REVIEW, EVALUATION AND PROPOSALS FOR SVPWM MODULATION TECHNIQUES
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Abstract: This paper reviews the methods of SVPWM (Space Vector Pulse Width Modulation) and studies its extension to other configurations of inverters. The space vector algorithm is worked on three topologies: 3-arms and 4-wires, 4-level multilevel inverter and four arms. The algorithms and the new proposals are implemented and validated on the software SIMULINK®️, demonstrating a low THD in the modulated signals.

Keywords: Power Electronics, Inverter, Modulation.

1. INTRODUCTION
Several modulation strategies, different in concept and performance, have been developed in recent decades to the modulation of voltage inverters [7]. From strategies for modulation operating at constant switching frequency, two methods stand out: the PWM (Pulse Width Modulation) with geometric approach [3] and especially for three-phase inverters, the SVPWM (Space Vector Pulse Width Modulation) [5]. The technique of pulse width modulation is made attractive by the benefits of high energy transfer efficiency of PWM inverter. Moreover, the PWM has been preferred in digital implementations due to the nature of the control signals [4]. PWM algorithms that use the comparison with the triangular wave are easier to process, being used in various applications. However, the techniques of space vector modulation have been widely applied because it allows reducing the number of commutations of the switches and the harmonic content of output voltage and increase the amplitude modulation of the inverter [2].

In the technical literature [6] the modeling of switching sequence is approached by the αβ plan that considers the neutral level of load and source are uncoupled. This leads to a modeling error if the neutral of the load and DC feeders of inverter are in the same reference, such as four-wire inverters or when the inverter and the load are grounded. This problem stems from the generalization of the SVPWM algorithm, which requires a single algorithm for a specific topology. Although there are unified approaches [2] it is required a further study and consequent extension of the generalized algorithm applied to a specific topology.

This article proposes to study, revise and extend the SVPWM method that can be found in many technical literatures [6] for the following topologies: 3-arm and 4-wire inverter, 4-levels multilevel inverter and 4-arm and 4-wire inverter. Specifically for the multilevel inverter is presented a new algorithm based on the division of the αβ plan in 18 subspaces. Is performed the analysis of these algorithms and presented some problems encountered and their solutions. Finally they are simulated and validated with software SIMULINK®️. This article is organized as follows: in section II is presented the algorithms and results of modulation for 3-arms and 4-wires inverter, and it is made some proposals for a reduced processing algorithm. In section III it is proposed the new space vector algorithm for multilevel inverter 4-levels. The results are presented in the same section in the second subsection. In the section IV a review of algorithms for 4-arms and 4-wires inverters is performed and the results presented in the same section. In section V the conclusions of the studies are made.

2. SVPWM for 4-arms 4-wires inverters
A typical three-phase 4-arms 4-wires inverter with LC filter and a 3-phase load coupled is shown in figure 1. This is the topology used in this second section for the validation of space vector algorithms. The electronics used in the construction of the drive certainly influence the responses of the modulation algorithm. For simulation, the components and their mathematical models used are typical for the similarities with the practice are as close as possible. LC filters, typically used in PWM inverters are needed to filter the signal from the switches and are used and all topologies of this study.

In the technical literature [6] the modeling of switching sequence is approached by the αβ plan that considers the neutral level of load and source are uncoupled. This leads to a modeling error if the neutral of the load and DC feeders of inverter are in the same reference, such as four-wire inverters or when the inverter and the load are grounded. This problem stems from the generalization of the SVPWM algorithm, which requires a single algorithm for a specific topology. Although there are unified approaches [2] it is required a further study and consequent extension of the generalized algorithm applied to a specific topology.

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2.2. Approach to 3-arms 4-wires inverter
The basic principle of space vector modulation is to synthesize the average voltage produced by the inverter over a period of switching, using a combination of possible
switching vectors [1]. For this is considered the decomposition of the modulated signal and the switching sequences in the $a\beta$ coordinate system. Thus, the first analysis required is the transformation of vectors obtained from all the possibilities of modulation. Each option generates a switching vector that can be mapped in the $a\beta$ plan. A hexagon consequent of all possibilities is formed and divided into sectors, which will be used for the development of the algorithm. Table 1 shows the values for the switching of each arm of the inverter.

Table 1. Sizes (in points) and font styles.

<table>
<thead>
<tr>
<th>Switching</th>
<th>Voltage (V) (centralizer)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>$-\frac{V_{dc}}{2}$</td>
</tr>
<tr>
<td>1</td>
<td>$\frac{V_{dc}}{2}$</td>
</tr>
</tbody>
</table>

In Figure 2, the switching values are described as: (arm 1, arm 2, arm 3), and DC represents the values described in table 1.

In general, the steps for Space Vector Modulation are:

1- From equation 1, calculate the reference vector of the voltage vectors $V_a$, $V_b$ e $V_c$.

$$V_{ref} = V_a + V_b + V_c$$  (1)

2- Calculate $a\beta\theta$ components for $V_{ref}$.

3- Finding sector of $V_{ref}$. Each sector is among the vectors $V_{a\beta}$ and $V_{n\beta}$, where $V_{a\beta}$ is a vector with the $a\beta$ components.

4- From equation 2, calculate switching periods:

$$T_{total} \cdot V_{ref,a\beta} = T_1 \cdot V_{a\beta} + T_2 \cdot V_{n\beta}$$  (2)

where:

$T_{total} = $ Full PWM cycle period.

$T_1 = $ Period of $V_{a\beta}$ sequence.

$T_2 = $ Period of $V_{n\beta}$ sequence.

5- Calculate the period $T_0$.

$$T_{total} = T_0 + T_1 + T_2$$  (3)

where:

$T_{total} = $ Switching periods of sequences (0,0,0) e (1,1,1).

The use of trigonometric functions to find the periods associated with the equation 2 requires processing of complex algorithms, and discouraged its use in real-time applications. This paper proposes a method for detection of sectors based on equations 4 to 6 and subsequently the implementation of the algorithm in figure 3. This method is the scalar product of vectors associated with the lines of the hexagon that determine its relative position on the plane.

$$L_1 = [0 \quad 1] \cdot V_{ref,a\beta}$$  (4)

$$L_2 = [-\frac{\sqrt{3}}{2} \quad \frac{1}{2}] \cdot V_{ref,a\beta}$$  (5)

$$L_3 = [\frac{1}{2} \quad \frac{\sqrt{3}}{2}] \cdot V_{ref,a\beta}$$  (6)

In Figure 3, the search algorithm vectors.

So, the switching periods can be calculated from the equation 7.

$$\begin{bmatrix} T_1 \\ T_2 \end{bmatrix} = \begin{bmatrix} V_{a\beta}^m \\ V_{n\beta}^m \end{bmatrix}^{-1} \cdot \begin{bmatrix} V_{ref,a\beta} \\ V_{ref,n\beta} \end{bmatrix} \cdot T_{total}$$  (7)

Each period is associated with a normed bigness that must be related to the total cycle of the PWM and the magnitude of the sources associated with DC power inverter. Due to devices gain errors involved, this can be adjusted empirically, but always related only to one gain equal to or less than the period of the PWM cycle to not occur saturation or distortion of modulated signal.

2.2. Simulation of SVPWM with 3-arms 4-wires inverter

The modulation method described has been implemented in SIMULINK®. The inverter circuit (figure 1) was built with electric models and simulated in conjunction with the algorithm command. The results obtained on the output load can be seen in Figure 4.

THD (Total Harmonic Distortion) of the voltage-to-neutral (figure 4) is 20.8%. The problem of the algorithm is the coupling of load and the DC source drive neutral. The line voltages do not have the same distortion despite this. The minimization of the harmonic distortion presented in
the phase voltages can be obtained by equating the correct neutral. Section 2.3 shows the approach that corrects the error of modulation found.

![Phase-Neutral Voltage on the load.](image)

### 2.3. Approach to SVPWM for 3-arms 4-wires inverter with neutral equation

The method described in section 2.1 is often described in technical literature [6], with the exception of the search algorithm of the sectors that has been proposed. This method gives good results in completely decoupled systems. However, inverters with coupled neutral, either by a wire either by grounding, the harmonics present in figure 4 are found. A new mathematical modeling should be done to counteract these harmonics as modeling with the neutral connected, or topology of arms 3 and 4 wires.

Each switching possibility, because it is not symmetrical, has components not present in the $\alpha \beta$ plane. Therefore, one solution is to modify equation 2 to equation 8:

$$ T_{total} \cdot V_{ref \alpha \beta 0} = T_0 \cdot V_{a \beta 0} + T_1 \cdot V_{a \beta 0} + T_2 \cdot V_{a \beta 0} + T_3 \cdot V_{a \beta 0} $$

The solution of the switching periods to this system has degrees of freedom. The unique solution is obtained by adding the condition of the sum of the periods from equation 9.

$$ T_{total} = T_0 + T_1 + T_2 + T_3 $$

Therefore, the resulting system has a solution and periods can be determined by the solution of the system shown in the equation 10.

$$ \begin{bmatrix} T_0 \\ T_1 \\ T_2 \\ T_3 \end{bmatrix} = \begin{bmatrix} V_1^{\alpha} & V_1^{\beta} & V_m^{\alpha} & V_m^{\beta} & V_0^{\alpha} & V_0^{\beta} \\ V_0^{\alpha} & V_0^{\beta} & V_m^{\alpha} & V_m^{\beta} & V_1^{\alpha} & V_1^{\beta} \\ 1 & 1 & 1 & 1 \end{bmatrix}^{-1} \cdot \begin{bmatrix} V_{ref \alpha} \\ V_{ref \beta} \\ V_{ref \alpha 0} \\ V_{ref \beta 0} \end{bmatrix} \cdot T_{total} $$

### 2.4. Simulation of SVPWM for 3-arms 4-wires inverter with neutral equation

The results obtained on the load can be seen in figures 5 and 6. Figure 5 shows the variation of periods of $T_0$ and $T_3$ which were equal in the previous method. Figure 6 shows the phase-to-neutral on the load. The parameters used in the electric model (resistances, inductances, etc.) are the same in the two simulations. The THD of the modulated signal in the figure 6 is 0.06%.

![Switching periods of $V^\alpha$ and $V^\beta$.](image)

![Phase-Neutral Voltage on the load.](image)

The results validate the mathematical model described in subsection 3 of section 2 of this article and solve the problems of distortion for inverters coupled with neutral.

### 3. SVPWM for 4-level multilevel inverters

The topology of a multilevel inverter with 4-levels and 4-wires is exposed in Figure 7. The difficulty in implementing algorithms based on vector space $\alpha \beta$ for these topologies is due to the number of possibilities of switching existing, some of those generating the same resultant vector. Consider all these possibilities require the process of complex algorithms that are not suitable for real-time applications processing non-dedicated. Figures 8 and 9, similar to the previous notation, the values of switching are described as: (arm 1, arm 2, arm 3).

An alternative to the problem of the amount of possibilities for switching is to consider only the vectors of greater magnitude, because it assumes that the drive operates at nominal levels. Thus the periods will be
maximized within the sector where the reference vector is founded, minimizing the switching transients.

3.1. An 18-subspaces space vector modulation for 4-level inverter

This paper proposes a new method of multilevel modulation in 18 subspaces based on vectors of greater magnitude in Figure 8. Figure 9 shows these vectors reflected in the $\alpha\beta$ plane.

The symmetry of the vectors depends on the magnitude of DC voltage, so for each different choice of vectors, it is needed new voltage levels of the power supply for the inverter. Table 2 shows the relationship between the DC values for the symmetry of the 18 subspaces. Only the proportions of these results are important. These values were obtained by numerical methods.

One way, proposed by this article, to determine the closest vectors of $\mathbf{V}_{\text{ref}}$ is to divide the plane of the figure 9 in 18 subspaces. The equations 11 through 19 are used for the localization of the sector. These equations are the scalar product of vectors perpendicular to each line of the diagram of figure 9.

Table 2. DC source levels for inverter.

<table>
<thead>
<tr>
<th>Switching</th>
<th>Voltage (V)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>$1.5 \cdot V_{dc}$</td>
</tr>
<tr>
<td>2</td>
<td>$0.4581 \cdot V_{dc}$</td>
</tr>
<tr>
<td>1</td>
<td>$-0.4581 \cdot V_{dc}$</td>
</tr>
<tr>
<td>0</td>
<td>$1.5 \cdot V_{dc}$</td>
</tr>
</tbody>
</table>

From the conditions then you can find the vectors of the sector. Figure 10 shows the used algorithm proposed by this work to search the vectors used in the sequence of switching. Once found the sequence is only necessary to apply equation 19, similar to that used for SVPWM in 2-levels inverters form section I.

$$L_1 = \begin{bmatrix} 0 & 1 \end{bmatrix} \cdot \mathbf{V}_{\text{ref}_{\alpha\beta}}$$  (11)

$$L_2 = \begin{bmatrix} \cos \left( \frac{\pi}{2} + \frac{\pi}{9} \right) & \sin \left( \frac{\pi}{2} + \frac{\pi}{9} \right) \end{bmatrix} \cdot \mathbf{V}_{\text{ref}_{\alpha\beta}}$$  (12)

$$L_3 = \begin{bmatrix} \cos \left( \frac{\pi}{2} + \frac{2\pi}{9} \right) & \sin \left( \frac{\pi}{2} + \frac{2\pi}{9} \right) \end{bmatrix} \cdot \mathbf{V}_{\text{ref}_{\alpha\beta}}$$  (13)

$$L_4 = \begin{bmatrix} \cos \left( \frac{\pi}{2} + \frac{3\pi}{9} \right) & \sin \left( \frac{\pi}{2} + \frac{3\pi}{9} \right) \end{bmatrix} \cdot \mathbf{V}_{\text{ref}_{\alpha\beta}}$$  (14)

$$L_5 = \begin{bmatrix} \cos \left( \frac{\pi}{2} + \frac{4\pi}{9} \right) & \sin \left( \frac{\pi}{2} + \frac{4\pi}{9} \right) \end{bmatrix} \cdot \mathbf{V}_{\text{ref}_{\alpha\beta}}$$  (15)

$$L_6 = \begin{bmatrix} \cos \left( \frac{\pi}{2} + \frac{5\pi}{9} \right) & \sin \left( \frac{\pi}{2} + \frac{5\pi}{9} \right) \end{bmatrix} \cdot \mathbf{V}_{\text{ref}_{\alpha\beta}}$$  (16)

$$L_7 = \begin{bmatrix} \cos \left( \frac{\pi}{2} + \frac{6\pi}{9} \right) & \sin \left( \frac{\pi}{2} + \frac{6\pi}{9} \right) \end{bmatrix} \cdot \mathbf{V}_{\text{ref}_{\alpha\beta}}$$  (17)

$$L_8 = \begin{bmatrix} \cos \left( \frac{\pi}{2} + \frac{7\pi}{9} \right) & \sin \left( \frac{\pi}{2} + \frac{7\pi}{9} \right) \end{bmatrix} \cdot \mathbf{V}_{\text{ref}_{\alpha\beta}}$$  (18)

$$L_9 = \begin{bmatrix} \cos \left( \frac{\pi}{2} + \frac{8\pi}{9} \right) & \sin \left( \frac{\pi}{2} + \frac{8\pi}{9} \right) \end{bmatrix} \cdot \mathbf{V}_{\text{ref}_{\alpha\beta}}$$  (19)

$$\begin{bmatrix} T_0 \\ T_1 \\ T_2 \\ T_3 \end{bmatrix} = \left[ \begin{bmatrix} V_{\text{ref}_{\alpha}} & V_{\text{ref}_{\alpha}} & V_{\text{ref}_{\alpha}} & V_{\text{ref}_{\alpha}} \\ V_{\text{ref}_{\alpha}} & V_{\text{ref}_{\alpha}} & V_{\text{ref}_{\alpha}} & V_{\text{ref}_{\alpha}} \\ V_{\text{ref}_{\alpha}} & V_{\text{ref}_{\alpha}} & V_{\text{ref}_{\alpha}} & V_{\text{ref}_{\alpha}} \\ V_{\text{ref}_{\alpha}} & V_{\text{ref}_{\alpha}} & V_{\text{ref}_{\alpha}} & V_{\text{ref}_{\alpha}} \end{bmatrix} \right]^{-1} \cdot \begin{bmatrix} T_{\text{total}} \\ T_{\text{total}} \\ T_{\text{total}} \\ T_{\text{total}} \end{bmatrix}$$  (20)
Where \( V^{000} \) and \( V^{333} \) are the sequences \((0,0,0)\) and \((3,3,3)\), and \( V^* \) and \( V^m \) are the sequences of vectors found in the algorithm of Figure 10.

Fig. 10. Search algorithm for vectors sequence switching.

### 3.2. Simulation of 18-subspaces space vector modulation for 4-level inverter

Figures 11 and 12 show the simulation results obtained with MATLAB®. Similar to section II, the model of the inverter was implemented with the equivalent models of electrical components of the inverter. The two figures refer to the voltage signs on the load. The modulated signal presented a THD of 0.08%. These validate the modulation technique for multilevel inverter proposed in this work.

Fig. 11. Phase-Neutral voltage on the load.

Fig. 12. Phase-Phase voltage on the load.

### 4. SVPWM for 4-arms and 4-wires inverters

A 4-arms typical inverter is shown in Figure 13. These inverters are useful in controlling the neutral point for phase systems with unbalanced loads [5].

Fig. 13. Typical 4-arms and 4-wires inverter.

Similar to other modulation techniques for 3-arms inverters, the algorithm of Space Vector used for modulation in this topology is the linear combination of vector sequence switching and reference space \( a\beta_0 \).

### 4.1. Approach to 24-subspaces space vector modulation for 4-arms inverter

The location of the closest vectors to the switching can be done by dividing the dodecahedron (Figure 14) by planes. Figure 14 shows the switching possibilities in \( a\beta_0 \) space. This can be divided into 24 subspaces whose basis vectors are used in modulation. The location of the subspace can be performed by the division of the plans that limit the space \( a\beta_0 \). Equations 20 through 25 are the scalar product of vectors used to identify its position in relation to the plans.

\[
P_1 = \begin{bmatrix} 0 & \sqrt{2} & 0 \end{bmatrix} \cdot V_{ref_{a\beta_0}} \tag{20}
\]

\[
P_2 = \begin{bmatrix} \frac{\sqrt{6}}{2} & \frac{\sqrt{2}}{2} & 0 \end{bmatrix} \cdot V_{ref_{a\beta_0}} \tag{21}
\]

\[
P_3 = \begin{bmatrix} \frac{\sqrt{6}}{2} & \frac{\sqrt{2}}{2} & 0 \end{bmatrix} \cdot V_{ref_{a\beta_0}} \tag{22}
\]

\[
P_4 = \begin{bmatrix} \frac{\sqrt{6}}{2} & 0 & \frac{\sqrt{3}}{3} \end{bmatrix} \cdot V_{ref_{a\beta_0}} \tag{23}
\]
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Fig. 14. Switching vectors from the 4-arms inverter.

Table 3 shows the necessary conditions to find the vectors associated with the subspace which \( \mathbf{v}_{ref,a0} \) belongs to. This table shows some corrections of the technical literature [1].

Table 3. Sizes (in points) and font styles.

<table>
<thead>
<tr>
<th>Conditions</th>
<th>Subspace</th>
<th>Vectors</th>
</tr>
</thead>
<tbody>
<tr>
<td>((P1;P5) &gt; 0; P2 \leq 0)</td>
<td>1</td>
<td>((1,0,0,0)(1,1,0,0)) ((1,1,1,0))</td>
</tr>
<tr>
<td>(P6 &gt; 0; (P2; P5) \leq 0)</td>
<td>2</td>
<td>((1,0,0,0)(1,1,0,0)) ((1,1,0,1))</td>
</tr>
<tr>
<td>((P1; P4) &gt; 0; P6 \leq 0)</td>
<td>3</td>
<td>((1,0,0,0)(1,0,1,0)) ((1,1,0,1))</td>
</tr>
<tr>
<td>(P1 &lt; 0; (P2; P4) \leq 0)</td>
<td>4</td>
<td>((0,0,0,1)(1,0,0,1)) ((1,1,0,1))</td>
</tr>
<tr>
<td>((P2; P3; P5) &gt; 0)</td>
<td>5</td>
<td>((0,1,0,0)(1,1,0,0)) ((1,1,1,0))</td>
</tr>
<tr>
<td>((P2; P4) &gt; 0; P5 \leq 0)</td>
<td>6</td>
<td>((0,1,0,0)(1,1,0,0)) ((1,1,1,0))</td>
</tr>
<tr>
<td>((P6; P3) &gt; 0; P4 \leq 0)</td>
<td>7</td>
<td>((0,1,0,0)(1,1,0,0)) ((1,1,1,0))</td>
</tr>
<tr>
<td>((P2; P3) &gt; 0; P6 \leq 0)</td>
<td>8</td>
<td>((0,0,0,1)(1,1,0,0)) ((1,1,1,0))</td>
</tr>
<tr>
<td>((P1; P4) &gt; 0; P3 \leq 0)</td>
<td>9</td>
<td>((0,0,1,0)(1,1,0,0)) ((1,1,1,0))</td>
</tr>
</tbody>
</table>

Combinations \((0,0,0,0)\) and \((1,1,1,1)\) are always part of the switching sequence, the same way as the previous algorithms, but in this case they have the same period, equal to \(T_0/2\). The algorithm for 4-arms inverter has 5 switching periods. Equation 26 shows the relationship between the vectors of the sequence of switching found in the algorithm proposed in this section and the periods associated with these. Equation 27 shows the achievement of the periods through the system of equations.

\[
T_{total} \cdot \mathbf{V}_{ref,a0} = \frac{T_0}{2} \cdot \mathbf{V}_{0000}^{a0} + T_1 \cdot \mathbf{V}_{m,a0} + T_2 \cdot \mathbf{V}_{1111}^{a0} \]

\[
\begin{bmatrix}
0 & V_{0}^n & V_{0}^m & V_{0}^p \\
V_{0}^n & 0 & \mathbf{V}_{a0}^{m} & \mathbf{V}_{a0}^{p} \\
V_{0}^m & \mathbf{V}_{a0}^{m} & 0 & \mathbf{V}_{a0}^{p} \\
V_{0}^p & \mathbf{V}_{a0}^{p} & \mathbf{V}_{a0}^{p} & 0
\end{bmatrix} \cdot \mathbf{V}_{ref,a0} = \mathbf{V}_{ref,a0} \cdot \mathbf{V}_{total}
\]

4.2. Simulation of space vector modulation for 4-arms inverter

The simulation results of the algorithm are shown in figures 15 and 16. The THD of the modulated signal simulation in 3-phase symmetric conditions is 0.07%. These results validate the modulation technique described for the 4-arms inverter. In figure 16 was inserted into a non-zero modulation signal to the neutral. The figure demonstrates...
the over-modulation in the system caused by the sinusoidal signal through to the neutral.

Fig. 15. Phase-Neutral Voltage to SVPWM algorithm for 4-arms inverter.

Fig. 16. Phase-Neutral Voltage to SVPWM algorithm for 4-arms inverter with neutral non-zero modulation.

5. CONCLUSION

In this article, a review and new proposals for Space Vector algorithms was performed. It has presented methods for sectors search algorithms without the use of trigonometric functions that have been simulated and validated with THDs less than 0.8%, thus making the SVPWM a light algorithm for applications that do not have dedicated processing for this purpose. For the multilevel topology was presented a new algorithm and validated through a simulation of electric mathematical models of the inverter in SIMULINK®.

The conclusions of these private reviews that the SVPWM algorithm is generic and can be extended to various available topologies, but needs to add specificity related to the topology in question. Thus, there are several variations of SVPWM have been and will be established, and each topology under consideration requires a study, as in this work, aiming to fulfill certain requirements of the process involved.

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REFERENCES


