MULTICARRIER WAVE DUAL REFERENCE VERY LOW FREQUENCY PWM CONTROL OF A NINE LEVELS NPC MULTI-STRING THREE PHASE INVERTER TOPOLOGY FOR PHOTOVOLTAIC SYSTEM CONNECTED TO THE MEDIUM ELECTRIC GRID

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Abstract: The multilevel multi-string inverter has gained much attention in recent years due to its advantages in lower switching loss, better electromagnetic compatibility, higher voltage capability, and lower harmonics. Solar Energy is one of the favorable renewable energy resources and the multilevel inverter has been proven to be one of the important enabling technologies in photovoltaic (PV) utilization. This paper proposes a diode-clamped three phase nine levels grid connected photovoltaic inverter topology with a multicarrier dual reference pulse-width modulated (PWM) control scheme. Eight carrier waves of the same frequency and different amplitudes are compared with two references (a sine wave and its opposite) for generating the control signals of the switches. Some DC/DC boost converters are used to amplify the voltage produced by the photovoltaic generators. Each of these converters is controlled by an MPPT algorithm in order to track the maximum power point of the GPV; Results of simulation in Matlab environment are given and discussed.

Keywords: Grid connected photovoltaic (PV) system, diode-clamped multilevel three phase multi-string inverter, multicarrier PWM, and medium voltage grid.

1. Introduction

A multilevel inverter is a power electronic device built to synthesize a desired AC voltage from several levels of DC voltages. Such inverters have been the subject of research in the last several years where the DC levels were considered to be identical in that all of them were capacitors, batteries, solar cells, etc. [1]. It has gained much attention due to its advantages in lower switching loss, better electromagnetic compatibility, higher voltage capability, and lower harmonics. Multilevel inverters, including an array of power semiconductors and capacitor voltage sources, the output of which generate voltages with stepped waveforms. The commutation of the switches permits the addition of the capacitor voltages, which reach high voltage at the output, while the power semiconductors must withstand only reduced voltages. Photovoltaic (PV), wind energy and hydro conversion are the most explored technologies due to their considerable advantages [2-3], such as reliability, reasonable installation and energy production costs, low environmental impact, capability to support micro grid systems and to connect to the electric grid [4]. A schematic diagram of one phase leg of inverters with different numbers of levels is shown, in Fig.1 for which the action of the power semiconductors is represented by an ideal switch with several positions. In this paper, we present a multi carrier dual reference very low frequency diode-clamped three phase 09 level inverter designed for photovoltaic system connected to a medium voltage grid. This inverter is controlled by a PWM strategy based on the comparison of several carrier waves with two reference signals. More control signals are obtained. Instead of a single photovoltaic generator at the input of the inverter, we have a multiple continuous source which is composed of several photovoltaic generators. Each of them consists of Np branches, each of which is composed of Ns solar panels in series. Each generator of this source generates a voltage which is amplified at the output by means of a dc / dc converter. This converter is controlled by an MPPT algorithm. The overall system is shown in Fig.2. The study is simulated in Matlab/Simulink and results are given and discussed.

Fig.1 One phase leg of an inverter with “n” levels
rent
MPPC
OCM
\( S \)
Equivalent circuit diagram of a PV cell is ref, Noperating temperature of the \( T \), MPPC - T SC
- OCC.

\[ T_{SCM} = \frac{V_{OCM}}{qT_{THC}} \]

Fig. 2 Schematic diagram of the overall PV system

2. Modeling of the global grid connected photovoltaic system structure

Modeling photovoltaic system is required as a crucial step to describe the functioning of all the elements that are all starting from the DC source arriving to the grid. It predicts the conceptual and energy performance of PV systems connected to the grid in different climatic conditions and under well-defined loads. Models of the various components will be presented as follows:

2.1 Model of the photovoltaic source

As already mentioned, the photovoltaic source consists of 04 parts, each of them represents a partial photovoltaic generator. Each partial PVG generates at its output a DC voltage which is then amplified by a DC / DC converter. Continuous output voltages of the converters are then summed to obtain an overall voltage that feeds the inverter. The equivalent circuit diagram of a PV cell is illustrated in fig. 3.

Fig. 3 Equivalent circuit diagram of a PV cell

The selected model in this work is inspired from references [5–7]. The advantage of this model can be established using only standard data for the module and cells provided by the manufacturer in the technical data (data and graphs). It is independent of the saturation current \( I_S \) of the diode (see Fig. 3). The current supplied by the solar module (\( I_M \)) in any conditions, is given by:

\[ I_M = I_{SCM} \left[ 1 - \exp \left( \frac{V_{M} - V_{OCM} - I_{SCM}R_{SM}}{\alpha V_{THM}} \right) \right] - \exp \left( \frac{V_{OCM}}{\alpha V_{THM}} \right) \]

(1)

Where:
- \( I_{SCM} \) and \( V_{OCM} \) are respectively the short circuit current and the open circuit voltage at the standard test conditions (STC).
- \( I_M \) and \( V_M \) are respectively the current and the voltage delivered by the module at any conditions.
- \( R_{SM} \) is the series resistance of the module.
- \( V_{THM} \) is the thermal voltage and \( n \) is the quality factor which varies typically from 1 to 2.

\( V_{OCM} \) and \( I_{SCM} \) are given by:

\[ V_{OCM} = V_{OCC} \times N_{SC} \]

(2)

\[ I_{SCM} = I_{SC} \times N_{PC} \]

(3)

The thermal voltage is given by:

\[ V_{THM} = V_{THC} \times N_{SC} \]

(4)

Where:
- \( V_{THC} \) is the thermal voltage of the PV cell.
- \( R_{SC} \) is the series resistance of the PV cell.
- \( k \) is the Boltzmann's constant.
- \( q \) is the electrical charge of the electron.
- \( N_{PC} \) is the number of branches of parallel cells in a module.
- \( N_{SC} \) is the series number of cells of each branch.

The open circuit voltage of the PV cell is given by:

\[ V_{OCC} = V_{OCC-ref} - \beta (T - T_{ref}) \]

(6)

Where:
- \( V_{OCC-ref} \) is the open circuit voltage of the PV cell in standard conditions.
- \( T_{ref} \) is the reference value of the temperature (\( T_{ref}=25^\circ C \)) and \( T \) is the operating temperature of the PV cell, it is given by:

\[ T = T_a - T_{ref} \]

(7)

\( T_a \) is ambient temperature of the PV cell.

The thermal voltage of the PV cell can be easily calculated using the coordinates of the maximum power point of the cell (\( V_{MPPC} \) and \( I_{MPPC} \)). The expression of \( V_{THC} \) is:

\[ V_{THC} = \frac{V_{MPPC} + R_{SC}I_{MPPC} - V_{OCC}}{\ln(1 - \frac{I_{MPPC}}{I_{SC}})} \]

(8)

The current delivered by each PVG is given by the following expression:
\[ l = N_{S} \Phi_{CM} \left[ \left( N_{p} \Phi_{OCM} \times N_{p} \Phi_{BM} \times \Phi_{OCM} \right) \right] \tag{9} \]

2.2 DC/DC Boost converter and its control

2.2.1 DC/DC Boost converter model

A boost converter (step-up converter) is a DC-to-DC power converter with an output voltage greater than its input voltage. A schematic of a boost power stage is shown in Fig. 4. The basic principle of a Boost converter consists of two distinct states.

![DC/DC Boost converter schematic](image)

If \( x_{1} = I_{L} \) and \( x_{2} = V_{C} \) the state equations are given by:

\[
\begin{align*}
\dot{x}_{1} &= \frac{V_{in}}{L} \quad \text{and} \\
\dot{x}_{2} &= \frac{1}{C_{cap}} \frac{V_{out}}{L}
\end{align*}
\]

\[
\begin{align*}
V_{out} &= V_{C} = x_{2}
\end{align*}
\]

In matrix form the system of equations (11) and (12) becomes:

\[
\begin{bmatrix}
\dot{x}_{1} \\
\dot{x}_{2}
\end{bmatrix} =
\begin{bmatrix}
0 & 0 \\
0 & \frac{1}{RC}
\end{bmatrix}
\begin{bmatrix}
x_{1} \\
x_{2}
\end{bmatrix}
+ \begin{bmatrix}
0 \\
\frac{1}{L}
\end{bmatrix} V_{in}
\]

\[
V_{out} = C_{cap} \begin{bmatrix}
x_{1} \\
x_{2}
\end{bmatrix}
\]

\[
\text{If: } A_{1} = \begin{bmatrix}
0 & 0 \\
0 & \frac{1}{RC}
\end{bmatrix}, \quad B_{1} = \begin{bmatrix}
\frac{1}{L} \\
0
\end{bmatrix}, \quad C_{1} = \begin{bmatrix}
0 & 1
\end{bmatrix}
\]

We obtain:

\[
\begin{bmatrix}
\dot{x}_{1} \\
\dot{x}_{2}
\end{bmatrix} = A_{1} \begin{bmatrix}
x_{1} \\
x_{2}
\end{bmatrix} + B_{1} V_{in}
\]

b) In the Off-state, the switch “S” is open and the only path offered to inductor current is through the flyback diode D, the capacitor C and the load R. Differential equations that govern the operation of the circuit are:

\[
\begin{align*}
\frac{dl_{1}}{dt} &= V_{in} - V_{C} \quad \text{(16)} \\
C \frac{dv_{C}}{dt} &= i_{L} - i_{out} \quad \text{(17)}
\end{align*}
\]

By substituting \( i_{L} \) by the state variable \( x_{1} \), and \( V_{C} \) by the state variable \( x_{2} \), the above equations become:

\[
\begin{align*}
x_{1} = \frac{1}{L} V_{in} - \frac{1}{L} x_{2} \\
x_{2} = \frac{1}{C} \frac{1}{RC} x_{2}
\end{align*}
\]

In matrix form the system of equations (18) becomes:

\[
\begin{bmatrix}
\dot{x}_{1} \\
\dot{x}_{2}
\end{bmatrix} = \begin{bmatrix}
0 & -\frac{1}{L} \\
\frac{1}{C} & -\frac{1}{RC}
\end{bmatrix}
\begin{bmatrix}
x_{1} \\
x_{2}
\end{bmatrix}
+ \begin{bmatrix}
\frac{1}{L} \\
0
\end{bmatrix} V_{in}
\]

\[
\text{If: } A_{2} = \begin{bmatrix}
0 & -\frac{1}{L} \\
\frac{1}{C} & -\frac{1}{RC}
\end{bmatrix}, \quad B_{2} = \begin{bmatrix}
\frac{1}{L} \\
0
\end{bmatrix}, \quad C_{2} = \begin{bmatrix}
0 & 1
\end{bmatrix}
\]

Then:

\[
\begin{bmatrix}
\dot{x}_{1} \\
\dot{x}_{2}
\end{bmatrix} = A_{2} \begin{bmatrix}
x_{1} \\
x_{2}
\end{bmatrix} + B_{2} V_{in}
\]

Finally, for a full period of operation (T) and by adding the two equations (15) and (20) the system of equations becomes:

\[
\begin{bmatrix}
\dot{x}_{1} \\
\dot{x}_{2}
\end{bmatrix} = \left( A_{1} D + A_{2} (1-D) \right) \begin{bmatrix}
x_{1} \\
x_{2}
\end{bmatrix} + B_{1} D V_{in} + B_{2} D (1-D) V_{in}
\]

After rearranging equation (21), the matrix form is:

\[
\begin{bmatrix}
\dot{x}_{1} \\
\dot{x}_{2}
\end{bmatrix} = \left( A_{1} D + A_{2} (1-D) \right) \begin{bmatrix}
x_{1} \\
x_{2}
\end{bmatrix} + B_{1} D + B_{2} (1-D) V_{in}
\]

Where:

\[
A = \left( A_{1} D + A_{2} (1-D) \right), \quad B = B_{1} D + B_{2} (1-D)
\]

D is the duty cycle, it represents the fraction of the commutation period T during which the switch “S” is on. Therefore D ranges between 0 (“S” is never on) and 1 (“S” is always on).
2.2.2 MPPT Control

The boost (step-up) DC/DC converter is modeled as a block whose inputs are the voltage delivered by the solar panels and the second input is the duty cycle $D$ generated by the Maximum Power Point Tracking (MPPT) controller. This MPPT is used on the basis of a search algorithm called perturb and observe (P & O) [8].

2.3 Model of the three-Phase nine levels NPC Inverter

Fig. 5 shows the diagram of the three-Phase nine levels Neutral Point Clamped (NPC) inverter.

It is composed of three arms; each one of them is composed of sixteen IGBTs that are noted as “Si”. The index (i) indicates the phase: if $i=1$, it means the phase “A”, $i=2$ the phase “B” and $i=3$ the phase “C”. The index (j) indicates the number of the switches noted as: $S_{i1}$, $S_{i2}$, $S_{i3}$, $S_{i4}$, $S_{i5}$, $S_{i6}$, $S_{i7}$ and $S_{i8}$ form the upper part of the arm in each phase and the switches noted as: $S'_{i1}$, $S'_{i2}$, $S'_{i3}$, $S'_{i4}$, $S'_{i5}$, $S'_{i6}$, $S'_{i7}$ and $S'_{i8}$ form the lower part of the arm in each phase. Each arm of the inverter also comprises fourteen clamped diodes, which are denoted “Di”. The output of the inverter is connected to the electric grid through a filter. The diode-clamped inverter can generate 09 voltage levels; four levels are positive, one level is zero and four levels are negative. The inverter is composed of 48 switches, hence the necessity of 48 control signals. These signals can be generated by a PWM controller.

2.4 Control circuit of the inverter

The control circuit of the inverter is shown in Fig.6. It is based on the use of the PWM strategy in a closed loop current. This strategy consists in comparing eight carrier signals of the same frequency ($f_c=400$ Hz) with a sinusoidal reference signal. PI controllers are also used; they are characterized by their coefficients $K_i$ and $K_p$ ($K_i=0.01$; $K_p=0.01$). A square signal is added.

As has already been mentioned, each arm of the inverter is composed of sixteen IGBTs, hence the necessity of sixteen control signals. So for these control signals, a small Matlab program is performed.

3. Simulation of the overall system

The overall diagram of the simulation is shown in Fig. 7.

The simulation results are:

3.1 Characteristic of the PV source
3.2 Parameters of the DC/DC converters

Fig. 10 illustrates the voltage at the input and the output of the DC/DC converter.

The amplification voltage is very clear. The voltage value of 5536V, generated by the PV source, becomes 12660V at the output of DC/DC converters in series.

3.3 Parameters of the NPC inverter

Fig. 11 shows the voltages at the inverter output before and after the filter. For each phase, the voltage before filtering, has a shape of a staircase waveform, with a maximum value of 6330V=Vdc/2. However, the voltage after filtering is sine wave that begins with a transitional phase during a time of 0.03s.
Fig. 16 Inverter output current for phase “c”
current after the filter (red), current injected in the
grid (green), current in the load (blue)

Fig. 17 DC/DC converter and Inverter output power

As illustrated in Fig. 18, the inverter input power is 1.05MW, however, the power at its output (after the filter) is 0.98MW, giving an efficiency of 94%.

4. Conclusion

In this paper, a multicarrier wave dual reference very low frequency PWM control of a diode-clamped nine levels multi-string three phase inverter topology for photovoltaic system connected to the medium electric grid has been presented. This control was based on the PWM strategy which used eight carrier signals with different amplitudes, and with the same frequency (equal to 400Hz) which is a very low value. The results are quite interesting. The efficiency of the inverter is very satisfying. However, the disadvantages of this system are the presence of a filter at the output, causing losses by Joule effect and the use of multiple carrier signals for the control of the inverter. So to remedy this, it is preferable to use an inverter that output has more than nine levels in order to avoid the filter, and reduce the number of carrier signals in the control of the inverter. On the other hand, the PV system requires a large number of solar modules with a power of 75W which requires a large area to install, so it is preferable to replace them by more powerful solar modules.

5. References


Annex

Parameters of ENIESOLAR module used in this work:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>value</th>
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<tbody>
<tr>
<td>Maximal power $P_{MPP}$</td>
<td>75W, +/- 10%</td>
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<tr>
<td>Short circuit current $I_{sc}$</td>
<td>4.67A</td>
</tr>
<tr>
<td>Open circuit voltage $V_{OC}$</td>
<td>21.6V</td>
</tr>
<tr>
<td>MPP voltage $V_{MPP}$</td>
<td>17.30V</td>
</tr>
<tr>
<td>MPP current $I_{MPP}$</td>
<td>4.34A</td>
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<tr>
<td>minimum value of the fuse in series</td>
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<tr>
<td>number of cells in series</td>
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<tr>
<td>number of cells in parallel</td>
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