Comparison of three phase two-level inverter operation with SPWM and SVPWM

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Abstract— A voltage source inverter (VSI) is primarily used to convert a fixed dc voltage to three-phase ac voltage with variable magnitude and frequency. For this purpose pulse width modulation (PWM) techniques are used to obtain the required output voltage of the inverter. PWM pulses can be generated using various techniques, example SPWM (Sinusoidal Pulse Width Modulation), SVPWM (Space Vector Pulse Width Modulation) techniques, Third Harmonic Injection PWM and many more. In this paper SPWM and SVPWM techniques are studied and analyzed using MATLAB simulation for each. The simulation results are obtained for voltages and current of three phase inverter employed with SPWM and SVPWM also harmonic analysis of output voltages and currents is done. The simulation study reveals that SVPWM utilizes more dc bus voltage and generates less THD when compared to SPWM.

Keywords*- Voltage Source Inverter(VSI),Pulse-Width Modulation (PWM) ,Sinusoidal PWM (SPWM),Space Vector PWM (SVPWM),Total harmonic Distortion (THD)*

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I. INTRODUCTION

AC drives are widely used. They require high power variable voltage variable frequency supply. PWM techniques are helpul to achieve variable voltage and frequency in ac-dc and dc-ac converters. PWM techniques are extensively used in different applications such as variable speed drives (VSD), static frequency changers (SFC), un-interruptible power supplies (UPS) etc [2]. Inverters which are used in low or medium power applications suffer a serious disadvantage such as lower order harmonics in the output voltage. To eliminate these lower order harmonics PWM control techniques are used. The objective of PWM techniques is to build a sinusoidal AC output voltage whose magnitude and frequency both can be controlled. PWM switching strategies addresses the issues like less THD, effective dc bus utilization, EMI reduction, switching loss, better spreading of Harmonics over the spectrum. Real-time method of PWM generation can be broadly classified into Sinusoidal PWM (SPWM) and Space Vector based PWM (SVPWM) [2].

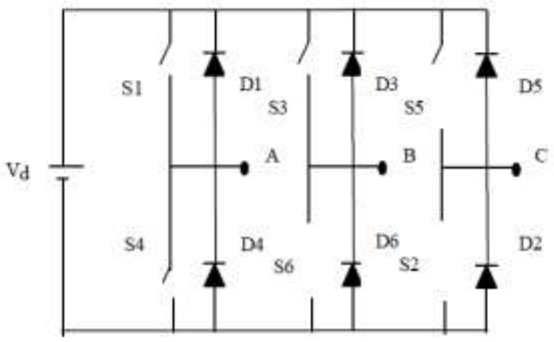


Fig 1.Three Phase Voltage Source inverter

In SPWM method, modulating reference wave of three phase input signals are compared with a triangular carrier wave to generate PWM pulses. The frequency of the carrier wave is very high as compared to the modulating reference wave. The change in magnitude and frequencies of the modulating signals controls the magnitude and frequency of the output waves from inverter. SPWM results in poor voltage utilization thus Voltage range has to be extended and harmonics has to be reduced.

In SVPWM methods, a revolving reference voltage provides the reference voltage. The magnitude and frequency of the output waves are controlled by the magnitude and frequency, respectively, of the reference voltage vector. Space vector modulation utilizes more amount of dc bus voltage and generates less THD in a three phase voltage source inverter.

II. BASIC TOPOLOGY

SPWM (SINUSOIDAL PULSE WIDTH MODULATION)

Three phase sine-wave is compared with a triangular wave to obtain gate pulses for six switches in an inverter. High switching frequency leads to better controlled sinusoidal output waveform. The fundamental frequency component in the inverter output voltage can be controlled by **amplitude modulation index** [1].

$$m_a = \frac{V_m}{V_{cr}}$$

Where Vm and Vcr are the peak values of the modulating and carrier waves respectively.

The amplitude modulation index m_a is usually adjusted by varying Vm while keeping Vcr fixed. The **frequency modulation index** is defined by [1],

$$m_f = \frac{f_{cr}}{f_m}$$

Where f_{cr} and f_m are the frequencies of the carrier and modulating waves respectively.

When $Vm \geq Vcr$ then switch S_1 on upper side of inverter leg A turns on and $V_{an} = +V_d$.
and when $Vm < Vcr$ then switch S_4 on the lower side of inverter leg A turns on and $V_{an} = -V_d$.

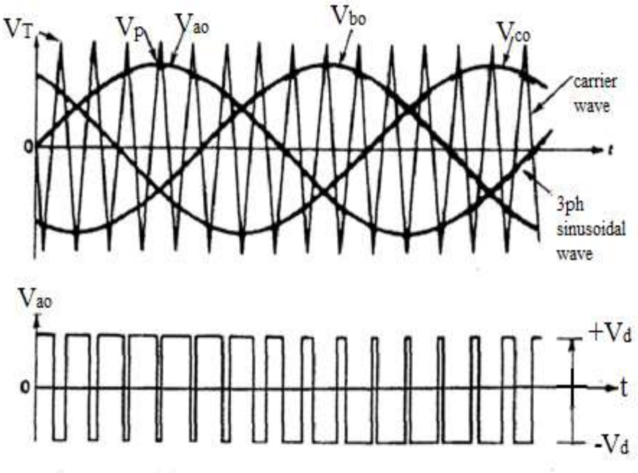


Fig 2.Sinusoidal Pulse width Modulation Technique

SVPWM (SPACE VECTOR PULSE WIDTH MODULATION)

Space Vector Modulation (SVM) was originally developed as vector approach to Pulse Width Modulation (PWM) for three phase inverters [2]. It is a more advanced technique for generating sine wave that gives higher voltage to the motor with lower total harmonic distortion. The main aim of any PWM technique is to get a variable output having a maximum fundamental component with minimum number of harmonics. Space Vector PWM (SVPWM) method is an sophisticated computational PWM method and possibly the best techniques for variable frequency drive application.

Space Vector Principle

Space vector modulation (SVM) for three-leg VSI is normally a representation of the three phase quantities as vectors in a two-dimensional (αβ) plane.
By using Clark's transformation matrix, the three phase voltages $v_{AO}(t)$, $v_{BO}(t)$ and $v_{CO}(t)$ are changed to $v_{\alpha}(t)$ and $v_{\beta}(t)$ which is given by following expression.

$$\begin{bmatrix} v_{\alpha}(t) \\ v_{\beta}(t) \end{bmatrix} = \frac{2}{3} \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} v_{AO}(t) \\ v_{BO}(t) \\ v_{CO}(t) \end{bmatrix} \quad \ldots(1)$$

Voltage source inverter for this technique has eight switching states so that the input lines must never be shorted and the output current must always be continuous. Out of these eight states, six produces a non zero output voltage known as **active** switching states and the remaining two produce zero output voltage known as **zero** switching states. Switching State '1' shows upper switch in an inverter leg is on and switching state '0' shows that lower switch is on.

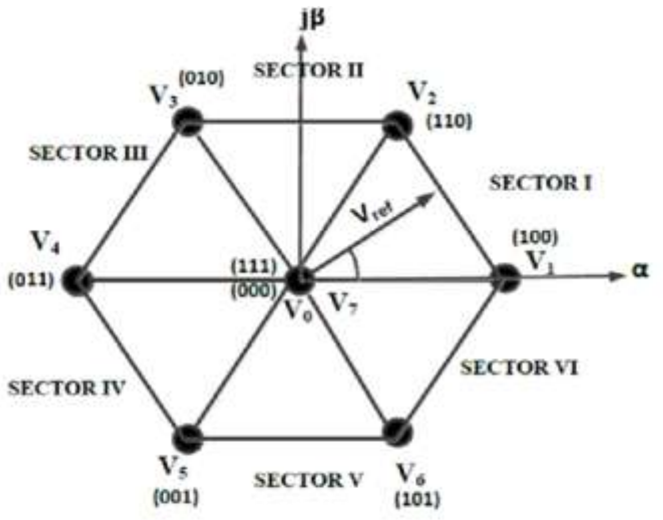


Fig 3. Space Vector Diagram

For a balanced three phase inverter,

$$v_{AO}(t) + v_{BO}(t) + v_{CO}(t) = 0 \quad \ldots (2)$$

In terms of the two-phase voltages that is in α-β plane a space vector can be generally expressed as

$$\overline{V}(t) = v_{\alpha}(t) + jv_{\beta}(t) \quad \ldots (3)$$

Thus from eq (1) and (3), we get

$$\overline{V}(t) = \frac{2}{3}[v_{AO}(t)e^{j0} + v_{BO}(t)e^{j2\pi/3} + v_{CO}(t)e^{j4\pi/3}]$$

Where $e^{jx} = \cos x + j\sin x$ and $x = 0$, $2\pi/3$ or $4\pi/3$. For active switching states [100],

Thus phase voltages generated at load side are,

$$v_{AO}(t) = \frac{2}{3}V_d \qquad v_{BO}(t) = -\frac{1}{3}V_d \quad and \quad v_{CO}(t) = -\frac{1}{3}V_d$$

The corresponding space vector denoted as V_1, thus can be obtained as

$$\overline{V}_1 = \frac{2}{3}V_d e^{j0}$$

All six vectors can be derived by following the above same procedure, thus we get,

$$\overline{V}_k = \frac{2}{3}V_d e^{j(k-1)\frac{\pi}{3}}, \qquad k = 1,2,.....6$$

Thus eight possible combinations of switching states in two-level inverter are listed below[1],

Space vector	Switching states	On-state switch	Vector defination
Zero Vector $\vec{V}_0$	[111] [000]	S_1,S_3,S_5 S_4,S_6,S_2	$\vec{V}_0 = 0$
Active Vector $\vec{V}_1$	[100]	S_1,S_6,S_2	$\overline{V}_1 = \frac{2}{3}V_d e^{j0}$
$\vec{V}_2$	[110]	S_1,S_3,S_2	$\overline{V}_1 = \frac{2}{3}V_d e^{j\frac{\pi}{3}}$
$\vec{V}_3$	[010]	S_4,S_3,S_2	$\overline{V}_1 = \frac{2}{3}V_d e^{j\frac{2\pi}{3}}$
$\vec{V}_4$	[011]	S_4,S_3,S_5	$\overline{V}_1 = \frac{2}{3}V_d e^{j\frac{3\pi}{3}}$
$\vec{V}_5$	[001]	S_4,S_6,S_5	$\overline{V}_1 = \frac{2}{3}V_d e^{j\frac{4\pi}{3}}$
$\vec{V}_6$	[101]	S_1,S_6,S_5	$\overline{V}_1 = \frac{2}{3}V_d e^{j\frac{5\pi}{3}}$

Dwell Time Calculation

For the stationary Vectors the duty cycle time (on-state or off-state) of the switches during a sampling period T_s of the modulation scheme can be represented by dwell time. The dwell time calculation is based on volt-second balancing principle ie the product of the reference voltage $\overline{V}_{ref}$ and sampling period T_s equals the sum of the voltage multiplied by the time interval of chosen space vectors[1].

When $\overline{V}_{ref}$ falls into sector 1 as shown in fig the reference vector can combined by $\overline{V}_1, \overline{V}_2,$ and $\overline{V}_0$ as shown in fig 4,

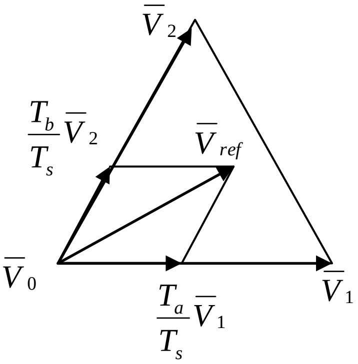


Fig 4. Dwell Time Calculation in Sector I

The volt –second balancing equation is

$$\overline{V}_{ref}T_s = \overline{V}_1 T_a + \overline{V}_2 T_b + \overline{V}_0 T_0$$

$$T_s = T_a + T_b + T_0$$

Where T_a, T_b and T_0 are the dwell times for vectors $\overline{V}_1, \overline{V}_2,$ and $\overline{V}_0$ respectively.

The space vectors can be expressed as

$$\overline{V}_{ref} = \overline{V}_{ref}e^{j\theta}, \quad \overline{V}_1 = \frac{2}{3}V_d, \quad \overline{V}_2 = \frac{2}{3}V_d e^{j\frac{\pi}{3}}, \quad and\ \overline{V}_0 = 0$$

Space vectors thus substituted in volt-balancing equation and then the resultant equation is split into real and imaginary components,

$$\text{Re}: \quad V_{ref}(\cos\theta)T_s = \frac{2}{3}V_d T_a + \frac{1}{3}V_d T_b$$

$$\text{Im}: \quad V_{ref}(\sin\theta)T_s = \frac{1}{\sqrt{3}}V_d T_b$$

Solving above equation together with $T_s = T_a + T_b + T_0$ yields

$$T_a = \frac{\sqrt{3}T_s V_{ref}}{V_d}\sin\left(\frac{\pi}{3} - \theta\right)$$

$$T_b = \frac{\sqrt{3}T_s V_{ref}}{V_d}\sin(\theta) \qquad for\ 0 \le \theta \le \frac{\pi}{3}$$

$$T_0 = T_s - T_a - T_b$$

Above equation is derived when $\overline{V}_{ref}$ is in sector 1, it can also be used when $\overline{V}_{ref}$ is in other sectors and modified angle can be obtained

$$\theta' = \theta - (k-1)\left(\frac{\pi}{3}\right) \qquad for\ 0 \le \theta \le \frac{\pi}{3}$$

Where k=1, 2,…,6 for sectors I,II,…VI respectively.

III. SIMULATION

1. Simulation of SPWM

In SPWM three phase reference wave are compared with triangular carrier wave to get the PWM pulses for different switches connected in three phase inverter. The model proposed here in Fig 5 is of two-level inverter with SPWM modulation operating at $m_a = 0.8$, $m_f = 20$, $f_m = 50Hz$, $f_{sw} = 1kHz$. The figure for gating pulses is shown in Fig 6.

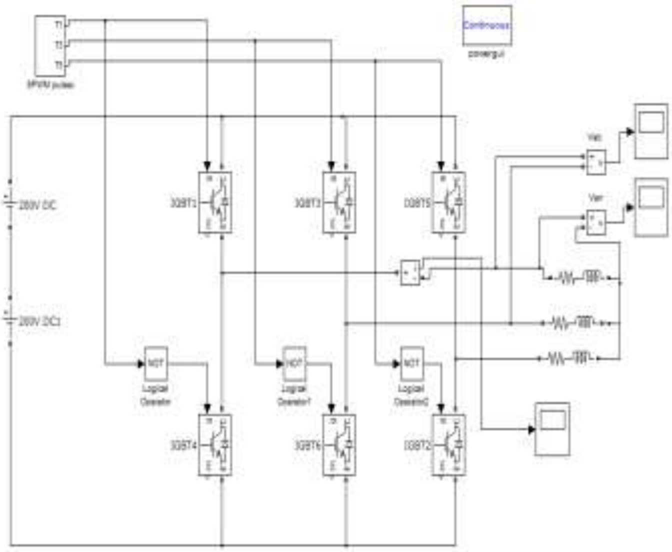


Fig 5. MATLAB model for Three-Phase inverter with SPWM

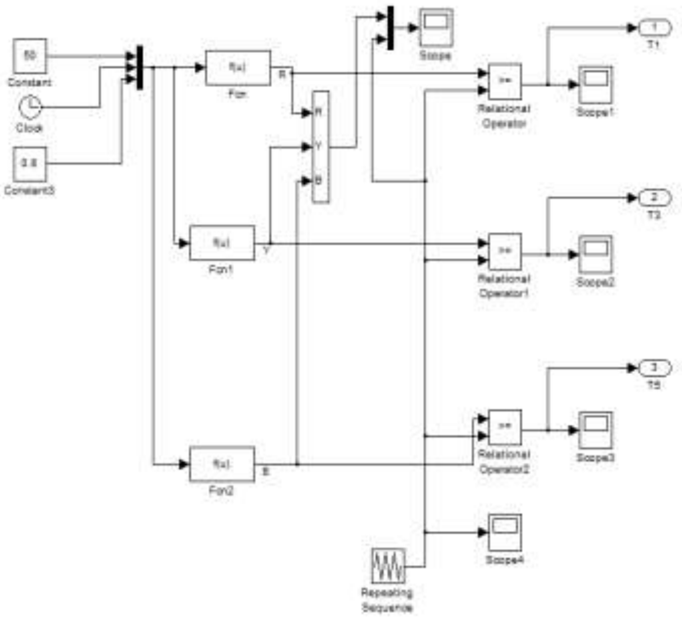


Fig 6. MATLAB model for Gating Pulse of SPWM

2. Simulation of SVPWM

Implementation of SVPWM is done by following steps:
Step-1: Determine, and angle V_d,V_q,Vref and angle(α).
Step-2: Determine the time duration T_1 T_2 and T_0
Step-3: Determine the switching time of each transistor

The *modulation index* for this model is *0.866* and *switching frequency is 1kHz*

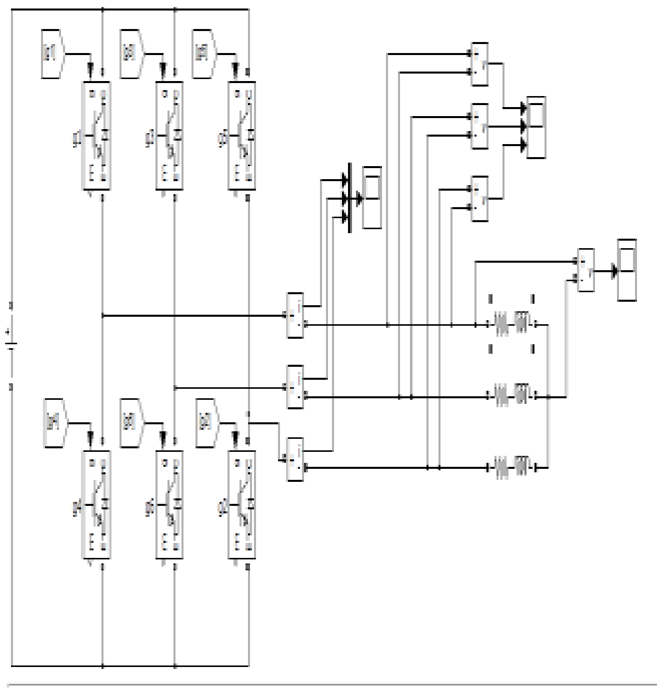


Fig 7. MATLAB model for Three-Phase inverter with SVPWM

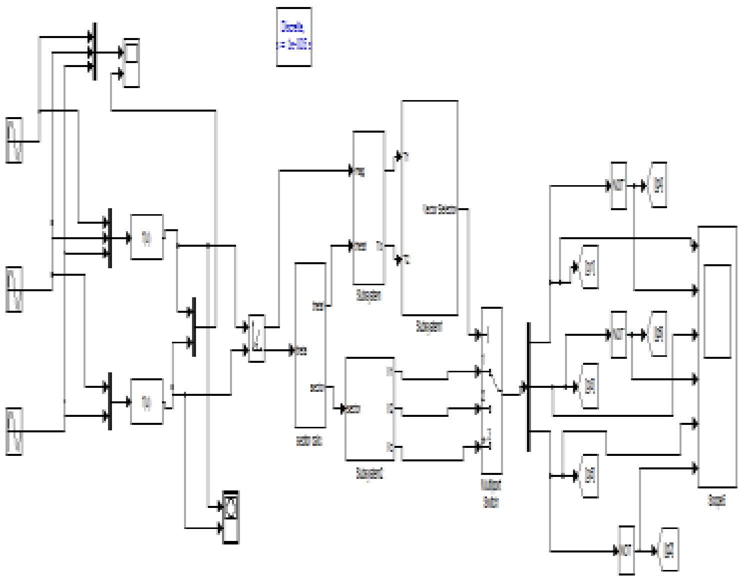


Fig 8. MATLAB model for gating pulses of SVPWM

1. Results of SPWM

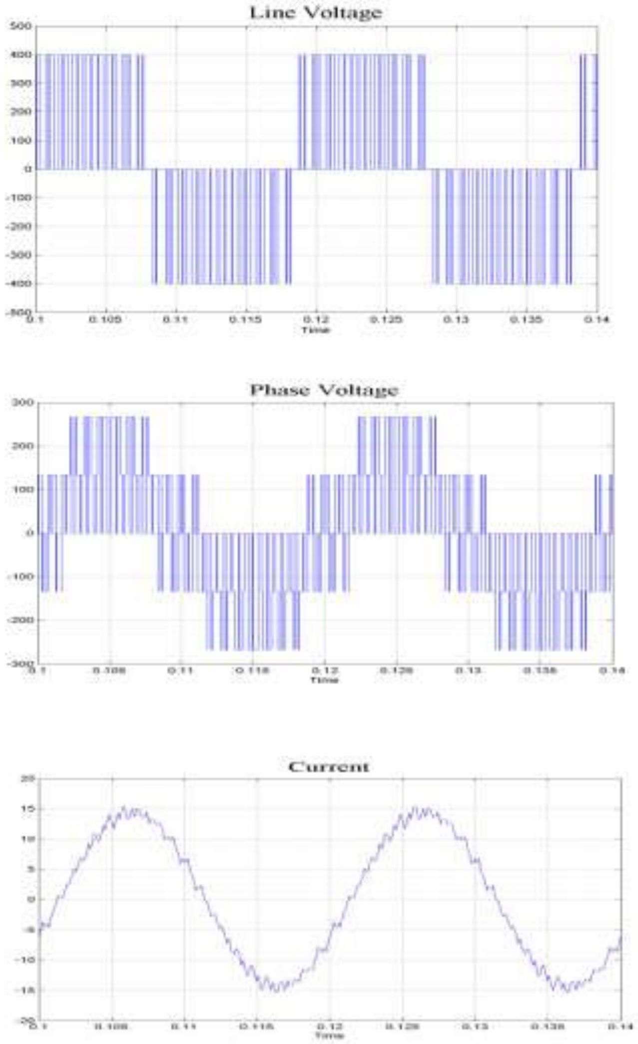


Fig 9. Simulated waves of Line Voltage, Phase Voltage and line current of 'R' phase for SPWM

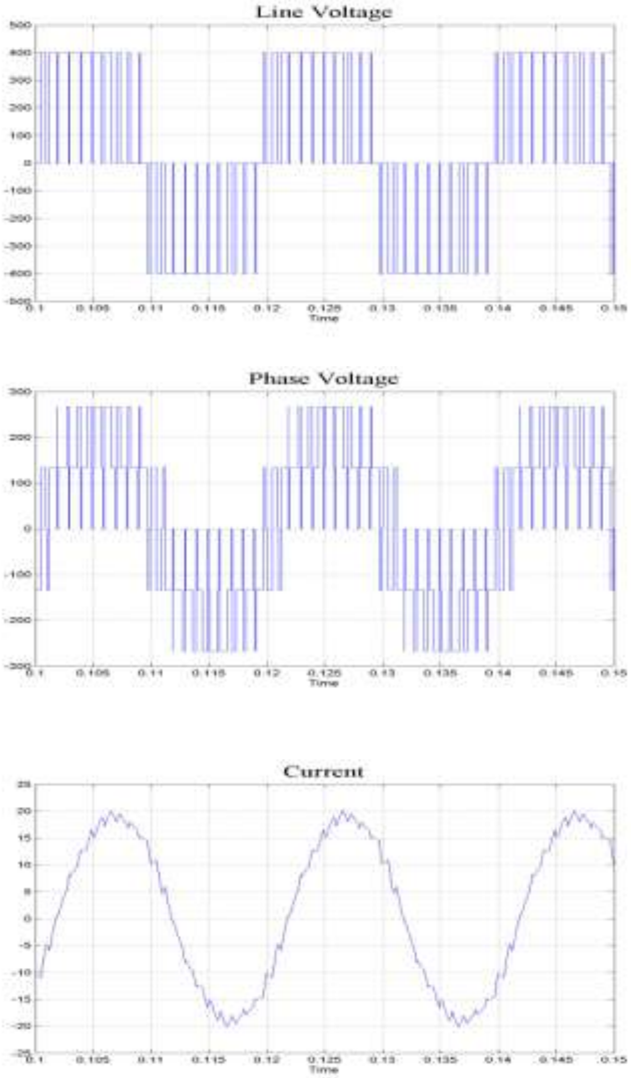
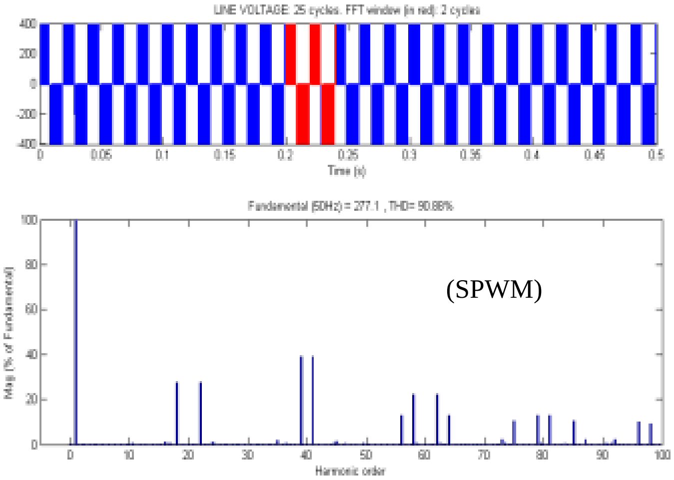


Fig 11. Simulated waves of Line Voltage, Phase Voltage and line current of 'R' phase for SVPWM

2. Harmonic Analysis



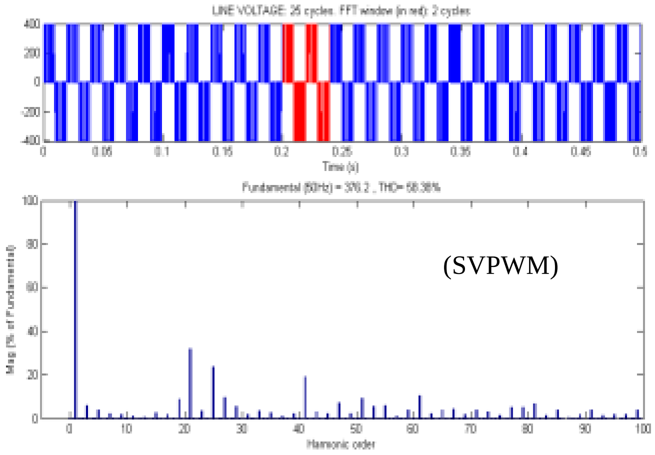
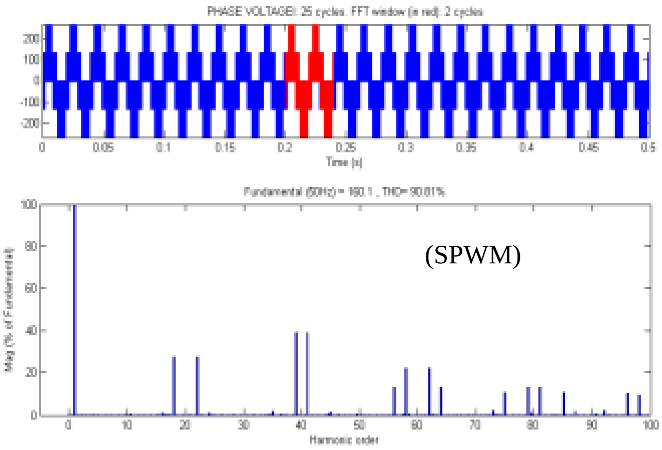


Fig 12. FFT analysis of Line Voltage of SPWM and SVPWM



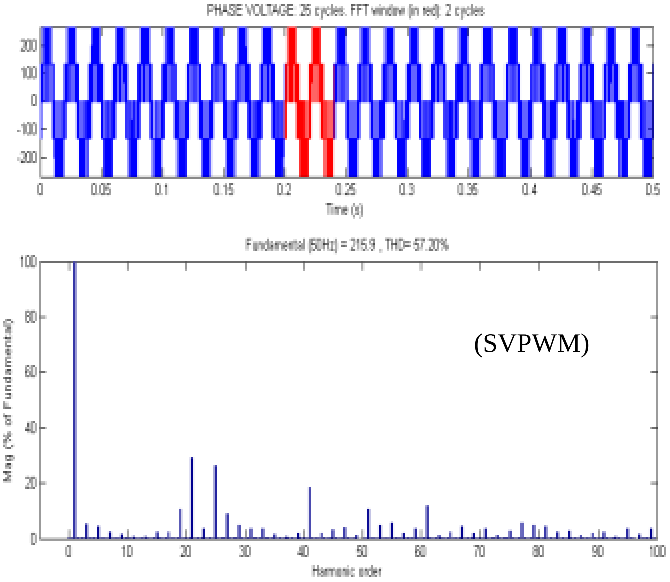


Fig 13. FFT analysis of Phase Voltage of SPWM and SVPWM

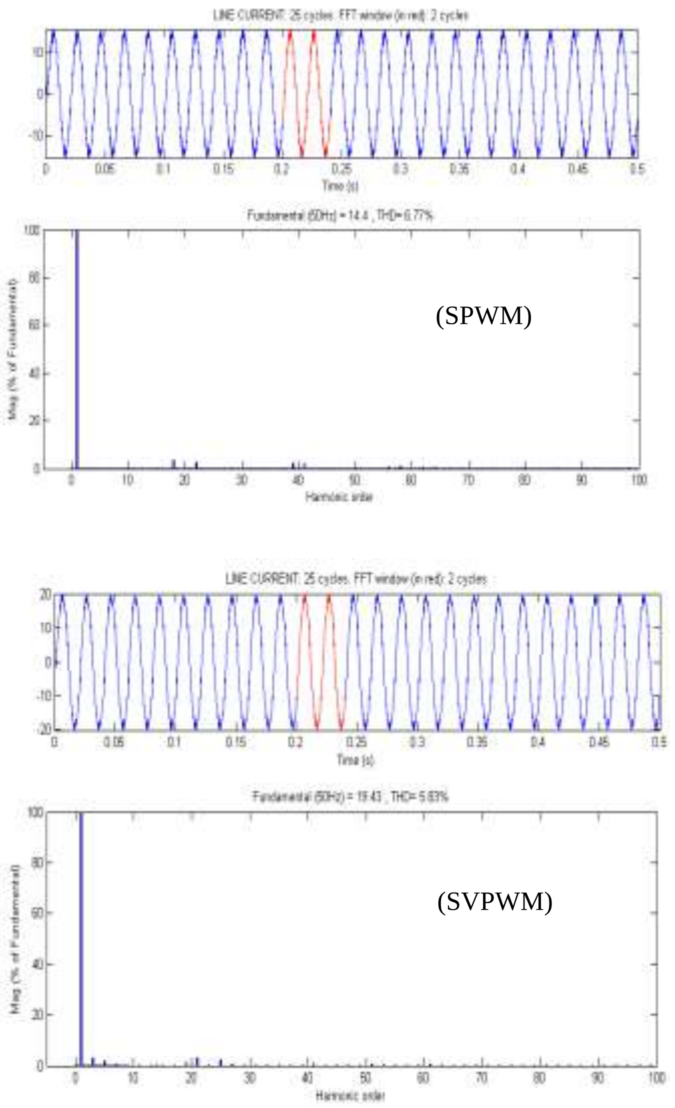


Fig 14. FFT analysis of Line Current of SPWM and SVPWM

IV. CONCLUSION

Space vector Modulation Technique as compared to Sinusoidal PWM is important PWM technique for Three Phase VSI's and popularly is used for the control of AC Induction, Brushless DC, Switched Reluctance and Permanent Magnet Synchronous Motors. In this paper simulated study of Space Vector PWM with conventional SPWM for a two level Inverter is carried out which gives output line and phase voltages also the line currents waveforms. The Harmonic analysis reveals that SVPWM gives more than 15% enhanced fundamental output with better quality of THD.PWM strategies viz. SPWM and SVPWM are implemented here in MATLAB/SIMULINK software.

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