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Analysis of Under-Modulation Technique for Space Vector PWM VFI on the Performance of Induction Motor Drive

HAFSA MUZAFAR
M.Tech. Power Electronics and Drives
Department of Electrical Engineering
Dehradun Institute of Technology University
Dehradun

TANEESHA BHANDARI
Assistant Professor
Department of Electrical Engineering
Dehradun Institute of Technology University
Dehradun

ABSTRACT:

This paper focuses on step by step development of SVPWM that fully covers the under modulation region. The model of a three-phase voltage source inverter is discussed based on space vector theory. In the first section, the basic principle of SVPWM has been briefly reviewed with mathematical analysis. Then, the equations for switching/ turn-on time for each sector have been developed in detail. Simulation and experimental results are presented to show reliable estimates of voltage THD for three phase inverter. Simulation results are obtained using MATLAB/Simulink environment for effectiveness of the study.

Keywords- Modulation Index, Space vector Pulse-Width Modulation (SVPWM), Total Harmonic Distortion (THD), Voltage Source Inverter (VSI), Clark's Transformation.

I. INTRODUCTION:

AC drives are widely used in applications such as pumps, fans, paper and textile mills, elevators, electric vehicle, home appliances, servo and robotic, etc. Accurate and precise speed control of these drives is the most important requirements in sophisticated engineering applications. With advances in solid-state power electronic devices and microprocessors, various inverter control techniques employing pulse-width-modulation (PWM) techniques are becoming increasingly popular in AC motor drive applications industrial applications.

These PWM-based drives are used to control both the frequency and the magnitude of the voltages applied to motors. Various PWM strategies, control schemes, and realization techniques have been developed in the past two decades. PWM strategy plays an important role in the minimization of harmonics and switching losses in converters, especially in three-phase applications.

SVPWM was first introduced in the mid-1980s and was greatly advanced by Van Der Broeck in 1988.There is an increasing trend of using space vector PWM because of its superior harmonic quality and extended linear range of operation and of their easier digital realization.

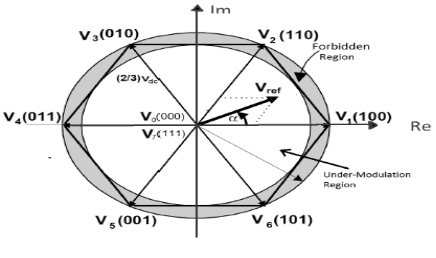


Figure 1

SVPWM is accomplished by rotating a reference vector around the state diagram, which is composed of six basic non-zero vectors forming a hexagon. A circle can be inscribed inside the state map and corresponds to sinusoidal operation. The area inside the inscribed circle is called the linear modulation region or under-modulation region. The area between the inside circle and outside circle of the hexagon is called the nonlinear modulation region or over-modulation region. The concepts in the operation of linear and nonlinear modulation regions depend on the modulation index, which indirectly reflects on the inverter utilization capability.

II. PRINCIPLE OF SPACE VECTOR PWM:

The main features of SVPWM are:

1. Treats the sinusoidal voltage as a constant amplitude vector rotating at constant frequency.
2. Coordinate Transformation.
3. Approximates the reference voltage V_{ref} by a combination of the eight switching patterns (V0 to V7).
4. Vref is generated by two adjacent non-zero vectors and two zero vectors.

The space vector concept, which is derived from the rotating field of induction motor, is used for modulating the inverter output voltage. In this modulation technique the three phase quantities can be transformed to their equivalent two-phase quantity either in synchronously rotating frame (or) stationary frame. From these two-phase components, the reference vector magnitude can be found and used for modulating the inverter output.

The space vector at any given time maintains its magnitude. As time increases, the angle of the space vector increases, causing the vector to rotate with a frequency equal to that of the sinusoidal waveforms. When the output voltages of a three-phase six-step inverter are converted to a space vector and plotted on the complex plane, the corresponding space vector takes only on one of six discrete angles as time increases. The central idea of SVWPM is to generate appropriate PWM signals so that a vector with any desired angle can be generated.

A typical two-level inverter has 6 power switches (labeled $S_1$to S6) that generate three phase voltage outputs. A detailed drawing of a three-phase bridge inverter is shown in Figure 1.

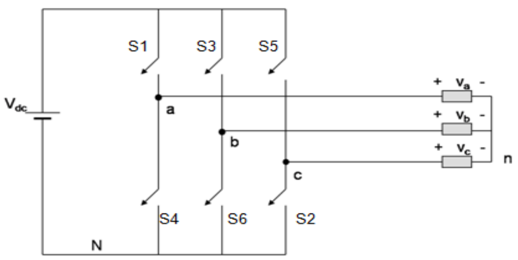


Figure 2

The circuit has a full-bridge topology with three inverter legs, each consisting of two power switches. The circuit allows only positive power flow from the supply system to the load via a full-bridge diode rectifier. Negative power flow is not possible through the rectifier diode bridge.

The six switching power devices can be constructed using power BJTs, GTOs, IGBTs, etc. The choice of switching devices is based on the desired operating power level, required switching frequency, and acceptable inverter power losses. When an upper transistor is switched on, the corresponding lower transistor is switched off. Therefore, the ON and OFF states of the upper transistors S_1; S_3 ; S_5 can be used to determine the current output voltage. The ON and OFF states of the lower power devices are complementary to the upper ones. Two switches on the same leg cannot be closed or opened at the same time.

The basic principle of SVPWM is based on the eight switch combinations of a three phase inverter. As there are three switches on each side i.e. upper and lower and two states of each switch is possible either 1 or 0. So there are total $2^3 = 8$ states. The three-phase inverter is therefore controlled by six switches and eight inverter configurations. The eight inverter states can be transformed into eight corresponding space vectors. In each configuration, the vector identification uses a ‘0’ to represent the negative phase voltage level and a ‘1’ to represent the positive phase voltage level. The relationship between the space vector and the corresponding switching states is given in Table 1

Space Vetor	Swtiching State	On-state Switch
$\vec{V}_0$	[000]	S4,S6,S2
$\vec{V}_1$	[100]	S1,S6,S2
$\vec{V}_2$	[110]	S1,S3,S2
$\vec{V}_3$	[010]	S4,S3,S2
$\vec{V}_4$	[011]	S4,S3,S5
$\vec{V}_5$	[001]	S4,S6,S5
$\vec{V}_6$	[101]	S1,S6,S5
$\vec{V}_7$	[111]	S1,S3,S5

Table 1

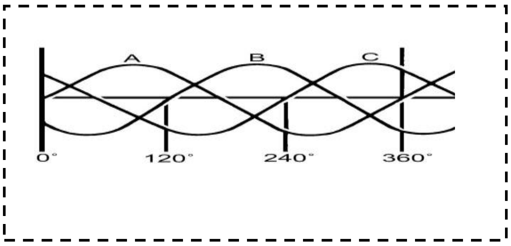
COORDINATE TRANSFORMATION:

Considering the stationary reference frame let the three-phase sinusoidal voltage component be,

$$v_a(t) = V_m \sin(\omega t)$$

$$v_b(t) = V_m \sin(\omega t - 120^o)$$

$$v_c(t) = V_m \sin(\omega t + 120^o)$$



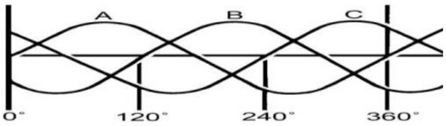
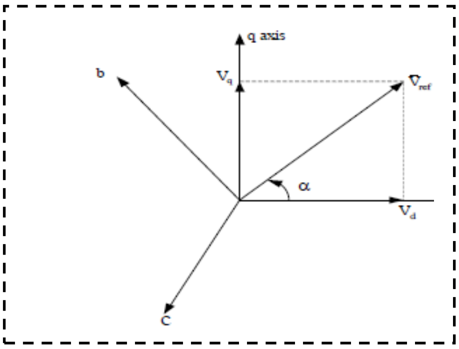


Figure 3

When this three-phase voltage is applied to the AC machine it produces a rotating flux in the air gap of the AC machine. This rotating resultant flux can be represented as single rotating voltage vector. The magnitude and angle of the rotating vector can be found by means of Clark's Transformation. To implement the space vector PWM, the three-phase voltage frame is converted to the stationary dq reference frame using equations:

$$Vd = V_a + V_b \cos120 + V_c \cos240$$
$$= V_a - \tfrac{1}{2}V_b - \tfrac{1}{2}V_c$$
$$Vq = 0 + V_b \cos30 - V_c \cos150$$
$$= \frac{\sqrt{3}}{2}Vbn - \frac{\sqrt{3}}{2}Vcn$$



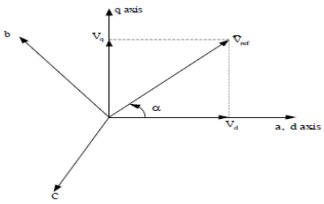


Figure 4

III. INVERTER STATES AND VOLTAGE VECTOR STATES OF INVERTER:

There are eight inverter voltage vectors (V0 to V7). The reference voltage vector V* rotates in space with angular velocity of ω= 2Π f , where f is the fundamental frequency of the inverter output voltage.

When the reference voltage vector rotates through one revolution in space, the inverter output varies one electrical cycle over time. The inverter output frequency coincides with the rotating speed of the reference voltage vector. The zero vectors (V0 and V7) and active vectors (V 1 to V 6) do not move in space. They are referred to as stationary vectors.

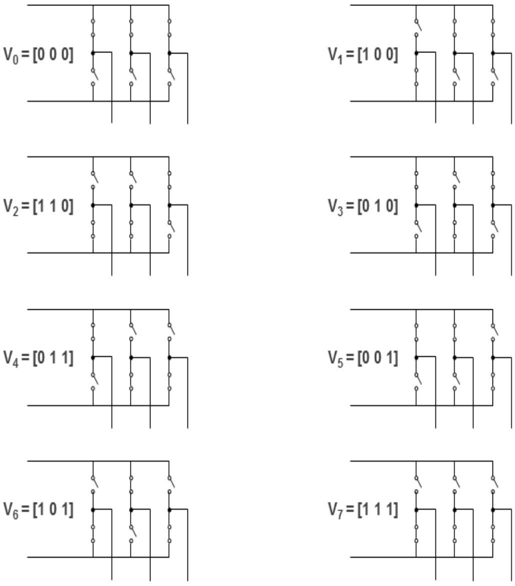


Figure 5

IV. MODES OF OPERATION:

A typical space vector diagram for the inverter is shown in figure 6.

The area inside the circle is linear or under modulation region. The area between inside and outside circle of hexagon is called non-linear or over modulation region. The concepts in the operation of linear and nonlinear modulation regions depend on the modulation index

$$m = \frac{V_{ref}}{V_{1sw}}$$

Where, V_{ref} is the magnitude of reference voltage vector and V_{1sw} is the peak value of square voltage wave. The modulation factor varies between 0 and 1.

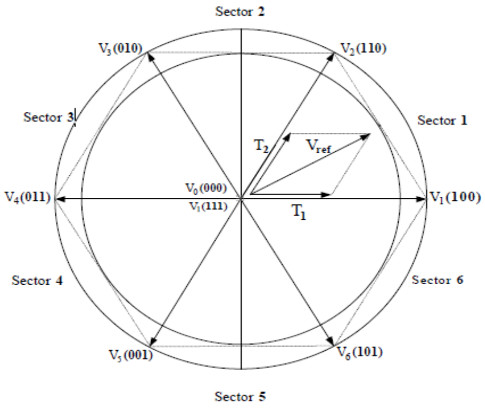


Figure 6

SVPWM works in two modes:

1. Under modulation
2. Over modulation

a) UNDERMODULATION:

This region is linear and V_{ref} remain inside the hexagon. The mode ends when V_{ref} describes an inside circle at m=0.907. The peak fundamental voltage can be as high as 0.577Vdc.
The radius of inscribed circle from Fig. is given as:

$$V_{ref} = \frac{2}{3} V_{dc} Cos \frac{\Pi}{6} = 0.577 V_{dc}$$

$$m = \frac{V_{ref}}{V_{1sw}} = \frac{0.577 V_{dc}}{\frac{2}{\Pi} V_{dc}} = 0.907$$

This means that 90.7 percent of the fundamental at the square wave is available at the under modulation region.

b) OVERMODULATION:

In under modulation region the peak fundamental voltage can be as high as 0.577Vdc. This value can be exceeded during over modulation region when the desired trajectory partly passes outside of the hexagon. The modulation index of the over modulation region ranges from 0.907 to1
Over modulation region is divided into two regions with two modes of operation depending on the modulation index values.

Over modulation region – 1
Over modulation region – 2

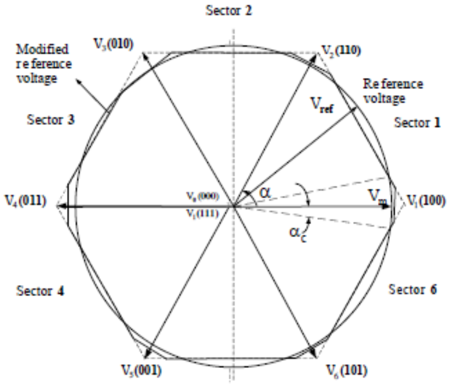


Figure 7

i. OVERMODULATION REGION-1:

The over modulation region starts when the reference voltage exceeds the hexagon boundary, and the MI is larger than 0.907.
In over modulation mode-1 as shown in Fig7 V_{ref} crosses the hexagon at two points in each sector. There is loss of fundamental voltage in this region. To compensate this loss, a modified reference voltage trajectory that remains partly on hexagon and partly on circle is selected

ii. OVERMODULATION REGION-2:

When the modulation index is higher than 0.952, the second region of over modulation is entered. The actual trajectory has to be modified so that the reference voltage matches the output fundamental voltage. As depicted in Fig, holding angle α_h holds the modified reference vector at the vertex of hexagon and for rest of the switching period it tracks the hexagon side in every sector.

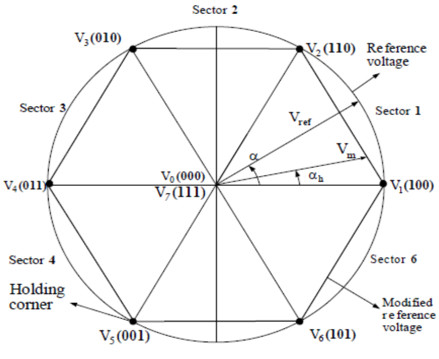


Figure 8

V. SIMULATION: IMPLEMENTATION AND RESULT:

A block diagram Fig. shows the implementation of SVPWM in Simulink.

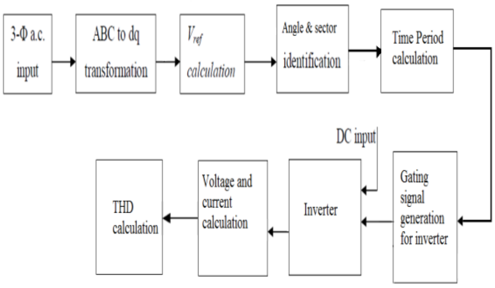


Figure 9

Development of SVPWM is discussed in following steps:

a. THREE-PHASE STATIONARY TO TWO-PHASE STATIONARY:

For SVPWM technique, three-phase balanced sinusoidal supply needs to be converted to two phase space vector that rotates in circular orbit So the first step in SVPWM implementation is to generate three-phase supply and further convert it into space vector in later steps. The conversion from three-phase stationary to two-phase stationary is done by using Clark's transformation equations.

b. GENERATION OF REFERENCE VOLTAGE AND CALCULATION OF ANGLE:

Space vector magnitude or reference voltage (Vref) and angle α are by using following expressions:

$$V_{ref} = \sqrt{(V_{ds}{}^{2} + V_{qs}{}^{2}}$$

$$\alpha = \tan^{-1}\left(\frac{V_{qs}}{V_{ds}}\right)$$

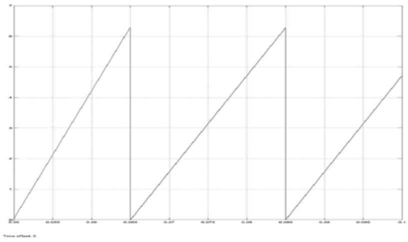


Figure10. Theta with respect to time

c. SECTOR IDENTIFICATION:

As already mentioned that there are six active vectors and two zero vectors, six active vectors are vertex of hexagon thus divides the plane into six sectors of 60° each in which reference voltage vector rotates with angular velocity ω= 2Π f .It becomes necessary to know in which sector the reference output lies in order to determine the switching time and sequence.

Sector	Degrees
1	$0^0 \le \alpha \le 60^0$
2	$60^0 \le \alpha \le 120^0$
3	$120^0 \le \alpha \le 180^0$
4	$180^0 \le \alpha \le 240^0$
5	$240^0 \le \alpha \le 300^0$
6	$300^0 \le \alpha \le 360^0$

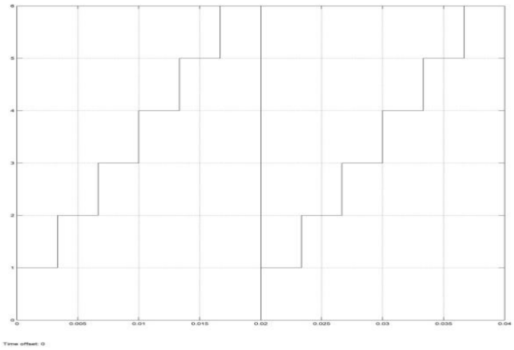


Figure 11 Sector Identification

d. CALCULATION OF TURN-ON TIME OF PHASES:

Phase A turn-on time for under modulation region is as follows:

$$T_A = T_s/4 + (V_m) \times g(\theta)$$

$$\text{Where, } g(\theta) = \begin{cases} K[-sin(\pi/3-\theta) - sin(\theta)], & S = 1,6 \\ K[-sin(\pi/3-\theta) + sin(\theta)], & S = 2 \\ K[sin(\pi/3-\theta) + sin(\theta)], & S = 3,4 \\ K[sin(\pi/3-\theta) - sin(\theta)], & S = 5 \end{cases}$$

$V_m = V_{ref}$

$K = (\sqrt{3}T_s)/(4V_{dc})$ and S represents different sectors.

The turn-on time for phases B, C are similar to turn-on T_A with phase shift of $+120^\circ$ and -120° respectively

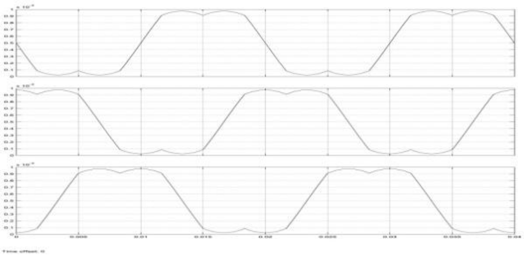


Figure11. Turn-on time as a function of time for modulation index=0.9063(under modulation region)

e. PULSE GENERATION:

Pulses for inverter switches are generated by comparing T_A, T_B ,T_C with high frequency triangle carrier wave by using comparator separately for each phase. The output of each comparator is applied at its respective leg of inverter.

The pole voltages V_{AO}, V_{BO},V_{CO} obtained as output of inverter are converted to line to neutral voltages by using following expressions and waveforms.

$$V_{BN} = \frac{2}{3}V_{BO} - \frac{1}{3}V_{AO} - \frac{1}{3}V_{CO}$$

$$V_{AN} = \frac{2}{3}V_{AO} - \frac{1}{3}V_{BO} - \frac{1}{3}V_{CO} \qquad V_{CN} = \frac{2}{3}V_{CO} - \frac{1}{3}V_{AO} - \frac{1}{3}V_{BO}$$

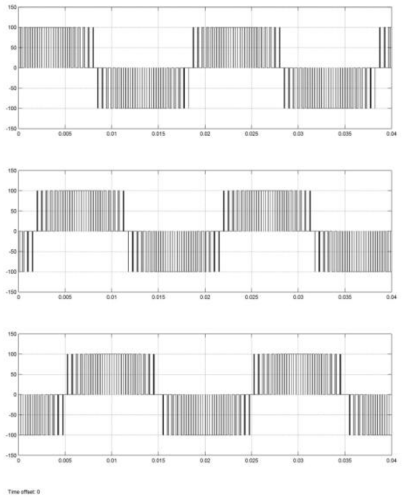


Figure 12 Line to neutral voltages of three-phase SVPWM inverter

VI. RESULTS:

1. TOTAL HARMONIC DISTORTION:

The ratio of the root-mean-square of the harmonic content to the root-mean-square value of the fundamental quantity expressed as a percent of the fundamental.

$$\text{THD} = \sqrt{\frac{\text{sum of squares of amplitudes of all harmonics}}{\text{square of amplitude of fundamental}}}\,.100\%$$

THD of phase voltage and current is measured using FFT analysis tool at different switching frequencies and the result is shown in Table below

Switching frequency (Hz)	Phase Voltage THD (%)			Phase Current THD (%)		
	V_a	V_b	V_c	I_a	I_b	I_c
1000	18.92	19.02	20.92	17.15	6.53	17.86
2000	18.88	19.84	20.55	17.04	5.90	17.67
3000	18.43	19.72	20.30	16.89	5.71	17.50
4000	18.42	19.19	20.19	16.75	5.60	17.49

Table2. THD at different switching frequencies

VII. CONCLUSION:

In this paper, SVPWM technique is used to reduce the harmonics. Here with increase in switching frequency, the THD decreases. The proposed scheme has been successfully implemented by using Simulink MATLAB. It is used for the further research in high voltage and high power application. The basic implementation is used for future works with high levels that is more than three level inverters. And also the present implementation is used for a new simplified space vector PWM method for three-level inverters.

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