A Simplified SVM method for multilevel cascade H-bridge inverter with Reducing computation time for photovoltaic application

M. NEJADMURI¹, Gh.SEIFOSSADAT², M. Seyed MOOSAVI³

¹,³Department of Engineering, Khuzestan Science and Research Branch, Islamic Azad University, Ahvaz, Iran
²Department of Engineering, Ahvaz Branch, Islamic Azad University, Ahvaz, Iran

Abstract. In the area of photovoltaic application of multilevel cascade H-bridge inverters (CHB) has been widely used recently. In this paper a new procedure for space vector modulation has been proposed which significantly reduces amount of mathematical calculation. The proposed procedure is simplified and considerably overcomes a number of problems as a result of complex equation for finding appropriate vectors. This technique does not reduce the output voltage qualifications and efforts involved in selecting suitable vectors of a seven level inverter. New proposed SVM scheme is discussed and detailed that simulation results are provided for a seven level inverter with 1kW and 220V nominal value. The value of the proposed technique is demonstrated experimentally by applying the novel SVM approach to a conventional multilevel inverter.

Keywords: Photovoltaic, multilevel inverter, SVM technique, cascade H-bridge, total harmonic distortion

1. INTRODUCTION

Recently a multi-level inverter has started to demand higher power equipment. A photovoltaic inverter in megawatt range power is commonly connected to a grid with approximately high level voltage such as 220, 20Kv or further, while the DC side is feeds on a low level DC voltage from PV panels. For this reasons, high level inverters have emerged a solution to problem of working with high level voltage [1-6]. Moreover, the higher level inverter reduce harmonic content in the output voltage, lower switching stress throughout the semiconductors, lower devices ratings, reduce switching frequency and so on. There are a lot of power structures for multilevel inverters that CHB provides more benefits when decoupled DC power source is accessible [6-13]. Main configuration of CHB inverters has been shown in Fig.1. Harmonic content is one of the most important aspects of these inverters. The amount of harmonics, introduced to the network, is lesser as compared with those of common inverters because of the staircase waveform of multilevel inverters. However, some studies have concentrated on proposing an effective technique to reduce harmonic contents further, and as a result, different methods have emerged: the selective harmonic elimination pulse width-modulation (SHE PWM) technique [14] and the optimal minimization of the total harmonic distortion (OMTHD) [17]. Resultant theory has been analytically used to find all the solutions in the SHE PWM technique [14-22]. There are a number of other modulation procedures which are mainly used to achieve a suitable output voltage with minimum THD (Total Harmonic Distortion). However, the SVM scheme provides more fundamental output voltage as compared with SPWM, provides flexibility in optimizing the switching pattern design and is more convenient for implementation as a result of recent progress in microprocessors, so flexibility of SVM causes it to become more popular for industrial applications [1,16,23].
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All of the possible vectors for a seven level CHB inverter is shown in Fig. 2. There are 7 different kinds of levels for each phase are \(+3V_{dc}\), \(+2V_{dc}\), \(+V_{dc}\), \(0\), \(-V_{dc}\), \(-2V_{dc}\), \(-3V_{dc}\). It can be easily estimated that possible vectors are \(7^3\), but there are just 127 independent vectors. \(P_i\) and \(N_i\) in Fig 2 represent the fact that corresponding phase has \(i\) bridges with \(+V_{dc}\) or \(-V_{dc}\) output voltage respectively. In addition, \(O\) in some points indicates that current phase has neutral voltage. In this paper a novel method for finding suitable vector corresponding to given reference has been proposed that amount of mathematic calculation would be significantly declined. Regarding to this fact that output references for fixed output voltage applications such as photovoltaic inverter are on the limited area of space vector diagram (SVD), several possible vectors are not applied at all. For this reasons, only 66 triangles in boundary area of SVD are more important than other. The proposed method is described definitely for a seven-level CHB inverter; it can easily be extended for higher level inverter. One of the most important advantages of this technique is that time for calculation has been considerably decreased that this is a vital item for implementation with recent high-tech microprocessors. Moreover, a switching pattern is used that causes inverter to have minimum switching without reduction in output voltage qualification as well as output current [1,23,26]. Simulation results for both SPWM and the proposed procedure for selecting suitable vector involved in SVM control are compared with each other throughout this paper.

Figure 1. Conventional seven level cascade H-bridge inverter.

2. EXPLANATION OF THE PROPOSED METHOD FOR SVM TECHNIQUE

The proposed technique is based on the concept of dividing the Space Vector Diagram into a number of hexagons which are just two-level and the same strategy for finding suitable vector in two-level inverters is utilized [15,16,19]. The Space Vector Diagram of a seven-level inverter is shown in Fig. 2. This Space Vector Diagram can initially be resolved into 30 two-level hexagons as shown in Fig. 4.[27]. In grid connected inverter, the range of output voltage variation is restricted and the reference vector is in the last level of triangles because variation of the grid is approximately fixed. The reference vector is commonly located throughout the mentioned triangles in Fig.3. The center of the first two-level hexagon lies along the \(0^\circ\)-axis. The center of each subsequent hexagon is shifted by \(12^\circ\). As seen in this figure, there exists a significant overlap between the adjacent hexagons. To provide selectivity between the hexagons, the appropriate hexagon is selected depending upon the angle \(\theta\) of the original reference vector \(V_{ref}\).
As shown in Table 1. When a two-level hexagon is selected, a new reference vector $V_{\text{ref}2}$ is generated such that it originates at the center of the two-level hexagon, whereas its tip coincides with the tip of $V_{\text{ref}}$. Consider the case where the tip of $V_{\text{ref}}$ lines in hexagon I, as shown in Fig. 5. The vector $V_{\text{ref}2}$ is related with $V_{\text{ref}}$ as per the following relations:

$$V_{\text{ref}2} = V_{\text{ref}} - 10V_{\text{dc}}/3 \quad (1)$$

$$V_{\text{Im2}} = V_{\text{Im}} \quad (2)$$

Where $V_{\text{ref}}, V_{\text{Im}}, V_{\text{ref}2}, V_{\text{Im2}}$ are the components of $V_{\text{ref}}$ and $V_{\text{ref}2}$ along the $\alpha$ (real) and $\beta$ (imaginary) axes, respectively in Eq.3. The computation of $V_{\text{ref}2}$ for all the 30two-level hexagons is described in Table 1. Generation of the vector $V_{\text{ref}2}$ reduces the problem of the seven-level SVM to the two-level SVM of six identical hexagons. The vector $V_{\text{ref}2}$ for each of the 30 hexagons has a modulation index ranging from zero to unity, and an angle $\theta_2$ ranging from zero to $2\pi$. Also, the angle $\theta_2$ for each of the 30 hexagons has its reference along the horizontal axis, hence, it may be assumed.
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\[
\begin{bmatrix}
V_\alpha \\
V_\beta
\end{bmatrix} = \frac{2}{3} \begin{bmatrix}
1 & -1 & -1 \\
\frac{2}{\sqrt{3}} & \frac{\sqrt{3}}{2} & \frac{\sqrt{3}}{2}
\end{bmatrix} \begin{bmatrix}
V_{A0} \\
V_{B0} \\
V_{C0}
\end{bmatrix}
\]

(3)

that any two-level hexagon selected is mapped along the two-level hexagon I shown in Fig. 4.

![Figure 3. Location of reference vector for grid tie inverter.](image)

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3. Adjusting appropriate time for each vector

The application of the SVM scheme is based on the fact that there are only two independent variables in a three-phase voltage system. We can use orthogonal coordinates to represent the three-phase voltage in the phasor diagram [23]. A three-phase voltage vector may be represented as two vectors. In the SVM scheme, the three phase output voltage is represented by a reference vector, which, rotates at an angular speed of \(\omega = 2\pi f\). The task of SVM is to use the combinations of switching states to approximate the locus of \(V_{ref}[23-24]\).

<table>
<thead>
<tr>
<th>Two level hexagon</th>
<th>Angle of (\theta)</th>
</tr>
</thead>
<tbody>
<tr>
<td>OH1</td>
<td>-6 to +6</td>
</tr>
<tr>
<td>OH2</td>
<td>+6 to +18</td>
</tr>
<tr>
<td>OH3</td>
<td>+18 to +30</td>
</tr>
<tr>
<td>OH4</td>
<td>+30 to +42</td>
</tr>
<tr>
<td>OH5</td>
<td>+42 to +54</td>
</tr>
<tr>
<td>OH6</td>
<td>+54 to +66</td>
</tr>
<tr>
<td>OH7</td>
<td>+66 to +78</td>
</tr>
<tr>
<td>OH8</td>
<td>+78 to +90</td>
</tr>
<tr>
<td>OH9</td>
<td>+90 to +102</td>
</tr>
<tr>
<td>OH10</td>
<td>+102 to +114</td>
</tr>
<tr>
<td>OH11</td>
<td>+114 to +126</td>
</tr>
<tr>
<td>OH12</td>
<td>+126 to +138</td>
</tr>
<tr>
<td>OH13</td>
<td>+138 to +150</td>
</tr>
<tr>
<td>OH14</td>
<td>+150 to +162</td>
</tr>
<tr>
<td>OH15</td>
<td>+162 to +174</td>
</tr>
<tr>
<td>OH16</td>
<td>+174 to -174</td>
</tr>
<tr>
<td>OH17</td>
<td>-174 to -162</td>
</tr>
<tr>
<td>OH18</td>
<td>-162 to -150</td>
</tr>
</tbody>
</table>
These vectors \((V_1 \sim V_6)\) can be used to frame the vector plane, which is illustrated in Fig.6. The rotating reference vector can be approximated in each switching cycle by switching between the adjacent active vectors and the zero vectors. In order to maintain the effective switching frequency at a minimal value, the sequence of the toggling between these vectors is organized in such a way that only one leg is affected in every step. For a given magnitude and position \(V_{\text{ref}}\), can be synthesized by three nearby stationary vectors, based on which, the switching states of the inverter can be selected and the gate signals for the active switches can be generated. When \(V_{\text{ref}}\), passes through sectors one by one, different sets of switches will be turned on and off. As a result, when \(V_{\text{ref}}\), rotates one revolution in space, the inverter output voltage varies one cycle over time. Three stationary vectors can synthesize the reference \(V_{\text{ref}}\). The dwell time for the stationary vectors essentially represents the duty-cycle time (on-state or off-state time) of the chosen switches during a sampling period \(T_s\) of the modulation scheme. The dwell time calculation is based on the ‘volt-second balancing’ principle, that is, the product of the reference voltage \(V_{\text{ref}}\) and sampling period \(T_s\) equals the sum of the voltage multiplied by the time interval of chosen space vectors. For example, when \(V_{\text{ref}}\) falls into sector I as shown in Fig. 6, it can be synthesized by \(V_1\), \(V_2\) and \(V_0\). The volt second balance equation is:

\[
V_{\text{ref}} T_s = V_1 T_a + V_2 T_b + V_0 T_0
\]

(4)

\[
T_s = T_a + T_b + T_c
\]

(5)

Consider the case where the two-level hexagon OH1 of the two-level hexagon I is selected, and the vector \(V_{\text{ref}}\) lies in sector I of the hexagon OH1, as shown in Fig. 6. The vector \(P_1N_2N_3\) can now be considered as an active vector \(V_1\), \(P_1N_2N_3\) as an active vector \(V_2\) and either of the vectors \(P_2N_2N_2\) or \(P_2N_3N_3\) as a zero vector \(V_0\). The volt-second-balancing equation for this sector is then given by Eq.4.

Where \(T_s\) is the sampling interval in Eq.5.; and \(T_a\), \(T_b\), \(T_0\) are the respective dwell times for the vectors \(V_1\), \(V_2\) and \(V_0\). The values of \(T_a\), \(T_b\) and \(T_0\) in sector I are given in:

\[
T_a = T_s \times m_a \times \sin \left( \frac{\pi}{3} - \theta_2 \right)
\]

(6)

\[
T_b = T_s \times m_a \times \sin(\theta_2)
\]

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\[ T_0 = T_s - T_a - T_b \]  
(8)

Figure 4. 30 two level Hexagonal.

Where \( m_a \) is the modulation index defined as:

\[ m_a = \frac{\sqrt{3} \times V_{\text{ref2}}}{V_{dc}} \]  
(9)

The next step is to design an appropriate switching sequence. The typical seven-segment switching sequence is used in this scheme. The switching sequence should be so designed that the change from one switching state to the next should involve only one inverter leg; and the change from one sector to the next should involve zero or minimum number of switching. With these considerations, the seven-segment switching sequence for the vector \( V_{\text{ref2}} \) in sector I of Fig. 6 is chosen as, \((P_3N_3N_3), (P_3N_2N_3)\). The switching sequence for \( V_{\text{ref2}} \) in sector II is chosen as, \((P_2N_3N_3)/(P_3N_2N_2), (P_3N_2N_3)\) and \((P_3N_1N_2)/(P_2N_2N_3)\).

Figure 5. Two-level hexagon I.
4. SYMMETRICAL SEGMENET SPACE VECTRO PRUDUCTION

The sector judgment and appropriated time of the possible vector for all SVM strategies are identical for all sectors. There are different procedures for adjusting enough time for null vector whose selection determined the SVM switching pattern. Two different kinds of vector provide null in the output of the two-level inverter ($V_0 = P_3N_2N_2, V_0 = P_2N_3N_3$). Therefore, null vector is created with different ways. It is mainly conventional to alternate these three ways in each switching cycle and to reverse priority after each null cycle. This will be referred to as the symmetric 7-segment technique [1,7,26]. Fig. 7 shows conventional 7-segment switching sequences of sector I. It is shown that the sequence $V_0 - V_1 - V_2 - V_0$ is used in the first $\frac{T_s}{2}$, and the sequence $V_0 - V_2 - V_1 - V_0$ is used in the second $\frac{T_s}{2}$. The sequences are symmetrical. The switching frequency is the same as sampling frequency of the inverter.

Figure 6. Switching vectors hexagon.

Figure 7. Suitable segment for achieving a $V_{ref2}$ adjusted in sector I.
The following sequence has been carried out for Matlab simulation of the system:

- Firstly 3 phase input voltage has been calculated in $F_{cn}$ and $V_\alpha$ and $V_\beta$ drive from amount of voltage in abc.
- Next step is calculation of $V_\alpha$ and $V_\beta$ (Magnitude and Angle).
- After that Calculation $V_{ref}$ and alpha (Polar to Rectangle block is used. The inputs to this block are $V_\alpha$ and $V_\beta$ and outputs of this block are $V_{ref}$ and alpha.)
- Appropriate hexagonal has been achieved from procedure which is described in section 3 of this paper.
- Calculation of $T_a$, $T_b$, $T_0$
- Calculation of sector value
- Calculation cumulative sum of $T_a$, $T_b$, $T_0$
- Calculation of $T_n$
- Determination of switching states
- Realization of switching states
- Derivation of 6 individual gate pulses to two level inverter

5. SIMULATION RESULT

In this section simulation results for the proposed SVM procedure for a seven level CHB inverter with a variation of $m_a$ has been illustrated. To validate the benefits of this technique, the results are compared with those obtained using SPWM and other schemes that recently have been mentioned in papers [25-27]. For all these schemes, $F_s$ is taken as 12 kHz. List of elements which is used for simulation has been shown in Table 2. Fig. 8 shows the output voltage waveforms before output LC filter for phase voltage in no load condition. It can be seen from the Fig.8(b) that the 3th harmonic has considerable magnitude in Phase voltage that would be eliminated in line-line output voltage and as a consequence there are a significant decrease in amount of THD.

**Table 2.** List of elements which has been used for simulation in Matlab.

<table>
<thead>
<tr>
<th>Item</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inductance of output filter</td>
<td>300 uH</td>
</tr>
<tr>
<td>Capacitor of output filter</td>
<td>50 uF</td>
</tr>
<tr>
<td>H-bridge DC supply voltage</td>
<td>100 V</td>
</tr>
<tr>
<td>Output voltage frequency</td>
<td>50Hz</td>
</tr>
<tr>
<td>Switching frequency</td>
<td>12kHz</td>
</tr>
<tr>
<td>Three phase resistive load</td>
<td>100 Ohm</td>
</tr>
</tbody>
</table>
Figure 8. Output voltage with no load condition before output filter, a) Phase output voltage b) FFT analysis of output voltage
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Figure 9. Output voltage with no load condition before output filter, a) line-line output voltage b) FFT analysis of output voltage.

Figure 9. Shows the output line voltage before the LC filter in No load condition. Moreover, according to Fig. 9(b), it is obvious that magnitude of 3th harmonics has decreased considerably and THD of output voltage is 10.72%.

Fig. 10 demonstrates the output line-line voltage of three phase inverter with SPWM control strategy that increases amount of THD by 4% compared to the SVM control strategy. For mentioning the inverter operation under full load condition simulation result has been introduced in Fig. 11. A 1Kw induction motor with 0.9 power factor is load used for testing the inverter in full load condition. Amount of THD in this condition steadily reduce in comparison with without filter condition this is because of the fact that induction motor is the same as a filter and causes THD to decline.

Table 3 demonstrates line voltage THD and the peak magnitude of the fundamental component at various values of $m_a$. 

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Figure 10. Output voltage with no load condition before output filter in SPWM control strategy, a) line-line output voltage b) FFT analysis of output voltage.
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Figure 11. Output voltage with full load condition after output filter In SVM control strategy, a) line-line output voltage b) FFT analysis of output voltage.

These results show in Table 3. the proposed techniques compare with the established SPWM.

<table>
<thead>
<tr>
<th>Modulation Technique</th>
<th>SPWM</th>
<th>SVM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ma=1</td>
<td>13.4</td>
<td>10.72</td>
</tr>
<tr>
<td>Ma=0.8</td>
<td>15.94</td>
<td>13.33</td>
</tr>
<tr>
<td>Ma=0.6</td>
<td>20.2</td>
<td>17.26</td>
</tr>
<tr>
<td>Ma=0.4</td>
<td>30.94</td>
<td>25.55</td>
</tr>
<tr>
<td>Ma=0.2</td>
<td>43.8</td>
<td>49.13</td>
</tr>
<tr>
<td>Ma=0.1</td>
<td>42.57</td>
<td>59.6</td>
</tr>
</tbody>
</table>
6. CONCLUSION

A new SVM technique has been presented in this paper which simplifies the SVM of multilevel inverters. It is based on resolving the multilevel inverter SVD into appropriate two-level hexagons. The technique is perfectly general and can be applied to the SVM of all three principal topologies of multilevel converters for any number of levels. The advantage of applying this technique increases as the number of levels increases. This technique brings the complexity and effort required for the SVM of a seven-level inverter. Specifically, the SVM technique reduces the seven-level SVM to solve a problem of two levels SVM with 78 different hexagons.

Simulation results have been presented with both the techniques for a seven-level CHB inverter. The results are compared. They prove the validity of these techniques for different values of the modulation index. Switching pattern is used that causes inverter to have minimum switching without reduction in output voltage qualification as well as output current. The use of these techniques significantly reduces the complexity and efforts involved in the SVM of higher level inverters.

7. REFERENCES

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