An Implementation Mechanisms of SVM Control Strategies Applied to Five Levels Cascaded Multi-Level Inverters

Mohammed Yaichi*, Mohammed-Karim Fellah**
* Photovoltaic Pumping Team, Research Unit in Renewable Energies in the Saharan Medium URER/MS-Adrar, CDER
** Intelligent Control and Electrical Power Systems Laboratory, Djillali Liabes University of Sidi-Bel-Abbes

ABSTRACT

In the area of the energy control with high voltage and power, the multilevel inverters constitute a relatively recent research orientation. The current applications of this technology are in the domains of the high voltage (over hundred kV), variable speed drives, transport and distribution of a good quality of electrical energy (HVDC, FACTS system, ...). To improve the output voltage for such inverters, many different modulation strategies have been developed. Among these strategies, the SVM (Space Vector Modulation). The technique provide the nearest switching vectors sequence to the reference vector without involving trigonometric functions and provide the additional advantages of superior harmonic quality. In this paper, we analyze different mechanisms of the output voltage synthesis and the problem of even order harmonic production. With the proposed a new trajectory SVM, which can eliminate all the even order harmonics for five levels inverter. Show clearly how to deduce the trajectories from the sequences allowing to have better performances among several possible trajectories. It is dedicated to the application of two particular trajectories.

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1. INTRODUCTION

The main interest of the multilevel inverters is the remarkable improvement of the spectral quality of its output signals. Multilevel inverters can reach the increasing demand for power quality and power ratings along with lower harmonic distortion and lesser electromagnetic interference (EMI). This spectrum is, by far, relatively better than the classical two levels inverter [1]-[5].

To improve much more quality of electrical energy, we apply the space vector modulation (SVM) strategy which stands out because it offers significant flexibility to optimize switching waveforms, and because it is well suited for implementation on a digital computer [1], [2], [6]-[9]. The technique provide the nearest switching vectors sequence to the reference vector and calculates the on-state durations of the respective switching state vectors without involving trigonometric functions and provide the additional advantages of superior harmonic quality. It will be studied on a five levels cascaded three-phase inverter. This converter consists of a series-connection of two 4-quadrant converter by phase [2].

The implementation of SVM produces, for some cases, even order harmonics. We will propose a new trajectory SVM for the cascaded inverter, allowing to eliminate the even order harmonics from the output voltage and resulting in a solution where the number of commutation and hence the switching losses may be reduced in the inverter.
2. PRINCIPLE OF SVM APPLIED FOR FIVE LEVELS INVERTERS

Figure 1 shows the simplified circuit of a five levels cascaded inverter. The output voltage of the inverter of a phase, characterize its state. It is defined by the formula (1) [2].

\[
V_{so} = \begin{cases} 
+2U & \text{noted (4) if } (K_{d1}, K_{d2}) \text{ and } (K_{d3}, K_{d4}) \text{ closed} \\
+U & \text{noted (3) if } (K_{d1}', K_{d2}) \text{ and } (K_{d3}, K_{d4}) \text{ closed} \\
0 & \text{noted (2) if } (K_{d1}, K_{d2}) \text{ and } (K_{d3}', K_{d4}) \text{ closed} \\
-U & \text{noted (1) if } (K_{d1}, K_{d2}) \text{ and } (K_{d3}, K_{d4}) \text{ closed} \\
-2U & \text{noted (0) if } (K_{d1}', K_{d2}) \text{ and } (K_{d3}', K_{d4}) \text{ closed} 
\end{cases}
\]

with \( s = a, b \) or \( c \);
\( d = 1, 2, 3 \): represent the number of the phase (leg).

Theoretical tools allowing evaluating and identifying the representation of the vectors and commutations (hexagonal structure) is corresponding to the vectors of output of the 2 levels and Multilevel inverters have been studied in detail by [2], [6], [10].

Figure 2 shows all the switching vectors (61 vectors) of a five levels inverter labelled with the position of the equivalent switching states (125 states) [2], [10]-[12]. These vectors of voltage divide the \( \alpha - \beta \) plane into 96 triangular portions.
It is the task of the modulator (SVM) to determine which position the switches should assume (switching state) in the \((\alpha, \beta)\) plane, the duration needed (duty cycle) and the triangular area in which it is, in order to synthesize the reference voltage vector \(V_{\text{ref}}\) \([2], [6]\). The generalized algorithm being used to determine, for the hexagonal structure, the exact position of the vector of reference (detection of nearest three vectors and duty cycles computation) was developed and studied in detail in \([2], [5], [8]\) and \([13]\).

3. **PRINCIPLE AND MECHANISM OF TRAJECTORY AND SELECTION OF THE VECTORS OF STATE OF THE FIVE LEVELS INVERTERS**

3.1. Description

Figure 3 illustrates a subset of a five level space vector plot, and Table 1 summarises all possible sequences for this subset that achieve the required minimum of three switching transitions per phase leg in a switching period, i.e. if we locate the exact triangle where \(V_{\text{ref}}\) is located, limited by some sort three switching states \((s_1, s_2, s_3)\) in one switching intervals \(T_e\), then the sequence is given like continuation: \(s_1 s_2 s_3 s_1 s_3 s_2 s_1\) \([2], [10]-[12]\).

![Figure 3. Subset of 5 levels space vector diagram](image)

<table>
<thead>
<tr>
<th>Triangle</th>
<th>Sequences</th>
</tr>
</thead>
<tbody>
<tr>
<td>((a_1)+ (a_2))</td>
<td>({432 \text{ to } 431 \text{ to } 421 \text{ to } 321})</td>
</tr>
<tr>
<td></td>
<td>(a(i)) ({321 \text{ to } 421 \text{ to } 431 \text{ to } 432})</td>
</tr>
<tr>
<td></td>
<td>(a(ii)) ({321 \text{ to } 320 \text{ to } 310 \text{ to } 210})</td>
</tr>
<tr>
<td></td>
<td>(a(iii)) ({210 \text{ to } 310 \text{ to } 320 \text{ to } 321})</td>
</tr>
<tr>
<td></td>
<td>(a(iv)) ({431 \text{ to } 421 \text{ to } 321 \text{ to } 320})</td>
</tr>
<tr>
<td></td>
<td>(a(v)) ({320 \text{ to } 321 \text{ to } 421 \text{ to } 431})</td>
</tr>
<tr>
<td>((a_2))</td>
<td>(a(vii)) ({421 \text{ to } 321 \text{ to } 320 \text{ to } 310})</td>
</tr>
<tr>
<td></td>
<td>(a(viii)) ({310 \text{ to } 320 \text{ to } 321 \text{ to } 421})</td>
</tr>
<tr>
<td>((b))</td>
<td>(b(i)) ({421 \text{ to } 420 \text{ to } 410 \text{ to } 310})</td>
</tr>
<tr>
<td></td>
<td>(b(ii)) ({310 \text{ to } 410 \text{ to } 420 \text{ to } 421})</td>
</tr>
<tr>
<td>((c_1))</td>
<td>(c(i)) ({431 \text{ to } 421 \text{ to } 420 \text{ to } 320})</td>
</tr>
<tr>
<td></td>
<td>(c(ii)) ({320 \text{ to } 420 \text{ to } 421 \text{ to } 431})</td>
</tr>
<tr>
<td>((c_2))</td>
<td>(c(iii)) ({421 \text{ to } 420 \text{ to } 320 \text{ to } 310})</td>
</tr>
<tr>
<td></td>
<td>(c(iv)) ({310 \text{ to } 320 \text{ to } 420 \text{ to } 421})</td>
</tr>
<tr>
<td>((d))</td>
<td>(d(i)) ({431 \text{ to } 430 \text{ to } 420 \text{ to } 320})</td>
</tr>
<tr>
<td></td>
<td>(d(ii)) ({320 \text{ to } 420 \text{ to } 430 \text{ to } 431})</td>
</tr>
</tbody>
</table>
3.2. Synthesis of the reference vector

The best way to synthesize the voltage reference vector is by using the nearest three vectors \((V_1, V_2\) and \(V_3\)) and their duty cycles \((d_1, d_2\) and \(d_3\)) [2]:

\[
V_{\text{ref}} = d_1 \cdot V_1 + d_2 \cdot V_2 + d_3 \cdot V_3
\]  
(2)

With the additional constraint:

\[
d_1 + d_2 + d_3 = T_e
\]  
(3)

For example, for triangles (b) and (d), there are two possible sequences. For triangles (a) and (c) the correct sequence can be identified from the possible alternatives by ensuring that no extra switching transitions occur when moving between triangles. For example, sequence c(iii) (or c(iv)) should be used when moving from triangle (b) to (c) since it begins with the same state as the sequence in (b), or sequence c(i) (or c(ii)) should be used when moving from triangle (c) to (d) since it begins with the same state as the sequence in (d). Applying this principle to triangle (a) means that sequences a(i) to a(iv) cannot be used because they will introduce extra switching transitions when moving into triangle (c).

Table 2 shows two seven-segment switching sequences for \(V_{\text{ref}}\) falling into region (a2).

<table>
<thead>
<tr>
<th>Segments</th>
<th>Sequence 1</th>
<th>Sequence 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>1st</td>
<td>(V_1[310])</td>
<td>(V_1[421])</td>
</tr>
<tr>
<td>2nd</td>
<td>(V_2[320])</td>
<td>(V_2[321])</td>
</tr>
<tr>
<td>3rd</td>
<td>(V_3[321])</td>
<td>(V_3[320])</td>
</tr>
<tr>
<td>4th</td>
<td>(V_1[421])</td>
<td>(V_1[310])</td>
</tr>
<tr>
<td>5th</td>
<td>(V_2[321])</td>
<td>(V_2[320])</td>
</tr>
<tr>
<td>6th</td>
<td>(V_3[320])</td>
<td>(V_3[321])</td>
</tr>
<tr>
<td>7th</td>
<td>(V_1[310])</td>
<td>(V_1[421])</td>
</tr>
</tbody>
</table>

It is interesting to note that for sequence 1, the switching sequence of the three vectors, \(V_1, V_2\) and \(V_3\), in the first three segment rotates in a counter clockwise (CCW) direction in the space vector diagram shown in Figure 4, whereas for sequence 2, the switching sequence for these vectors rotating in a clockwise (CW) direction. These notations “+” and “-“ indicate the direction of the switching sequence rotation.

![Figure 4. The switching sequence rotation directions in region (a2)](image)

While basing itself on the sequence 1, the switching sequence for all the triangular regions is shown in Figure 5.
By carrying out the first simulation for:

- Input voltage $U = 311\text{Volts}$;
- The modulation index $r = 0.7$ and $r = 1.15$ for sampling frequency $f_e = 600\text{Hz}(m = 12)$ and $f_e = 650\text{Hz}(m = 13)$.

With $m = f_e / f_r$: $f_r$: fundamental frequency = 50Hz.

We obtain the results given in Figure 6. In the spectrum of output signal, the amplitude of fundamental is equal to 100%.

![Figure 6](image)

**Figure 6. Waveforms produced by the SVM sequence**
By analyzing the spectrum of the SVM signal on five levels, it is noted that it is made up, in addition to the fundamental one which is at the frequency \( f_0 \) and whose peak value is equal to \( rU \), components of harmonics gathered in families. However, the above discussed trajectory SVM produces even order harmonics for even values of \( m \) because of the no-symmetry of the output voltage.

To explain that, now consider the region (Figure 7) which is symmetrical by report to the origin with the area represented on Figure 3. When \( V_{ref} \) lies in regions (a2) and (a3) (which are 180° apart in space), the switching sequence and corresponding waveform of \( v_{ao} \) are shown in Figure 8.

![Figure 7. Vref in region (a3)](image)

![Figure 8. Switching sequence for Vref in region (a2) and (a3)](image)

To eliminate even order harmonics, the waveforms have to be of half-wave symmetry. Obviously, the waveforms shown in Figure 8 do not meet this condition, which indicates that it contains even order harmonics. This phenomenon can be more clearly demonstrated in Figure 6(a), where the inverter phase voltage \( v_{ao} \) for one cycle of the fundamental frequency is shown. None of the waveforms is half-wave symmetrical.

### 4. EVEN ORDER HARMONIC ELIMINATION (SECOND TRAJECTORY)

As discussed earlier, waveform with half-wave symmetry does not contain any even order harmonics. To achieve this, the switching sequence should be arranged such that the inverter phase voltage
generated by $V_{\text{ref}}$ in any two regions symmetrical to the origin of the space vector diagram should have mirror image.

Consider two regions $(a_2)$ and $(a_3)$, which are symmetrical to the origin of the space diagram. To make the waveform of $v_{ao}$ for $V_{\text{ref}}$ in region $(a_2)$ a mirror image of that for $V_{\text{ref}}$ in region $(a_3)$, the switching sequence of the three vectors, $V_1, V_2$ and $V_3$, should be changed from its original CCW to CW. The resultant waveform of $v_{ao}$ is shown in Figure 9, which becomes a mirror image of that shown in Figure 8(b).

It is worth noting that although the waveforms of $v_{ao}$ in Figure 9 and Figure 8(a) seems quite different, Figure 10 shows a new switching sequence arrangement, where the switching sequences, in some areas, are modified for even order harmonic elimination.

![Switching sequence](image1)

![Switching sequence](image2)

Figure 9. New switching sequence for $V_{\text{ref}}$ in region $(a_2)$

Figure 10. New switching sequence (second trajectory)

5. SIMULATION AND INTERPRETATION OF THE RESULTS

We made a simulation test for a five levels inverter supplying an asynchronous motor, for $(r=0.9, m=25)$, then for $(r=0.9, m=26)$. In the Figures 11 and 12, we have represented the output voltages $v_{ao}, v_{an}$ and its spectral analysis, the current $i_a$ and the speed.

The switch trigger signal $K_{11}$ is plotted in Figure 13.

For the trajectory 1 (Figure 11), we note that there is no symmetry of simple voltage $v_{ao}$ in half-wave for even values of $m$, thus, in addition to the odd harmonics, the voltage contains both even order harmonics. In addition, the harmonic spectre shows that all the even order harmonics are eliminated for odd $m$, and gather in family centered around the multiple frequencies of $m \cdot f_r$.

For the trajectory 2 (Figure 12), we note that there is no symmetry of simple voltage $v_{ao}$ in half-wave for odd values of $m$, thus, in addition to the odd harmonics, the voltage contains both even order harmonics. In addition, the harmonic spectre shows that all the even order harmonics are eliminated for even $m$, and gather in family centered around the multiple frequencies of $m \cdot f_r$.

This is understandable since the switching pattern generation mechanism, including the selection of the stationary vectors and dwell time calculations, is the same for both trajectories. The only difference is that some of the switching sequences are rearranged for the new trajectory.
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Figure 11. Simulation results on 5 levels inverter ordered by the SVM (trajectory 1)

Figure 12. Simulation results on 5 levels inverter ordered by the SVM (trajectory 2)
It should be pointed out that the device switching frequency of the SVM trajectory 2 is slightly higher than that of the trajectory 1 for a given sampling frequency data corresponding to \( m \) odd. However, the device switching frequency of the SVM trajectory 1 is slightly higher than that of the trajectory 2 for a given sampling frequency data corresponding to even \( m \) (Figure 13).

![SVM Trajectory 1, m=25](image1)

![SVM Trajectory 1, m=26](image2)

![SVM Trajectory 2, m=25](image3)

![SVM Trajectory 2, m=26](image4)

Figure 13. Signals waveforms of the switch attack K11 for the inverter on five levels

6. CONCLUSION

Two space vector modulation trajectories are proposed for five levels cascaded inverters. The main feature lies in its ability to eliminate even order harmonics in the inverter output voltage of the modulation trajectory 1 for even \( m \) and of the modulation trajectory 2 for odd \( m \).

Considering the similar form of the hexagonal structure of the SVM for the multilevel inverters, we thus can carry out an algorithm which uses either trajectory 1 or trajectory 2, according to the value of \( m \), so as to obtain output signals which contain only odd harmonics, and this for any levels of voltage.

The advantage of the SVM technique is that all the even order harmonics can be eliminated. This is favorable in the industry applications.

REFERENCES


BIOGRAPHIES OF AUTHORS

Mohammed Yaichi was born on 1980 in Adrar, Algeria. He received the engineer degree in electrical engineering from the the University of Bechar, Bechar, Algeria, in 2003. And the magister degree from Djillali Liabes University, Sidi-Bel-Abbes, Algeria in 2006. He is currently working toward the doctorate degree in the Power Electronics, and the Photovoltaic Pumping System, Djillali Liabes University of Sidi-Bel-Abbes, Algeria. Since 2009, he is with the Photovoltaic Pumping Team, Research Unit in Renewable Energies in The Saharan Medium (URER/MS) Adrar, Algeria. His research interests include a study on performance improvement of a stand-alone photovoltaic pumping system, variable-speed AC motor drives, and different multilevel inverter circuit topologies thus its technique of control PWM.

Mohammed-Karim Fellah was born in Oran, Algeria, in 1963. He received the Eng. degree in Electrical Engineering from University of Sciences and Technology, Oran, Algeria, in 1986, and The Ph.D. degree from National Polytechnic Institute of Lorraine (Nancy, France) in 1991. Since 1992, he is Professor at the University of Sidi Bel-Abbes (Algeria) and Member of the Intelligent Control and Electrical Power. His current research interest includes Power Electronics, HVDC links, and Drives.