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3D SVM for Three Phase Four Leg Inverters using ghϒ Coordinate System to Reduce Computational Complexity

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Abstract: ***Three dimensional space vector modulation technique (3DSVM) for three phase four leg inverters with ghϒ coordinate system is discussed in this paper. 3DSVM is the improved version to deal with unbalanced load in three phase inverters. To deal unbalanced load condition in three phase inverters, different modulation techniques like αβϒ and abc coordinate system are used. ghϒ is the new system that combines the positive aspects of previous versions.***

Keywords: 3DSVM, SVM, Inverter, αβϒ coordinate, abc coordinate, ghϒ coordinate

1. Introduction

An ideal three phase system must be capable to supply a balanced sinusoidal voltage and current, irrespective of load, whether it is balanced or not. The power quality problems increase day by day due to the increase of decentralised generation of power using renewable energy sources such as solar energy and wind energy [2][3]. The power quality is characterised by harmonics, reactive power, neutral current, voltage sags and voltage swells , and quality decreases with population of non-linear single phase loads and unbalanced three phase loads[4]. The power quality improvement is being raised by industrial, commercial as well as residential power users[5]. Non-uniformly connected non-linear loads like static converters, electric machines and other unbalanced loads results into harmonic currents and thereby degradation of power quality. Common methods of power quality improvements are transient suppressers, line voltage regulators, uninterrupted power supplies, static filters and active power filters [1] [6]. Harmonic pollution can be addressed by a four wire three phase system, and a converter with four wires provides a flexible control over the neutral currents [7] caused by loads.

3DSVM found applications in power quality improvement by using active power filters or Active power compensators, by injecting harmonics into the three phase system, equal to the distortion provided by the loads, in phase opposite, applied at the point of common coupling[8].

This paper explains ghϒ coordinate system in details. In section 2, it explains the structure of a three leg and four leg inverters. In next section 3DSVM is explained in detail with the need for 4L system. As the last section, ghϒ coordinate is explained with comparison with older coordinate systems.

2. Three Phase Four Wire Systems

a) Types of Three Phase Four Wire system

Inverter configuration to mitigate the unbalance in three phase system must have a neutral line for the flow of neutral current. Four wire inverter topology is used to produce balanced output voltages by controlling the neutral current, even under unbalanced load [26]. The two popular configurations of converter that provide a neutral connection are,

a) Split DC link capacitor type [25][27].
b) Four leg inverter topology [25][28].

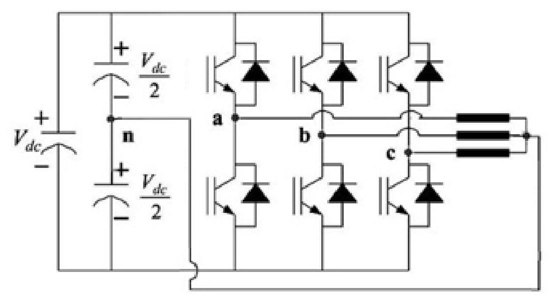


Fig 1 Four leg split DC lnk cpacitor topology

b) Split DC Link capacitor type

This is the conventional and simple approach to handle neutral current by linking it to the centre point of DC link capacitors, so that the neutral current can flow through the capacitors [25][19][29] Fig.1. This configuration has only six switches and thereby reduced cost of installation and switching loss. As the neutral point is connected to the centre point of DC link, the compensation current will flow through the upper and lower capacitors, causes variations in DC link voltages. In [19] an algorithm that simultaneously control current harmonics, neutral current and DC voltage variation across capacitors, using 3DSVM is presented. Here two zero vectors that point to the opposite axis are utilized for balancing the voltages across the upper and lower capacitors.

The drawbacks of this method are (i) high value capacitor requirement for DC link voltage regulation and (ii) poor utilization of DC link voltage[30][26][31].

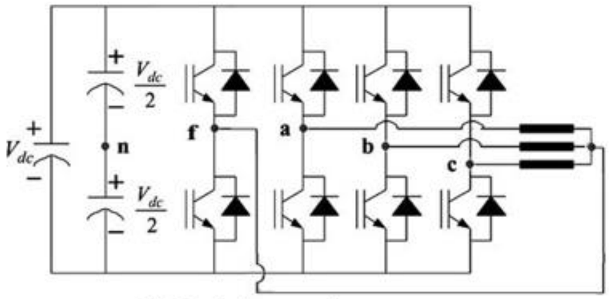


Fig 2 Four leg inverter topology

c) Four leg inverter topology

This topology is the advanced alternate inverter configuration to handle neutral due to unbalanced load[32]. The drawbacks of split DC link capacitor system can be solved using this configuration by tying neutral link with fourth leg. Neutral link is accessible for current compensation and provides maximum DC link utilization [30], with other advantages requires small capacitance value, EMI and CMV reduction[31]. Compared to conventional three legged converter controlled by 2D space vector modulation, a four legged converter requires 3DSVM with sixteen switching vectors[33]. The switching vector controllability of this topology is better than split capacitor topology [21][26].

3. Three-dimensional space vector modulation

a) Three Dimensional Space Vector

3D space vector is the equivalent resultant rotating vector from a three phase quantity. The instantaneous voltage space vector can be expressed as$V_s = \sqrt{\frac{2}{3}}\,(V_a + \alpha.V_b + \alpha^2.V_c$, where $\alpha = e^{j\frac{2\pi}{3}}$ $and\ \alpha^2 = e^{-j\frac{2\pi}{3}}$

In conventional three phase inverter, an assumption of $V_a + V_b + V_c = 0$ is made, where the variables are in a, b, c coordinates. V_{abc} can be transformed into variables in $\alpha\beta$ orthogonal coordinates $V_{\alpha\beta}$. Using 3 sets of switches, a conventional inverter can represent 8 possible switching vectors, and is represented as a regular hexagon in 2D space [25].

The necessity of 3DSVM is first discussed with a scheme in [25][28],1997, and it is considered to be the best switching scheme for a three phase four-leg inverter with balanced or unbalanced load. It directly represents the neutral current resulted by unbalanced load as a third dimension, and the scheme is a generalization of conventional 2DSVM.

In unbalanced system $V_a + V_b + V_c \neq 0$, due to zero and negative sequence current. These three phase quantities are three independent variables that can be transformed into three dimensional orthogonal coordinates $V_{\alpha\beta\gamma}$ [25][13][7]. The transformation equation of three phase quantity into αβγ coordinate is given by Clarke transformation (7)

$$\begin{bmatrix} V_\alpha \\ V_\beta \\ V_\gamma \end{bmatrix} = \frac{2}{3} \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{bmatrix} \begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} \quad (7)$$

The orientation of switching vectors in 3D space is shown in Fig.3.

b) Switching Vectors in 3D Space

In 2D system, a traditional three leg inverter has only eight switching combinations using three switches and its complements. In 3DSVM, the four-leg inverter has sixteen switching combinations using four switches and its complements. The switching pattern can be expressed as $[S_a, S_b, S_c, S_f]$, whereas a, b, c and f correspond to four legs in inverter and each switch, for example $S_a$can be turned on or off and is denoted using $'p'$ for indicating switch is on and $'n'$ for indicating off. Therefore using these switches, total sixteen switching patterns are possible, in which two of them are zero switching vectors$(pppp, nnnn)$, and fourteen are non-zero vectors [34].

c) Reference Vector in 3D Space

In order to maintain a balanced output in steady state, the control reference voltage must be a balanced three phase voltage with positive sequence load current. In actual three phase system with non linear loads, load current becomes corrupted by positive, negative and zero sequence load currents, and the reference vector becomes irregular[30]. If the reference vector is balanced and rotating in a 2D plane, the switching vectors need to have only eight possibilities which can be represented in αβ plane. The presence of load unbalance makes the system to be represented in 3D using three orthogonal axes αβγ.

d) Reference vector Synthesis

In 3D-SVM the reference vector is in a 3D space, whereas in 2D system it is in a regular hexagon. Similar to 2D-SVM, switching vector selection and projection of reference vector into the selected vectors are to be done in 3DSVM also [33][24]. In 3DSVM the selection of switching vector involves complex steps like prism identification and tetrahedron identification, equivalent to triangular sector identification in 2D-SVM [28][25][34]. The tetrahedron corresponds to the nearest vectors for reference vector synthesis. The switching time duration calculation of the selected vectors is very similar to that in 2D system by projecting the reference vector into adjacent non zero reference vectors.

e) Sequencing of Switchning Vectors

Similar to 2D-SVM, the selected switching vectors may be arranged in different schemes based on the different optimization criteria[30]. Sequencing schemes are categorized into Class I and Class II based on the selection of zero sequence vectors [30].

3.1 ghϒ Coordinate System

Improvement in the 3DSVM using 60^0 coordinate system, in which the voltage vectors were placed into $gh\gamma$coordinates was introduced in [34]. Intermediate variables found as a function of reference vectors V_g, V_h, V_γ were used for the determination of switching vectors and calculation of duty cycles. For a 4L inverter, projection of switching vectors in 3D space on a 2D plain is a regular hexagon, so it is feasible to create a 60^0 coordinate system as gh coordinate. In $gh\gamma$ system, the axis g is taken to coincide with α of αβ coordinate system in 2D, h is taken at 60^0 counter clockwise with g and γ axis is taken perpendicular to both g and h at the origin. The reference vector V_{ref} in abc coordinate

(V_{af}, V_{bf}, V_{cf}) can be transformed into (V_g, V_h, V_γ) $gh\gamma$system [34].

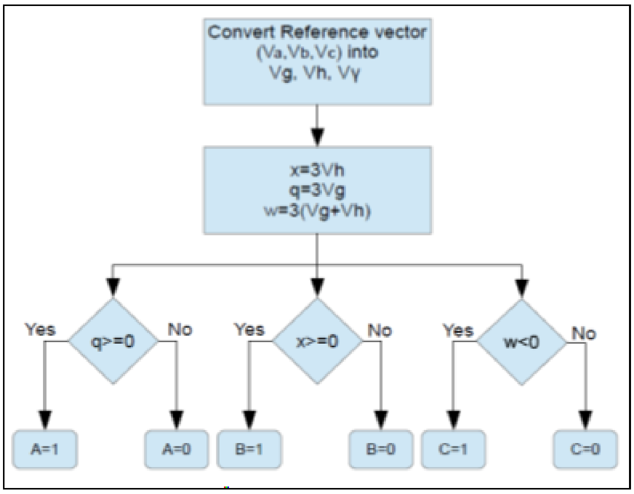
$$\begin{bmatrix} V_g \\ V_h \\ V_\gamma \end{bmatrix} = \frac{2}{3}\begin{bmatrix} 1 & -1 & 0 \\ 0 & 1 & -1 \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{bmatrix}\begin{bmatrix} V_{af} \\ V_{bf} \\ V_{cf} \end{bmatrix} \quad (3)$$

In [34] six numbers of intermediate variables are obtained from (V_g, V_h, V_γ) ,on which linear transformations are performed for prism identification, tetrahedron identification and for duty cycle calculation[34]. The intermediate variables obtained from V_g, V_h, V_γ are,

$x(V_g, V_h, V_\gamma) = 3V_h$
$y(V_g, V_h, V_\gamma) = 2V_g + V_h + 2V_\gamma$
$z(V_g, V_h, V_\gamma) = V_g - V_h - 2V_\gamma$
$s(V_g, V_h, V_\gamma) = V_g + 2V_h - 2V_\gamma$
$q(V_g, V_h, V_\gamma) = 3V_g$
$w(V_g, V_h, V_\gamma) = 3V_g + 3V_h$

Table of Switching vectors in $gh\gamma$coordinates

Switching Vector	V_{af}/V_{dc}	V_{bf}/V_{dc}	V_{cf}/V_{dc}	$V_g/\frac{1}{3}V_{dc}$	$V_h/\frac{1}{3}V_{dc}$	$V_\gamma/\frac{1}{3}V_{dc}$	Vector Name
0000	0	0	0	0	0	0	V_1
0001	0	0	1	0	2	1	V_2
0010	0	1	0	-2	2	1	V_3
0011	0	1	1	-2	0	2	V_4
0100	1	0	0	2	0	1	V_5
0101	1	0	1	2	-2	2	V_6
0110	1	1	0	0	2	2	V_7
0111	1	1	1	0	0	3	V_8
1000	-1	-1	-1	0	0	-3	V_9
1001	-1	-1	0	0	-2	-2	V_{10}
1010	-1	0	-1	-2	2	-2	V_{11}
1011	1	0	0	-2	0	-1	V_{12}
1100	0	-1	-1	2	0	-2	V_{13}
1101	0	-1	0	2	-2	-1	V_{14}
1110	0	0	-1	0	2	-1	V_{15}
1111	0	0	0	0	0	0	V_{16}



$S = A + 2 \times B + 4 \times C$

Prism identification in $gh\gamma$ system

Prism	I	II	III	IV	V	VI
S	3	2	6	4	5	1

As per the table shown above, the vectors in $gh\gamma$are obtained from the transformation and scaling. The control space becomes a hexagonal prism like the 3D space in conventional space vector system in αβγ. Similar to αβγ the projection of vectors into 2D plane forms a hexagon in gh plane. The hexagon can be divided into six triangles in ghplane, and it represents the projection of prism in which the reference vector resides into 2D space [34]. The prism identification can be made easy using the intermediate values q, x and w.

Each prism accommodates four tetrahedrons and is defined by five numbers of planes with three boundary planes. To identify the current tetrahedron, boundary planes are used. Using the intermediate variables x, y, z, s, q and w the tetrahedrons and their duty cycles can be obtained[34] ,and the procedure is same as that of abc coordinate system.

4. Comparative Study of 3D Systems

Comparison of 3DSVM techniques

Characteristics	Types of 3DSVM		
	αβγ	***abc***	***ghγ***
Control area	Hexagonal Prism	Dodecahedron	Hexagonal Prism
No of switchning Vectors	14 NZV & 2 ZV	14 NZV & 2 ZV	14 NZV & 2 ZV
Computational complexity with multilevel	Increases with number of levels	Remains same	Increases with number of levels
Computational Complexity	Higher	Moderate	Less
Dwell time calculation	Look-up table based	Online calculation	Using interediate variables
Computation stages	1. Prism identification 2. Tetrahedron Identification	1. Tetrahedron Identification 2. Vector Identification	1. Prism identification 2. Tetrahedron identification

Characteristics	Types of 3DSVM		
	$\alpha\beta\gamma$	abc	$gh\gamma$
	3. Vector Identification 4. Duty cylce calculation 5. Sequencing	3. Duty cycle calculation 4. Sequencing	3. Vector Identification 4. Duty cycle calculation 5. Sequencing

5. Research in 3DSVM

DC input voltage balancing in a three level four leg inverter using abc coordinate system is presented in [2][40][41] with switching loss minimization techniques. This system inherits all the advantages of abc coordinate system and uses the redundant vectors selection to balance the neutral current flow through the DC link capacitors [40][41].

Simplified algorithm for four leg NPC converters with DC link voltage balancing is presented in [7][41]. Conventional αβγ system is reduced into αβ system for vector selection through tetrahedron identification. It can be extended to higher levels with reduced computational cost.

Modified 3DSVM technique [26][40] without zero vectors with the aim of reducing the switching loss about 33% compared to conventional 3DSVM, with improved DC bus utilization.

The relationships between $\alpha\beta\gamma$ coordinate system and abc coordinate system is explained in [39][40][41] along with algorithm for continuous and discontinuous 3DSVM. It proposes a new technique for tetrahedron identification and active vectors using the relation between reference vector and corresponding tetrahedron.

6. Conclusions

This paper discussed ghϒ coordinate system in detail. The three-phase inverter topology is explained with three-dimensional space vector modulation in the first and second sections. The improvements promised by ghϒ coordinate system is explained with the help of comparison with abc and $\alpha\beta\gamma$ coordinate systems.

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