Space Vector Modulation Technique for 3-Level NPC Converter with Constant Switching Frequency

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Abstract

This paper presents a simple Space Vector Modulation (SVM) methodology for a three-level NPC converter. Nearest three vectors (NTV) and corresponding duty cycles are deduced through simple generic mathematical expressions. Extra degrees of freedom of NPC converter are used to fully benefit from SVM advantages and to control the switching frequency. Simulation and experimental results are presented and discussed to validate the proposed methodology.

1. Introduction

Power conversion investigation attracted attention particularly in Medium Voltage/High Power ranges [1, 2]. During the three last decades, advancements in power electronics fields have led to innovative converter topologies, called multilevel converters [3, 4]. In fact, compared to classical two-level converters, multilevel converters are an attractive solution since they support higher operation voltages, reduce common mode voltages, minimize output current and voltage distortions, and optimize output filter size and cost. One of the most widely used and investigated multilevel topologies is the neutral point clamped converter. This topology was firstly introduced by Richard Baker in the early eighties [5]. Later on, several converters based on the NPC were proposed such as the Active NPC [6–9] and the Optimized NPC [10–12]. These converters are classified as the Diode Clamped Converters [13]. The three-phase \( N \)-level NPC converter uses \( (N−1) \) series-connected capacitors to divide the DC bus into a set of intermediary voltage levels as presented in Figure 1.

Simultaneously, classical modulation algorithms proposed for two-level converters such as Pulse Width Modulation (PWM) [14], hysteresis current control [15], and selective harmonic elimination [16] have been extended to multilevel topologies. Among the proposed algorithms, the Space Vector Modulation (SVM) is the most widely used due to its better utilization of the DC bus [9] and higher harmonic performances in linear and nonlinear operating zones [17, 18] compared to conventional PWM strategies. Detecting the nearest three vectors (NTV) among the numerous available ones, selecting and fully defining the corresponding switches duty cycles with respect to possible additional criteria are the main issues of SVM technique in multilevel converter context.

In this paper, a simple approach for a 3-level Space Vector Modulation technique available for the NPC converter is presented. In the proposed method, the nearest three vectors and their corresponding on-times application are simply expressed using generic mathematical expressions. The choice of the Phase Level Sequence (PLS) is used as
an extra degree of freedom in order to control the switching frequency. Simulation and experimental results are presented to verify the effectiveness of the proposed SVM strategy.

2. NPC Converter and Space Vector Modulation (SVM)

2.1. Neutral Point Clamped Converter. One phase of an n-level neutral point clamped inverter consists of \((n - 1)\) capacitors, \(6 \times (n - 1)\) power switches, and \(6 \times (n - 2)\) clamping diodes and is able to generate \((n - 2)\) capacitive midpoints. The output voltage \(V_s\) is equal to the voltage of the capacitive midpoint connected to it. Hence, \(V_s\) can take \((n - 2)\) values as \(V_{dc} \cdot n - 1, 2V_{dc} \cdot n - 1, \ldots, (n - 2)V_{dc} \cdot n - 1\).

\[
\frac{V_{dc}}{n - 1} \cdot \frac{2V_{dc}}{n - 1} \cdot \ldots \cdot \frac{(n - 2)V_{dc}}{n - 1}.
\]

In order to generate the output voltage \(V_s\), the IGBTs \(T_1\) to \(T_k\) and \(T_{k+1}\) to \(T_{n-1}\) must be ON. The current is then flowing from the diodes \(D_k\) through the switches \(T_1\) to \(T_k\) to the output \(V_s\). It is to note that any other configuration is not permitted and each voltage level is realized by an only one configuration \([19,20]\).

Hence, \(V_s\) can take \((n - 2)\) values as

\[
\frac{V_{dc}}{n - 1} \cdot \frac{2V_{dc}}{n - 1} \cdot \ldots \cdot \frac{(n - 2)V_{dc}}{n - 1}.
\]

2.2. Space Vector Modulation (SVM). For a three-phase two-level converter, the aim of the Space Vector Modulation is to select the appropriate space vectors to apply and their respective application times \([21,22]\). Given a voltage reference \(V^*_s\), the SVM strategy selects the two nearest active vectors \((V_k, V_{k+1})\) and the zero vectors \((0,0,0)\) and \((1,1,1)\) as shown in Figure 4(a). The application times for these 4 vectors are calculated using the volt-second balance as

\[
T_{k+1}V_{k+1} + T_kV_k + (T_{SVM} - (T_{k+1} + T_k)) \cdot V_0 = T_{SVM} \cdot V^*_s,
\]

where \(V_k, V_{k+1}\), and \(V_0\) are space vectors, \(T_k\) and \(T_{k+1}\) are the application times corresponding to \(V_k\) and \(V_{k+1}\), respectively, and \(T_{SVM}\) is the SVM period. \(T_{SVM} = (T_{k+1} + T_k)\) is the application time of zero voltages: during the first half of this time slot \((0,0,0)\) is applied and during the second half \((1,1,1)\) is applied if symmetrical SVPWM technique is used.
Compared to conventional PWM strategies, the Space Vector Modulation leads to better dynamic performances and a higher modulation index even if the calculation complexity is comparatively increased.

For an $n$-level converter, the increased number of space vectors and switching states further enhances the dynamic performances but needs additional calculation capabilities and introduces considerable implementation complexity.

In this paper, a simple approach to implement a three-level SVM algorithm using mathematical analysis of the obtained $(\alpha, \beta)$ frame is proposed. Active vectors to be applied, switching states, and IGBT on-times calculation are easily deduced using the proposed method.

3. Proposed Algorithm

Figure 5 shows the block diagram of the proposed method, where the main task of each step is written in bold and criterion for each task is written in italic in the neighboring box.

3.1. Step 1: Localization of $V_s^*$. The aim of $V_s^*$ Localization block is to identify the appropriate three vectors $V_i$, $i = 1, 2, 3$, to apply and consequently their corresponding PLS in order to generate an output voltage with a mean value on the switching period equal to the reference voltage. The space vectors needed for the SVM are the nearest three vectors to $V_s^*$.

In order to localize the reference voltage vector, its module and phase, noted, respectively, as $\|V_s^*\|$ and $\theta_s$, are used. They are calculated using basic $(abc-\alpha\beta)$ transformation.

The $(\alpha, \beta)$ frame is divided into 6 sectors and 4 quadrants according to Figure 6. This sectorization represents the first step to deduce to which triangle (among the available 24 ones) the reference voltage vector belongs. Once this triangle selected, a lookup table gives the three nearest voltage vectors the inverter must generate.

Dependong on the modulation depth $m$, specific triangles are used: if $0 < m < 0.75$, space vector $V_s$ crosses triangles $T_1$, $T_5$, $T_9$, $T_{13}$, $T_{17}$, and $T_{21}$ and if $0.75 < m < 1.15$, the remaining triangles ($T_2$, $T_3$, $T_4$, $T_6$, $T_7$, $T_8$, $T_{10}$, $T_{11}$, $T_{12}$, $T_{14}$, $T_{15}$, $T_{16}$, $T_{18}$, $T_{19}$, $T_{20}$, $T_{22}$, $T_{23}$, and $T_{24}$) are used. It is to be noted that the modulation index $m = \frac{\|V_s^*\|}{V_{dc}}$ and the maximum modulation index $m = 1.15$ is obtained when $\|V_s^*\| = V_{dc}/\sqrt{3}$.
3.2. Step 2: Primary ON-Times Calculation. The “Primary ON-Times Calculation” block aims to determine the on-time for each of the three vectors $V_i$, $i = 1, 2, 3$, that is, the activation time over switching period $T_{SVM}$. Step 2 outputs are as follows:

(i) The corresponding on-time $T_i$, $i = 1, \ldots, 3$, for the three needed vectors the converter has to perform on the next $T_{SVM}$.

These vectors $V_i$, $i = 1, \ldots, 3$, correspond to the localized triangle’s vertices.

(ii) The PLS leading to the specified space vectors. The PLS choice affects the converter switching frequency.

To perform a rigorous on-times calculation, fine modeling of the three-level converter voltage vectors is needed. The proposed algorithm divides the 24 triangles among 4 families given by Figure 7. In fact, the 3 vectors of all the triangles belonging to the same family can be expressed using a unique generic form. Thus, on times are deduced as generic forms depending on the selected family.
3.2.1. \( V_i \) Generic Expressions. Family 1 is formed by triangles 1, 5, 9, 13, 17, and 21 as shown in Figure 8. \( V_1 \), \( V_2 \), and \( V_3 \) are represented for each triangle belonging to this family and their expressions are

\[
V_1 = \frac{V_{dc}}{3} e^{j(k-1)(\pi/3)} = \frac{V_{dc}}{3} \left( \cos \left( k - 1 \right) \frac{\pi}{3} \right),
\]

\[
V_2 = \frac{2V_{dc}}{3} e^{j(k)(\pi/3)} = \frac{2V_{dc}}{3} \left( \cos \left( k \right) \frac{\pi}{3} \right),
\]

\[
V_3 = \frac{V_{dc}}{\sqrt{3}} e^{j(k)(\pi/3)} = \frac{V_{dc}}{\sqrt{3}} \left( \cos \left( k - 0.5 \right) \frac{\pi}{3} \right),
\]

where \( k \) is the sector’s index corresponding to each triangle.

Family 2 is formed by triangles 2, 6, 10, 14, 18, and 22, as shown in Figure 9. \( V_1 \), \( V_2 \), and \( V_3 \) corresponding to this family are given by

\[
V_1 = \frac{V_{dc}}{3} e^{j(k-1)(\pi/3)} = \frac{V_{dc}}{3} \left( \cos \left( k - 1 \right) \frac{\pi}{3} \right),
\]

\[
V_2 = \frac{2V_{dc}}{3} e^{j(k)(\pi/3)} = \frac{2V_{dc}}{3} \left( \cos \left( k \right) \frac{\pi}{3} \right),
\]

\[
V_3 = \frac{V_{dc}}{\sqrt{3}} e^{j(k)(\pi/3)} = \frac{V_{dc}}{\sqrt{3}} \left( \cos \left( k - 0.5 \right) \frac{\pi}{3} \right).
\]

Family 3 is formed by triangles 3, 7, 11, 15, 19, and 23 as shown in Figure 10, and associated space vectors are given by

\[
V_1 = \frac{V_{dc}}{3} e^{j(k-1)(\pi/3)} = \frac{V_{dc}}{3} \left( \cos \left( k - 1 \right) \frac{\pi}{3} \right),
\]

\[
V_2 = \frac{2V_{dc}}{3} e^{j(k)(\pi/3)} = \frac{2V_{dc}}{3} \left( \cos \left( k \right) \frac{\pi}{3} \right),
\]

\[
V_3 = \frac{V_{dc}}{\sqrt{3}} e^{j(k)(\pi/3)} = \frac{V_{dc}}{\sqrt{3}} \left( \cos \left( k - 0.5 \right) \frac{\pi}{3} \right).
\]

The remaining triangles labeled 4, 8, 12, 16, 20, and 24 form family 4, as shown in Figure 11.
Family 4 $V_i$ expressions are

\[
V_1 = \frac{V_{dc}}{3} e^{j(k\pi/3)} = \frac{V_{dc}}{3} \left( \cos k\frac{\pi}{3} \right), \\
V_2 = \frac{2V_{dc}}{3} e^{j(k\pi/3)} = \frac{2V_{dc}}{3} \left( \cos k\frac{\pi}{3} \right), \\
V_3 = \frac{V_{dc}}{\sqrt{3}} e^{j(k-0.5)(\pi/3)} = \frac{V_{dc}}{\sqrt{3}} \left( \cos (k-0.5)\frac{\pi}{3} \right). 
\] (6)

3.2.2. $T_i$ Calculation. $T_i$ correspond to the application time of $V_i$, $i = 1, 2, 3$. They are the solutions of the three-level volt-second balance given by

\[
T_1 \cdot V_1 + T_2 \cdot V_2 + T_3 \cdot V_3 = T_{SVM} \cdot V_s^* 
\] (7)

and verifying

\[
T_1 + T_2 + T_3 = T_{SVM}. 
\] (8)

The resolution of (7) and (8) for given $V_1$, $V_2$, and $V_3$ can lead to a potentially complex calculation. But, thanks to the proposed families repartition described above, $T_i$ calculation can be easily performed. As an example, we detail this step for family 2.

The substitution of (4) in (7) leads to

\[
T_{SVM} \cdot V_s^* \left( \begin{array}{c}
\cos \theta_s \\
\sin \theta_s 
\end{array} \right) = \left[ \begin{array}{c}
\frac{V_{dc}}{3} \left( \cos (k-1)\frac{\pi}{3} \right) \\
\frac{V_{dc}}{\sqrt{3}} \left( \cos (k-0.5)\frac{\pi}{3} \right) \\
\frac{2V_{dc}}{3} \left( \sin (k-1)\frac{\pi}{3} \right) \\
\frac{V_{dc}}{3} \left( \sin (k-0.5)\frac{\pi}{3} \right) \\
\end{array} \right] \cdot T_i 
+ \frac{2V_{dc}}{3} \left( \cos (k-1)\frac{\pi}{3} \right) \cdot T_2 \\
+ \frac{V_{dc}}{\sqrt{3}} \left( \cos (k-0.5)\frac{\pi}{3} \right) \cdot T_3 
\] (9)

Consequently,

\[
\left( \begin{array}{c}
\cos \theta_s \\
\sin \theta_s 
\end{array} \right) = \frac{V_{dc}}{3T_{SVM} \cdot V_s^*} \cdot B \cdot \left( T_1 + 2T_2 \right) \left( \sqrt{3} \cdot T_3 \right), 
\] (10)

where

\[
B = \left( \begin{array}{c}
\cos(k-1)\frac{\pi}{3} & \cos(k-0.5)\frac{\pi}{3} \\
\sin(k-1)\frac{\pi}{3} & \sin(k-0.5)\frac{\pi}{3} 
\end{array} \right), \\
B^{-1} = 2 \cdot \left( \begin{array}{c}
\sin(k-0.5)\frac{\pi}{3} & -\cos(k-0.5)\frac{\pi}{3} \\
-\sin(k-1)\frac{\pi}{3} & \cos(k-1)\frac{\pi}{3} 
\end{array} \right). 
\] (11)

From (10) and (11) it can be deduced that

\[
T_1 + 2T_2 = \frac{6T_{SVM} \cdot V_{sm}}{V_{dc}} \left[ \sin \left( (k-0.5)\frac{\pi}{3} \right) \cos \theta_s \\
- \cos \left( (k-0.5)\frac{\pi}{3} \right) \sin \theta_s \right], \\
T_3 = \frac{2\sqrt{3}T_{SVM} \cdot V_{sm}}{V_{dc}} \left[ \cos \left( (k-1)\frac{\pi}{3} \right) \sin \theta_s \\
- \sin \left( (k-1)\frac{\pi}{3} \right) \cos \theta_s \right]. 
\] (12)

Equation (13) gives

\[
T_3 = \frac{2\sqrt{3}T_{SVM} \cdot V_{sm}}{V_{dc}} \sin \left( \theta_s - (k-1)\frac{\pi}{3} \right). 
\] (14)

To simplify $T_i$ expressions, we introduce $\theta_i$ defined as

\[
\theta_i = \theta_s - (k-1)\frac{\pi}{3}. 
\] (15)

Considering (15), $T_3$ final expression is

\[
T_3 = \frac{2\sqrt{3}T_{SVM} \cdot V_{sm}}{V_{dc}} \sin \left( \theta_i \right). 
\] (16)
the reference space vector is in triangle 3 and the
resulting phase voltage. It is seen in Figure 15(b) that the

where

Comparing (7) and (17) gives

After substituting (15) in (12) one can write

The final $T_1$ expressions for family 2 are as follows:

The same computation method is applied for the remaining 3 families. Consequently, the obtained on-times vectors applications for the 4 families are summarized in Table 1, where

3.3. Step 3: Secondary On-Times Calculation. As explained in Section 1, each vector can be reached by multiple PLS. The aim of Step 3 is to choose which PLS has to be activated over its corresponding time slot. Obviously, the inverter performance significantly depends on this PLS management.

The aim of the PLS management is to operate with fixed switching frequency: this is easily reachable when each IGBT switches once during a switching period. In fact, for a selected triangle, the available PLS are applied, so they are all used during a switching period and the transition from one PLS to the other requires only one commutation. For example, if $V^*_m$ is localized in triangle 4, the order of application of PLS is

$$(1,1,0) \rightarrow (2,1,0) \rightarrow (2,2,0) \rightarrow (2,2,1) \rightarrow (2,2,0) \rightarrow (2,1,0) \rightarrow (1,1,0).$$

3.4. Step 4: Dispatching within $T_{SVM}$. According to the described PLS management strategy, each PLS is realized first by defining the appropriate space vector ($V_1$, $V_2$, or $V_3$). Since the previously calculated on-times $T_i$ are the total application time for the space vector $V_i$ within $T_{SVM}$, they are evenly spread over the switching period. For example, if $V^*_m$ is localized in triangle 4, $V_1$ (of family 4) is applied 3 times during $T_{SVM}$, and $V_2$ and $V_3$ must be applied twice. Therefore, $T_i$ is equally divided into 3 time slots: each PLS that generates $V_1$ is applied during $T_i/3$. $T_2$ and $T_3$ are also divided into 2 time slots equal to $T_2/2$ and $T_3/2$, respectively. The resulting control signals of triangle 3 are shown in Figure 12.

4. Simulation Results

The three-level NPC converter is simulated using PSIM software, where the converter is connected to an RL load, as shown in Figure 13. Simulation parameters are presented in Table 2.

As mentioned in Section 3.1, the triangles covered by the space vector reference depend on the modulation depth $m$. Figure 13 shows the sectors and triangles covered by the space vector for a reference magnitude equal to 100 V. Thus, modulation depth $m$ is equal to $m = 100/270 = 0.37$.

For $m = 0.37$, when the space vector is circulating in sector 1 (2, 3, 4, 5, and 6, resp.), the triangle containing the space vector is T1 (T5, T9, T13, T17, and T21, resp.). It is to be noted that all of the 6 triangles are covered during 20 ms, corresponding to the reference voltage's frequency of 50 Hz.

Similarly, Figure 14 presents the sectors and triangles covered by the space vector when the reference magnitude is equal to 250; that is, $m = 0.92$.

The lookup table implemented on PSIM generates the appropriate control signals depending on the selected sector and triangle. Figure 15 presents the converter’s control signals when the reference space vector is in triangle 3 and the resulting phase voltage. It is seen in Figure 15(b) that the

\[ T_1 = T_{k1} = \frac{T_{SVM} - T_3 - T_2}{T_{k2}} \]

\[ T_2 = T_{k2} = \frac{T_{SVM} - T_1 - T_2}{T_{k1}} \]

\[ T_3 = T_{k3} = \frac{T_{SVM} - T_1 - T_3}{T_{k3}} \]

Table 1: On-times calculation.

<table>
<thead>
<tr>
<th>Family</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
</tr>
</thead>
<tbody>
<tr>
<td>$T_1$</td>
<td>$T_{k1}$</td>
<td>$T_{SVM} - T_3 - T_2$</td>
<td>$T_{SVM} - T_{k2}$</td>
<td>$T_{SVM} - T_3 - T_2$</td>
</tr>
<tr>
<td>$T_2$</td>
<td>$T_{k2}$</td>
<td>$T_{SVM} - T_1 - T_2$</td>
<td>$T_{SVM} - T_{k1}$</td>
<td>$T_{SVM} - T_1 - T_2$</td>
</tr>
<tr>
<td>$T_3$</td>
<td>$T_{SVM} - T_1 - T_2$</td>
<td>$T_{SVM} - T_{k3}$</td>
<td>$T_{SVM} - T_2 - T_3$</td>
<td>$T_{SVM} - T_{k3}$</td>
</tr>
</tbody>
</table>

Figure 12: Switching signals for triangle 3.
proposed sequencing of the PLS ensures that the phase level (consequently voltage level) changes only once per commutation cell.

In order to validate the converter performances of the proposed scheme, the output line currents are presented in Figure 16. Maximum magnitude is equal to 28 A. Line-to-line and phase leg voltages are shown in Figure 17. The expected multilevel waveforms insure the power quality improvement. This is illustrated by line a current spectrum given in Figure 18. THD value is estimated to be 0.69%. On this spectrum, the main harmonic is equal to 20 kHz which corresponds to the switching frequency $f_{sw}$.

It is shown in Figure 18 that $f_{sw}$ for each leg is a constant equal to 10.4 kHz. The additional 400 Hz compared to the SVM design (one commutation per IGBT within one $T_{SVM}$) is due to the $V_s$ transition from one triangle to another.

5. Experimental Results

The proposed algorithm is experimentally tested. A 4 kW three-phase three-level NPC converter laboratory prototype was conceived as shown in Figure 20. The setup parameters are listed in Table 3. The power devices are the F3L150R07W2E3 from Infineon. The proposed modulation method is implemented with a TI TMS320F2809 DSP.

Figure 21 shows the triangles crossed by $V_s$ for different modulation depths. When $m < 0.5$, $V_s$ crosses 6 triangles which are T1, T5, T9, T13, T17, and T21 (Figure 21(a)). When $m > 0.5$, $V_s$ crosses the remaining triangles (Figure 21(b)).

Figure 22 shows the steady state waveforms of the line-to-line voltages and line a current. The spectral analysis of the line current given in Figure 23 shows that first carrier harmonics appear at 20 kHz and then 40 kHz according to theoretical and simulation investigations.
Figure 24 shows the control signals of one commutation cell of leg a during two switching periods. The control signals are complementary, and the IGBTs switch once per period.

Table 3: Parameters of the 3-phase 3-level NPC converter.

<table>
<thead>
<tr>
<th>Item</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rated active power</td>
<td>4 kW</td>
</tr>
<tr>
<td>Switching frequency</td>
<td>20 kHz</td>
</tr>
<tr>
<td>Line frequency</td>
<td>50 Hz</td>
</tr>
<tr>
<td>DC link voltage</td>
<td>400 V</td>
</tr>
<tr>
<td>Line current amplitude</td>
<td>10 A</td>
</tr>
</tbody>
</table>

6. Conclusion

This paper proposes a Space Vector Modulation (SVM) technique for a three-level NPC converter. The proposed method consists in dividing the space vector diagram into four categories leading to a simple nearest three-vector detection and on-times calculation. Moreover, the choice of the converter Phase Level Sequence is used as an extra degree of freedom in order to control the converter’s switching frequency. In fact, once the vectors to apply are detected, their corresponding Phase Level Sequences are dispatched.
Figure 17: NPC voltages: (a) simple phase voltage; (b) line-to-line voltage.

Figure 18: (a) Line a current spectral analysis; (b) zoom around 20 kHz; (c) zoom around 40 kHz.

Figure 19: NPC legs switching frequencies: (a) leg a; (b) leg b; (c) leg c.
among the SVM period such that they are all applied and the transition from one PLS to the following requires only one commutation. This SVM can be extended to higher levels if the space vector diagram available triangles are appropriately defined.
The proposed methodology is verified by simulation and through a 4kW experimental test bed: the resulting output currents show a constant switching frequency and a reduced current THD. For applications such as renewable energies, this is a valuable improvement since it reduces the commutation power losses and lowers the output and grid connection filters size.

**Nomenclature**

- **NPC**: Neutral point clamped
- **SVM**: Space Vector Modulation
- **$V_{dc}$**: DC bus voltage
- **$V_s$**: Space vector output voltage
- **THD**: Total Harmonic Distortion
- **$SC_i$**: $i$th cell control signal
- **$X, Y, Z$**: Phase level related to phase a, b, and c, respectively
- **PLS**: Phase Level Sequence
- **$V_r^*$**: Reference voltage vector
- **$V_k$**: Nonzero voltage space vector in the ($\alpha, \beta$) frame
- **$T_k$**: Application time related to $V_k$
- **$T_{SYM}$**: SVM period
- **PWM**: Pulse Width Modulation
- **$\theta_r$**: Phase of the reference voltage vector
- **$f_{sw}$**: Switching frequency.

**Competing Interests**

The authors declare that there are no competing interests related to this paper.

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