Modelling and Realisation of a Three - Level P.W.M Inverter Using a D.S.P Controller

H. DENOUN, N. BENYAHIA, M. ZAOUIA, N. BENAMROUCHE, S. HADDAD, S. AIT MAMAR

Abstract — To overcome the limitations in voltage and power conventional two-level inverters and in order to improve the spectrum of the output voltage, multilevel inverters are being widely used. In the first part of this paper, the structure and the model of this power inverter are presented. After that, a SPWM control strategy is developed and implemented. Finally, experimental results are presented using a DSP controller.

Key words — Multilevel inverter, Neutral point clamping, Numerical control, Pulse-Width Modulation.

I. INTRODUCTION

Multilevel converters are based on the neutral point clamped inverter topology proposed by Nabae[1]. The multilevel voltage source inverter is recently applied in many industrial applications such as power supplies, static VAR compensatory, drive systems, etc.

One of the most significant advantages of multilevel configurations is the harmonic reduction in the output waveform without increasing frequency, thus three level inverters can be operated at lower switching frequencies (fsw < 500 Hz) leading to smaller commutation losses and hence higher efficiencies. Moreover they have great interests in overcoming the series connections problems [2]. In fact, the three-level inverter is able to generate voltages without output transformer and its harmonic components are fewer than those of conventional two-level inverters at the same switching frequency. In addition, when the blocking voltage of each switching device is half of the dc- link voltage, it is easy to produce high voltage and power inverter systems. In recent years huge advances have been made in digital control strategies leading to improving the performances of multi-level inverters and thus spreading their use.

In this paper the modelling and the simulation of a three level PWM inverter are carried out using a TMS320LF2407 DSP controller. Emphasis is made on elaborating the PWM control strategy using this DSP programmed using software developed by Texas Instruments “Code composer”. Furthermore, its experimental implementation is performed and the built system is tested. The experimental results are used to validate those obtained theoretically. In addition, the performance of this inverter are analysed with respect to its output voltage contents.

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II. MODELING OF A THREE-LEVEL INVERTER

A. General structure

The NPC multilevel inverter uses capacitors in series to divide the DC bus voltage into different voltage levels. To produce m-levels in the phase voltage, an m-level NPC inverter needs m-1 capacitors on the dc bus. A three-phase three-level NPC inverter is shown in fig.1. The dc bus consists of two capacitors C. For a dc bus voltage Uc, the voltage across each capacitor is Uc/2 and each device voltage stress will be limited to one capacitor voltage level Uc/2 through clamping diodes [3],[4].

![Fig.1. Power circuit of NPC inverter](image)

B. Different configurations of the inverter

To describe the different sequences of the inverter function, let us consider the possible states of the first leg switches fig.2.

The three-level inverter has the advantages that the blocking voltage of each switching device is one half of dc-link voltage whereas full dc-link voltage for two-level inverter.
Fig. 2. Different configurations of a leg

C. Complementary command

We define the complementary control of the inverter leg as follows [5]:

\[
\begin{align*}
B_{k1} &= \overline{B}_{k4} \\
B_{k2} &= \overline{B}_{k3}
\end{align*}
\] (1)

It was demonstrated [5] that the command given by relationship (1) is the one which gives the three levels \(U_c\), \(O\), \(-U_c\) in an optimum way.

Table 1 shows the state of the switches and the corresponding output voltage of the inverter. Where \(V_k\) \((k = a, b, c)\) is the potential of the leg.

Table I: Switches states and corresponding voltage

<table>
<thead>
<tr>
<th>(B_{k1})</th>
<th>(B_{k2})</th>
<th>(B_{k3})</th>
<th>(B_{k4})</th>
<th>(V_k)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
<td>1</td>
<td>1</td>
<td>(-U_c)</td>
</tr>
<tr>
<td>0</td>
<td>1</td>
<td>0</td>
<td>1</td>
<td>Unknown</td>
</tr>
<tr>
<td>1</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>1</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>(U_c)</td>
</tr>
</tbody>
</table>

D. Model control of the three-level inverter - Connection functions

These functions define the state of the switches. They are equal to 1 if the switch is ON and 0 if the switch is OFF. They are defined by following relationship.

\[
\begin{align*}
F_{k1} &= 1 - F_{k4} \\
F_{k2} &= 1 - F_{k3}
\end{align*}
\] (2)

Therefore, the branch voltages \(V_{AM}\), \(V_{BM}\), \(V_{CM}\) are expressed as follow:

\[
\begin{align*}
V_{AM} &= F_{11} \cdot F_{12} \cdot (F_{11} \cdot F_{14} + F_{12} \cdot F_{13} + F_{14} \cdot F_{12} + F_{11} \cdot F_{13} + F_{12} \cdot F_{14} - F_{11} \cdot F_{13} - F_{12} \cdot F_{14}) \\
V_{BM} &= F_{21} \cdot F_{22} \cdot F_{23} \cdot F_{24} \cdot U_{c2} \\
V_{CM} &= F_{31} \cdot F_{32} \cdot F_{33} \cdot F_{34} \cdot U_{c2}
\end{align*}
\] (3)

However, the output phase voltages of the inverter can be deduced from equation (3) as follows:

\[
\begin{align*}
V_A &= \frac{2V_{AM} - V_{BM} - V_{CM}}{3} \\
V_B &= \frac{2V_{BM} - V_{CM} - V_{AM}}{3} \\
V_C &= \frac{2V_{CM} - V_{AM} - V_{BM}}{3}
\end{align*}
\] (4)

And these equations can be rewritten using the voltage branches which give:

\[
\begin{align*}
V_A &= \frac{1}{3} \left[ 2 -1 -1 \right] \begin{bmatrix} F_{11} & F_{12} \\ F_{21} & F_{22} \\ F_{31} & F_{32} \end{bmatrix} U_{c1} - \begin{bmatrix} F_{13} & F_{14} \\ F_{23} & F_{24} \\ F_{33} & F_{34} \end{bmatrix} U_{c2}
\end{align*}
\] (5)

III. PWM STRATEGY AND SIMULATION RESULTS

The parameters of PWM control technique are defined as: Amplitude modulation index \(m_a\) and the frequency ratio \(m_f\).

\[
\begin{align*}
m_a &= \frac{A_m}{A_c} \quad (6) \\
m_f &= \frac{f_c}{f_m} \quad (7)
\end{align*}
\]

Where \(A_m\) is the peak amplitude of the control signal, while \(A_c\) is the peak amplitude of triangle signal (carrier).

\(m_f\) is the ratio between the carrier and the control frequency.

The PWM three level inverter algorithm of one carrier is given by:

\[
\begin{align*}
\left( V_{ref,1} \leq U_p \right) & \Rightarrow B_{11} = 1, B_{12} = 0 \\
\left( V_{ref,1} > U_p \right) & \Rightarrow B_{11} = B_{12} = 0 \quad (8)
\end{align*}
\]

Where: \(V_{ref}\) is called modulating signal and \(U_p\) is the carrier signal.

Table II: shows the truth table of the algorithm [5].

<table>
<thead>
<tr>
<th>(A)</th>
<th>(B)</th>
<th>(B_{11})</th>
<th>(B_{12})</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>0</td>
<td>1</td>
<td>0</td>
<td>0</td>
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<tr>
<td>1</td>
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<td>1</td>
</tr>
<tr>
<td>1</td>
<td>0</td>
<td>1</td>
<td>0</td>
</tr>
</tbody>
</table>

Where:

\[ A = 1 \text{ when } V_{ref} > 0 \quad \text{ if not } A = 0 \]
\[ B = 1 \text{ when } V_{ref} > U_p \quad \text{ if not } B = 0 \]

The logical expressions of \(B_{11}\) and \(B_{12}\) are:

\[
\begin{align*}
B_{11} &= \overline{B}_{14} + \overline{B} + A \\
B_{12} &= \overline{B}_{13} + AB
\end{align*}
\] (9)
The synoptic diagram of the proposed simulation of the strategy is shown in fig.3 [6], [7].

![Synoptic Diagram](image)

**Fig.3 Synoptic of the proposed PWM strategy**

To illustrate the performance of the three-level PWM inverter, the system is investigated through computer simulation using a passive load. By taking the following parameters:

- $R = 22 \, \Omega$, $L = 340 \, \text{mH}$, $m_f = 24$, $m_a = 0.8$, $U_c/2 = 30 \, \text{V}$, $f = 50 \, \text{Hz}$.

And after running the simulation program under Matlab Simulink environment the following results are obtained. They are presented in figs.4, 5, 6, 7, and 8.

![Control Pulses](image)

**Fig.4 Control pulses for $m_f = 24$, $m_a = 0.8$**

![Output Voltage](image)

**Fig.6 Output voltage of phase $V_A$**

![Voltage AB](image)

**Fig.5 Voltage $V_{AB}$**
Fig. 4 shows the simulation sequences of the upper-arm. Fig. 5 shows the line voltage $V_{ab}$, it has five voltage levels $U_c$, $U_c/2$, 0, -$U_c/2$, $U_c$. Fig. 6 shows the output voltage of the first phase of the inverter.

Fig. 7 shows the spectral analysis of the phase voltage. The voltage spectrum shows that the harmonics are grouped into multiple frequencies centered around the switching frequency families. Harmonic numbers 23 and 25 are the most important harmonics present in the voltage waveform.

Fig. 8 shows the voltage $V_{AM}$ with the three levels of output voltage of an arm: $U_c/2$, 0, -$U_c/2$.

Fig. 9 shows the evolution of the amplitude of the fundamental output voltage $V_A$ versus the modulation index $m_a$.

Fig. 10 shows the THD versus $m_a$. We note that the harmonics decrease as $m_a$ increases.

These results are much better than those which could be obtained with a conventional two–level inverter as the harmonics content is pushed to their higher order and thus easily filtered. It should be that the comparison of the reference sinusoidal signal with the triangular waveform is done in the PWM generator of the DSP to generate the control signals for the switching devices along with the inverted signals with the required dead band.

IV. EXPERIMENTAL INVESTIGATION

The schematic diagram of the converter circuit implemented is given in fig. 11. It consists of two parts: the power circuit, and the control circuit.

The power circuit is formed by two arms, formed by twelve transistors I.G.B. Ts and eighteen diodes connected in anti-parallel. The generated control signals are obtained using several control cards such as conditioning, monitoring, D/A conversion cards etc.

The shaded part is the control circuit containing the DSP controller TMS320LF2407 that generates the PWM signals and also provides soft start functions [8]. The DSP programming is based a software developed by Texas Instruments (Code Composer). The control algorithm is written in assembly language in order to optimize the whole tasks cooperation and to ensure communication between the DSP, the converter, and the passive load [10] [11] [12] [13].

Fig. 13 shows a photograph of the experimental bench including the inverter and all the peripherals.

It should be noted that the parameters used in the experimental investigation are similar to those used earlier in the simulation in order to validate the developed models. Furthermore, for the same triangular-sinusoidal strategy, a frequency ratio equals to 0.8 and an index of modulation equals to 24 is taken.
After the construction of the various electronic circuits and the development of the software, the three-level converter was tested in the laboratory. It was used as an inverter supplying a passive load formed by a resistance and an inductance. The oscillographic results obtained are given in Figs. 12, 13, 14, and 15.

Fig. 12 $V_{AM}$ voltage (15V/Div)

Fig. 13 Output voltage of phase VA (15V/Div)

Fig. 14 Voltage $V_{AB}$ (30V/Div)
Fig. 15 Control pulses (1V/Div)

Fig. 12 clearly shows the $V_{AM}$ voltage variation. The waveform of the voltage is similar to that obtained from the simulation, except the small shift observed around the zero level of the voltage. This is may be due to the imbalance of the midpoint.

Fig. 13, 14, and 15 show respectively the voltage of the zero level of the voltage. This is may be due to the control voltage being controlled by a microcomputer in a much more sophisticated manner than those using analogue circuits. This opens ways to undertake to use this system to feed an asynchronous machine and will be published in the near future.

V. CONCLUSION

Simulation and experimental results show that the developed test rig (the hardware and the software) works properly. The low commutation frequency of three-level inverters permits a realisation of an optimal control by relatively simple tools. With a high number of semiconductors devices, current quality can also be improved and weight reduced by avoiding heavy current filters. Moreover, the output harmonic contents of the phase voltage are fewer than those obtained in conventional two-level inverters at the same switching frequency.

The control voltage was controlled by a microcomputer in a much more sophisticated manner than those using analogue circuits. This opens ways to many other investigations. In fact, work is being undertaken to use this system to feed an asynchronous machine and will be published in the near future.

REFERENCES


H. Denoun was born in Algiers, Algeria. He received his Bsc degree in electrical engineering from the Mouloud Mammeri University, Tizi-Ouzou, Algeria, and the D.E.A degree from Paris 6, France and the Master degree from Polytechnic School, Algiers, Algeria in 1998 and 2001 respectively. He got his PhD degree in Electrical Engineering from The University of Mouloud Mammeri University, Tizi-Ouzou. He is currently a senior lecturer at the same university. His research interests include electrical machines and drives, power electronics and control systems.