG

We can note that the simulation results used the proposed model are nearly of the real case and then we can validate our model.

## 5. Cascade of Two Photovoltaic Generator – Five-Level NPC VSI - PMSM

Until now, we have supposed the input DC voltages of the five-level NPC VSI constants. In this part, the authors study a generation input DC voltage technique. For this, we propose a cascade constituted by two photovoltaic generator-five-level NPC VSI which feeds a PMSM (Figure10).

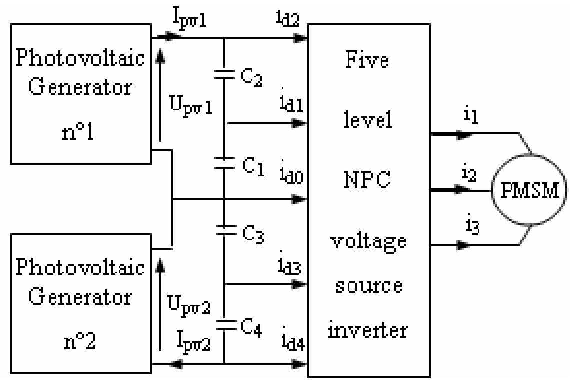


Figure 10. Two photovoltaic generator-filter-five-level NPC VSI-PMSM cascade

5.1. Modelling of Intermediate Filter

Figure11 shows the structure of the intermediate filter of the studied cascade.

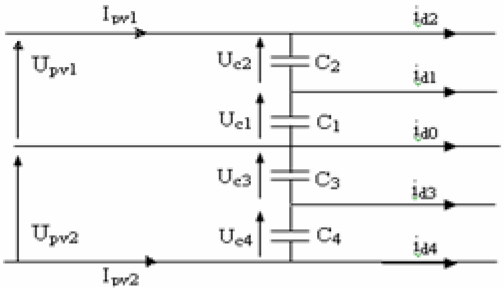


Figure 11. Structure of the intermediate filter

The model of this filter is defined by the following system:

$$\begin{cases} C_1 \dfrac{dU_{c1}}{dt} = I_{pv1} - i_{d2} - i_{d1} \\ C_2 \dfrac{dU_{c2}}{dt} = I_{pv1} - i_{d2} \\ C_3 \dfrac{dU_{c3}}{dt} = I_{pv2} - i_{d2} - i_{d1} - i_{d0} \\ C_4 \dfrac{dU_{c4}}{dt} = I_{pv2} - i_{d2} - i_{d1} - i_{d3} - i_{d0} \end{cases}$$

5.2. Simulation results

The five-level NPC inverter is controlled by the space vector modulation strategy with four bipolar carriers, any photovoltaic generator delivered a voltage $V_{pvi}$=140V.

We note : $U_{c13}=U_{c1}-U_{c3}$, $U_{c24}=U_{c2}-U_{c4}$ et $U= U_{PV1}+U_{PV2}$. The parameters of the intermediate capacitors filter are: $C_1=C_2=C_3=C_4$=20mF.

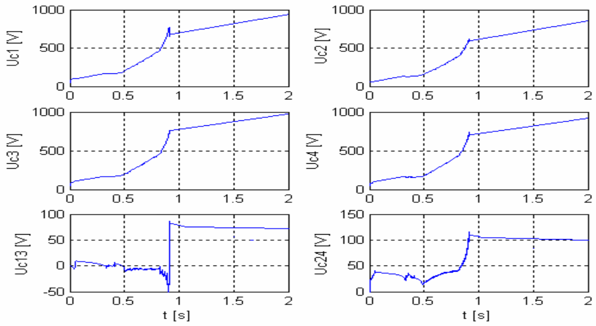


Figure 12. Input voltages of the inverter and their differences

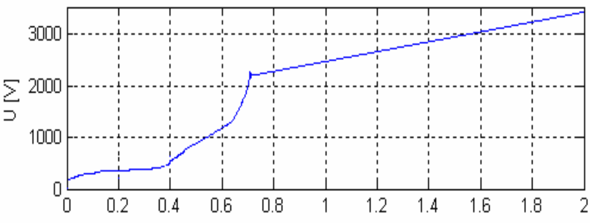


Figure 13. Output voltage of photovoltaic generator

The different input voltages of the VSI are not stables and their differences are not null (Figure12). The output voltages of the photovoltaic generator decrease continually (Figure13).

## 6. Stabilisation of Input Voltage of Five Level NPC VSI

To improve the input voltages of the five-level NPC inverter, we propose to use a clamping bridge, constituted by a transistor and a resistor [1]. The transistors are controlled to maintain equal the different input DC voltages of the inverter (Figure14).

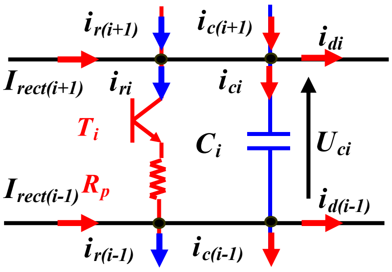


Fig. 14. Clamping bridge cell

The model of the clamping bridge-filter set is defined by the following equation:

$$\begin{cases} C_1 \dfrac{dU_{c1}}{dt} = I_{PV1} - i_{d2} - i_{d1} - i_{r1} \\ C_2 \dfrac{dU_{c2}}{dt} = I_{PV1} - i_{d2} - i_{r2} \\ C_3 \dfrac{dU_{c3}}{dt} = I_{PV2} - i_{d2} - i_{d1} - i_{d0} - i_{r3} \\ C_4 \dfrac{dU_{c4}}{dt} = I_{PV2} - i_{d3} - i_{d2} - i_{d1} - i_{d0} - i_{r4} \end{cases}$$

Where $i_{r1} = \dfrac{U_{ci}}{Rp}$

The control algorithm of the resistive clamping circuits can be summarized as follows:

if $U_{c1} > \dfrac{U_{PV1}}{2} \Rightarrow$ (T1=1) & (T2=0)

if $U_{c2} > \dfrac{U_{PV1}}{2} \Rightarrow$ (T2=1) & (T1=0)

if $U_{c3} > \dfrac{U_{PV2}}{2} \Rightarrow$ (T3=1) & (T4=0)

if $U_{c4} > \dfrac{U_{PV4}}{2} \Rightarrow$ (T4=1) & (T3=0)

The parameters of the intermediate capacitors filter are: $C_1=C_2=C_3=C_4=20$mF and $R_p=25\Omega$. The figures 15 and 16 show the simulation results when using the clamping bridge

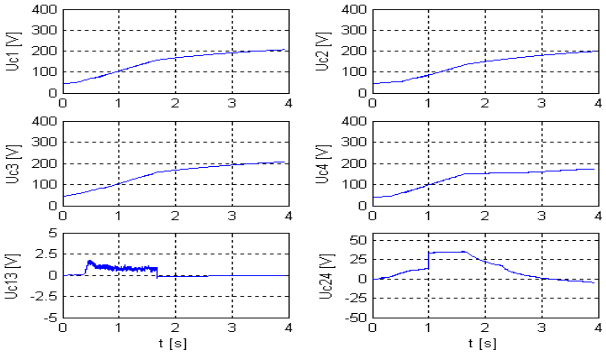


Figure 15. Tensions du pont de clamping et leurs différences

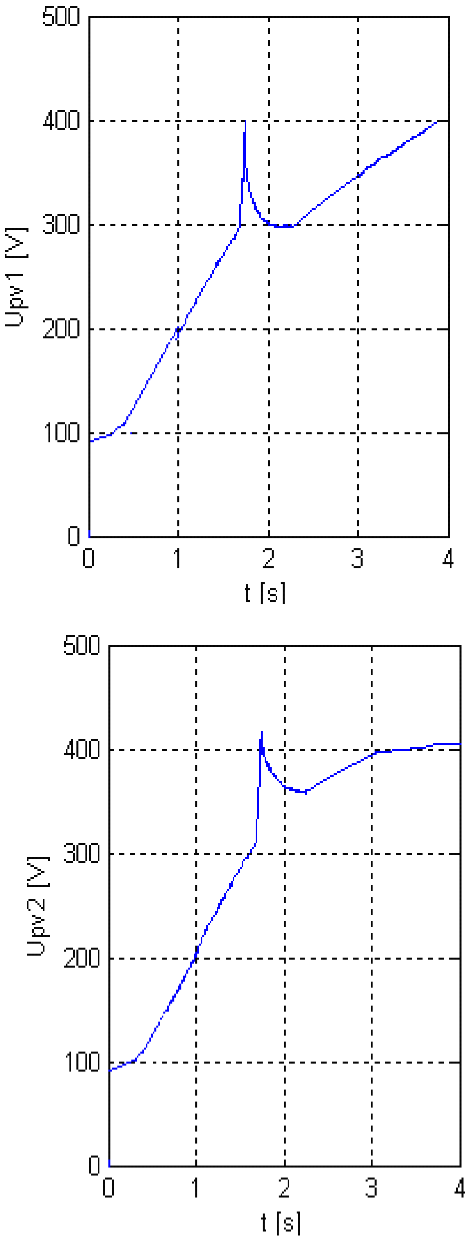


Figure 16. Output voltage of two Photovoltaic generator

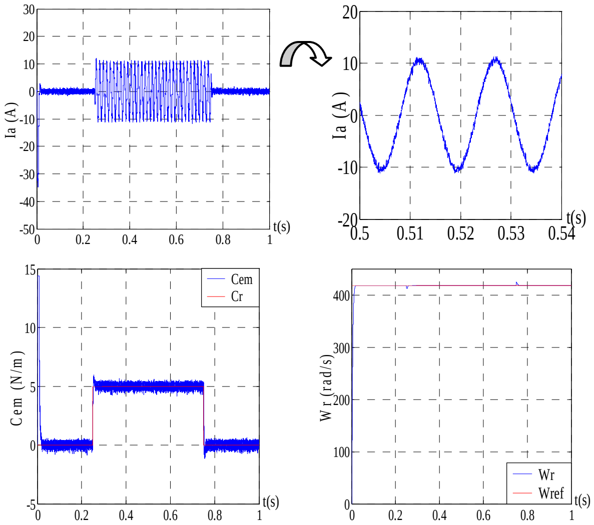


Figure18. Performances of PMSM

We observe that the differences between the input voltages of the five-level NPC inverter are decreased to have a value practically null in steady state (Figure15). The output voltage of the three two-level rectifiers is lightly increased (Figure16). The current $i_{d0}$ has a mean value practically null (Figure17). The performance of the speed control algorithm of the PMSM shows that the current of the machine nearly is sinusoidal. The speed and the torque effect for the charge variation between two instants t=1.5s and t=2.5s (Figure18).

## 7. Conclusions

In this paper, we have studied the performances of the cascade of the photovoltaic cell panels with the multilevel inverter. The modelling of the five-level NPC inverter shows that it is equivalent to four two-level inverters in series. This characteristic lets us to extrapolate the strategies used for the two-level inverter to the five-level NPC inverter. Also, we have presented a space vector modulation strategy with four bipolar carriers.

The study of the stability problem of the input DC voltages of five-level NPC inverter using a cascade constituted by two photovoltaic generator-five-level NPC VSI shows that the different input voltages of this VSI are not stables and their differences are not zero. To solve this problem, we propose to use clamping bridge, because this bridge allows improve the input voltage of five-level inverter.

The performances obtained with this cascade are full of promise to be using this inverter in renewable energy

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