ISSN (Print) : 2320 – 3765
ISSN (Online): 2278 – 8875

International Journal of Advanced Research in Electrical, Electronics and Instrumentation Engineering

(An ISO 3297: 2007 Certified Organization)

Vol. 5, Issue 1, January 2016

Analysis of Space Vector PWM for Three Phase Inverter and Comparison with SPWM

Renu Sharma[*1], Deepak Kumar Goyal[*2], Harpreet Singh[*3]

PG Student (Power System), Dept. of EE, I.E.T College, Alwar, Rajasthan, India[1]

Assistant Professor, Dept. of EE, Government Engineering College, Bharatpur, Rajasthan, India[2]

Assistant Professor, Dept. of EE, I.E.T College, Bharatpur, Rajasthan, India[3]

ABSTRACT: Three phase voltage source inverters are being used extensively nowadays in industries to supply three-phase induction motor with variable frequency and variable voltage for variable speed applications. Pulse width modulation (PWM) technique is employed to obtain the suitable output voltage at output of inverter. Various PWM techniques have been developed in past decades among which Sinusoidal Pulse Width Modulation and Space Vector Modulation (SVM) are most widely used. This paper aims to achieve two goals. One is to introduce base theory of Space Vector Modulation when applied to three phase voltage source inverter and other is to present comparative analysis with SPWM using MATLAB/SIMULINK software. Results indicate better DC bus utilization and fewer harmonic with SVM. It is shown that all the drawn conclusions are independent of the load type.

KEYWORDS: Voltage Source Inverter, Space Vector, Space Vector Modulation, Sinusoidal Pulse Width Modulation

I. INTRODUCTION

Due to predominant use of AC drives in today's era; requirement for its variable voltage variable frequency is being achieved by use of converters. Power converters simply control electric power supplied to load. This power transfer is achieved by switching mode operation to ensure efficient conversion. The algorithms that generate switching functions are called Pulse Width Modulation techniques. Various PWM methods have been developed to achieve the following aims: wide linear modulation range; less switching loss; less total harmonic distortion (THD); easy implementation and less computation time. Objective of PWM is to basically restrict magnitude and frequency of sinusoidal output voltage. With the development of state of the art technologies space vector has emerged as one of the most important technology for modulation in inverters. It basically uses the space-vector concept to compute the duty cycle of the switches and works on digital implementation of PWM. In Space Vector Pulse Width Modulation (SVPWM) method, the voltage reference is provided using a revolving reference vector. In this case magnitude and frequency of the fundamental component in the line side are controlled by the magnitude and frequency of the reference voltage vector. SVPWM involves unique correspondence between a space vector in complex plane and a three-phase system which is represented mathematically.

II. SPACE VECTOR CONCEPT

Most of our electrical machines are three phase system having three phase quantities. These quantities are not independent of each other but zero sequence components are usually absent or can be independently dealt also resultant of three phase quantities sum up to zero hence these quantities can be expressed by two phase quantities in orthogonal plane in terms of vector. For e.g. in case of induction motor three phase sinusoidal supply currents produce revolving mmf. Since revolving mmf is vector and rotating in space, it can be called space vector. Similar technique is used for modulating the inverter output voltage and determining two phase components of inverter output voltage. The process of obtaining the rotating space vector is explained in the following section, considering the stationary reference frame. Considering the stationary reference frame let the three-phase sinusoidal voltage components are,

$$Va = VmSin\omega t \quad (1)$$

$$Vb = VmSin(\omega t - 2\pi/3) \quad (2)$$

$$Vc = VmSin(\omega t - 4\pi/3) \quad (3)$$

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This rotating resultant flux can be uniquely represented by single rotating voltage vector (say Vref) as:

$$Vref = 2/3\ [Va(t) + \alpha\ Vb(t) + \alpha^2 Vc(t)]\ ,\text{where } \alpha = e^{j2\pi/3} \text{and } \alpha^2 = e^{j4\pi/3} \quad (4)$$

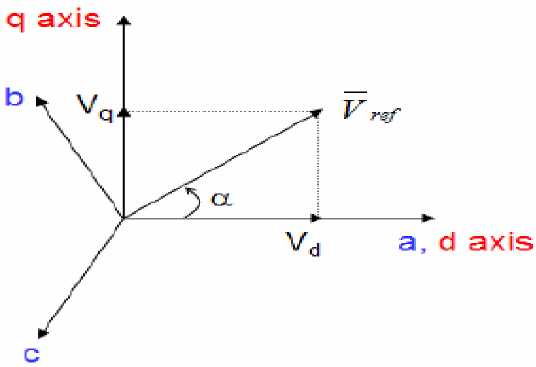

Fig.1 Relationship between abc reference frame and d(direct axis)-q(qurdrature axis) stationary frame

Relationship between abc reference frame and stationary d-q reference can be given by following transformation:

$$\begin{bmatrix} Vd \\ Vq \\ V0 \end{bmatrix} = 2/3 \begin{bmatrix} 1 & -1/2 & -1/2 \\ 0 & \sqrt{3}/2 & -\sqrt{3}/2 \\ 1/2 & 1/2 & 1/2 \end{bmatrix} \begin{bmatrix} Va \\ Vb \\ Vc \end{bmatrix} \quad (5)$$

Where (Vd, Vq) are forming two orthogonal system and Vref = Vd + jVq. A vector can be defined in complex plane with the help of these components.

III. SPACE VECTOR ANALYSIS OF THREE PHASE VOLTAGE SOURCE INVERTER

The three-phase voltage source inverter is shown in below fig.2 is considered herein.

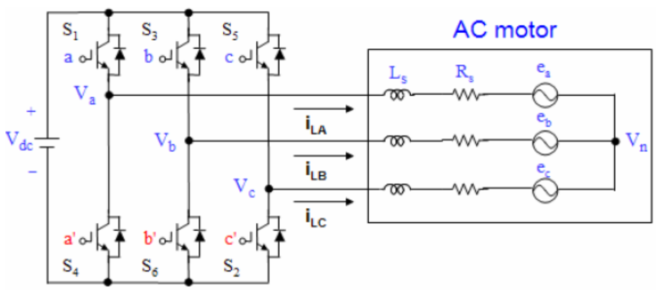

Fig.2 Three phase voltage source inverter

Each state of output voltage lead to switching vector in complex plane giving eight switching states having six non-zero vectors and two vectors corresponding to zero state. These six non-zero vectors are also called active vectors. Complex vector expression for these eight vectors can be given as :

$$Vk = \begin{cases} \frac{2}{3} Vdc\ e^{\frac{j(k-1)\pi}{3}} & if\ K=1,2,3,4,5,6 \\ 0 & if K = 0,7 \end{cases} \quad (6)$$

Meanwhile, two zero vectors (V_0 and V_7) and are at the origin and apply zero voltage to the load.S1 to S6 are the six power switches that shape the output and are controlled by the switching variables a, a′, b, b′, c and c′. For continuity of ac supply and to prevent short circuit in input lines it is necessary that when an upper transistor is switched on, the corresponding lower transistor should be switched off. Hence, upper transistors S1, S3 and S5 solely can be used to determine the output voltage. Following rules are obeyed in vector space as per equivalence principle:

V1= -V4; V2= -V5; V3= -V6; V0=V7=0

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$$V1+V3+V5=-0 \quad (7)$$

The relationship between the switching variable vector [a, b, c] and the line-to-line voltage vector [Vab Vbc Vca] is given by

$$\begin{bmatrix} Vab \\ Vbc \\ Vca \end{bmatrix} = Vdc \begin{bmatrix} 1 & -1 & 0 \\ 0 & 1 & -1 \\ -1 & 0 & 1 \end{bmatrix} \begin{bmatrix} a \\ b \\ c \end{bmatrix} \quad (8)$$

The relationship between the switching variable vector [a, b, c] and the phase voltage vector [Va Vb Vc] is given by

$$\begin{bmatrix} Va \\ Vb \\ Vc \end{bmatrix} = Vdc/3 \begin{bmatrix} 2 & -1 & -1 \\ -1 & 2 & -1 \\ -1 & -1 & 2 \end{bmatrix} \begin{bmatrix} a \\ b \\ c \end{bmatrix} \quad (9)$$

Since inverter output has eight switching states hence to represent it in binary code it needs three bit (2^3=8). Let '1' represents ON state and '0' OFF state of switch. Following figure displays the eight states:

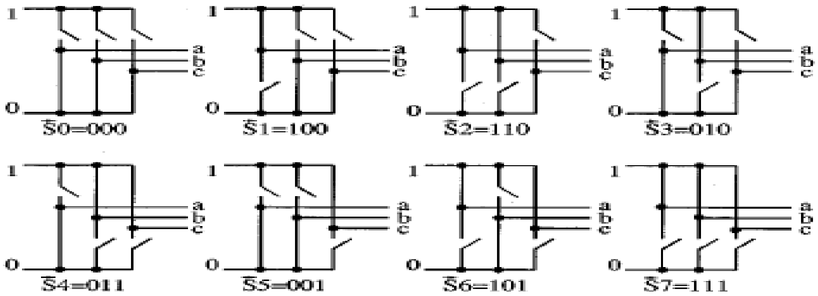

Fig.3 Eight Switching States of Inverter Switches

IV. SPACE VECTOR PWM IMPLEMENTATION

Space Vector PWM (SVPWM) refers to a special switching sequence of the upper three power transistors of a three-phase power inverter. Main function of SVPWM is to approximate reference voltage (Vref) vector using inverter's eight switching pattern and this approximation is done by generating output voltage of inverter in small sampling period, to be same as that of Vref in same period. This Vref voltage vector has discrete movement in complex plane between positions portioned at 60 degree sectors hence forms hexagon trajectory. Decomposition of this vector on **Real** and **Imaginary** axis indicates that it coincides with the switching vector that has generated it. Following figure represents relationship between Vref and voltage sectors.

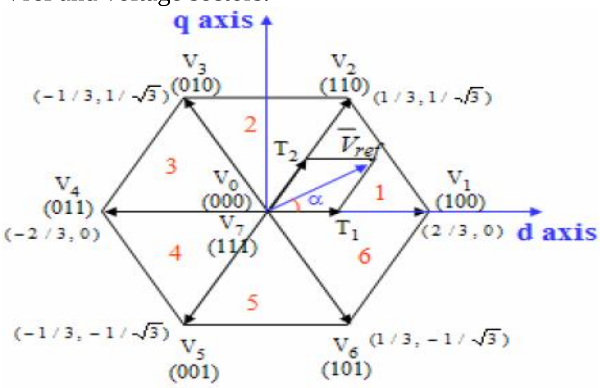

Fig.4 Relationship between Voltage Factor and Vref

Following steps are followed for SVPWM implementation:

1. Determine Vd, Vq, Vref and angle

As deduced from Fig. 1 Vd and Vq can be written as:

Vd= Va – Vb cos 60 – Vc cos60, or Vd= Va – ½ Vb- ½ Vc

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Vq= 0+ Vb cos30-Vc cos30, or Vq= $0+\frac{\sqrt{3}}{2}Vb - \frac{\sqrt{3}}{2}Vc$

Thus Vd & Vq can be written in matrix form as:

$$\begin{bmatrix} Vd \\ Vq \end{bmatrix} = 2/3 \begin{bmatrix} 1 & -1/2 & -1/2 \\ 0 & \sqrt{3}/2 & -\sqrt{3}/2 \end{bmatrix} \begin{bmatrix} Van \\ Vbn \\ Vcn \end{bmatrix} \quad (10)$$

Since Vref= Vd+jVq, or Vref= $\sqrt{Vd2 + Vq2}$ (11)

$$\alpha = \tan^{-1}(Vq/Vd) \quad (12)$$

Fig.4 represents values of each voltage vector in terms of Vd, Vq by using equation (11) & (12)

2. Determination of Sector

It is necessary to know in which sector reference output lies in order to determine the switching time and sequence. The identification of the sector is done where the reference vector is located. Depending on the reference voltages Vd and Vq, the angle of the reference vector can be used to determine the sector. Sector changes at each 60 degree angle thus sectors can be divided as: Sector 1 for 0<α<60º, Sector 2 for 60º <α<120º, Sector 3 for 120º <α<180º, Sector 4 for 180º <α<240º, Sector 5 for 240º <α<300º and Sector 6 for 300º <α<360º.

3. Determine time duration T1, T2 and T0

Switching time in Sector1 for voltage vector V1 to be applied i.e. T1 sec duration and for vector V2 i.e. T2 sec duration can be found out by applying volt-second balance for reference voltage and applied voltage as stated below

VrefTz= V1T1+ V2T2+ V0T0 or

Vref= V1(T1/Tz)+ V2(T2/Tz) + 0 since V0T0= null vector

Here V1= 2/3 Vdc and V2= 2/3 Vdc$\angle$60

From Fig.4 by decomposing T1 & T2 at d-q axis

$$T1 = \frac{Vref.\sin(60-\alpha).Tz}{2/3.Vdc.\sin60} \quad (13)$$

$$T2 = \frac{Vref.\sin\alpha.Tz}{2/3.Vdc.\sin60} \quad (14)$$

Since Tz= T1+ T2+ T0 thus

$$T0 = Tz - T1 - T2 \quad (15)$$

General expression for Switching Time in any sector can be found out as

$$T1 = \frac{\sqrt{3}.Tz.\ Vref\ \ (\sin.n.60.\cos\alpha - \cos60.\sin\alpha)}{Vdc} \quad (16)$$

$$T2 = \frac{\sqrt{3}\ .Tz.\ Vref\ \ (-\cos\alpha.\ \sin(n-1)\ 60 + \sin\alpha.\cos(n-1)60)}{Vdc} \quad (17)$$

4. Determine Switching time of each Switch

It is necessary to arrange the switching sequence so that the switching frequency of each inverter leg is minimized. To minimize the switching losses, only two adjacent active vectors and two zero vectors are used in a sector. To meet this optimal condition, each switching period starts with one zero vector and end with another zero vector during the sampling time Ts.The binary representations of two adjacent basic vectors differ in only one bit. Following table presents asymmetric switching sequence.

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Table 3 Switching Sequences

Sector	Switching Segment						
	1	2	3	4	5	6	7
1	$\vec{V}_0$,[000]	$\vec{V}_1$,[100]	$\vec{V}_2$,[110]	$\vec{V}_7$,[111]	$\vec{V}_2$,[110]	$\vec{V}_1$,[100]	$\vec{V}_0$, [000]
2	$\vec{V}_0$,[000]	$\vec{V}_3$,[010]	$\vec{V}_2$,[110]	$\vec{V}_7$,[111]	$\vec{V}_2$,[110]	$\vec{V}_3$,[010]	$\vec{V}_0$, [000]
3	$\vec{V}_0$,[000]	$\vec{V}_3$,[010]	$\vec{V}_4$,[011]	$\vec{V}_7$,[111]	$\vec{V}_4$,[011]	$\vec{V}_3$,[010]	$\vec{V}_0$, [000]
4	$\vec{V}_0$,[000]	$\vec{V}_5$,[001]	$\vec{V}_4$,[011]	$\vec{V}_7$,[111]	$\vec{V}_4$,[011]	$\vec{V}_5$,[001]	$\vec{V}_0$, [000]
5	$\vec{V}_0$,[000]	$\vec{V}_5$,[001]	$\vec{V}_6$,[101]	$\vec{V}_7$,[111]	$\vec{V}_6$,[101]	$\vec{V}_5$,[001]	$\vec{V}_0$, [000]
6	$\vec{V}_0$,[000]	$\vec{V}_1$,[100]	$\vec{V}_6$,[101]	$\vec{V}_7$,[111]	$\vec{V}_6$,[101]	$\vec{V}_1$,[100]	$\vec{V}_0$, [000]

V. RESULT AND DISCUSSION

This part of paper discusses software implementation of SPWM and SVPWM in linear and undermodulation region. The main objective of any pulse width modulation technique is to obtain variable output voltage having maximum fundamental component with minimum harmonics by switching the inverter power devices on and off many times in order to generate the proper RMS voltage levels. In this paper two most popular PWM techniques i.e. Sinusoidal Pulse Width Modulation technique (SPWM) and SVPWM are compared in terms of Total Harmonic Distortion (THD). Simulink Models for above mentioned techniques are developed using MATLAB software. The Block Diagram of Space Vector Pulse width modulated inverter is shown in below figure 5. Simulation of both techniques i.e. SPWM and SVPWM is performed under the following conditions:
Vdc = 600 V
Sampling frequency = 12000 Hz
Output frequency = 60 Hz

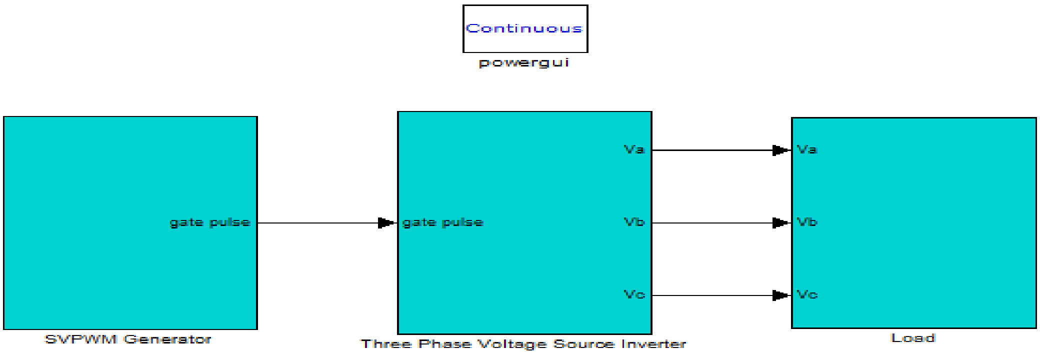

Fig.5 Block Diagram of SVPWM Inverter

Simulation Results at various Modulation Index (MI) are as displayed below

Modulation Index =.4

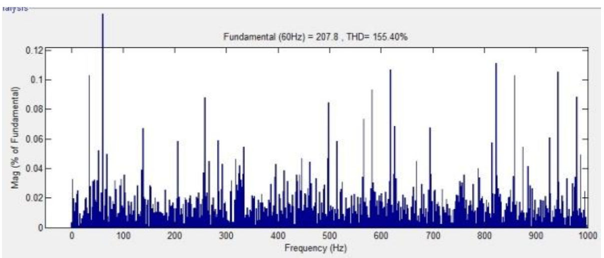

Fig.6 (a) FFT Analysis of THD in SPWM at MI=.4

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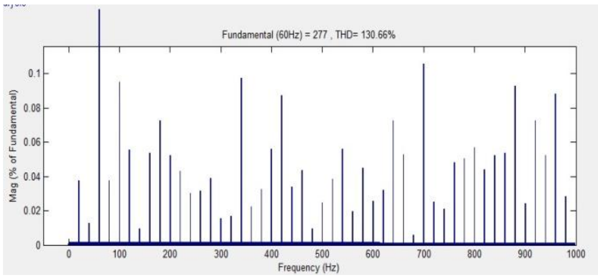

Fig.6 (b) FFT Analysis of THD in SVPWM at MI=.4

Modulation Index =.6

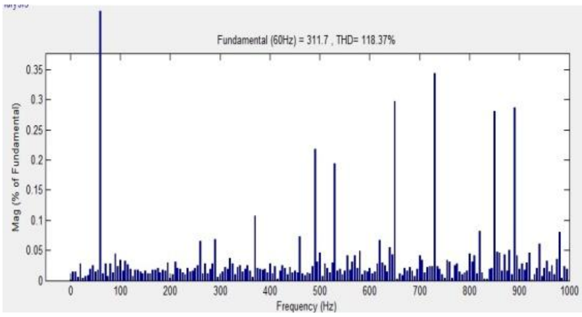

Fig.6 (c) FFT Analysis of THD in SPWM at MI=.6

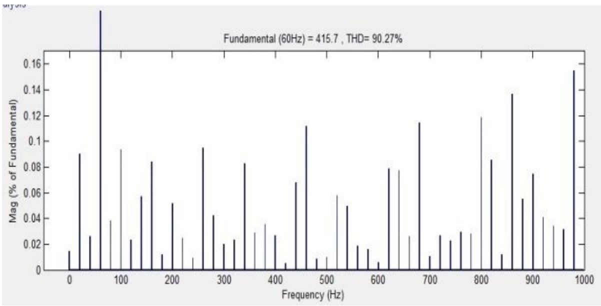

Fig.6 (d) FFT Analysis of THD in SVPWM at MI= .6

Modulation Index =.8

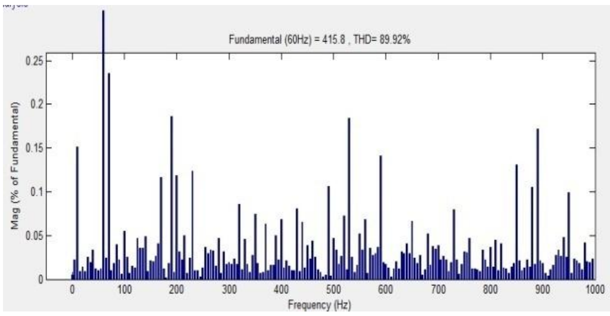

Fig.6 (e) FFT Analysis of THD in SPWM at MI=.8

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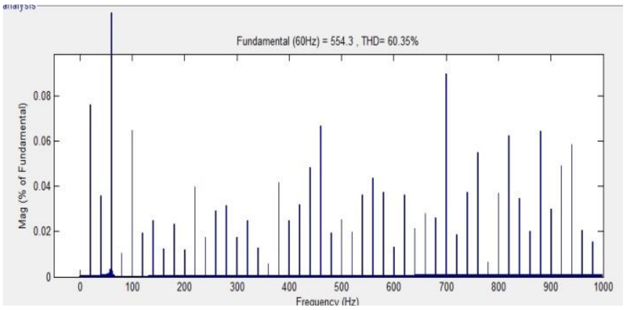

Fig.6 (f) FFT Analysis of THD in SVPWM at MI=.8

Modulation Index =1

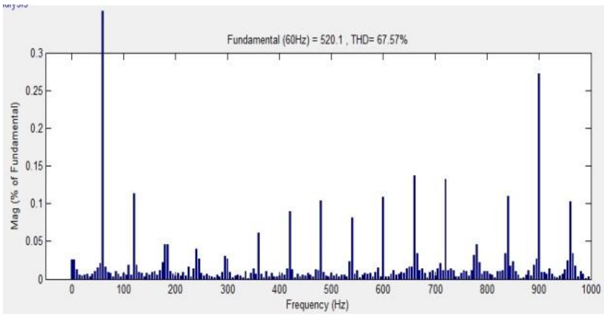

Fig.6 (g) FFT Analysis of THD in SPWM at MI=1

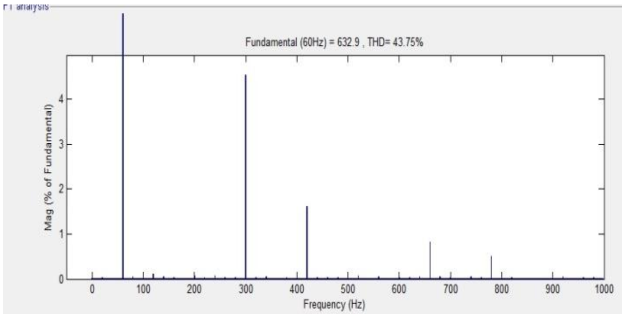

Fig.6 (h) FFT Analysis of THD in SVPWM at MI=1

Below table represents fundamental component of line to line voltage and their FFT analysis result in terms of THD at various values of modulation index indicating SVPWM superiority.

Table 4 Comparison of THD between SPWM and SVPWM

Modulation Index	SPWM Technique		SVPWM Technique	
	THD	Output Line-Line Voltage (Peak) in Volt	THD	Output Line-Line Voltage (Peak) in Volt
.4	155.40	207.8	133.66	277
.6	118.37	311.7	90.27	415.7
.8	89.92	415.8	60.35	554.3
1	67.57	520.1	43.75	632.9

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VI. CONCLUSION & FUTURE SCOPE

Space vector Modulation Technique has become the most popular and important PWM technique for Three Phase Voltage Source Inverters for the control of AC Induction, Brushless DC, Switched Reluctance and Permanent Magnet Synchronous Motors. Sinusoidal PWM is most widely used in industrial converters due to its ease of implementation. This techniques is based on generating gate pulses of variable width by comparison of three phase reference modulating signals against a common triangular carrier of much higher frequency than modulating signals. It is simple and linear between 0% and 78.5% of six step voltage values, which results in poor voltage utilization whereas SVPWM works on principle of calculating duty cycles for switches of inverter. It utilizes dc bus voltage more effectively and generates less THD in the three phase voltage source inverter as indicated in Table 4. Further improved techniques like Wavelet modulation, multilevel SVPWM techniques can also being developed for reduction in harmonics.

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BIOGRAPHY

Mrs. Renu Sharma, received her B.E degree in Electrical Engineering with "Honours" from Institute of Engineering. & Technology, Alwar (Raj) in 2007 & pursuing M.Tech in Power System from Institute of Engineering & Technology, RTU, Kota (Raj.). Her areas of interest are A.C. drives, Modulation Techniques.

Mr. Deepak Kr. Goyal, received his B.E. degree in Electrical Engineering from M.B.M Engineering College Jodhpur (Raj.) in 2002 & M.Tech in Power Apparatus & Electric Drives from Indian Institute of Technology, Roorkee in 2005. Presently he is Head of Electrical Engineering Department, Government Engineering College, Bharatpur (Raj.). His areas of interest are Automation, A.C. Drives & Modulation Techniques.

Mr. Harpeet Singh received his B.E. degree in Electrical Engineering from GNDEC Bidar, Gulbarga University in 1999 and M.Tech. in Power System from Institute of Engineering & Technology College, RTU Kota (Raj.) in 2012. Presently he is Head of Electrical Engineering department, Institute of Engineering & Technology College, Alwar (Raj.). His areas of interest are Automation, Electrical Drives.