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1 author:

Ayman Yousef
Faculty of Engineering Shoubra - Benha University

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Space Vector Pulse Width Modulation Technique

Ayman Y. Yousef[#]

[#]*Electrical Engineering Department, Faculty of Engineering at Shoubra, Benha University, Cairo, Egypt.*

Ayman.youssef@feng.bu.edu.eg

***Abstract*— This paper studies the space vector pulse width modulation technique (SVPWM) for the three-phase two position six switches voltage source inverter. Space vector pulse width modulation (SVPWM) provides a superior technique compared to the other PWM techniques. The SVPWM is easier digital realization, reduced harmonics, reduced switching losses and better dc bus utilization. In SVPWM the three phase quantities can be represented by a single complex vector. In this paper, the required parameters of SVPWM implementation such as time duration and the switching patterns of the inverter switches are discussed.**

Keywords— **SVPWM, Voltage source inverter, Complex reference voltage, Sectors, Switching states**

I. INTRODUCTION

A completely different approach results from representing the three phase inverter output voltages in space vector system. In space vector system, the voltage is formed by a space vector of defined quantity and angle in the complex plane (x-y plane). The space vector modulation is recently reported digital PWM generation technique which is based on the concept of Park (space) vector representation of three phase waveforms [1]. On other words, the space vector method of analysis enables representation of the three phase quantities (voltages or currents) by a single complex vector.This method of analysis has been effectively used in analysis of the three phase machines and also of the three phase inverters. It also gives the possibility of several schemes of waveform optimization during transient and steady state operation. The advantages of space vector pulse width modulation are:

1) Higher value of the maximum fundamental output voltage as compared with
2) the suboscillation technique and various sampling techniques.
3) It does not carry much weight in high frequency PWM control.
4) Produces less harmonic distortion in the critical range where the ratio of switching frequency to fundamental frequency is low.

Generally, the space vector technique is essentially based around the decomposition of a reference voltage vector into voltage vectors realizable on a six pulse inverter although, space vector modulation is actually a special case of the triangulation technique [2].

II. DEFINITION OF 3-PHASECOMPOSITE VECTOR

When the space vector method is applied to three output voltages of the inverter bridge, a single vector of fixed length

is obtained. This vector occupies one of eight positions in x-y plane according to the switching state of the inverter. Fig. 1 shown a three-phase voltage source inverter model with six power transistors Q1 to Q6 that shape the output voltage exits across a balanced three phase star connected load such as AC motor.

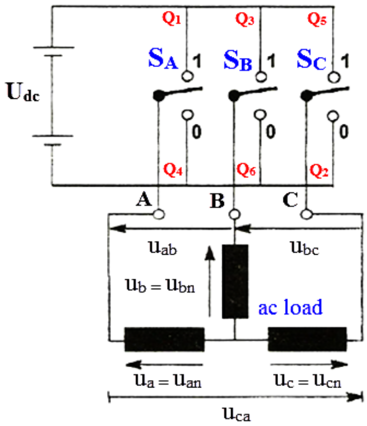

Fig. 1 Three phase star connected load

The individual phase-to-phase voltages U_{an}, U_{bn}, and U_{cn} appearing across each of the phase loads can be written as:

$$u_{an} = U_s \cos \omega t \quad (1)$$

$$u_{bn} = U_s \cos(\omega t - 2\pi/3) \quad (2)$$

$$u_{cn} = U_s \cos(\omega t - 4\pi/3) \quad (3)$$

It is well known that any three phase system may be transformed into an equivalent two phase system as follow:

$$u_\alpha = (2/3)[u_a - (1/2)u_b - (1/2)u_c] \quad (4)$$

and

$$u_\beta = (2/3)[(\sqrt{3}/2)u_b - (\sqrt{3}/2)u_c] \quad (5)$$

Where u_α and u_β together form an orthogonal instantaneous two phase ac set whose vector sum is equal to the vector $\underline{u}_s$ as shown in Fig. 2.

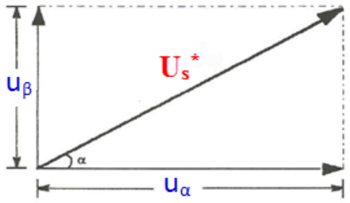

Fig. 2 Decomposition of space vectorto u_α and u_β .

Where; $\underline{u}_s$ is the composite vector and given by:

$$\underline{u}_s = u_\alpha - ju_\beta \quad (6)$$

Substituting from Equ. 4 and Equ. 5 in Equ. 6

$$\underline{u}_s = (2/3)[u_a - (1/2)u_b - (1/2)u_c + j(\sqrt{3}/2)u_b - j(\sqrt{3}/2)u_c] \quad (7)$$

$$\underline{u}_s = (2/3)[u_a - au_b - a^2 u_c] \quad (8)$$

Where

$$a = -(1/2) + j(\sqrt{3}/2 = e^{j\frac{2\pi}{3}} \quad (9)$$

$$a^2 = -(1/2) - j(\sqrt{3}/2 = e^{j\frac{4\pi}{3}} \quad (10)$$

By using Equ. 9 and Equ. 10, the composite vector becomes:

$$\underline{u}_s = (2/3)(u_a + u_b(t)e^{j\frac{2\pi}{3}} + u_c(t)e^{j\frac{4\pi}{3}} \quad (11)$$

Considering the states for the inverter switches (inverter transistors) shown in Fig. 1 and combining them yields the eight possible switching states listed in Table 1, each of these eight states is defined by the positions of the three transistors (or switches) according to the switching sequence. When an upper transistor is switched ON, the corresponding lower transistor is switched OFF. Therefore, the ON and OFF states of the upper transistors Q1, Q3 and Q5 can be used to determine the output voltage.

TABLE I
List of switching states according to the conducting transistors

$\underline{u}_s$	Q_1	Q_3	Q_5
$\underline{u}_0$	4	6	2
$\underline{u}_1$	1	6	2
$\underline{u}_2$	1	3	2
$\underline{u}_3$	4	3	2
$\underline{u}_4$	4	3	5
$\underline{u}_5$	4	6	5
$\underline{u}_6$	1	6	5
$\underline{u}_7$	1	3	5

Thus, The inverter has six states when a voltage is applied to the motor and two states when the motor is shorted through the upper or lower transistors resulting in zero volts being applied to the motor as shown in Fig. 3.

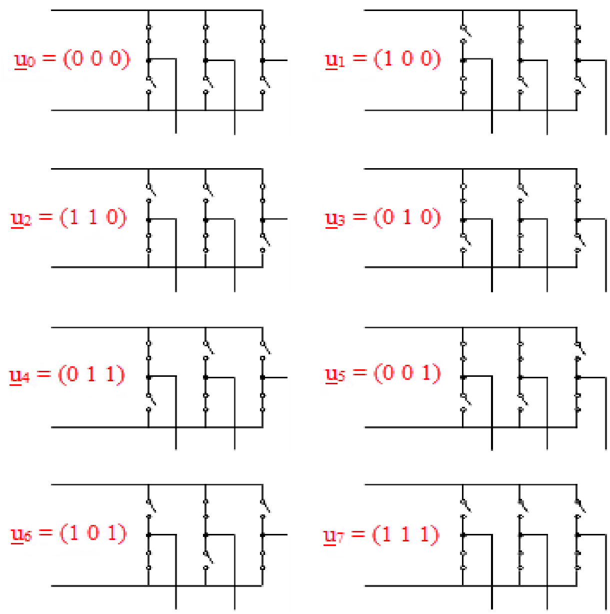

Fig. 3 The eight inverter switching states

III. POSSIBLE SPACE VECTOR POSITIONS

As shown in Fig.(3), the possible space vector positions of three phaseinverter output can be evaluated according to the states of inverter switches andthe corresponding values of phase voltages (u_a, u_b, and u_c) by using Equ. 9 as follow:

- For u_1 = [100] i.e. transistors 612 ON:

$$\underline{u}_1 = (2/3)[(2/3)U_{dc} - (a/3)U_{dc} - (a^2/3)u_{dc}] \quad (12)$$

By using the values of a and a^2 from Equ. 9 and Equ. 10, the vector u_1 becomes:

$$\underline{u}_1 = \frac{2}{3}U_{dc}\angle 0^0 \quad (13)$$

-For u_2 = [110] i.e. transistors 132 ON :

$$\underline{u}_2 = (2/3)[(1/3)U_{dc} - (a/3)U_{dc} - (2a^2/3)u_{dc}] \quad (14)$$

Hence

$$\underline{u}_2 = \frac{2}{3}U_{dc}\angle 60^0 \quad (15)$$

Similarly the magnitude and angle of space vector for all possible switching states becomes:

-For u_3 = [010] i.e. transistors 432 ON:

$$\underline{u}_3 = \frac{2}{3}U_{dc}\angle 120^0 \quad (16)$$

-For u_4= [011] i.e. transistors 435 ON:

$$\underline{u}_4 = \frac{2}{3}U_{dc}\angle 180^0 = -\underline{u}_1 \quad (17)$$

-For u_5= [001] i.e. transistors 465 ON:

$$\underline{u}_5 = \frac{2}{3}U_{dc}\angle 240^0 = -\underline{u}_2 \quad (18)$$

-For u_6= [101] i.e. transistors 165 ON:

$$\underline{u}_6 = \frac{2}{3}U_{dc}\angle .300^0 = -\underline{u}_3 \quad (19)$$

-For u_0 = [000] and u_7 = [111] i.e. transistors 462 and 135 ON respectively:

$$\underline{u}_0 = \underline{u}_7 = 0 \quad (20)$$

Then, the output of the 3-phase inverter can be represented by one vector occupy six position (u_1 to u_6) in the space according to the time instant and two zero vectors (u_0 and u_7) as shown in Table 2, which summaries the switching vectors along withthe corresponding line to neutral voltage and line to line voltages applied to the motor.

TABLE III
Switching vectors, Phase voltages and Output Line to Line voltages

Voltage Vectors	Switching Vectors			Line to neutral voltage			Line to line voltage		
	S_1	S_2	S_3	U_{an}	U_{bn}	U_{cn}	U_{ab}	U_{bc}	U_{ca}
$\underline{u}_0$	0	0	0	0	0	0	0	0	0
$\underline{u}_1$	1	0	0	2/3	-1/3	-1/3	1	0	-1
$\underline{u}_2$	1	1	0	1/3	1/3	-2/3	0	1	-1
$\underline{u}_3$	0	1	0	-1/3	2/3	-1/3	-1	1	0
$\underline{u}_4$	0	1	1	-2/3	1/3	1/3	-1	0	1
$\underline{u}_5$	0	0	1	-1/3	-1/3	2/3	0	-1	1
$\underline{u}_6$	1	0	1	1/3	-2/3	1/3	1	-1	0
$\underline{u}_7$	1	1	1	0	0	0	0	0	0

IV. PRINCIPLE OF SPACE VECTOR

The object of the three phase inverter bridge is to synthesize a balanced set of three phase ac voltage at its output terminals from a constant dc voltage supply. This subsection describes how the inverter switches are operated upon to produce different values for the space vector of stator voltage thereby ensuring a desired three phase output waveforms.In the three phase two position inverter, each leg consists of two switches which may not be closed (or opened) simultaneously. The output of each inverter leg may therefore be either at the dc link voltage (when the top switch is on) or zero (when the bottom switch is on) [3].Considering these two states for each inverter leg and combining them yields the eight possible switching states.Each of these eight states is defined by the positions of the switches (S_1, S_2, and S_3) and a "1" indicates a closed position while a "0" indicates an open position as shown in Fig. 4. On the other hand, the eight states is defined by the case of each transistor in each arm of the inverter bridge, switched-on or switched-off.

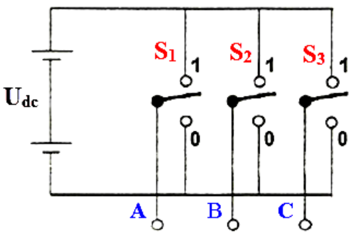

Fig. 4Switching representation of three phase two position inverter

Consequently, the output of the six pulse three phase inverter bridge has eight possible output vectors depending on the possible switching states as shown in Table 3.

TABLE III
List of switching states

$\underline{u}_s$	S_1	S_2	S_3
$\underline{u}_0$	0	0	0
$\underline{u}_1$	1	0	0
$\underline{u}_2$	1	1	0
$\underline{u}_3$	0	1	0
$\underline{u}_4$	0	1	1

u_5	0	0	1
u_6	1	0	1
u_7	1	1	1

In other words, Two of these possible output voltage vectors (u_0 and u_7) are null or zero vectors in which all three phases are equal to (000 or 111), while the six remaining vectors (u_1,.., u_6) are non-zero values and all spatially separated by 60^o as shown in Fig. 5.

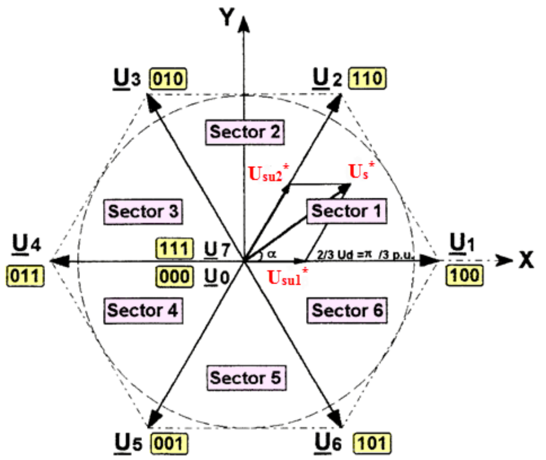

Fig. 5The Desired space vector Us* and the possible space vectors of the inverter output

Each of these space vectors of the stator voltage is defined by the formula:

$$U_s(t) = \frac{2}{3}(u_{s1}(t) + u_{s2}(t)e^{j\frac{2\pi}{3}} + u_{s3}(t)e^{j\frac{4\pi}{3}}) \quad (21)$$

The Stepped waveform of the output phase voltage of the three phase voltage source inverter driving three phase load without any further modulation is shown in Fig. 6.

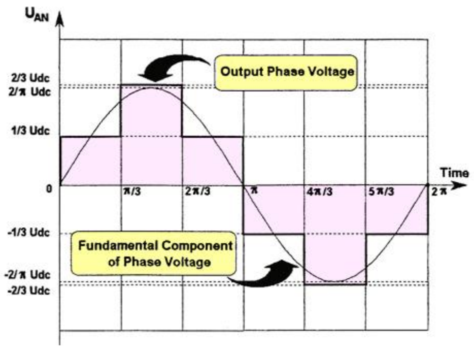

Fig. 6Output phase voltage of two position six pulses inverter.

This waveform gives amplitude of the fundamental phase voltage of ($2/\pi$) U_{dc}, where U_{dc} is the total dc voltage produced from the rectifier bridge. This value ($2/\pi$) U_{dc} is used as the base value in normalizing the voltage quantities included in the system.As a consequence the length of every output space vector in per unit isgiven by:

$$U_{1\,p.u.} = (2/\pi\ U_{dc}) / (2/\pi\ U_{dc}) = \pi/3 \quad (22)$$

To ensure that, the output of the inverter is a sinusoidal waveform, the values ofu_s* must be lieying inside the maximum circular locus shown by the dotted line in Fig. 5. This circle has radius of ($1/\sqrt{3}$) U_{dc} or ($\pi/2\sqrt{3}$) p.u.

Then, the maximum fundamental phase component that can be obtained with a circular trajectory of the stator voltage vector using the definition of space vector modulator is given by:

$$U_{1max} = (1/\sqrt{3})\ U_{dc} = 0.577\ U_{dc} \quad (23)$$

and the per unit value of this voltage is given by:

$$U_{1max\ p.u.} = \pi/2\sqrt{3} = 0.906 \quad (24)$$

which is defined as the maximum modulation index of space vector modulator. Generally, the normal three phase sinusoidal voltage can be represented by a space vector occupies any point in the x-y plane. The length of this vector depends upon the amplitude of the sinusoidal voltage while its direction depends on the phase angle.

V. Space Vector Modulator Strategy

The space vector modulator strategy is based on geometrically approximating the reference space vector us* by the two adjacent inverter vectors together with the zero vector. The problem in trying to synthesize a set of three phase voltages from an inverter lies in the inherently discrete nature. To overcome this problem, the inverter must modulate the widths of its output pulses such that their instantaneous time average becomes equal that of the vector u_s* [3].

In the case of a three phase inverter this requires the inverter to produce the switching voltage vectors (u_1,…., u_6)in such a way that their instantaneous average value equals that of the desired composite voltage vectors us* over an entire period. Fig. 5 illustrates how this may be done using SVM.

In Fig.5the desired composite voltage vector has been superimposed upon the inverter switching voltage vectors. Note that, the switching voltage vectors are symmetrically spaced at 60^o intervals and that the area enclosed between any of these vectors is called Sector or Sextant.

It is clear that, the three phase inverter produces only six discrete (non zero) switching voltage vectors (u_1, …., u_6) and the remaining two (u_0 and u_7) are of zero voltage as shown in Fig. 5. As an example sector 2 in Fig. 5 is the area flanked by the switching voltage vectors u_2 and u_3 and so on.

The importance of defining such sectors is that should the desired voltage vector at any stage fall into a particular sector then only the flanking switching voltage vectors are used to reconstruct the desired voltage vector u_s*. For the case shown in Fig. 5, the desired (reference) voltage vector lies in sector 1 and therefore only switching voltage vectors u_1 and u_2 are used.

VI. Switching Sequence of SVM

Consider Fig. 7 which is an expanded view of sector 1 in Fig. 5 where the desired voltage vector us* has been projected on to the switching voltage vectors u_1 and u_2. This projection represents the average value that must be produced by each switching voltage vector during a given time interval which shall be referred to from now on words as the sampling interval. The reason for this definition is that during this sampling interval, both switching vectors u_1 and u_2 must be selected. Thus a new desired value can only be sampled or responded to after a sampling interval has been completed.

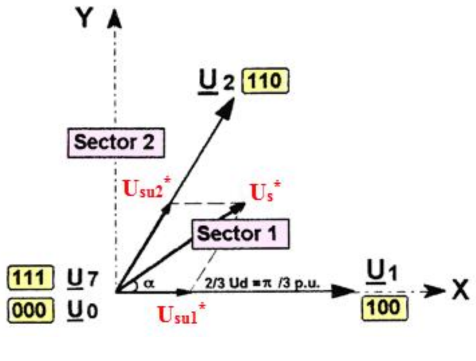

Fig. 7Producing the Required Vector Us*.

On the other hand, as shown in Fig. 8the reference voltage vector $\underline{u}_s$* may be generated by using the immediately adjacent inverter output voltage vectors $\underline{u}_1$ and $\underline{u}_2$ to provide the required phase displacement while the null voltage vectors u0 and u7 control the magnitude $U_s^* = f(\underline{u}_1, \underline{u}_2)$.

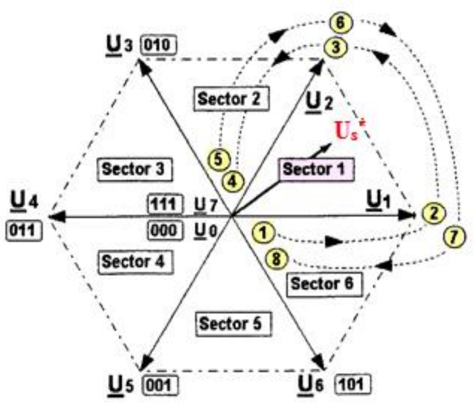

Fig. 8 single pulse width modulation cycle (stage 1-8)

The generation direction of the reference voltage vector u_s* should be taken intoaccount as in sector 1 in Fig. 8 the generation direction of $\underline{u}_s$* using the immediately adjacent vectors $\underline{u}_1$ and $\underline{u}_2$is ($\underline{u}_0\underline{u}_1\underline{u}_2\,\underline{u}_7\,\underline{u}_7\,\underline{u}_2\,\underline{u}_1\,\underline{u}_0$)while in case of sector 2 generation direction of u_s* becomes ($\underline{u}_0\underline{u}_3\underline{u}_2\,\underline{u}_7\,\underline{u}_7\,\underline{u}_2\,\underline{u}_3\,\underline{u}_0$).

Fig. 9 illustrates the equivalent representation of single space vector modulation cycle in a triangulation modulator, highlighting the equivalence of the two generation concepts and the resultant three phase PWM waveforms (expanded for clarity of notation).

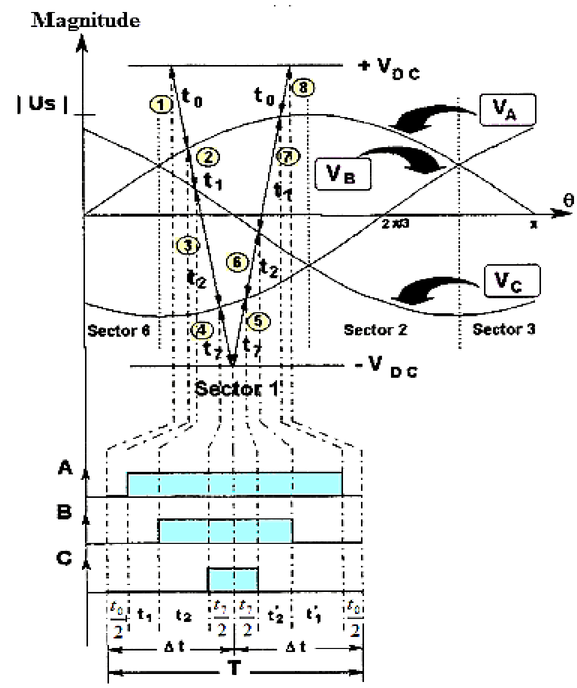

Fig. 9 Resultant three phase PWM waveforms

Tabel 4 shows all switching states in the different sectors according to the angle α..

TABLE IV
Switching states for Two level inverter

Sectors	Switching States	Angle α
Sector 1	$\underline{u}_0\underline{u}_1\underline{u}_2\,\underline{u}_7\,\underline{u}_7\,\underline{u}_2\,\underline{u}_1\,\underline{u}_0$	$0^0 \leq \alpha < 60^0$
Sector 2	$\underline{u}_0\underline{u}_3\underline{u}_2\,\underline{u}_7\,\underline{u}_7\,\underline{u}_2\,\underline{u}_3\,\underline{u}_0$	$60^0 \leq \alpha < 120^0$
Sector 3	$\underline{u}_0\underline{u}_3\underline{u}_4\,\underline{u}_7\,\underline{u}_7\,\underline{u}_4\,\underline{u}_3\,\underline{u}_0$	$120^0 \leq \alpha < 180^0$
Sector 4	$\underline{u}_0\underline{u}_5\underline{u}_4\,\underline{u}_7\,\underline{u}_7\,\underline{u}_4\,\underline{u}_5\,\underline{u}_0$	$180^0 \leq \alpha < 240^0$
Sector 5	$\underline{u}_0\underline{u}_5\underline{u}_6\,\underline{u}_7\,\underline{u}_7\,\underline{u}_6\,\underline{u}_5\,\underline{u}_0$	$240^0 \leq \alpha < 300^0$
Sector 6	$\underline{u}_0\underline{u}_1\underline{u}_6\,\underline{u}_7\,\underline{u}_7\,\underline{u}_6\,\underline{u}_1\,\underline{u}_0$	$300^0 \leq \alpha < 360^0$

The modulation cycle consists of the following sequence of switching voltage vector chosen to produce the desired space voltage vector $\underline{u}_s$* annotated as stages 1 to 8 in Fig. 10.

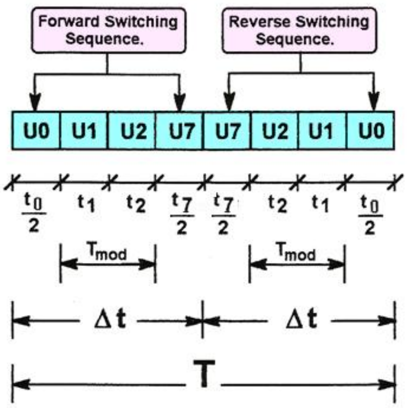

Fig. 10 Switching Sequence of Voltage Vector.

Where:

T_0, t_1, t_2, and t_7: are the time interival.

T_{mod}: is the modulation time.

Δt: is the sampling interval.

T: is the switching time (switching cycle).

During each switching cycle T shown in Fig. 10, the inverter output must give $\underline{u}_1$, $\underline{u}_2$ and $\underline{u}_0$ or $\underline{u}_7$ for times t_1, t_2 and t_o or t_7 respectively.Equating the colt-second intervals over half of a PWM switching cycle gives:

$$\underline{u}_s^* \Delta t = \underline{u}_0 (t_o /2) + \underline{u}_1 t_l + \underline{u}_2 t_2 + \underline{u}_7 (t_7 /2) \quad (25)$$

For the traditional space vector technique, it was arbitrarily assumed that, the null voltage vector time was equally divided between t_0 and t_7, then

$$t_0 = t_7 \quad (26)$$

Therefore, Equ. 25becomes:

$$\underline{u}_s^* \Delta t = \underline{u}_0 t_0 + \underline{u}_1 t_l + \underline{u}_2 t_2 \quad (27)$$

And $\Delta t = t_0 + t_l + t_2$ (28)

or

$$\Delta t = t_0 + T_{mod} \quad (29)$$

where

$$T_{mod} = t_0 + t_2 \quad (30)$$

In order to determine the time intervals (t_1, t_2, and t_0), the reference space vector u_s* must be resolved into two components u_{su1} and u_{su2} in the direction of u_1 and u_2 respectively as shown in Fig. 11.

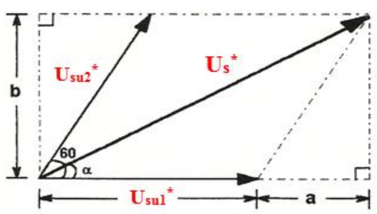

Fig. 11 Decomposition of reference space vector.

From Fig. 11, the distance a and b can be found from:

$$a = u_{su2}^* \cos 60^o = (1/2)\, u_{su2}^* \quad (31)$$

$$b = u_s^* \sin \alpha \quad (32)$$

and

$$u_{sul}^* = u_s^* \cos \alpha - a \quad (33)$$

$$u_{su2}^* = b / \sin 60 = (2/\sqrt{3})\, b \quad (34)$$

Substituting from Equ. 32 in Equ. 34, we get:

$$u_{su2}^* = (2/\sqrt{3})\, u_s^* \sin \alpha \quad (35)$$

Substituting from Equ. 31 in Equ. (33), then:

$$u_{sul}^* = u_s^* \cos \alpha - (1/2)\, u_{su2}^* \quad (36)$$

Substituting from Equ. 35 in Equ. 36 , we get:

$$u_{sul}^* = u_s^* [\cos \alpha - (1/\sqrt{3}) \sin \alpha] \quad (37)$$

The times t_1 and t_2 are proportional to the components u_{su1}* and u_{su2}* respectively and the switching time T is proportional to (2/3) U_{dc}. Then, the time intervals t_1 and t_2 can be found as:

$$t_1 = (2/3)\, u_{sul}^*\, T/U_{dc} \quad (38)$$

and

$$\mathbf{t_1 = (2/3)\, u_{su2}^*\, T/U_{dc}} \quad (39)$$

Substituting from Equ.35 and Equ. 37 in Equ. 38) and (19) and taking into account the values of u_s* inside the maximum circular locus shown by the dotted circle in Fig. 5of radius ($1/\sqrt{3}$) or ($\pi/2\sqrt{3}$) per unit, then:

$$t_1 = (\sqrt{3}/2)\, [u_s^* / (\pi/3)]\, T\, [\cos \alpha - (1/\sqrt{3}) \sin \alpha] \quad (40)$$

$$t_2 = (\sqrt{3}/2)\, [u_s^* / (\pi/3)]\, T\, [(2/\sqrt{3}) \sin \alpha] \quad (41)$$

and

$$t_0 = T - T_{mod} \quad (42)$$

Equ. 40 and Equ. 41 can be rewritten in a simplified form as:

$$t_1 = A \,.\, u_s^* \cos \alpha - (t_2/2) \quad (43)$$

$$t_2 = B \,.\, u_s^* \sin \alpha \quad (44)$$

where

A and B are a constants and given by:

$$A = (3\sqrt{3}/2\pi)\, T \quad (45)$$

$$B = (3/\pi) T \quad (46)$$

Thus, the on-time for each different inverter switching voltage is given by Equ. 43 and Equ. 44. The switching sequence for the upper switches in the six sectors defined in Fig. 5 and the three phase output waveforms of the space vector modulator are shown in Fig 12. The switching period T is divided into two equally sampling intervals. The sequence of switching in the first interval is reversed in the second interval.

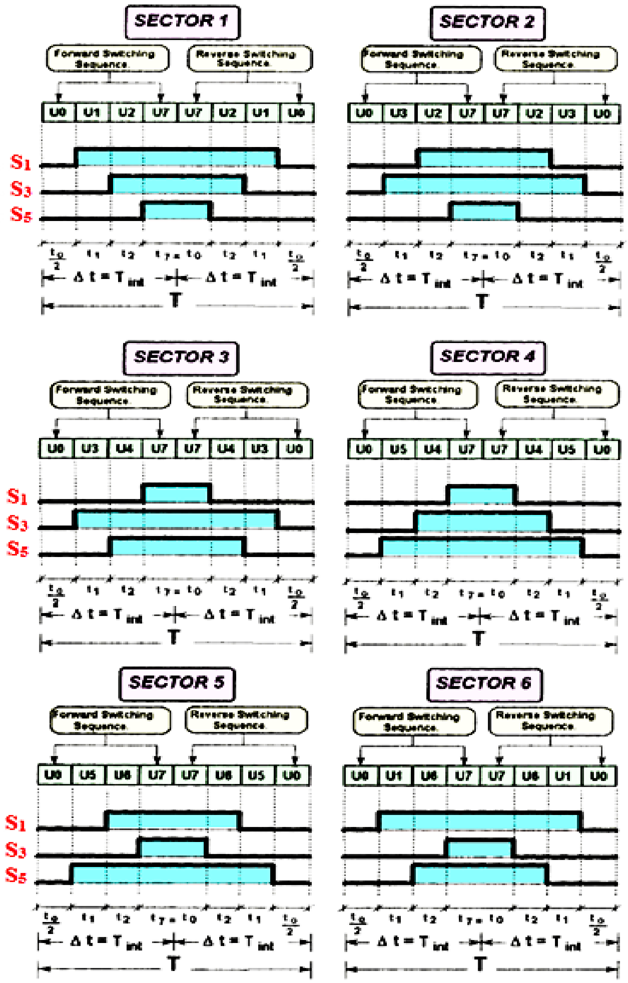

Fig. 12Switching sequence of SVM output in different sectors

According to Fig. 12, the switching time at each sector for the upper and lower switches is summarized in Table 5.

TABLE V

Calculation ofSwitching Time at each Sector

Sectors	Upper Switches (S_1, S_3, S_5)	Lower Switches (S_4, S_6, S_2)
Sector 1	$S_1 = t_1 + t_2 + t_0/2$ $S_3 = t_2 + t_0/2$ $S_5 = t_0/2$	$S_4 = t_0/2$ $S_6 = t_1 + t_0/2$ $S_2 = t_1 + t_2 + t_0/2$
Sector 2	$S_1 = t_1 + t_0/2$ $S_3 = t_1 + t_2 + t_0/2$ $S_5 = t_0/2$	$S_4 = t_1 + t_0/2$ $S_6 = t_0/2$ $S_2 = t_1 + t_2 + t_0/2$
Sector 3	$S_1 = t_0/2$ $S_3 = t_1 + t_2 + t_0/2$ $S_5 = t_2 + t_0/2$	$S_4 = t_1 + t_2 + t_0/2$ $S_6 = t_0/2$ $S_2 = t_1 + t_0/2$
Sector 4	$S_1 = t_0/2$ $S_3 = t_1 + t_0/2$ $S_5 = t_1 + t_2 + t_0/2$	$S_4 = t_1 + t_2 + t_0/2$ $S_6 = t_2 + t_0/2$ $S_2 = t_0/2$
Sector 5	$S_1 = t_2 + t_0/2$ $S_3 = t_0/2$ $S_5 = t_1 + t_2 + t_0/2$	$S_4 = t_1 + t_0/2$ $S_6 = t_1 + t_2 + t_0/2$ $S_2 = t_0/2$
Sector 6	$S_1 = t_1 + t_2 + t_0/2$ $S_3 = t_0/2$ $S_5 = t_1 + t_0/2$	$S_4 = t_0/2$ $S_6 = t_1 + t_2 + t_0/2$ $S_2 = t_2 + t_0/2$

VII. Conclusions

A SVPWM technique which is a digital modulating technique based on a reduced computation method was presented. In SVPWM technique, the inverter gating signals derived from the sampled amplitudes of the reference phase voltages. The SVPWM scheme drive the inverter with eight switching states, this switching states can be represented by a state vector in the two-axis space formed a hexagon shape with six sectors. The time interval of switching the state vectors in each sector calculated in a sampled time T in order to implement the required modulation procedure. The modulation index approaches to (90.6%) and the maximum output fundamental is ($0.577U_{dc}$) because the linear region in SVPWM is larger than other types of PWM technique. SVPWM technique provides a constant switching frequency and gives an excellent harmonic reduction in output voltage and current.

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