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The Space Vector Modulation PWM Control Methods Applied on Four Leg Inverters

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1. Introduction

Up to now, in many industrial applications, there is a great interest in four-leg inverters for three-phase four-wire applications. Such as power generation, distributed energy systems [1-4], active power filtering [5-20], uninterruptible power supplies, special control motors configurations [21-25], military utilities, medical equipment[26-27] and rural electrification based on renewable energy sources[28-32]. This kind of inverter has a special topology because of the existence of the fourth leg; therefore it needs special control algorithm to fulfil the subject of the neutral current circulation which was designed for. It was found that the classical three-phase voltage-source inverters can ensure this topology by two ways in a way to provide the fourth leg which can handle the neutral current, where this neutral has to be connected to the neutral connection of three-phase four-wire systems:

- 1. Using split DC-link capacitors Fig. 1, where the mid-point of the DC-link capacitors is connected to the neutral of the four wire network [34-48].

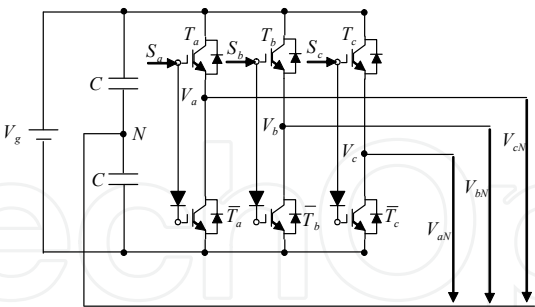


Fig. 1. Four legs inverter with split capacitor Topology.

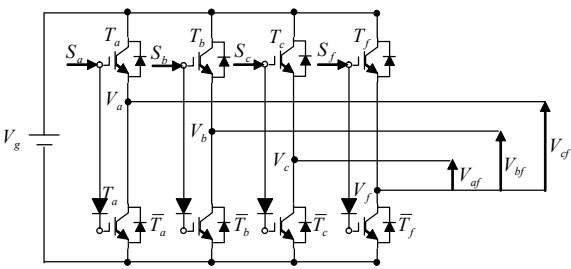


Fig. 2. Four legs inverter with and additional leg Topology.

2. Using a four-leg inverter Fig. 2, where the mid-point of the fourth neutral leg is connected to the neutral of the four wire network,[22],[39],[45],[48-59].

It is clear that the two topologies allow the circulation of the neutral current caused by the non linear load or/and the unbalanced load into the additional leg (fourth leg). But the first solution has major drawbacks compared to the second solution. Indeed the needed DC side voltage required large and expensive DC-link capacitors, especially when the neutral current is important, and this is the case of the industrial plants. On the other side the required control algorithm is more complex and the unbalance between the two parts of the split capacitors presents a serious problem which may affect the performance of the inverter at any time, indeed it is a difficult problem to maintain the voltages equally even the voltage controllers are used. Therefore, the second solution is preferred to be used despite the complexity of the required control for the additional leg switches Fig.1. The control of the four leg inverter switches can be achieved by several algorithms [55],[58],[60-64]. But the Space Vector Modulation SVM has been proved to be the most favourable pulse-width modulation schemes, thanks to its major advantages such as more efficient and high DC link voltage utilization, lower output voltage harmonic distortion, less switching and conduction losses, wide linear modulation range, more output voltage magnitude and its simple digital implementation. Several works were done on the SVM PWM firstly for three legs two level inverters, later on three legs multilevel inverters of many topologies [11],[43-46],[56-57],[65-68]. For four legs inverters there were till now four families of algorithms, the first is based on the $\alpha\beta\gamma$ coordinates, the second is based on the abc coordinates, the third uses only the values and polarities of the natural voltages and the fourth is using a simplification of the two first families. In this chapter, the four families are presented with a simplified mathematical presentation; a short simulation is done for the fourth family to show its behaviours in some cases.

2. Four leg two level inverter modelisation

In the general case, when the three wire network has balanced three phase system voltages, there are only two independents variables representing the voltages in the three phase system and this is justified by the following relation :

$$V_{af} + V_{bf} + V_{cf} = 0 \quad (1)$$

Whereas in the case of an unbalanced system voltage the last equation is not true:

$$V_{af} + V_{bf} + V_{cf} \neq 0 \quad (2)$$

And there are three independent variables; in this case three dimension space is needed to present the equivalent vector. For four wire network, three phase unbalanced load can be expected; hence there is a current circulating in the neutral:

$$I_{La} + I_{Lb} + I_{Lc} = I_n \neq 0 \quad (3)$$

I_n is the current in the neutral. To built an inverter which can response to the requirement of the voltage unbalance and/or the current unbalance conditions a fourth leg is needed, this leg allows the circulation of the neutral current, on the other hand permits to achieve unbalanced phase-neutral voltages following to the required reference output voltages of

the inverter. The four leg inverter used in this chapter is the one with a duplicated additional leg presented in Fig.1. The outer phase-neutral voltages of the inverter are given by:

$$V_{if} = \left[S_a - S_f \right] \cdot V_g \quad \text{where : } i = a, b, c$$

(4)

f designed the fourth leg and S_f its corresponding switch state. The whole possibilities of the switching position of the four-leg inverter are presented in Table 1. It resumes the output voltages of different phases versus the possible switching states

| Vector | $S_a S_b S_c S_f$ | V_{af} / V_g | V_{bf} / V_g | V_{cf} / V_g |
|----------|-------------------|----------------|----------------|----------------|
| V^1 | 1111 | 0 | 0 | 0 |
| V^2 | 0010 | 0 | 0 | +1 |
| V^3 | 0100 | 0 | +1 | 0 |
| V^4 | 0110 | 0 | +1 | +1 |
| V^5 | 1000 | +1 | 0 | 0 |
| V^6 | 1010 | +1 | 0 | +1 |
| V^7 | 1100 | +1 | +1 | 0 |
| V^8 | 1110 | +1 | +1 | +1 |
| V^9 | 0001 | -1 | -1 | -1 |
| V^{10} | 0011 | -1 | -1 | 0 |
| V^{11} | 0101 | -1 | 0 | -1 |
| V^{12} | 0111 | -1 | 0 | 0 |
| V^{13} | 1001 | 0 | -1 | -1 |
| V^{14} | 1011 | 0 | -1 | 0 |
| V^{15} | 1101 | 0 | 0 | -1 |
| V^{16} | 0000 | 0 | 0 | 0 |

Table 1. Switching vectors of the four leg inverter

Equation (4) can be rewritten in details:

$$\begin{bmatrix} V_{af} \\ V_{bf} \\ V_{cf} \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 & -1 \\ 0 & 1 & 0 & -1 \\ 0 & 0 & 1 & -1 \end{bmatrix} \cdot \begin{bmatrix} S_a \\ S_b \\ S_c \\ S_f \end{bmatrix} \cdot V_g$$

(5)

Where the variable S_i is defined by:

$$S_i = \begin{cases} 1 & \text{if the upper switch of the leg } i \text{ is closed} \\ 0 & \text{if the upper switch of the leg } i \text{ is opened} \end{cases} \quad \text{where : } i = a, b, c, f$$

3. Three dimensional SVM in $a-b-c$ frame for four leg inverters

The 3D SVM algorithm using the $a-b-c$ frame is based on the presentation of the switching vectors as they were presented in the previous table [34-35],[69-72]. The vectors were normalized dividing them by V_g . It is clear that the space which is containing all the space vectors is limited by a large cube with edges equal to two where all the diagonals pass by (0,0,0) point inside this cube Fig. 3, it is important to remark that all the switching vectors are located just in two partial cubes from the eight partial cubes with edges equal to one Fig. 4. The first one is containing vectors from V^1 to V^8 in this region all the components following the a , b and c axis are positive. The second cube is containing vectors from V^9 to V^{16} with their components following the a , b and c axis are all negative. The common point (0,0,0) is presenting the two nil switching vectors V^1 and V^{16} .

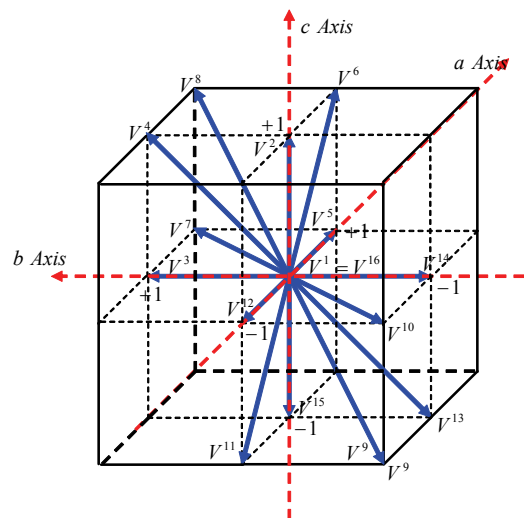


Fig. 3. The large space which is limiting the switching vectors

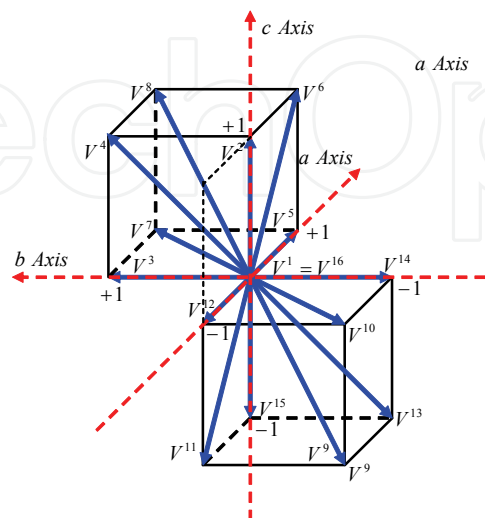


Fig. 4. The part of space which is limiting the space of switching vectors

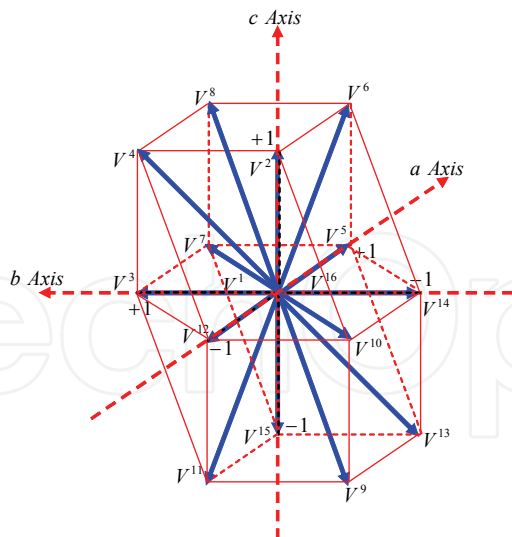


Fig. 5. The possible space including the voltage space vector (the dodecahedron) .

The instantaneous voltage space vector of the reference output voltage of the inverter travels following a trajectory inside the large cube space, this trajectory is depending on the degree of the reference voltage unbalance and harmonics, but it is found that however the trajectory, the reference voltage space vector is remained inside the large cube. The limit of this space is determined by joining the vertices of the two partial cubes. This space is presenting a dodecahedron as it is shown clearly in Fig. 5. This space is containing 24 tetrahedron, each small cube includes inside it six tetrahedrons and the space between the two small cubes includes 12 tetrahedrons, in Fig. 6 examples of the tetrahedrons given. In this algorithm a method is proposed for the determination of the tetrahedron in which the reference vector is located. This method is based on a region pointer which is defined as follows:

$$RP = 1 + \sum_{i=1}^6 C_i \cdot 2^{(i-1)} \tag{6}$$

Where:

$$C_i = \text{Sign}(\text{INT}(x(i) + 1)) \quad i = 1 : 6 \tag{7}$$

The values of $x(i)$ are:

$$x = \begin{bmatrix} V_{aref} \\ V_{bref} \\ V_{cref} \\ V_{aref} - V_{bref} \\ V_{bref} - V_{cref} \\ V_{aref} - V_{cref} \end{bmatrix}$$

Where the function *Sign* is:

$$\text{Sign}(V) = \begin{cases} +1 & \text{if } V > 1 \\ -1 & \text{if } V < 1 \\ 0 & \text{if } V = 1 \end{cases} \tag{8}$$

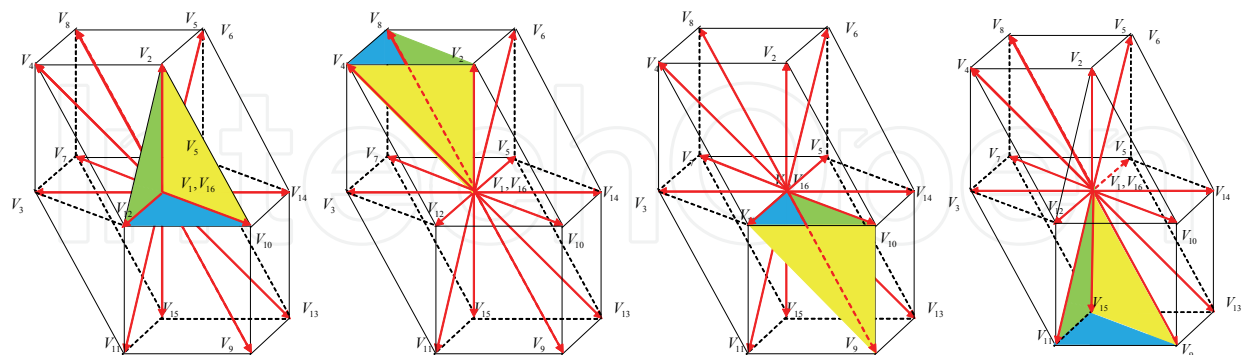


Fig. 6. The possible space including the voltage space vector (the dodecahedron).

| RP | V ₁ | V ₂ | V ₃ | RP | V ₁ | V ₂ | V ₃ |
|----|----------------|-----------------|-----------------|----|----------------|-----------------|-----------------|
| 1 | V ⁹ | V ¹⁰ | V ¹² | 41 | V ⁹ | V ¹³ | V ¹⁴ |
| 5 | V ² | V ¹⁰ | V ¹² | 42 | V ⁵ | V ¹³ | V ¹⁴ |
| 7 | V ² | V ⁴ | V ¹² | 46 | V ⁵ | V ⁶ | V ¹⁴ |
| 8 | V ² | V ⁴ | V ⁸ | 48 | V ⁵ | V ⁶ | V ⁸ |
| 9 | V ⁹ | V ¹⁰ | V ¹⁴ | 49 | V ⁹ | V ¹¹ | V ¹⁵ |
| 13 | V ² | V ¹⁰ | V ¹⁴ | 51 | V ³ | V ¹¹ | V ¹⁵ |
| 14 | V ² | V ⁶ | V ¹⁴ | 52 | V ³ | V ⁷ | V ¹⁵ |
| 16 | V ² | V ⁶ | V ⁸ | 56 | V ³ | V ⁷ | V ⁸ |
| 17 | V ⁹ | V ¹¹ | V ¹² | 57 | V ⁹ | V ¹³ | V ¹⁵ |
| 19 | V ³ | V ¹¹ | V ¹² | 58 | V ⁵ | V ¹³ | V ¹⁵ |
| 23 | V ³ | V ⁴ | V ¹² | 60 | V ⁵ | V ⁷ | V ¹⁵ |
| 24 | V ³ | V ⁴ | V ⁸ | 64 | V ⁵ | V ⁷ | V ⁸ |

Table 2. The active vector of different tetrahedrons

Each tetrahedron is formed by three NZVs (non-zero vectors) confounded with the edges and two ZVs (zero vectors) (V^1 , V^{16}). The NZVs are presenting the active vectors nominated by V_1 , V_2 and V_3 Tab. 2. The selection of the active vectors order depends on several parameters, such as the polarity change, the zero vectors ZVs used and on the sequencing scheme. V_1 , V_2 and V_3 have to ensure during each sampling time the equality of the average value presented as follows:

$$V_{ref} \cdot T_z = V_1 \cdot T_1 + V_2 \cdot T_2 + V_3 \cdot T_3 + V_{01} \cdot T_{01} + V_{016} \cdot T_{016} \quad T_z = T_1 + T_2 + T_3 + T_{01} + T_{016} \tag{9}$$

The last thing in this algorithm is the calculation of the duty times. From the equation given in (9) the following equation can be deducted:

$$\begin{bmatrix} V_{aref} \\ V_{bref} \\ V_{cref} \end{bmatrix} = \underbrace{\begin{bmatrix} V_{1a} & V_{2a} & V_{3a} \\ V_{1b} & V_{2b} & V_{3b} \\ V_{1c} & V_{2c} & V_{3c} \end{bmatrix}}_M \cdot \frac{1}{T_z} \cdot \begin{bmatrix} T_1 \\ T_2 \\ T_3 \end{bmatrix} = M \cdot \frac{1}{T_z} \cdot \begin{bmatrix} T_1 \\ T_2 \\ T_3 \end{bmatrix} \quad (10)$$

Then the duty times:

$$\begin{bmatrix} T_1 \\ T_2 \\ T_3 \end{bmatrix} = T_z \cdot M^{-1} \cdot \begin{bmatrix} V_{aref} \\ V_{bref} \\ V_{cref} \end{bmatrix} \quad (11)$$

4. 3D-SVM in $\alpha - \beta - \gamma$ coordinates for four leg inverter

This algorithm is based on the representation of the natural coordinates a , b and c in a new 3-D orthogonal frame, called $\alpha - \beta - \gamma$ frame [72-80], this can be achieved by the use of the Edit Clark transformation, where the voltage/current can be presented by a vector V :

$$V = \begin{bmatrix} V_\alpha \\ V_\beta \\ V_\gamma \end{bmatrix} = C \cdot \begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} \quad I = \begin{bmatrix} I_\alpha \\ I_\beta \\ I_\gamma \end{bmatrix} = C \cdot \begin{bmatrix} I_a \\ I_b \\ I_c \end{bmatrix} \quad (12)$$

C represents the matrix transformation:

$$C = \frac{2}{3} \cdot \begin{bmatrix} 1 & -1/2 & -1/2 \\ 0 & \sqrt{3}/2 & -\sqrt{3}/2 \\ 1/2 & 1/2 & 1/2 \end{bmatrix} \quad (13)$$

When the reference voltages are balanced and without the same harmonics components in the three phases, the representations of the switching vectors have only eight possibilities which can be represented in the $\alpha - \beta$ plane. Otherwise in the general case of unbalance and different harmonics components the number of the switching vectors becomes sixteen, where each vector is defined by a set of four elements $[S_a, S_b, S_c, S_f]$ and their positions in the $\alpha - \beta - \gamma$ frame depend on the values contained in these sets Tab. 3.

Each vector can be expressed by three components following the three orthogonal axes as follows:

$$V^i = \begin{bmatrix} V_\alpha^i \\ V_\beta^i \\ V_\gamma^i \end{bmatrix}$$

Where:

$$i = \overline{1, 16} \quad (12)$$

It is clear that the projection of these vectors onto the $\alpha\beta$ plane gives six NZVs and two ZVs; these vectors present exactly the 2D presentation of the three leg inverters, it is explained by the nil value of the γ component where there is no need to the fourth leg. On the other side Fig. 7 represents the general case of the four legs inverter switching vectors. The different possibilities of the switching vectors in the $\alpha - \beta - \gamma$ frame are shown clearly, seven vectors are localised in the positive part of the γ axis, while seven other vectors are found in the negative part, the two other vectors are just pointed in the $(0,0,0)$ coordinates, this two vectors are very important during the calculation of the switching times.

| Vector | $S_aS_bS_cS_f$ | V_γ | V_α | V_β |
|----------|----------------|----------------|----------------|-----------------------|
| V^9 | 0001 | -1 | 0 | 0 |
| V^{10} | 0011 | $-\frac{2}{3}$ | $-\frac{1}{3}$ | $-\frac{1}{\sqrt{3}}$ |
| V^{11} | 0101 | | $-\frac{1}{3}$ | $+\frac{1}{\sqrt{3}}$ |
| V^{13} | 1001 | | $+\frac{2}{3}$ | 0 |
| V^{12} | 0111 | $-\frac{1}{3}$ | $-\frac{2}{3}$ | 0 |
| V^{14} | 1011 | | $+\frac{1}{3}$ | $-\frac{1}{\sqrt{3}}$ |
| V^{15} | 1101 | | $+\frac{1}{3}$ | $+\frac{1}{\sqrt{3}}$ |
| V^{16} | 0000 | 0 | 0 | 0 |

| Vector | $S_aS_bS_cS_f$ | V_γ | V_α | V_β |
|--------|----------------|----------------|----------------|-----------------------|
| V^1 | 1111 | 0 | 0 | 0 |
| V^2 | 0010 | $+\frac{1}{3}$ | $-\frac{1}{3}$ | $-\frac{1}{\sqrt{3}}$ |
| V^3 | 0100 | | $-\frac{1}{3}$ | $+\frac{1}{\sqrt{3}}$ |
| V^5 | 1000 | | $\frac{2}{3}$ | 0 |
| V^4 | 0110 | $+\frac{2}{3}$ | $-\frac{2}{3}$ | 0 |
| V^6 | 1010 | | $+\frac{1}{3}$ | $-\frac{1}{\sqrt{3}}$ |
| V^7 | 1100 | | $+\frac{1}{3}$ | $+\frac{1}{\sqrt{3}}$ |
| V^9 | 1110 | +1 | 0 | 0 |

Table 3. Switching vectors in the $\alpha\beta\gamma$ frame

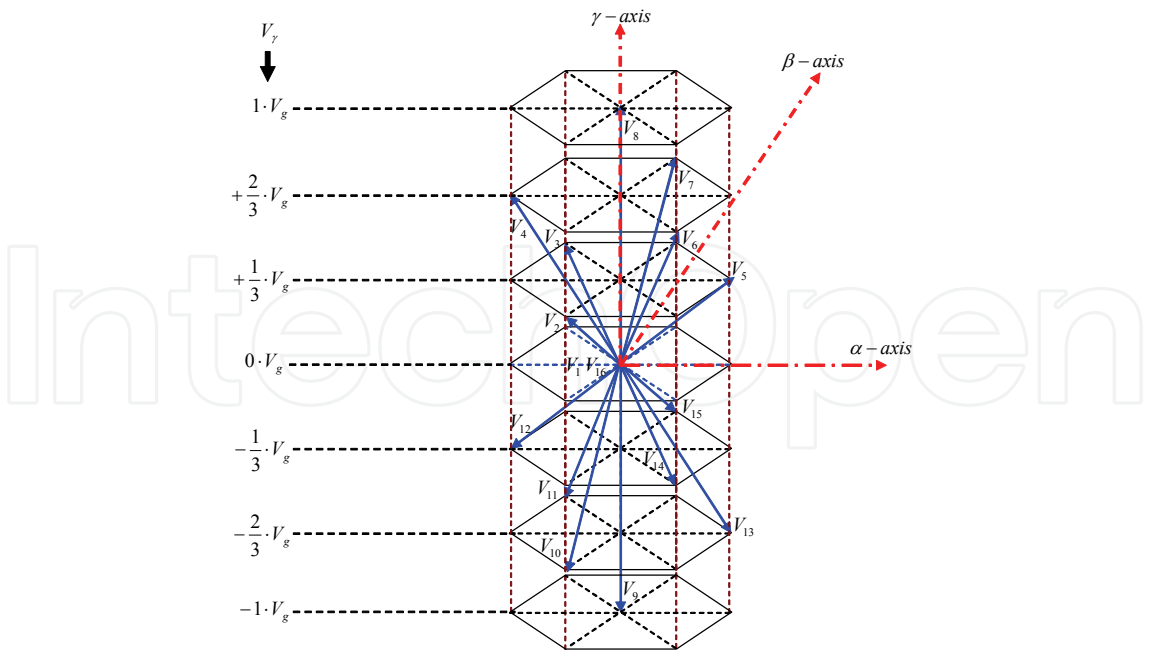


Fig. 7. Presentation of the switching vector in the $\alpha\beta\gamma$ frame

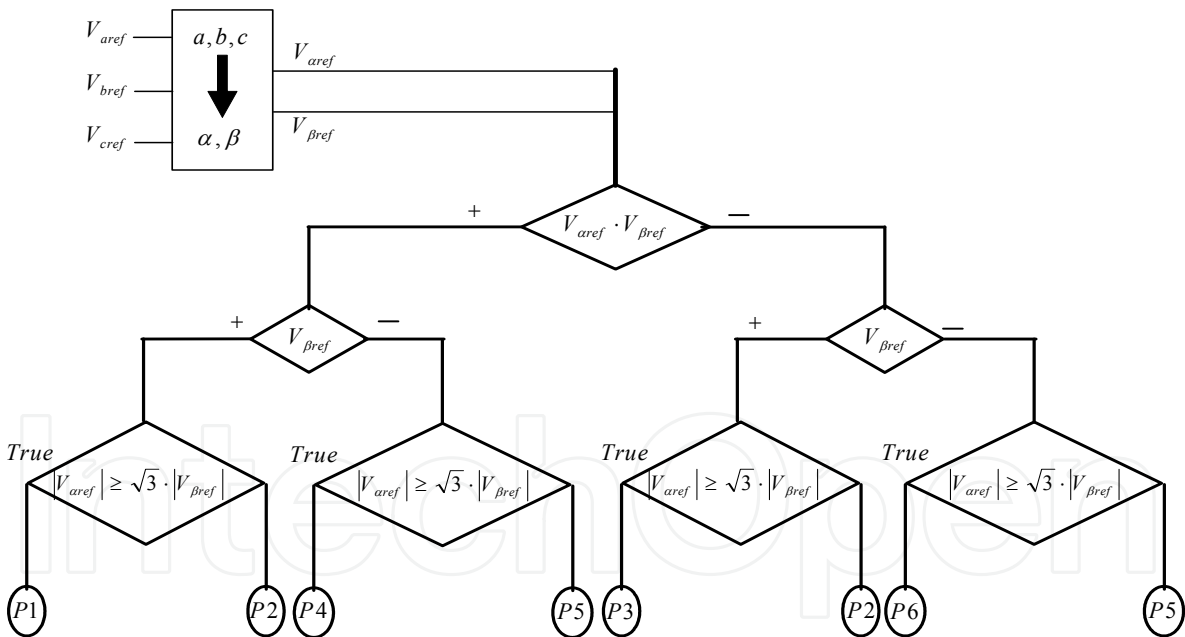


Fig. 8. Determination of the prisms

The position of the reference space vector can be determined in two steps.

1. Determination of the prism, in total there are six prisms. The flowchart in Fig.8 explains clearly, how the prism in which the reference space vector is found can be determined.
2. Determination of the tetrahedron in which the reference vector is located. Each prism contains four tetrahedrons Fig. 9, the determination of the tetrahedron in which the reference space vector is located is based on the polarity of the reference space vector components in $a-b-c$ frame as it is presented in Tab. 4.

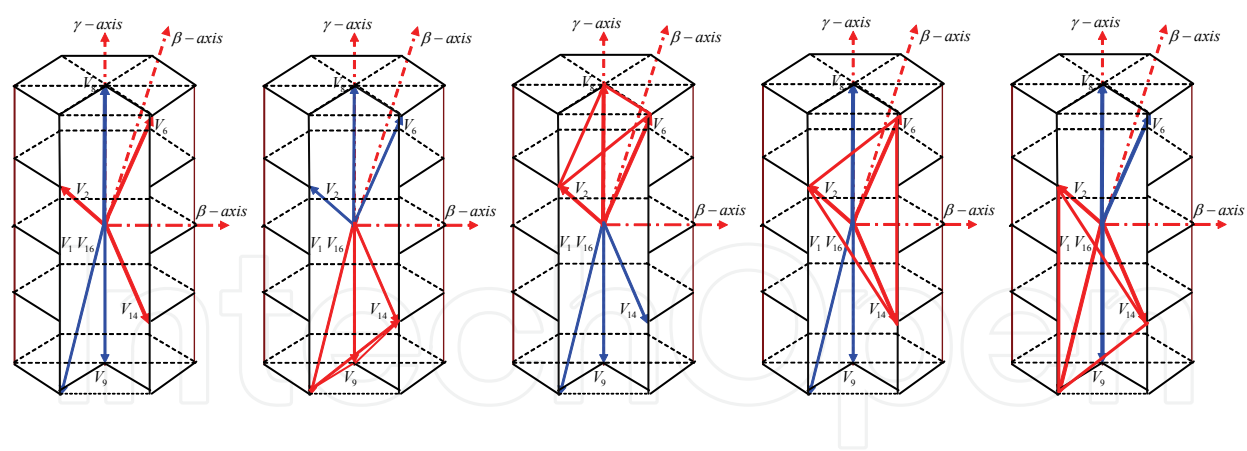


Fig. 9. Presentation of the switching vector in the $\alpha\beta\gamma$ frame

| Prism | Tetrahedron | Active vectors | | | | | | Reference vector components | | |
|-------|-------------|----------------|-------------|----------|-------------|----------|-------------|-----------------------------|----------|----------|
| | | V_1 | V_1 | V_2 | V_2 | V_3 | V_3 | V_{af} | V_{bf} | V_{cf} |
| P_1 | T_1 | V^{15} | 1101 | V^{13} | 1001 | V^5 | 1000 | \geq | \prec | \prec |
| | T_2 | V^5 | 1000 | V^7 | 1100 | V^{15} | 1101 | \geq | \geq | \prec |
| | T_{13} | V^9 | 0001 | V^{13} | 1001 | V^{15} | 1101 | \prec | \prec | \prec |
| | T_{14} | V^8 | 1110 | V^7 | 1100 | V^5 | 1000 | \geq | \geq | \geq |
| P_2 | T_3 | V^3 | 0100 | V^7 | 1100 | V^{15} | 1101 | \geq | \geq | \prec |
| | T_4 | V^{15} | 1101 | V^{11} | 0101 | V^3 | 0100 | \prec | \geq | \prec |
| | T_{15} | V^9 | 0001 | V^{11} | 0101 | V^{15} | 1101 | \prec | \prec | \prec |
| | T_{16} | V^8 | 1110 | V^7 | 1100 | V^3 | 0100 | \geq | \geq | \geq |
| P_3 | T_5 | V^{12} | 0111 | V^{11} | 0101 | V^3 | 0100 | \prec | \geq | \prec |
| | T_6 | V^3 | 0100 | V^4 | 0110 | V^{12} | 0111 | \prec | \geq | \geq |
| | T_{17} | V^9 | 0001 | V^{11} | 0101 | V^{12} | 0111 | \prec | \prec | \prec |
| | T_{18} | V^8 | 1110 | V^4 | 0110 | V^3 | 0100 | \geq | \geq | \geq |
| P_4 | T_7 | V^2 | 0010 | V^4 | 0110 | V^{12} | 0111 | \prec | \geq | \geq |
| | T_8 | V^{12} | 0111 | V^{10} | 0011 | V^2 | 0010 | \prec | \prec | \geq |
| | T_{19} | V^9 | 0001 | V^{10} | 0011 | V^{12} | 0111 | \prec | \prec | \prec |
| | T_{20} | V^8 | 1110 | V^4 | 0110 | V^2 | 0010 | \geq | \geq | \geq |
| P_5 | T_9 | V^{14} | 1011 | V^{10} | 0011 | V^2 | 0010 | \prec | \prec | \geq |
| | T_{10} | V^2 | 0010 | V^6 | 1010 | V^{14} | 1011 | \geq | \prec | \geq |
| | T_{21} | V^9 | 0001 | V^{10} | 0011 | V^{14} | 1011 | \prec | \prec | \prec |
| | T_{22} | V^8 | 1110 | V^6 | 1010 | V^2 | 0010 | \geq | \geq | \geq |
| P_6 | T_{11} | V^{14} | 1011 | V^{13} | 1001 | V^5 | 1000 | \geq | \prec | \prec |
| | T_{12} | V^5 | 1000 | V^6 | 1010 | V^{14} | 1011 | \geq | \prec | \geq |
| | T_{23} | V^9 | 0001 | V^{13} | 1001 | V^{14} | 1011 | \prec | \prec | \prec |
| | T_{24} | V^8 | 1110 | V^6 | 1010 | V^5 | 1000 | \geq | \geq | \geq |

Table 4. Tetrahedron determination.

By the same way, using (9) the duty times of the active vectors can be calculated using the following expression:

$$\begin{bmatrix} V_{\alpha ref} \\ V_{\beta ref} \\ V_{\gamma ref} \end{bmatrix} = \underbrace{\begin{bmatrix} V_{1\alpha} & V_{2\alpha} & V_{3\alpha} \\ V_{1\beta} & V_{2\beta} & V_{3\beta} \\ V_{1\gamma} & V_{2\gamma} & V_{3\gamma} \end{bmatrix}}_N \cdot \frac{1}{T_z} \cdot \begin{bmatrix} T_1 \\ T_1 \\ T_1 \end{bmatrix} = N \cdot \frac{1}{T_z} \cdot \begin{bmatrix} T_1 \\ T_1 \\ T_1 \end{bmatrix} \quad (13)$$

Finally:

$$\begin{bmatrix} T_1 \\ T_1 \\ T_1 \end{bmatrix} = T_z \cdot N^{-1} \cdot \begin{bmatrix} V_{\alpha ref} \\ V_{\beta ref} \\ V_{\gamma ref} \end{bmatrix} \quad (14)$$

5. 3D-SVM new algorithm for four leg inverters

A new method was recently proposed for the identification of tetrahedron and the three adjacent nonzero vectors [81]. It exposes the relationship between the reference voltages and the corresponding tetrahedron, on the other side the relationship between the three adjacent vectors and their duty times in each sampling period. This method is based on the idea that the three adjacent vectors are automatically in a tetrahedron, but it is not required to identify this tetrahedron. The authors of this method proposed two algorithms for the implementation of 3-D SVPWM where the phase angle is necessary to be determined. Each of the tetrahedrons is appointed by $T(x, y, z)$, it is composed of three non-zero vectors V_x , V_y and V_z as it is exposed in the other methods. On the other side the authors of this method have noticed that the shape of sliced prisms in two methods have the same shapes but with differences of scale and spatial position Fig. 10. On this basis the initial transformation used between the $a-b-c$ frame and $\alpha-\beta-\gamma$ frame is decomposed to three matrixes:

$$\begin{bmatrix} U_\alpha \\ U_\beta \\ U_0 \end{bmatrix} = \frac{1}{3} \cdot \begin{bmatrix} 2 & 1 & 1 \\ 0 & \sqrt{3} & -\sqrt{3} \\ 1 & 1 & 1 \end{bmatrix} \cdot \begin{bmatrix} U_a \\ U_b \\ U_c \end{bmatrix} = T_1 \cdot T_2 \cdot T_3 \cdot \begin{bmatrix} U_a \\ U_b \\ U_c \end{bmatrix} \quad (15)$$

Where:

$$T_1 = \begin{bmatrix} \sqrt{2/3} & 0 & 0 \\ 0 & \sqrt{2/3} & 0 \\ 0 & 0 & \sqrt{1/3} \end{bmatrix}, T_2 = \begin{bmatrix} \sqrt{2/3} & 0 & \sqrt{1/3} \\ 0 & \sqrt{3} & 0 \\ -\sqrt{1/3} & 0 & \sqrt{2/3} \end{bmatrix}, T_3 = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \sqrt{1/2} & -\sqrt{1/2} \\ 0 & \sqrt{1/2} & \sqrt{1/2} \end{bmatrix} \quad (16)$$

The first matrix rotates the $a-b-c$ coordinates around the a axis by an angle of 45° . Then the second matrix rotates the $a-b-c$ coordinates around the b axis by an angle of 36.25° . Finally, the third matrix modifies its scale by multiplying the a and b axis by $\sqrt{2/3}$ and $\sqrt{1/3}$ respectively. After this transformation, it was noticed that the vector used in each tetrahedron are the same in either frames $a-b-c$ and $\alpha-\beta-\gamma$, of course with two

different spatial positions, Hence, it is deducted that the duration of the adjacent vectors are independent of coordinates.

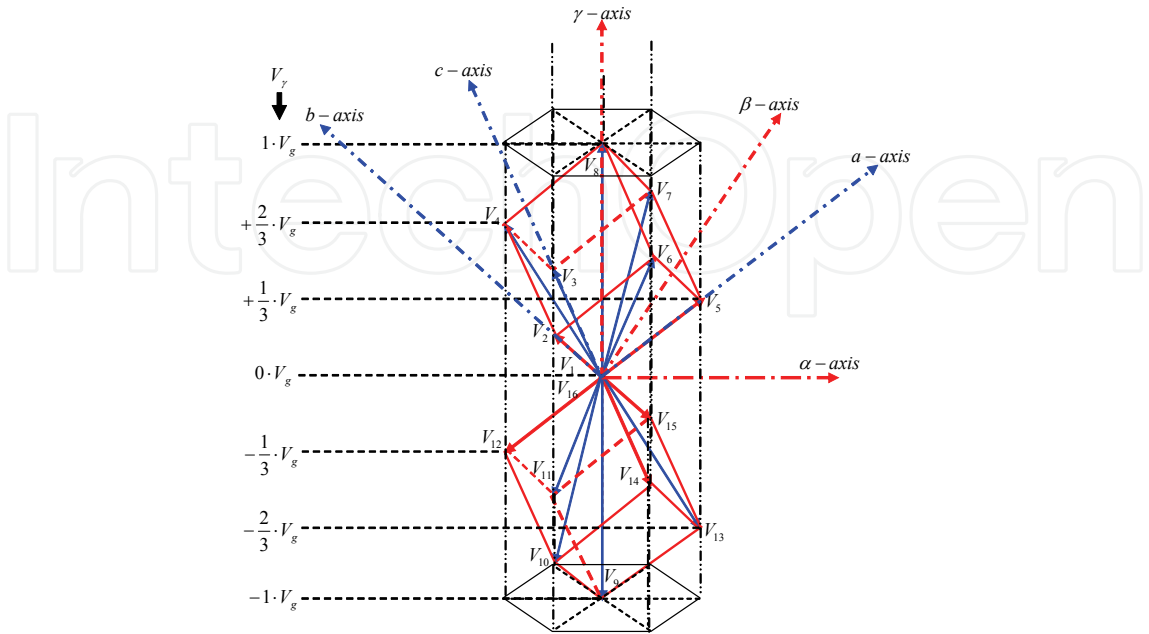


Fig. 10. Presentation of the switching vector in the $\alpha\beta\gamma$ frame

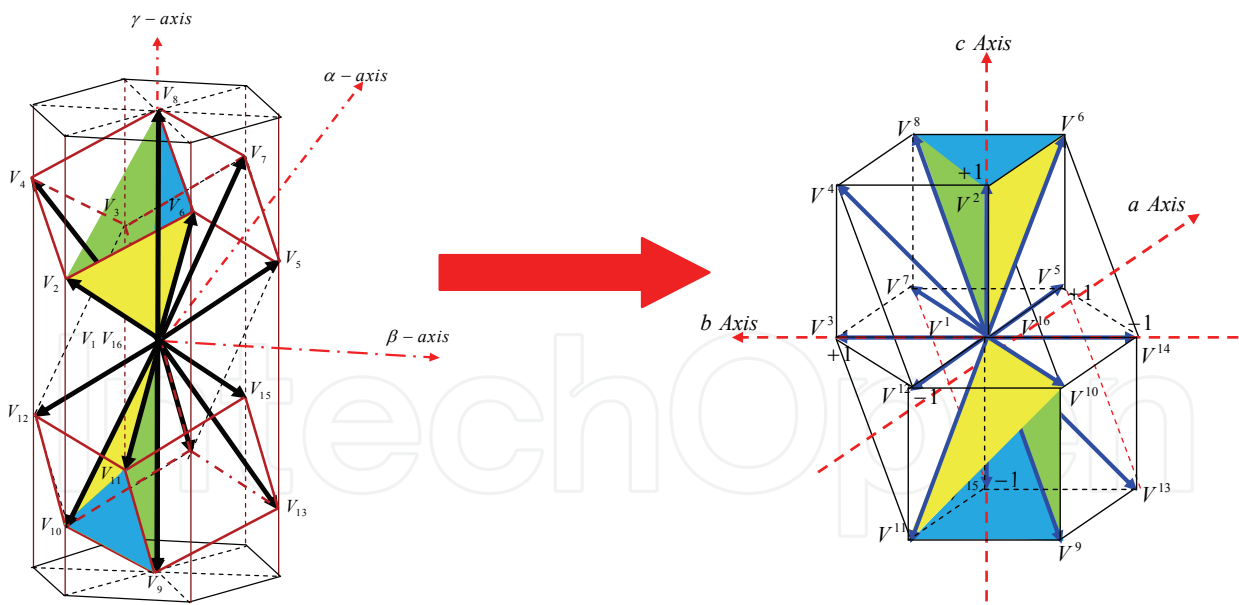


Fig. 11. Presentation of the switching vector in the $\alpha\beta\gamma$ frame

The determination of the tetrahedron can be extracted directly by comparing the relative values of U_a , U_b , U_c and zero. The Zero value is used in the comparison for determining the polarity of the voltages in three phases. If the voltages U_a , U_b , U_c and zero are ordered in descending order, the possible number of permutations is 24 which is equal to the number of Tetrahedron. Tab. 5 shows the relationship between Terahedrons and the

order of U_a, U_b, U_c and zero. Therefore the tetrahedron $T(x,y,z)$ can be determined without complex calculations. These elements are respectively denoted U_1, U_2, U_3 and U_4 in descending order.

$$U_1 \geq U_2 \geq U_3 \geq U_4$$

(17)

For example for: $U_a \geq 0 \geq U_c \geq U_b$
It can be found that: $U_1 = U_a, U_2 = 0, U_3 = U_c, U_4 = U_b$.

| Tetrahedron | Vecteurs | $U_1 \geq U_2 \geq U_3 \geq U_4$ | Tetrahedron | Vecteurs | $U_1 \geq U_2 \geq U_3 \geq U_4$ |
|-------------|--------------|----------------------------------|-------------|--------------|----------------------------------|
| 1 | $T(1,3,7)$ | $0 \geq U_c \geq U_b \geq U_a$ | 13 | $T(4,5,7)$ | $U_b \geq 0 \geq U_c \geq U_a$ |
| 2 | $T(1,3,11)$ | $0 \geq U_c \geq U_a \geq U_b$ | 14 | $T(4,5,13)$ | $U_b \geq 0 \geq U_a \geq U_c$ |
| 3 | $T(1,5,7)$ | $0 \geq U_b \geq U_c \geq U_a$ | 15 | $T(4,6,7)$ | $U_b \geq U_c \geq 0 \geq U_c$ |
| 4 | $T(1,5,13)$ | $0 \geq U_b \geq U_a \geq U_c$ | 16 | $T(4,6,14)$ | $U_b \geq U_c \geq U_c \geq 0$ |
| 5 | $T(1,9,11)$ | $0 \geq U_a \geq U_c \geq U_b$ | 17 | $T(4,12,13)$ | $U_b \geq U_a \geq 0 \geq U_c$ |
| 6 | $T(1,9,13)$ | $0 \geq U_a \geq U_b \geq U_c$ | 18 | $T(4,12,14)$ | $U_b \geq U_a \geq U_c \geq 0$ |
| 7 | $T(2,3,7)$ | $U_c \geq 0 \geq U_b \geq U_a$ | 19 | $T(8,9,11)$ | $U_a \geq 0 \geq U_c \geq U_b$ |
| 8 | $T(2,3,11)$ | $U_c \geq 0 \geq U_a \geq U_b$ | 20 | $T(8,9,13)$ | $U_a \geq 0 \geq U_b \geq U_c$ |
| 9 | $T(2,6,7)$ | $U_c \geq U_b \geq 0 \geq U_a$ | 21 | $T(8,10,11)$ | $U_a \geq U_c \geq 0 \geq U_b$ |
| 10 | $T(2,6,14)$ | $U_c \geq U_b \geq U_a \geq 0$ | 22 | $T(8,10,14)$ | $U_a \geq U_c \geq U_b \geq 0$ |
| 11 | $T(2,10,11)$ | $U_c \geq U_a \geq 0 \geq U_b$ | 23 | $T(8,12,13)$ | $U_a \geq U_b \geq 0 \geq U_c$ |
| 12 | $T(2,10,14)$ | $U_c \geq U_a \geq U_b \geq 0$ | 24 | $T(8,12,14)$ | $U_a \geq U_b \geq U_c \geq 0$ |

Table 5. Determination of tetrahedron vectors

If an equality occurs between two elements, then the reference voltage is in the boundary between two neighboring tetrahedrons. If two neighboring equalities occur, then the reference voltage is within the boundary of six Tetrahedrons. If an equality is occurs between the first and the second element and at the same time an equality occurs between the third and fourth element, the reference voltage is within the boundary of four Tetrahedron.if three equalities occur, this means that the space vector is passing in the point (0,0,0) connecting all the tetrahedrons. For example:

1.

For $U_c \geq U_a \geq U_b = 0$ the reference voltage is located in the interface of $T(2,10,11)$ and $T(2,10,14)$, which contains the two vectors V_2 and V_{10} .
2.

For $U_b \geq U_c = 0 = U_a$ the reference voltage is parallel to V_4 and it is located in the interface among $T(4,5,7), T(4,5,13), T(4,6,7), T(4,6,14), T(4,12,13)$ and $T(4,12,14)$.
3.

For $U_b = U_c \geq 0 = U_a$ the reference voltage is parallel to V_6 and is located in the interface among $T(2,6,7), T(2,6,14), T(4,6,7)$ and $T(4,6,14)$.
4.

For $U_c = U_b = U_a = 0$ the reference voltage is nil.

It is clear, that as the other methods the determination of the tetrahedron $T(x, y, z)$ allows the selection of the three vectors V_x , V_y and V_z , and the calculation of the application duration of the switching states. These switching states have a binary format x , y and z . Using the relationship between the tetrahedrons and the voltages U_a , U_b , U_c and 0 Tab. 5. The rule for the determination of switching states is derived as follows:

$$x = 2^i, y = x + 2^j, z = y + 2^k \quad (18)$$

i, j and k are determined from the elements U_1 , U_2 and U_3 . Similarly the parameter r can be deduced, this parameter is used subsequently for the calculation of the application durations of the three vectors.

$$i = \begin{cases} 0 & U_1 = 0 \\ 1 & U_1 = U_c \\ 2 & U_1 = U_b \\ 3 & U_1 = U_a \end{cases}, j = \begin{cases} 0 & U_1 = 0 \\ 1 & U_1 = U_c \\ 2 & U_1 = U_b \\ 3 & U_1 = U_a \end{cases}, k = \begin{cases} 0 & U_1 = 0 \\ 1 & U_1 = U_c \\ 2 & U_1 = U_b \\ 3 & U_1 = U_a \end{cases}, r = \begin{cases} 0 & U_1 = 0 \\ 1 & U_1 = U_c \\ 2 & U_1 = U_b \\ 3 & U_1 = U_a \end{cases} \quad (19)$$

The determination of the duration of each vector is given by:

$$\begin{bmatrix} T_1 \\ T_2 \\ T_3 \end{bmatrix} = \frac{T_p}{U_{dc}} \begin{bmatrix} a_1 & a_4 & a_7 \\ a_2 & a_5 & a_8 \\ a_3 & a_6 & a_9 \end{bmatrix} \cdot \begin{bmatrix} U_a \\ U_b \\ U_c \end{bmatrix} \quad (20)$$

This method can be applied in both frames $a-b-c$ and $\alpha-\beta-\gamma$ in the same way. The switching states x , y and z or the voltage vectors V_x , V_y and V_z are independent of the coordinates and are determined only from the relative values of U_a , U_b and U_c . All matrix elements a_i take the values 0, 1 or -1. Therefore, the calculations need only the addition and subtraction of U_a , U_b and U_c except the coefficient T_p/U_{dc} . The a_i values are determined from the following relations where they can be presented as a function of elementary relative voltages:

$$\begin{aligned} a_1 &= \begin{cases} 1 & U_a = U_1 \\ -1 & U_a = U_2 \\ 0 & \text{otherwise} \end{cases}, a_2 = \begin{cases} 1 & U_a = U_2 \\ -1 & U_a = U_3 \\ 0 & \text{otherwise} \end{cases}, a_3 = \begin{cases} 1 & U_a = U_3 \\ -1 & U_a = U_4 \\ 0 & \text{otherwise} \end{cases} \\ a_4 &= \begin{cases} 1 & U_b = U_1 \\ -1 & U_b = U_2 \\ 0 & \text{otherwise} \end{cases}, a_5 = \begin{cases} 1 & U_b = U_2 \\ -1 & U_b = U_3 \\ 0 & \text{otherwise} \end{cases}, a_6 = \begin{cases} 1 & U_b = U_3 \\ -1 & U_b = U_4 \\ 0 & \text{otherwise} \end{cases} \\ a_7 &= \begin{cases} 1 & U_c = U_1 \\ -1 & U_c = U_2 \\ 0 & \text{otherwise} \end{cases}, a_8 = \begin{cases} 1 & U_c = U_2 \\ -1 & U_c = U_3 \\ 0 & \text{otherwise} \end{cases}, a_9 = \begin{cases} 1 & U_c = U_3 \\ -1 & U_c = U_4 \\ 0 & \text{otherwise} \end{cases} \end{aligned} \quad (21)$$

If we substitute these values in (20) and according to the given definitions of i , j , k and r , the application duration of adjacent vectors, can be expressed in (22), it shows that they are only depending on the relative voltage vectors U_1 , U_2 , U_3 and U_4 .

$$\begin{bmatrix} T_1 \\ T_2 \\ T_3 \end{bmatrix} = \frac{T_p}{U_{dc}} \cdot \begin{bmatrix} U_1 - U_2 \\ U_2 - U_3 \\ U_3 - U_4 \end{bmatrix} \quad (22)$$

6. 3D-SVM new algorithm for four leg inverters

A new algorithm of tetrahedron determination applied to the SVPWM control of four leg inverters was presented by the authors in [82]. In this algorithm, a new method was proposed for the determination of the three phase system reference vector location in the space; even the three phase system presents unbalance, harmonics or both of them. As it was presented in the previous works the reference vector was replaced by three active vectors and two zero vectors following to their duty times [34-35], [69-80]. These active vectors are representing the vectors which are defining the special tetrahedron in which the reference vector is located.

In the actual algorithm the numeration of the tetrahedron is different from the last works, the number of the active tetrahedron is determined by new process which seems to be more simplifiers, faster and can be implemented easily. Form (5) and (12) the voltages in the $\alpha\beta\gamma$ frame can be presented by:

$$\begin{bmatrix} V_\alpha \\ V_\beta \\ V_\gamma \end{bmatrix} = C \cdot \begin{bmatrix} S_a - S_f \\ S_b - S_f \\ S_c - S_f \end{bmatrix} \cdot V_g \quad (23)$$

It is clear that there is no effect of the fourth leg behaviours on the values of the components in the $\alpha - \beta$ plane. The effect of the fourth leg switching is remarked in the γ component. The representation of these vectors is shown in Fig. 12 -c-.

6.1 Determination of the truncated triangular prisms

As it is shown in the previous sections, the three algorithms are based on the values of the $a-b-c$ frame reference voltage components. In this algorithm there is no need for the calculation of the zero (homopolar) sequence component of the reference voltage. Only the values of the reference voltage in $a-b-c$ frame are needed. The determination of the truncated triangular prism (TP) in which the reference voltage space vector is located is based on four coefficients. These four coefficients are noted as C_0 , C_2 , C_3 and C_4 . Their values can be calculated via two variables x and y which are defined as follows:

$$x = \frac{V_\alpha}{\|V\|} \quad (24)$$

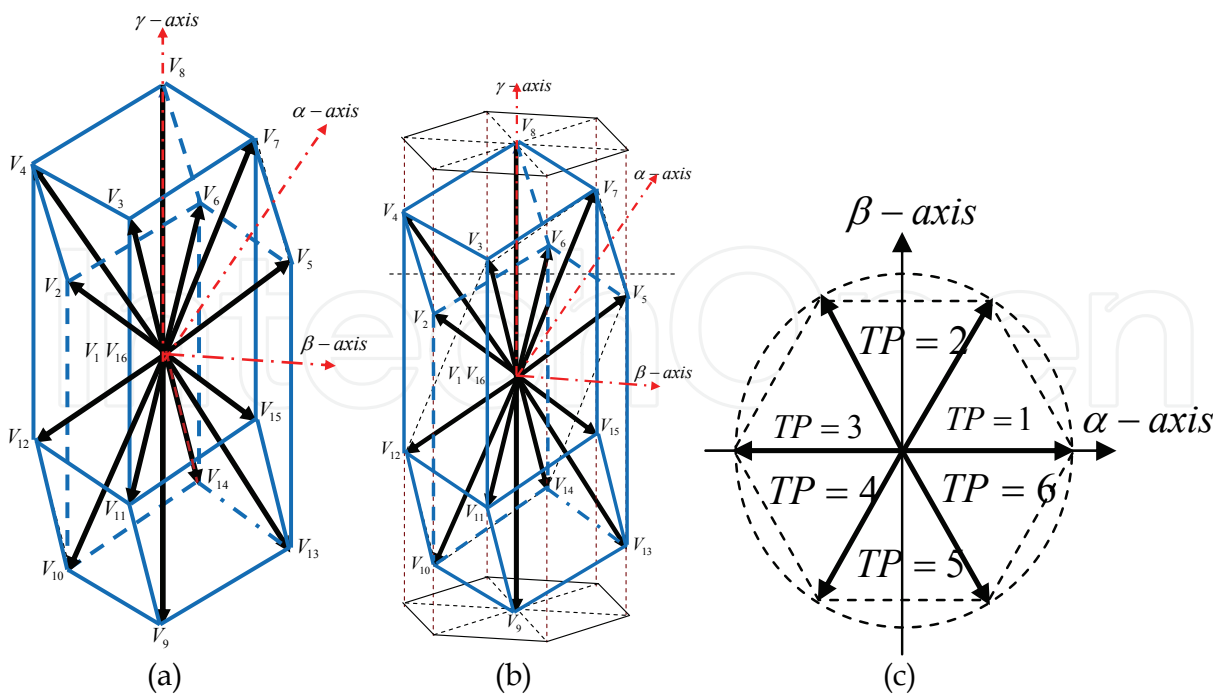


Fig. 12. Presentation of the possible switching vectors in $a - b - c$

$$y = \frac{V_{\beta}}{\|V\|} \tag{25}$$

Where:

$$\|V\| = \sqrt{V_{\alpha}^2 + V_{\beta}^2} \tag{26}$$

The coefficients can be calculated as follows:

$$\begin{bmatrix} C_0 \\ C_1 \\ C_2 \\ C_3 \end{bmatrix} = \begin{bmatrix} 1 \\ INT\left(\frac{5}{2} - x - \varepsilon\right) \\ INT(1 - y - \varepsilon) \\ INT\left(\frac{5}{2} + x + \varepsilon\right) \end{bmatrix} \tag{27}$$

ε is used to avoid the confusion when the reference vector passes in the boundary between two adjacent triangles in the $\alpha\beta$ plane, the reference vector has to be included at each sampling time only in one triangle Fig. 12-c-. On the other hand, as it was mentioned in the first family works, the location of the reference vectors passes in six prism Fig. 12-b-, but effectively this is not true as the reference vector passes only in six pentahedron or six truncated triangular prism (TP) as the two bases are not presenting in parallel planes following to the geometrical definition of the prism Fig. 12-a-. The number of the truncated prism TP can be determined as follows:

$$TP = 3C_2 + \sum_{i=0}^2 (-1)^i C_i C_{i+1} \tag{28}$$

6.2 Determination of the tetrahedrons

In each TP there are six vectors, these vectors define four tetrahedrons. Each tetrahedron contains three active vectors from the six vectors found in the TP . The way of selecting the tetrahedron depends on the polarity changing of each switching components included in one vector. The following formula permits the determination of the tetrahedron in which the voltage space vector is located.

$$T_h = 4(TP - 1) + 1 + \sum_{i=1}^3 a_i \quad (29)$$

Where:

$$a_i = 1 \quad \text{if} \quad V_i \geq 0 \quad \text{else} \quad a_i = 0 \\ i = a, b, c$$

To clarify the process of determination of the TP and T_h for different three phase reference system voltages cases which may occurred. Figures 13 and 14 are presenting two general cases, where:

- Figures noted as 'a' present the reference three phase voltage system;
- Figures noted as 'b' present the space vector trajectory of the reference three phase voltage system ;
- Figures noted as 'c' present the concerned TP each sampling time, where the reference space vector is located;
- Figures noted as 'd' present the concerned T_h in which the reference space vector is located.

Case I: unbalanced reference system voltages

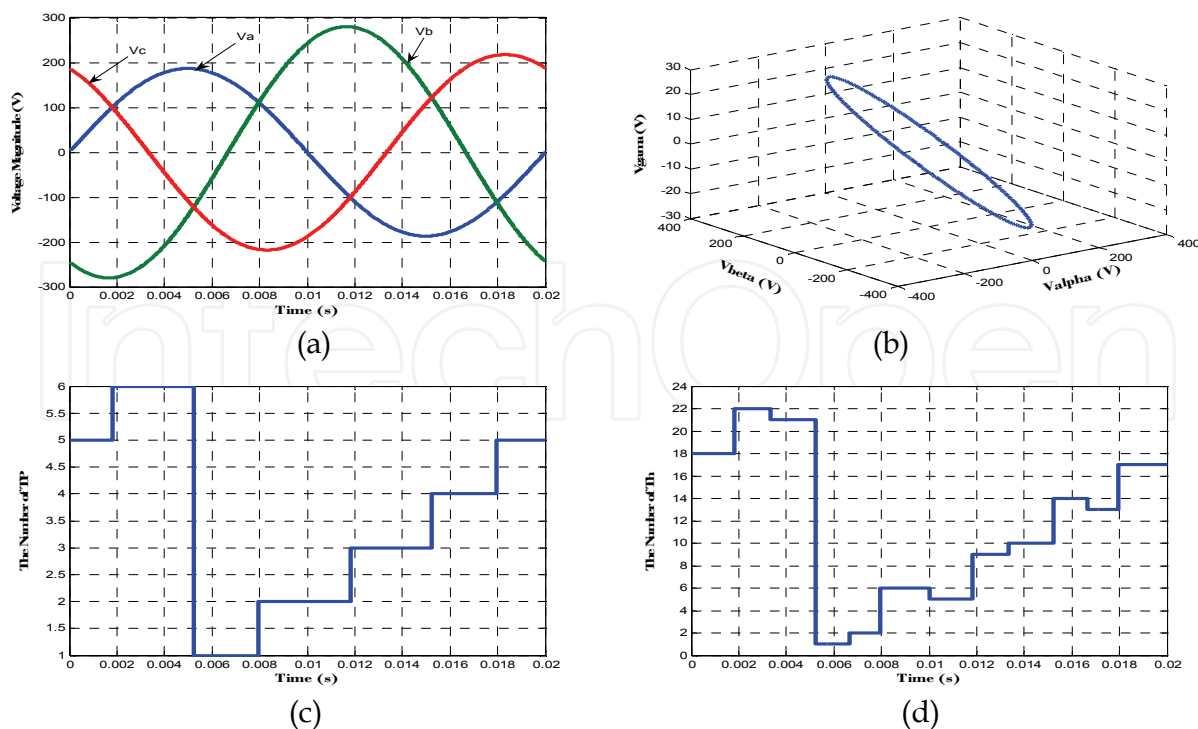


Fig. 13. Presentation of instantaneous three phase reference voltages, reference space vector, TP and T_h

Case II Unbalanced reference system voltages with the presence of unbalanced harmonics

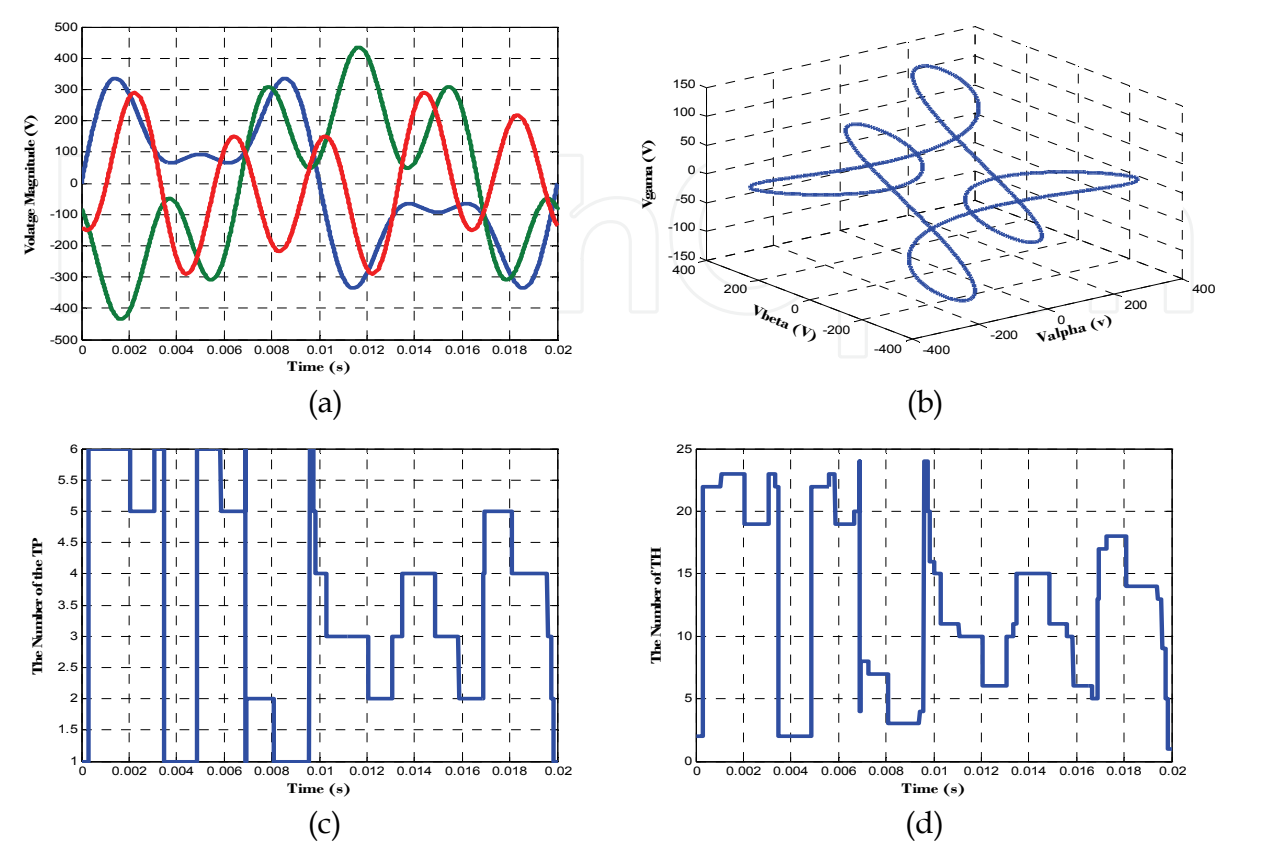


Fig. 14. Presentation of instantaneous three phase reference voltages, reference space vector, TP and T_h

6.3 Calculation of duty times

To fulfill the principle of the SVPWM as it is mentioned in (9) which can be rewritten as follows:

$$V_{ref} \cdot T_z = \sum_{i=0}^3 T_i \cdot V_i \tag{30}$$

Where:

$$T_z = \sum_{i=0}^3 T_i \tag{31}$$

In this equation the $a-b-c$ frame components can be used, either than the use of the $\alpha-\beta-\gamma$ frame components of the voltage vectors for the calculation of the duty times, of course the same results can be deduced from the use of the two frames. The vectors V_1, V_2 and V_3 present the edges of the tetrahedron in which the reference vector is lying. So each vector can take the sixteen possibilities available by the different switching possibilities. On the other hand these vectors have their components in the $\alpha-\beta-\gamma$ frame as follows:

$$V_i = \begin{bmatrix} V_{\alpha i} \\ V_{\beta i} \\ V_{\gamma i} \end{bmatrix} = C \cdot \begin{bmatrix} S_{ai} - S_{fi} \\ S_{bi} - S_{fi} \\ S_{ci} - S_{fi} \end{bmatrix} \cdot V_g \quad (32)$$

From (30), (31) and (32) the following expression is deduced:

$$\sum_1^3 T_i \cdot \begin{bmatrix} S_{ai} - S_{fi} \\ S_{bi} - S_{fi} \\ S_{ci} - S_{fi} \end{bmatrix} = \frac{1}{V_g} \cdot C^{-1} \cdot V_{ref} \cdot T_z \quad (33)$$

In the general case the following equation can be used to calculate the duty time for the three components used in the same tetrahedron:

$$T_i = \sigma \cdot \begin{bmatrix} (S_{ai} - S_{fi}) \cdot ((S_{bj} - S_{ff}) \cdot (S_{ck} - S_{fk}) - (S_{bk} - S_{fk}) \cdot (S_{cj} - S_{ff})) \\ (S_{bi} - S_{fi}) \cdot ((S_{ak} - S_{fk}) \cdot (S_{cj} - S_{ff}) - (S_{aj} - S_{ff}) \cdot (S_{ck} - S_{fk})) \\ (S_{ci} - S_{fi}) \cdot ((S_{aj} - S_{ff}) \cdot (S_{bk} - S_{fk}) - (S_{ak} - S_{fk}) \cdot (S_{bj} - S_{ff})) \end{bmatrix}^t \cdot \begin{bmatrix} V_{refa} \\ V_{refb} \\ V_{refc} \end{bmatrix} \quad (34)$$

Where:

$$\sigma = \frac{1}{\sum_1^3 (S_{ai} - S_{fi}) \cdot [(S_{bj} - S_{ff}) \cdot (S_{ck} - S_{fk}) - (S_{bk} - S_{fk}) \cdot (S_{cj} - S_{ff})]} \quad (35)$$

Variable j and k are supposed to simplify the calculation where:

$$j = i + 1 - 3 \cdot INT(i / 3); \quad k = i + 2 - 3 \cdot INT((i + 1) / 3) \quad i = 1, 2, 3$$

A question has to be asked. From one tetrahedron, how the corresponding edges of the existing switching vectors can be chosen for the three vectors used in the proposed SVPWM. Indeed the choice of the sequence of the vectors used for V_1 , V_2 and V_3 in one tetrahedron depends on the SVPWM sequencing schematic used [108],[115], in one sampling time it is recommended to use four vectors, the fourth one is corresponding to zero vector, as it was shown only two switching combination can serve for this situation that is V^{16} (0000) and V^1 (1111). On the other hand only one changing state of switches can be accepted when passing from the use of one vector to the following vector. For example in tetrahedron 1 the active vectors are: V^{11} (1000), V^3 (1001) and V^4 (1101), it is clear that if the symmetric sequence schematic is used and starts with vector V^1 then the sequence of the use of the other active vectors can be realized as follow:

$$V^1, V^{11}, V^3, V^4, V^{10}, V^4, V^3, V^{11}, V^1$$

| Active vector | V^1 | V^{11} | V^3 | V^4 | V^{10} | V^4 | V^3 | V^{11} | V^1 |
|-------------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| S_a | 1 | 1 | 1 | 1 | 0 | 1 | 1 | 1 | 1 |
| S_b | 1 | 1 | 0 | 0 | 0 | 0 | 0 | 1 | 1 |
| S_c | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 |
| S_f | 1 | 1 | 1 | 0 | 0 | 0 | 1 | 1 | 1 |
| $T_a^{1\cdots 0}$ | | | | | | | | | |
| $T_b^{1\cdots 0}$ | | | | | | | | | |
| $T_c^{1\cdots 0}$ | | | | | | | | | |
| $T_f^{1\cdots 0}$ | | | | | | | | | |
| | $\frac{t_0}{4}$ | $\frac{t_1}{2}$ | $\frac{t_2}{2}$ | $\frac{t_3}{2}$ | $\frac{t_0}{2}$ | $\frac{t_3}{2}$ | $\frac{t_2}{2}$ | $\frac{t_1}{2}$ | $\frac{t_0}{4}$ |

Otherwise, if it starts with vector V^{16} then the sequence of the active vectors will be presented as follow Tab.9:

$$V^{16}, V^4, V^3, V^{11}, V^1, V^{11}, V^3, V^4, V^{16}$$

| Active vector | V^{16} | V^4 | V^3 | V^{11} | V^1 | V^{11} | V^3 | V^4 | V^{16} |
|-------------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| S_a | 0 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 0 |
| S_b | 0 | 0 | 0 | 1 | 1 | 1 | 0 | 0 | 0 |
| S_c | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 |
| S_f | 0 | 0 | 1 | 1 | 1 | 1 | 1 | 0 | 0 |
| $T_a^{1\cdots 0}$ | | | | | | | | | |
| $T_b^{1\cdots 0}$ | | | | | | | | | |
| $T_c^{1\cdots 0}$ | | | | | | | | | |
| $T_f^{1\cdots 0}$ | | | | | | | | | |
| | $\frac{t_0}{4}$ | $\frac{t_1}{2}$ | $\frac{t_2}{2}$ | $\frac{t_3}{2}$ | $\frac{t_0}{2}$ | $\frac{t_3}{2}$ | $\frac{t_2}{2}$ | $\frac{t_1}{2}$ | $\frac{t_0}{4}$ |

6.4 Applications

To finalize this chapter two applications are presented here to show the effectiveness of the four-leg inverter. The first application is the use of the four-leg inverter to feed a balanced resistive linear load under unbalanced voltages. The second application is the use of the four-leg inverter as an active power filter, where the main aim is to ensure a sinusoidal balanced current circulation in the source side. In the two cases an output filter is needed between the point of connection and the inverter, in the first case an “L” filter is used, while for the second case an “LCL” filter is used as it is shown in Fig. 15 and Fig. 20.

6.4.1 Applications1

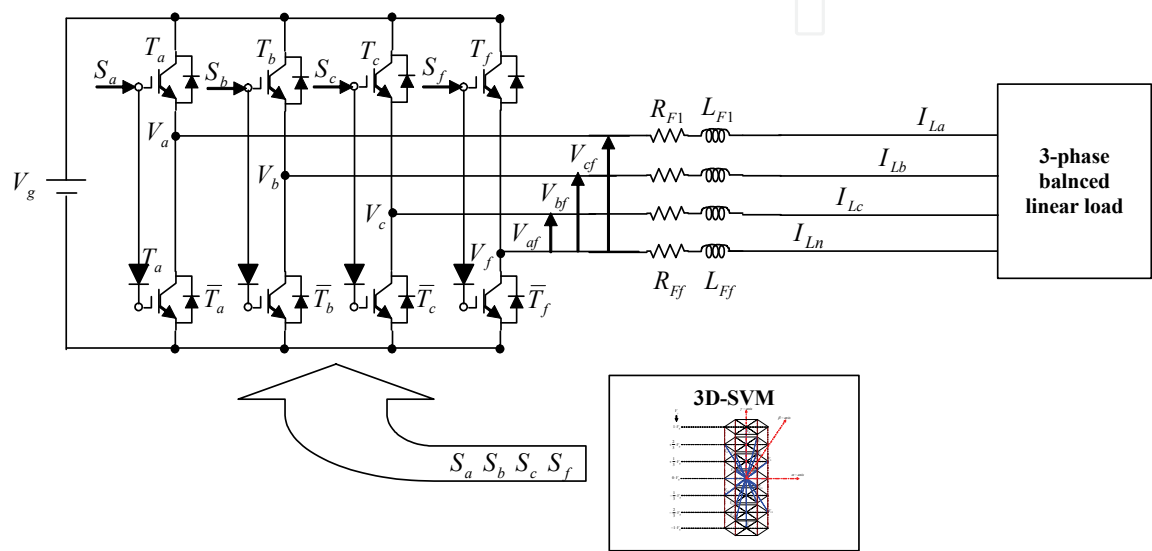


Fig. 15. Four-leg inverter is used as a Voltage Source Inverter ‘VSI’ for feeding balanced linear load under unbalanced voltages.

In this application, the reference unbalanced voltage and the output voltage produced by the four leg inverter in the three phases a, b and c are presented in Fig. 16. The currents in the four legs are presented in Fig. 17, it is clear that because of the voltage unbalance the fourth leg is handling a neutral current. To clarify the flexibility of the four leg inverter and the control algorithm used, Fig. 18 shows the truncated prisms and the tetrahedron in which the reference voltage space vector is located.

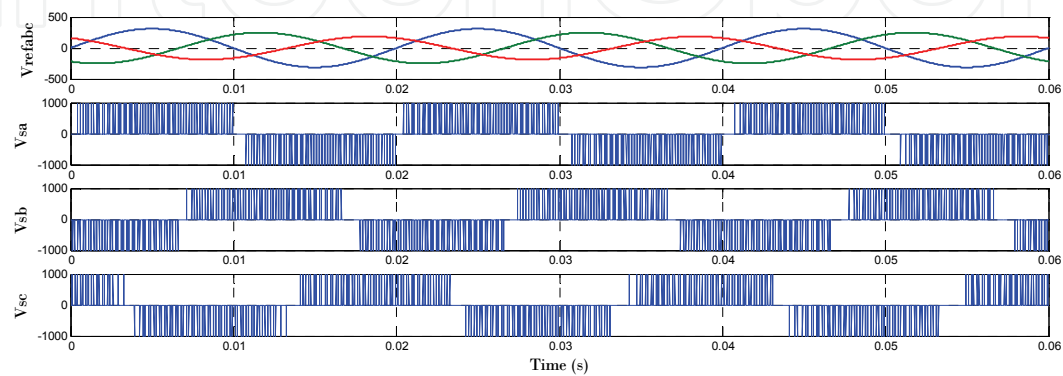


Fig. 16. Presentation of three phase reference voltages and the output voltage of the three legs.

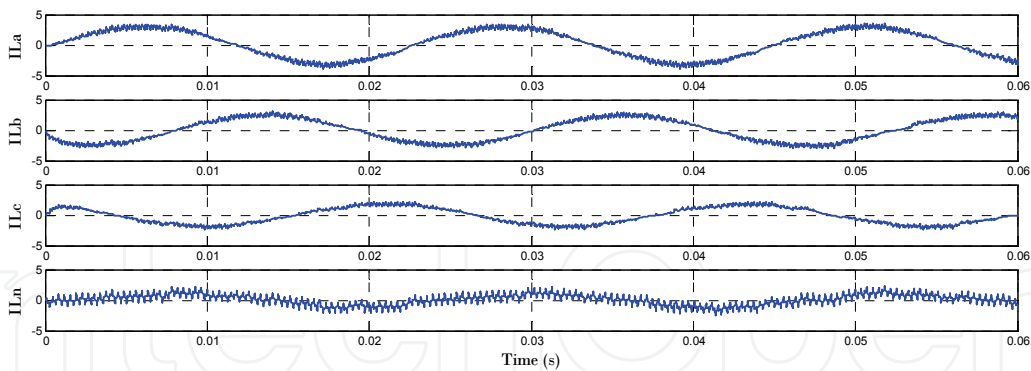


Fig. 17. Presentation of instantaneous load currents generated by the four legs

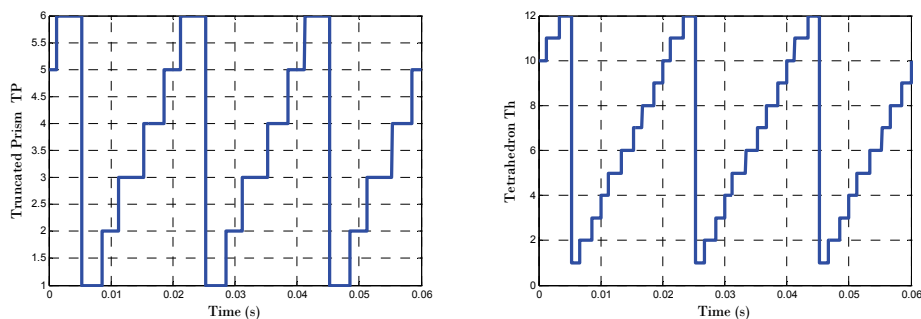


Fig. 18. Determination of the Truncated Prism TP and the tetrahedron T_h in which the reference voltage space vector is located.

The presentation of the reference voltage space vector and the load current space vector are presented in the both frames $\alpha - \beta - \gamma$ and $a - b - c$, where the current is scaled to compare the form of the current and the voltage, just it is important to keep in mind that the load is purely resistive.

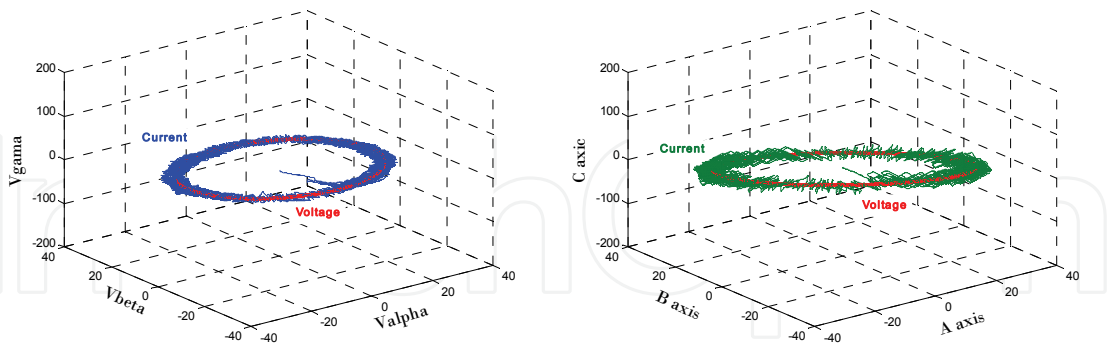


Fig. 19. Presentation of the instantaneous space vectors of the three phase reference system voltages and load current in $\alpha - \beta - \gamma$ and $a - b - c$ frames (the current is multiplied by 10, to have the same scale with the voltage)

6.4.2 Applications2

The application of the fourth leg inverter in the parallel active power filtering has used in the last years, the main is to ensure a good compensation in networks with four wires, where the three phases currents absorbed from the network have to be balanced, sinusoidal

and with a zero shift phase, on the other side the neutral wire has to have a nil current circulating toward the neutral of power system source. Figures 21, 22, 23 and 24 show the behavior of the four leg inverter to compensation the harmonics in the current. The neutral current of the source is nil as it is shown in Fig 24. Finally the current space vectors of the load, the active filter and the source in the both frames $\alpha - \beta - \gamma$ and $a - b - c$ are presented.

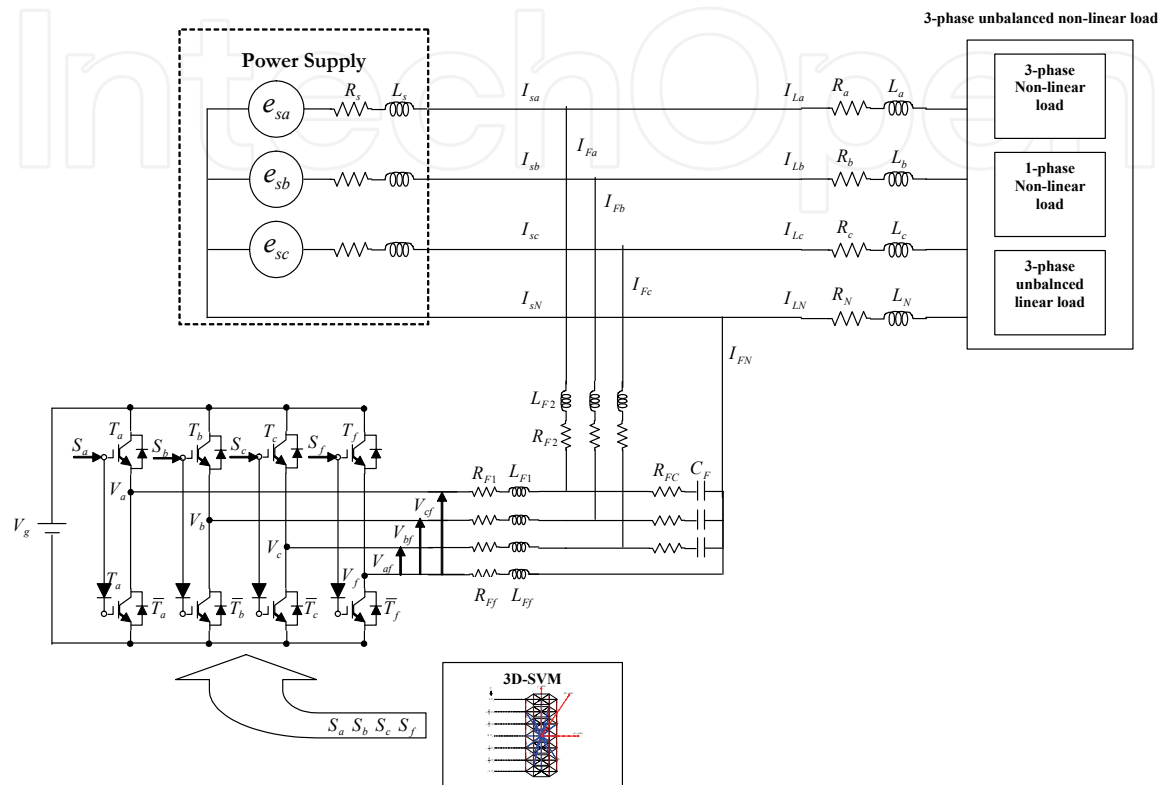


Fig. 20. Four-leg inverter is used as a Parallel Active Power Filter ‘APF’ for ensuring a sinusoidal source current.

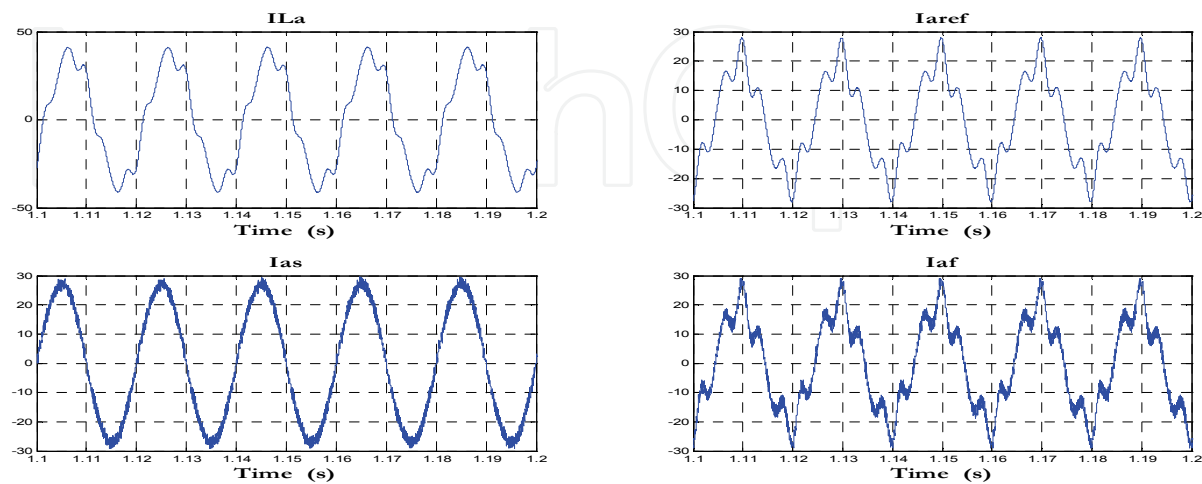


Fig. 21. Presentation of the instantaneous currents of Load, reference, active power filter and source of phase ‘a’

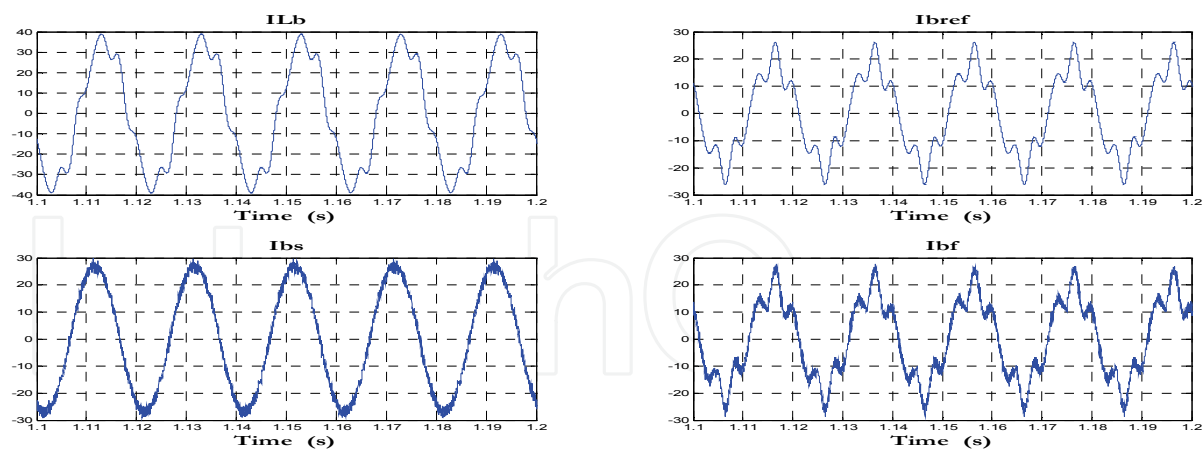


Fig. 22. Presentation of the instantaneous currents of Load, reference, active power filter and source of phase ‘b’

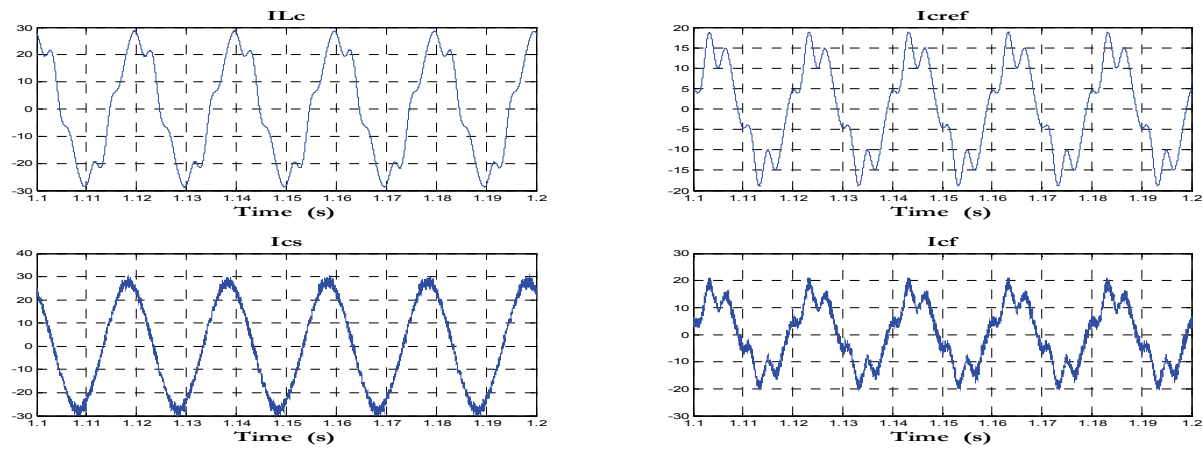


Fig. 23. Presentation of the instantaneous currents of Load, reference, active power filter and source of phase ‘c’

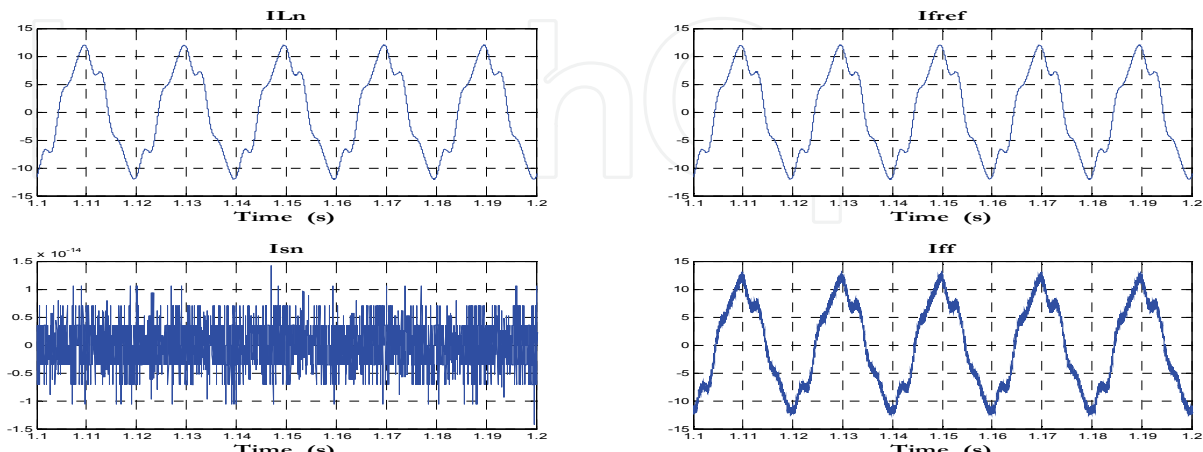


Fig. 24. Presentation of the instantaneous currents of Load, reference, active power filter and source of the fourth neutral leg ‘f’

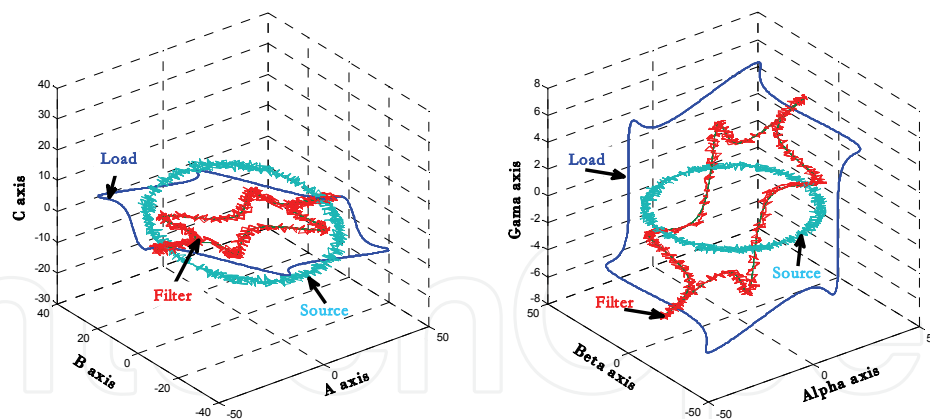


Fig. 25. Presentation of the instantaneous currents space vectors of the load, active power filter and the source in $\alpha - \beta - \gamma$ and $a - b - c$ frames

7. Conclusion

This chapter deals with the presentation of different control algorithm families of four leg inverter. Indeed four families were presented with short theoretical mathematical explanation, where the first one is based on $\alpha - \beta - \gamma$ frame presentation of the reference space vector, the second one is based on $a - b - c$ frame where there is no need for matrix transformation. The third one which was presented recently where the determination of the space vector is avoided and there is no need to know which tetrahedron is containing the space vector, it is based on the direct values of the three components following the three phases, the duty time can be evaluated without the passage through the special location of the space vector. The fourth method in benefiting from the first and second method, where the matrix used for the calculation of the duty time containing simple operation and the elements are just 0,1 and -1. As a result the four methods can lead to the same results; the challenge now is how the method used can be implemented to ensure low cost time calculation, firstly on two level inverters and later for multilevel inverters. But it is important to mention that the SVM PWM gave a great flexibility and helps in improving the technical and economical aspect using the four leg inverter in several applications.

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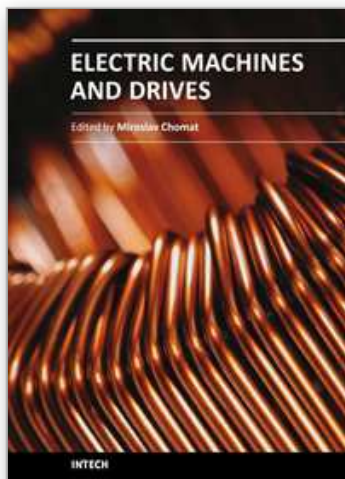
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