MODELLING AND ANALYSIS OF MULTI LEVEL INVERTERS USING SPACE VECTOR PULSE WIDTH MODULATION (SVPWM)

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Abstract -- **Space Vector Modulation (SVM) 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. This paper proposes implementation of Three Level Diode-Clamped Inverter based on Two Level Inverter using Space Vector Modulation technique. This paper presents a novel space vector pulse width modulation (SVPWM) scheme to reduce switching loss. Using this novel modulation strategy, the changing of switch states cause only one single phase voltage change every time. The simulation study of space vector modulation technique of two level Inverter reveals that space vector modulation technique utilizes DC bus voltage more efficiently and generates less harmonic distortion. The proposed scheme has been implemented by using MATLAB / SIMULINK and its feasibility has been verified by the experimental results.**

Keywords -- SVPWM, Diode – Clamped Inverter, Switching loss.

I. INTRODUCTION

It is well known that multilevel inverters have been receiving more and more attention for high-voltage and high-power applications. Numbers of topologies and modulation strategies have been investigated for utility and drive applications in recent years. Multilevel inverters are suitable in high-voltage and high-power applications due to their ability to synthesize waveforms with better harmonic spectrum and attain higher voltages with a Limited maximum device rating. The best known topologies are the H-bridge cascaded inverter, the flying capacitor inverter, and the diode-clamped inverter. The most attractive features of multilevel inverters are as follows.

1) They can generate output voltages with extremely low distortion and dv/dt.
2) They draw input current with very low distortion.
3) They generate smaller common-mode (CM) voltage, thus reducing the stress of the motor
   bearing. In addition, we can use sophisticated modulation methods, then CM voltage can be eliminated.
4) They can operate with a lower switching frequency.

Based on the analysis of the diode-clamped three-level inverter topology and the review of space vector PWM (SVPWM) method, this paper proposes a novel space vector PWM modulation strategy to reduce switching loss. In comparison with the traditional modulation scheme, under the novel strategy, the changing of switch states cause only one single phase voltage change at a time. Thus, the switching loss can be reduced.

Via coordinate conversion, three-phase sinusoidal AC fundamental voltage can be transformed into d-q DC signals. The whole control system has been implemented by using MATLAB/SIMULINK. Finally, experimental results are provided to verify the scheme in this paper.

II. INVERTER TOPOLOGY

Fig. 1 shows the popular topology of diode-clamped (neutral-point clamped) three-level inverter. The circuit employs 12 power switching devices (e.g. S_1-S_4) and 6 clamped diodes (e.g. D_5-D_6). And the dc-bus voltage is split into three-level by two series-connected bulk capacitors, C_1 and C_2. The middle point of the two capacitors can be defined as the neutral point 'o'. As the result of the diode clamped, the switch voltage is limited to half the level of the dc-bus

voltage $U_d/2$. Thus, the voltage stress of switching device is greatly reduced. The output voltage u_{Ao} has three different states: $+U_d/2$, 0 , $-U_d/2$. Here takes phase A as an example. For voltage level $+U_d/2$, S_1 and S_2 need to be turned on; for 0 level, S_2 and S_3 need to be turned on; and for $-U_d/2$, S_3 and S_4 need to be turned on. We can define these states as 2, 1, and 0,respectively. Then, the switching variable S_a is shown in Table 1. Be similar to three-phase two-level inverter, the switching states of each bridge leg of three-phase three level inverter is described by using switching variables S_a, S_b, and S_c. Whereas the difference is that, in three-level inverter, each bridge leg has three different switching states.
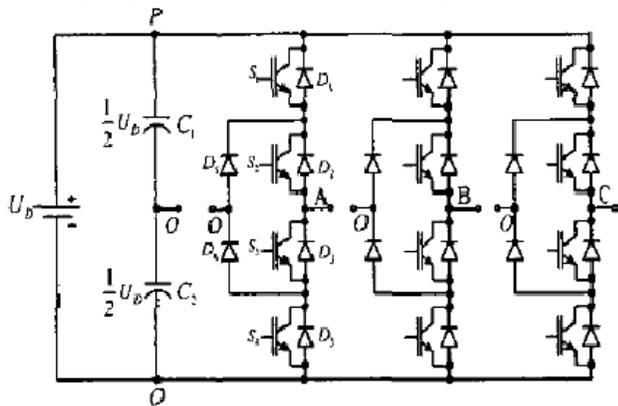

Fig. 1. Schematic of the Diode - Clamped three level Inverter

TABLE I

The Switching Variable of Phase A

U_{ao}	S_{a1}	S_{a2}	S_{a3}	S_{a4}	S_a
$+U_D/2$	1	1	0	0	2
0	0	1	1	0	1
$-U_D/2$	0	0	1	1	0

Using switching variable S_a and dc-bus voltage U_D, the output phase voltage u_{AO} is obtained as follows:

$$u_{AO} = \frac{S_a - 1}{2}.U_D \qquad (1)$$

And the output line voltage of phase A and B can be expressed as follows:

$$u_{AB} = u_{AO} - u_{BO} = \frac{1}{2}.U_D.(S_a - S_b) \qquad (2)$$

The matrix form of output line voltage equations is given as follow:

$$\begin{bmatrix} u_{AB} \\ u_{BC} \\ u_{CA} \end{bmatrix} = \frac{1}{2}.U_D.\begin{bmatrix} 1 & -1 & 0 \\ 0 & 1 & -1 \\ -1 & 0 & 1 \end{bmatrix}.\begin{bmatrix} S_a \\ S_b \\ S_c \end{bmatrix} \qquad (3)$$

III. SPACE VECTOR PWM MODULATION

Two Level Inverter

The concept of space vector is derived from the rotating field of AC machine which is used for modulating the inverter output voltage. In this modulation technique the three phase quantities can be transformed to their equivalent 2-phase quantity either in synchronously rotating frame (or) stationary frame. From this 2-phase component the reference vector magnitude can be found and used for modulating the inverter output. The process of obtaining the rotating space vector is explained in the following section, considering the stationary reference frame.

Let the three phase sinusoidal voltage component be,
$$Va = Vm \sin \omega t$$
$$Vb = Vm \sin (\omega t - 2\prod/3)$$
$$Vc = Vm \sin(\omega t - 4\prod/3)$$

When this 3-phase voltage is applied to the AC machine it produces a rotating flux in the air gap of the AC machine. This rotating flux component can be represented as single rotating voltage vector. The magnitude and angle of the rotating vector can be found by mean of Clark's Transformation as explained below in the stationary reference frame. The representation of rotating vector in complex plane is shown in Figure 2.
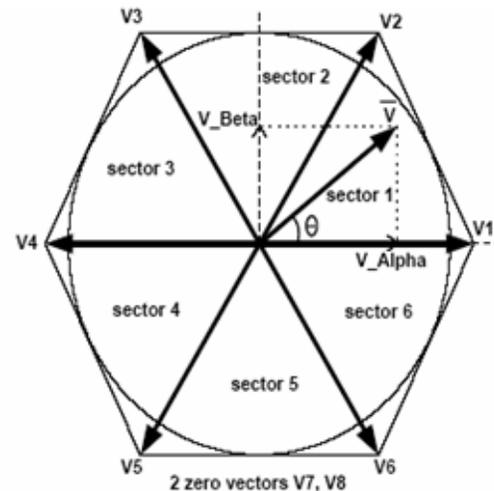

Fig. 2. Representation of Rotating Vector in Complex Plane

$$\overrightarrow{v^*} = V_\alpha + jV_{\beta = \frac{2}{3}} (V_a + aV_b + a^2 V_c)$$

$$\begin{bmatrix} V_\alpha \\ V_\beta \end{bmatrix} = \frac{2}{3} \cdot \begin{bmatrix} 1 & -0.5 & -0.5 \\ 0 & \frac{\sqrt{3}}{2} & \frac{-\sqrt{3}}{2} \end{bmatrix} \cdot \begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix}$$

Principle of Space Vector PWM:

1. Treats the sinusoidal voltage as a constant amplitude vector rotating at constant frequency.
2. This PWM technique approximates the reference voltage V_{ref} by a combination of the eight switching patterns (V_0 to V_7).
3. Coordinate Transformation (abc reference frame to the stationary d-q frame): A three-phase voltage vector is transformed into a vector in the stationary d-q coordinate frame which represents the spatial vector sum of the three-phase voltage.

Realization of Space Vector PWM:

The space vector PWM is realized based on the following steps:

Step1: Determine V_d, V_q, V_{ref}, and angle (α).
Step2: Determine time duration T_1, T_2, T_0.
Step3: Determine the switching time of each transistor (S_1 to S_6)

Three Level Inverter

As shown in Fig.3, there are altogether 27 switching states in diode-clamped three-level inverter. They correspond to 19 voltage vectors (V_0 to V_{18}) whose positions are fixed. These space voltage vectors can be classified into 4 groups: large voltage vector (V_{13} ,V_{14},etc.), medium voltage vector (V_7,V_8 etc.), small voltage vector (V_1, V_2, etc.), and zero voltage vector (V_0). The plane can be divided into 6 major triangular sectors (I to VI enclosed by solid lines) by large voltage vectors and zero voltage vector. Each major section represents 60' of the fundamental cycle. Within each major sector, there are 4 minor triangular sectors (enclosed by the dotted lines).There are totally 24 minor sectors in the plane. And the vertices of these sectors represent the voltage vectors. Notice Table II, each small voltage vector and zero voltage vector have 2 and 3 redundant switching states, respectively. This will be analyzed in detail in Section IV.

In three-phase three-level inverter, when the rotating voltage vectors falls into one certain sector, adjacent voltage vectors are selected to synthesize the desired rotating voltage vector based on the vector synthesis principle, resulting in three-phase PWM waveforms. By the examination of the phase

angle and the magnitude of a rotating reference voltage vector V^*, the sector wherein V^* resides can be easily located

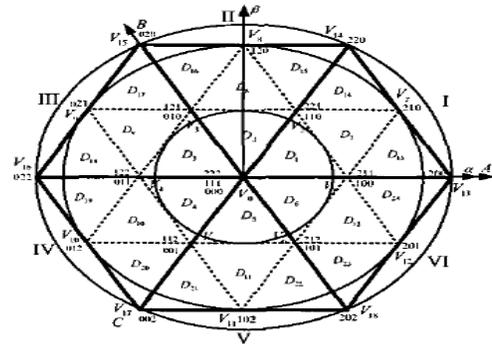Fig. 3. Space Vector Diagram of Three - Level Inverter

Switches	S_a	S_b	S_c	voltage vectors
S_1	0	0	0	V_0
S_2	1	1	1	V_0
S_3	2	2	2	V_0
S_4	1	0	0	V_1
S_5	1	1	0	V_2
S_6	0	1	0	V_3
S_7	0	1	1	V_4
S_8	0	0	1	V_5
S_9	1	0	1	V_6
S_{10}	2	1	1	V_1
S_{11}	2	2	1	V_2
S_{12}	1	2	1	V_3
S_{13}	1	2	2	V_4
S_{14}	1	1	2	V_5
S_{15}	2	1	2	V_6
S_{16}	2	1	0	V_7
S_{17}	1	2	0	V_8
S_{18}	0	2	1	V_9
S_{19}	0	1	2	V_{10}
S_{20}	1	0	2	V_{11}
S_{21}	2	0	1	V_{12}
S_{22}	2	0	0	V_{13}
S_{23}	2	2	0	V_{14}
S_{24}	0	2	0	V_{15}

S_{25}	0	2	2	V_{16}
S_{26}	0	0	2	V_{17}
S_{27}	2	0	2	V_{18}

If the triangle sector is defined by vector V_x, V_y, and V_z, then V* can be synthesized by V_x, V_y, and V_z . Assuming the duration of vector V_x, V_y, and V_z are T_x, T_y, and T_z respectively, and $T_x + T_y + T_z = T_s$, where T_s is switching period. Then X,Y and Z can be defined as the following equations:

$$X = \frac{T_X}{T_S} \qquad (4)$$

$$Y = \frac{T_Y}{T_S} \qquad (5)$$

$$Z = \frac{T_Z}{T_S} \qquad (6)$$

Based on the principle of vector synthesis, the following equations can be written:

$$X + Y + Z = 1 \qquad (7)$$

$$V_X X + V_Y Y + V_Z Z = V^* \qquad (8)$$

The modulation ratio of three-phase three-level inverter is represented as follows

$$m = \frac{|V^*|}{\frac{2}{3}.U_D} = \frac{3|V^*|}{2.U_D} \qquad (9)$$

Where ($|V^*|$ is the magnitude of the reference voltage vector V^*, which rotates with an angle speed of $\varpi = 2\pi f$ in d-q co-ordinate plane. And 2/3 U_d is magnitude the of the large voltage vector, e.g. V_{13}.
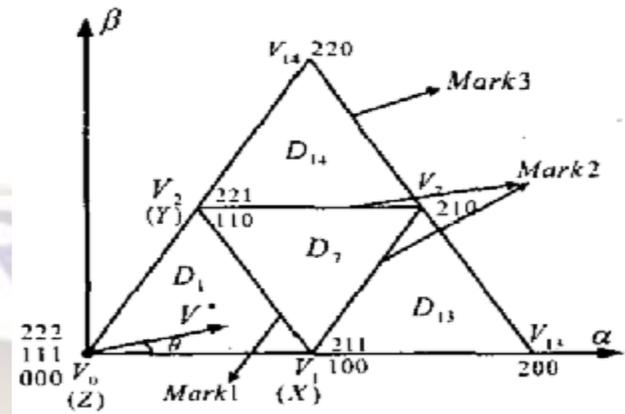
As shown in Fig. 4, the boundaries of modulation ratio are Mark l, Mark 2, and Mark 3. The equation forms of them are obtained as follows:

$$Mark\ 1 = \frac{\sqrt{3}/2}{\sqrt{3}\cos\theta + \sin\theta} \qquad (10)$$

$$Mark\ 2 = \frac{\sqrt{3}/2}{\sqrt{3}\cos\theta - \sin\theta}, \theta \le \frac{\pi}{6} \qquad (11)$$
$$= \frac{\sqrt{3}/4}{\sin\theta}, \qquad \frac{\pi}{6} \le \theta \le \frac{\pi}{3}$$

$$Mark\ 3 = \frac{\sqrt{3}}{\sqrt{3}\cos\theta + \sin\theta} \qquad (12)$$

Here takes an example. As illustrated in Fig. 4, we can suppose that the rotating voltage V* falls into sector I ($0 < \theta < 60°$). Notice that there are 4 minor sectors, D_1, D_7, D_{13} and D_{14} in this sector, then X, Y, and Z can be calculated with the following four cases, respectively.

When the modulation ratio m < Mark l, the rotating voltage vector V* is in sector D_1. As shown in Fig. 5.3, V* is synthesized by V_0, V_1 and V_2. According to (8), the following equation is acquired:

$$\frac{1}{2} X + \frac{1}{2} (\cos(\frac{\pi}{3}) Y + j\ \sin(\frac{\pi}{3}) \qquad (13) \qquad = m [\cos(\theta) + j\ \sin(\theta)]$$

Using (7) and (13), we can obtain X, Y, and Z as follows:

$$X = 2\ m.[\cos\theta - \frac{\sin\theta}{\sqrt{3}}]$$

$$Y = m.\frac{4\sin\theta}{\sqrt{3}}$$

$$Z = 1 - 2\ m.[\cos\theta + \frac{\sin\theta}{\sqrt{3}}] \qquad (14)$$

B. Similarly, when Mark l < m < Mark 2, V* is in sector D_7. V* can be synthesized by V_1, V_2 and V_7 .And the corresponding X, Y, and Z are:

$$X = 1 - m.\frac{4\sin\theta}{\sqrt{3}}$$

$$Y = 1 - 2.m.[\cos\theta - \frac{\sin\theta}{\sqrt{3}}]$$

$$Z = -1 + 2.m.[\cos\theta + \frac{\sin\theta}{\sqrt{3}}] \qquad (15)$$

C. When Mark 2 < m < Mark 3 and 0° < θ < 60°, V* is in sector D_{13}. V_1, V_{13} and V_7 are selected to synthesize V*. The durations of them are obtained as follows:

$$X = -1 + 2.m.[\cos\theta - \frac{\sin\theta}{\sqrt{3}}]$$

$$Y = m.\frac{4\sin\theta}{\sqrt{3}}$$

$$Z = 2 - 2.m.[\cos\theta + \frac{\sin\theta}{\sqrt{3}}] \qquad (16)$$

D. When Mark 2 < m < Mark 3 and, $30° < \theta < 60°$, V^* is in sector D_{14}. Vectors V_2, V_7 and V_{14} will be employed to generate the required voltage. X, Y, and Z can be expressed as follows:

$$X = 2.m. \left[\cos\theta - \frac{\sin\theta}{\sqrt{3}} \right]$$

$$Y = -1 + m. \frac{4\sin\theta}{\sqrt{3}}$$

$$Z = 2 - 2.m. \left[\cos\theta + \frac{\sin\theta}{\sqrt{3}} \right] \qquad (17)$$

When the reference vector falls into the others major sectors, similar argument can be applied. Replacing θ of (14), (15), (16), and (17) by θ -60°, θ -120°, θ -180°, θ -240°, and θ -300° respectively, the calculation of the entire coordinate plane can be established.

IV. THE ALGORITHM OF REDUCING SWITCHING LOSS

In three-level inverter, the redundant switching states cause a certain voltage vector corresponds to two or three switching states. So they can be employed to realize a novel algorithm to reduce the switching times and switching loss of power devices. The main principle of the algorithm is that, the changing of switch states cause only the voltage (switch state) of one phase change every time. That is to say, only the driver signals of two complementary switches (such as S_1 & S_3 or S_2 & S_4) change.

Take an example, when the rotating vector rotates from sector D_{14} to sector D_{15}, the switching states will modulate as following sequence: $(221 \rightarrow 220 \rightarrow 210 \rightarrow 110 \rightarrow 110 \rightarrow 210 \rightarrow 220 \rightarrow 221) \rightarrow$ $(221 \rightarrow 220 \rightarrow 120 \rightarrow 110 - 110 \rightarrow 120 \rightarrow 220 \rightarrow 221)$. When the rotating space vector V^* is in sector D_{14}, V^* can be synthesized by space vector V_2 (expressed by switching state 221 or 11O), V_7(210), and V_{14} (220). And the switching sequence in the first parentheses above presents the modulation procession. When V^* falls into sector D_{15}, space vectors, V_2 (221 or 110), V_{14} (220), and V_8 (120), are selected to synthesize V^*.

The switching sequence shown in the second parentheses above describes this modulation procession. The switching states 221 and 110 express the same vector V_2. Thus, V_2 is used as the starting state and ending state to complete the modulation process.

It is necessary to explain that, there are a certain number of transitional switching states, but such approach will not change the overall output voltage magnitude and the duration of each output voltage vector. On the contrary, under this modulation strategy, only the switching state of one phase changes every time. Compared with the traditional strategy, at a fixed switching frequency, with the reducing of the switching times, the switching loss is reduced. of one

phase changes every time. Compared with the traditional strategy, at a fixed switching frequency, with the reducing of the switching times, the switching loss is reduced.

V. EXPERIMENTAL VERIFICATION

The control schematic diagram of Two Level & Three Level Inverters are illustrated in Fig. 5 & Fig. 6 Via co-ordinate conversion, three-phase sinusoidal AC fundamental voltage can be transformed into d-q DC signals V_d, and V_q. Then with the implementation of the novel SVPWM algorithm, the inverter is close-loop controlled.

The whole control system is realized based on MATLAB/SIMULINK.

The SimCoupler Module is an add-on module to the PSIM software. It provides interface between PSIM and Matlab / Simulink for co-simulation, so that part of a system can be implemented and simulated in PSIM, and the rest in Matlab / Simulink.

The SimCoupler Module enables Matlab/Simulink users to implement and simulate power circuits in their original circuit form, thus greatly shortening the time to set up and simulate a system which includes electric circuits and motor drives. First, the power circuit is simulated in PSIM, and the control in Matlab/Simulink. The SimCoupler Module is straightforward and easy to use with minimum input from users. The interface is done through link nodes in PSIM, and the SimCoupler model block in Simulink. With the SimCoupler Module, one can make full use of PSIM's capability in Power simulation and Matlab/Simulink capability in control simulation in a Complementary way.
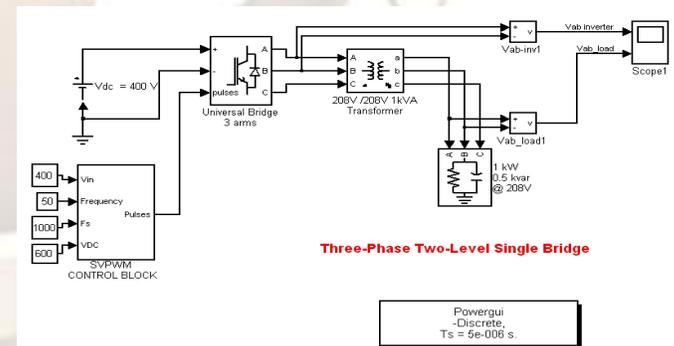

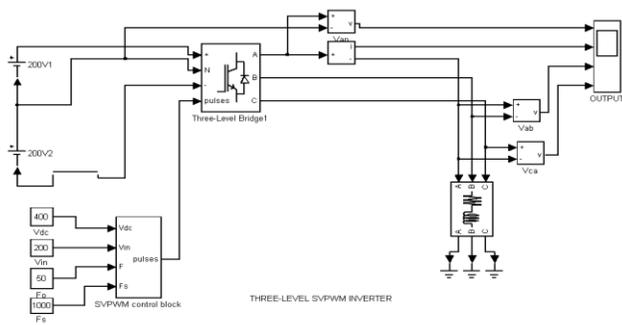**Fig. 5 Simulink Block Diagram of Two-Level Inverter Using SVPWM**

Fig. 6 Simulink Block Diagram of Three-Level Inverter Using SVPWM

VI. SIMULATION RESULTS

The simulation parameters are as follows:

DC link voltage $V_{dc} = 400V$,

Switching frequency $F_s = 1000$ Hz,

The load is a balanced star connected load.
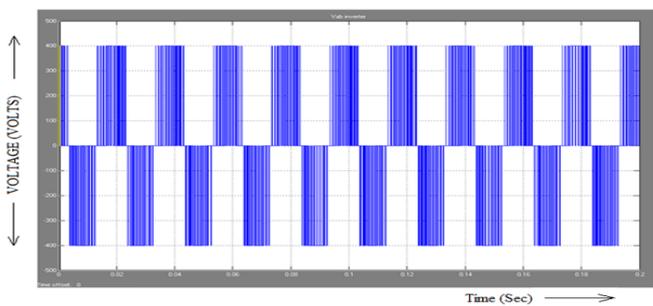
Two Level Inverter:
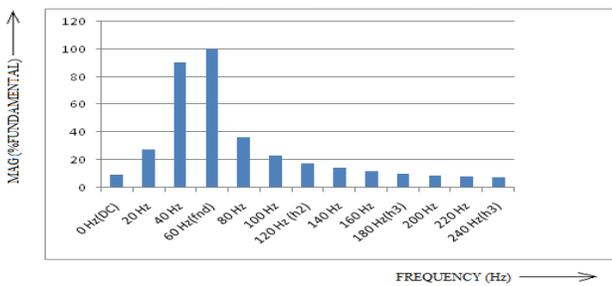

Fig. 7 Line Voltage of a Two-Level SVPWM Inverter
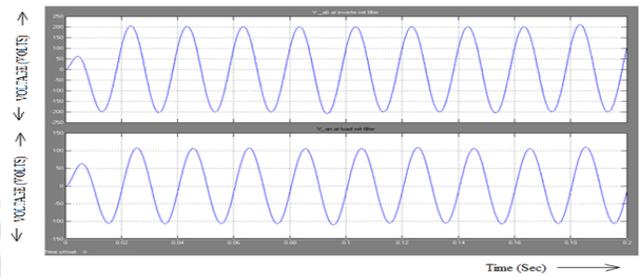

Fig. 8 FFT Analysis for Two-Level SVPWM Inverter

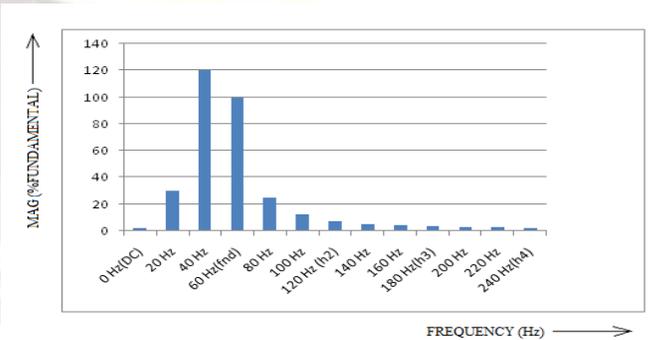**Fig 9 Line Voltage & Phase Voltage of a Two-level SVPWM Inverter with Filter**

Fig. 10 FFT Analysis for Two-Level SVPWM Inverter with Filter
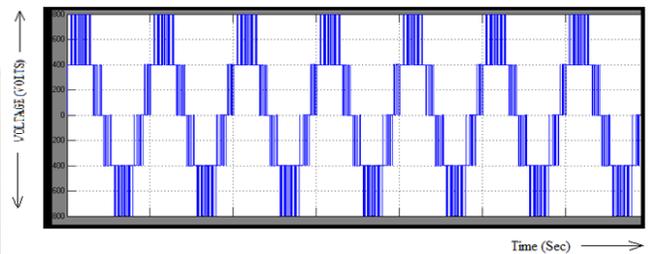
Three Level Inverter:

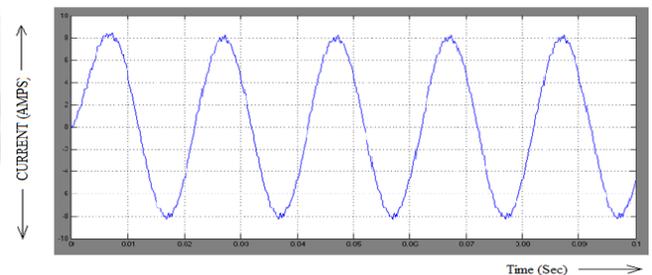**Fig. 11 Line Voltage of Three-Level Inverter V_{ab}**

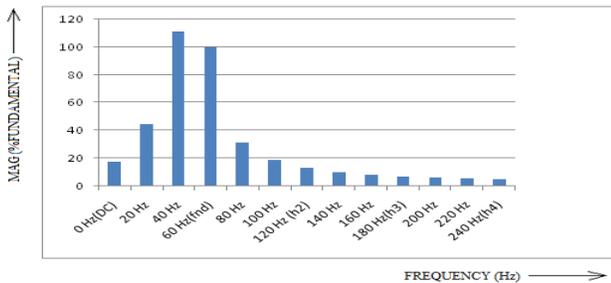**Fig. 12 Load Current of Three-Level Inverter**

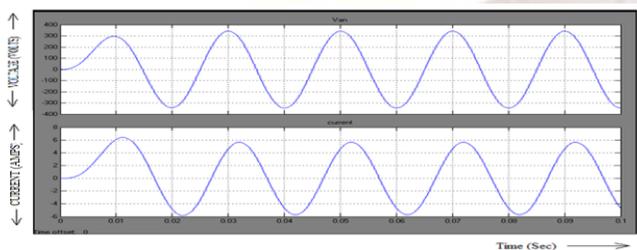**Fig. 13 FFT Analysis of Phase Voltage of Three-Level Inverter**

Fig. 14 Phase Voltage & Current of Three - Level SVPWM Inverter with Filter
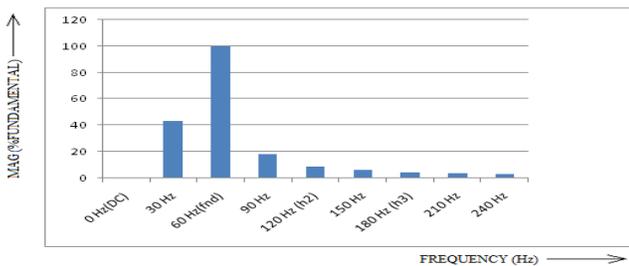

Fig. 15 FFT Analysis of Phase Voltage of Three-Level Inverter with Filter

VII. CONCLUSIONS

The performance of PWM technique of voltage source inverter is characterized by Total Harmonic Distortion (THD).The PWM voltage output of inverter will contain harmonics which will circulate harmonic current in the load. Since the triplen harmonics are of zero sequence, they do not appear in the line voltage. SVPWM is simulated and one cycle of line voltage is taken to compute THD. The frequency spectrum is computed using MATLAB FFT routine. The V_{THD} is computed for linear range of Modulation Index. Compared with sinusoidal PWM, space vector PWM can work with a higher modulation index (m>1) and the harmonic content of the inverter voltage is less in the space vector PWM than in sinusoidal PWM. The SVPWM

technique can be further applied to three level, four leg and multilevel inverters. This software implementation used in this paper can be extended further to over modulation region i.e. modulation index m>1which will be a future enhancement.

VIII. REFERENCES

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