Performance Analysis of Three Level Five Phase Voltage Source Inverter with SVPWM Switching Technique for Induction Motor Drive

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Abstract: This paper investigates the dynamic performance of 5-ϕ induction motor drive with three level space vector PWM (SVPWM) technique. First, a 5-ϕ three level VSI model is presented in terms of space vectors. Next, three level SVPWM switching technique is introduced based on large vectors, which provide its working with reduced %THD in the output voltages. The proposed scheme uses the full DC bus voltage, and the output response superior with low lower order harmonics than the conventional SVPWM methods. The performances of the 5-ϕ three level VSI fed IM drive tested with SVPWM switching technique, and the results observed in terms of harmonic contents present in the output voltage waveform. MATLAB/Simulink software results are included in this paper to show and verify the theoretical concepts.

***Index Terms* - SVPWM, five-phase three level VSI, five-phase induction motor, total harmonic distortion.**

I. INTRODUCTION

In general, multi-phase systems have many advantages, and they are used in applications such as automotive industry, aeronautics and electric power generation due to a variety of benefits provided by multi-phase drives over 3-ϕ drives. [1]. In the case of even number phases, the poles are coinciding with each other, and it will reduce the motor performance. So, odd number phases are preferred over even number phases [2]-[3]. Also, the output power of a 5-ϕ system is greater than that of the 3-ϕ system. This has attracted the interest in the development of multi phase machines [4], [5].

The broad choice of switching techniques can be used for the VSI to produce the expected output [6]-[9]. The techniques start with sin triangle PWM, conventional SVPWM, and modified SVPWM. SVPWM technique is more suitable for multiphase VSI, and the no. of vectors increase with the no. of a levels and no. of phases (i.e., 'm' is the no. of level of VSI and 'n' is the no. of phases) [10], [11].

A 3 level VSI has 242 vectors represented into d_1-q_1 , d_2-q_2 & d_3-q_3 subspaces. All subspaces are a source of lower order harmonics except the d1-q1 subspace. The switching techniques proposed in [12] can eliminate the harmonics present in d_3-q_3. In addition, this method can generate a sinusoidal phase voltage waveform. There are few SVPWM techniques proposed in [13]-[16] to minimize the switching losses of a 5-ϕ inverter.

The three level SVPWM switching scheme is proposed in this paper for the 5-ϕ VSI fed IM drive. The MATLAB/ Simulink is used to construct the system. The performances of the proposed techniques are compared with conventional SVPWM technique.

II. Modeling of Five-Phase Induction Motor

A Mathematical model can be represented for an induction motor. The 5-ϕ system variables are transformed into 2-ϕ variables in d-q plane rotating with synchronous speed. The displacement between two phases is 72 degrees, and the number of phases must be the same before and after the transformation. The relationships between 5-ϕ and 2-ϕ variables are as follows.

$$V^s_{dq=}K_S\, V^s_{abcde} \qquad i^s_{dq=}K_S\, i^s_{abcde} \qquad \Psi^s_{dq=}K_S\, \Psi^s_{abcde} \tag{1}$$

$$V^r_{dq=}K_r\, V^r_{abcde} \qquad i^r_{dq=}K_r\, i^r_{abcde} \qquad \Psi^r_{dq=}K_r\, \Psi^r_{abcde} \tag{2}$$

$$\text{Where, } K = \sqrt{\frac{2}{5}}\begin{bmatrix} 1 & \cos\left(\frac{2\pi}{5}\right) & \cos\left(\frac{4\pi}{5}\right) & \cos\left(\frac{4\pi}{5}\right) & \cos\left(\frac{2\pi}{5}\right) \\ 0 & \sin\left(\frac{2\pi}{5}\right) & \sin\left(\frac{4\pi}{5}\right) & \sin\left(\frac{4\pi}{5}\right) & \sin\left(\frac{2\pi}{5}\right) \\ 1 & \cos\left(\frac{4\pi}{5}\right) & \cos\left(\frac{8\pi}{5}\right) & \cos\left(\frac{8\pi}{5}\right) & \cos\left(\frac{4\pi}{5}\right) \\ 0 & \sin\left(\frac{4\pi}{5}\right) & \sin\left(\frac{8\pi}{5}\right) & -\sin\left(\frac{8\pi}{5}\right) & -\sin\left(\frac{4\pi}{5}\right) \\ \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \end{bmatrix} \tag{3}$$

'K' is the 5-ϕ induction machine decoupling transformation matrix given in equation 2. The 5-ϕ machine is represented in the d-q-x-y-o arbitrary plane. The d-q components are responsible for power generation, fluxes and torque production in the machine.

System losses are accounted by x-y components, and the reason for zero components being used is to show unchanged in the system. The 5-ϕ IM is modeled in the MATLAB Simulink, and the characteristics responses are obtained.

Essential machine model equations for stator sides and rotor sides in stationary reference frame are represented as follows:

$V_{ds} = R_s i_{ds} + p\Psi_{ds}$ $\quad$ $V_{qs} = R_s i_{qs} + p\Psi_{qs}$ (4)

$\Psi_{xs} = L_{ls} i_{xs}$ $\quad$ $\Psi_{ys} = L_{ls} i_{ys}$ (5)

$V_{dr} = R_r i_{dr} + p\Psi_{dr}$ $\quad$ $V_{qr} = R_r i_{qr} + p\Psi_{qr}$ (6)

$\Psi_{xr} = L_{lr} i_{xr}$ $\quad$ $\Psi_{yr} = L_{lr} i_{yr}$ (7)

Flux Linkage equations for stator and rotor sides are expressed as follows:

$\Psi_{xs} = L_{ls} i_{xs}$ $\quad$ $\Psi_{xr} = L_{lr} i_{xr}$ (8)

$\Psi_{ds} = (L_{ls} + L_m) i_{ds} + L_m i_{dr}$ $\quad$ $\Psi_{qs} = (L_{ls} + L_m) i_{qs} + L_m i_{qr}$ (9)

$\Psi_{dr} = (L_{lr} + L_m) i_{dr} + L_m i_{ds}$ $\quad$ $\Psi_{qr} = (L_{lr} + L_m) i_{qr} + L_m i_{qs}$ (10)

Where, $L_s = L_{ls} + L_m$ $\quad$ $L_r = L_{lr} + L_m$ (11)

$\Psi_{ys} = L_{ls} i_{ys}$ $\quad$ $\Psi_{yr} = L_{lr} i_{yr}$ (12)

The equation for torque can be denoted as:

$T_e = PL_m(i_{dr} i_{qs} - i_{ds} i_{dr})$ (13)

$w_r = \int \frac{P}{2J}(T_e - T_L)$ (14)

III. TWO-LEVEL AND THREE LEVEL FIVE-PHASE VSI

Fig.1 shows the circuit diagram for 5-ϕ two VSI fed 5-ϕ IM drive comprises ten power switches, two switches per leg. The pole voltage is equal to Vdc when the upper switch is ON and it is zero when it is OFF. To avoid the direct short circuit of same leg switches, they switched opposite to each other.

Phase to neutral voltages (Va ~ Ve) of 5-ϕ VSI can be expressed in terms of inverter pole voltages as given in equation (15) and (16) [12].

$V_j = \frac{4}{5} V_j - \frac{1}{5} \sum_{i,i \neq j}^{5} V_j, \text{ if } j < 5$ (15)

$V_j = \frac{4}{5} V_j - \frac{1}{5} \sum_{i,i \neq j}^{4} V_j, \text{ if } j = 5$ (16)

In general, a 5-ϕ 2-level VSI has 32 combinations of switching states (ie., 2^n, where n is the number of phases) and can be represented in two space vector planes (d_1-q_1 and d_3-q_3) includes thirty active and two zero vectors.

Binary numbers are used to represent the states on each space vectors. Bit '0' represents that the lower switch is ON while a bit '1' represents that the upper switch is on. The three coordinated decagons formed by 30 active vectors originate at the 2 zero vectors. Inner, middle and outer decagons magnitudes are 0.2472, 0.4, and 0.6472. Fig. 2 shows the three level VSI fed IM drive. The two level SVPWM switching technique is extended to the three level SVPWM by using phase disposition switching scheme.

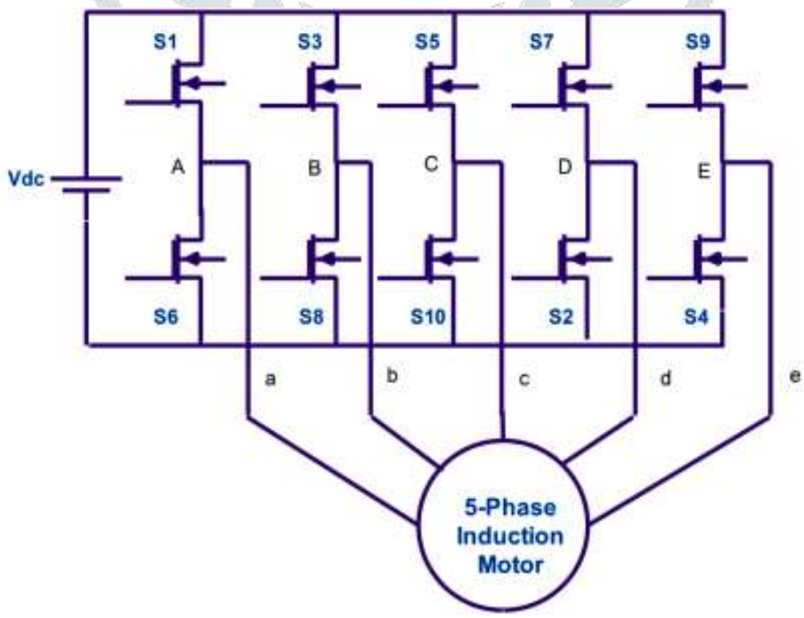


Fig. 1 5-ϕ two level VSI fed 5-ϕ IM drive

Fig 3 and Fig. 4 shows the space vector representation in a d-q plane. The phase sequence in d_1q_1 is ABCDE while in d_3q_3 it is ACEBD. The middle decagon is the same in both subspaces while the inner and outer decagons are interchanged between d1q1 and d3q3.equation (17) and (18) represents the 5-ϕ inverter voltage in a two-phase d-q plane. The value of a, a^2, a^3, & a^4 is given in equation (19) to (22).

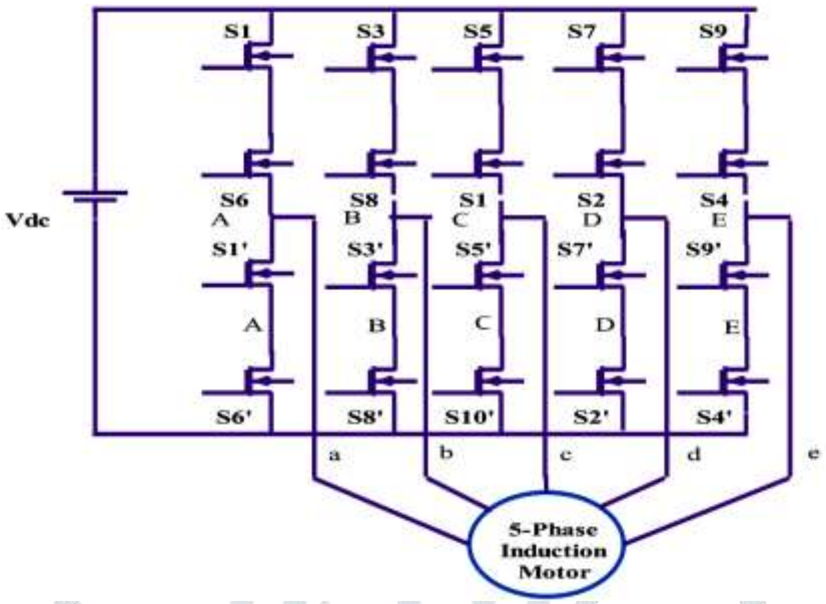


Fig. 2 5-ϕ three level VSI fed 5-ϕ IM drive

The concept of 2 level SVPWM control is extended to three level SVPWM by adapting the Phase Disposition SVPWM (PDSVPWM) pulse generation scheme. Four different pulses are generated per phase and it is applied to the power circuit.

IV. SVPWM SWITCHING SCHEME FOR 5-Φ VSI

Switching Scheme : Using Large Vectors (d1q1 plane)

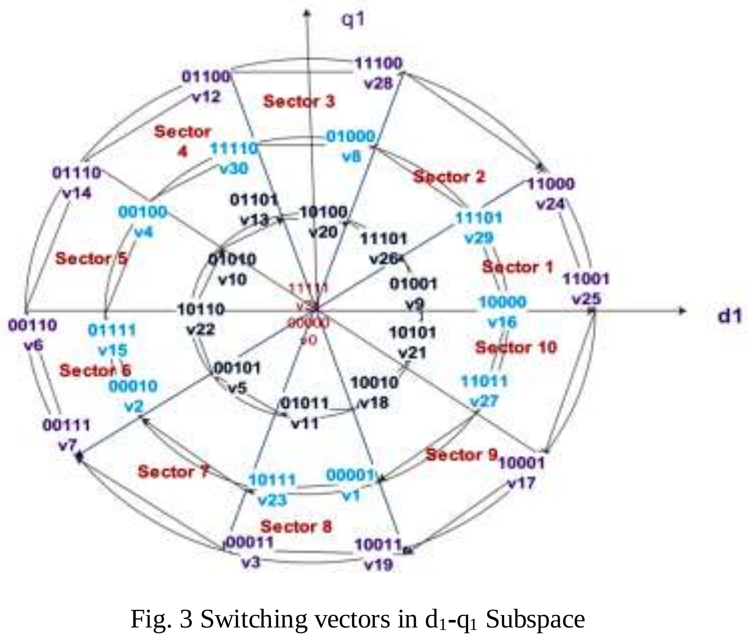


Fig. 3 Switching vectors in d_1-q_1 Subspace

The Space Vectors in the large decagon of d1q1 plane are considered. The switching vector rotates in an anti-clockwise direction starting from V25 until V17 as shown in Fig. 3. The equations (17), (18) & (19) used to calculate the conduction time in each switching state. Fig. 5 shows the upper IGBT switching pattern in each phase and the respective switching vector has shown in Fig. 6 (a). In conventional switching scheme, the switching vectors start from 0, 25, 24, 31, 31, 24, 25, and 0 for one switching cycle Ts in sector I. Fig. 6 (b) shows the modulating signals for VSI switching scheme. After generating the modulating signal using two level SVPWM switching scheme, the carrier signals of PDPWM are in same phase and they are compared with the modulating signals to generate the pulses for the three level SVPWM based five phase inverter circuit as shown in Fig.7 and Fig. 8.

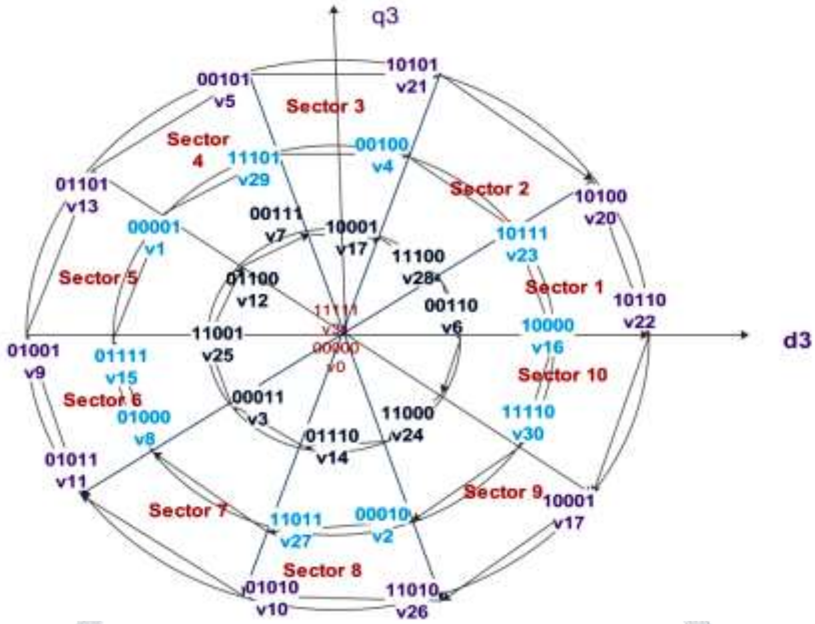


Fig. 4 Switching vectors in d_3-q_3 Subspace

The following expressions are used to calculate the conduction time t_{al}, t_{bl} and to.

$$t_{al} = \frac{|V_{ref}|\sin\left(\left(K\frac{\pi}{5}\right)-\theta\right)}{V_l\sin\left(\frac{\pi}{5}\right)} t_s \quad (17)$$

$$t_{bl} = \frac{|V_{ref}|\sin\left(\theta-\left((K-1)\frac{\pi}{5}\right)\right)}{V_l\sin\left(\frac{\pi}{5}\right)} t_s \quad (18)$$

$$t_0 = \frac{t_s-t_{al}-t_{bl}}{2} \quad (19)$$

Maximum possible fundamental peak voltage of large space vector is

$$V_{max} = |V_l|\cos\frac{\pi}{10}V_{dc} = 0.6155V_{dc} \quad (20)$$

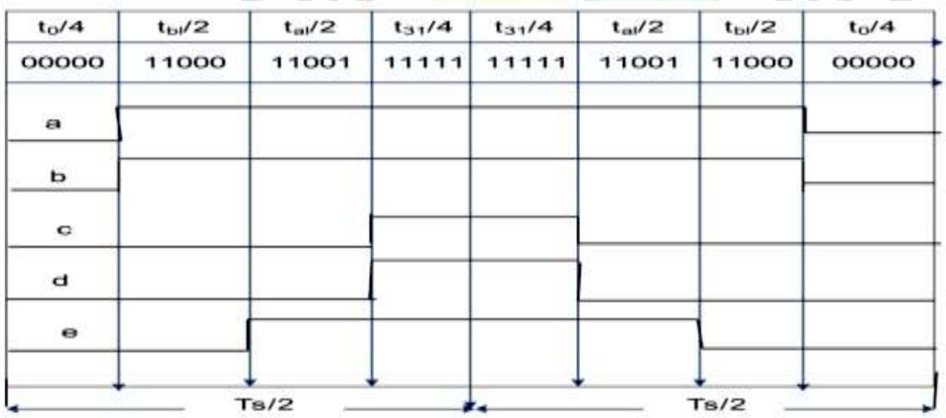
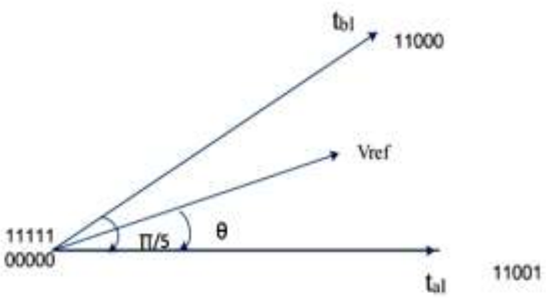
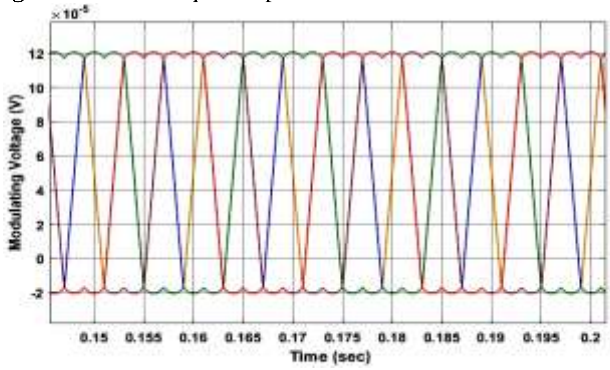


Fig. 5 switching pattern for large vectors in d_1-q_1 Subspace in Sector -I



(a)



(b)

Fig.6 (a) Time Switching for Large vectors in d_1-q_1 subspace in Sector –I (b) Modulating signal

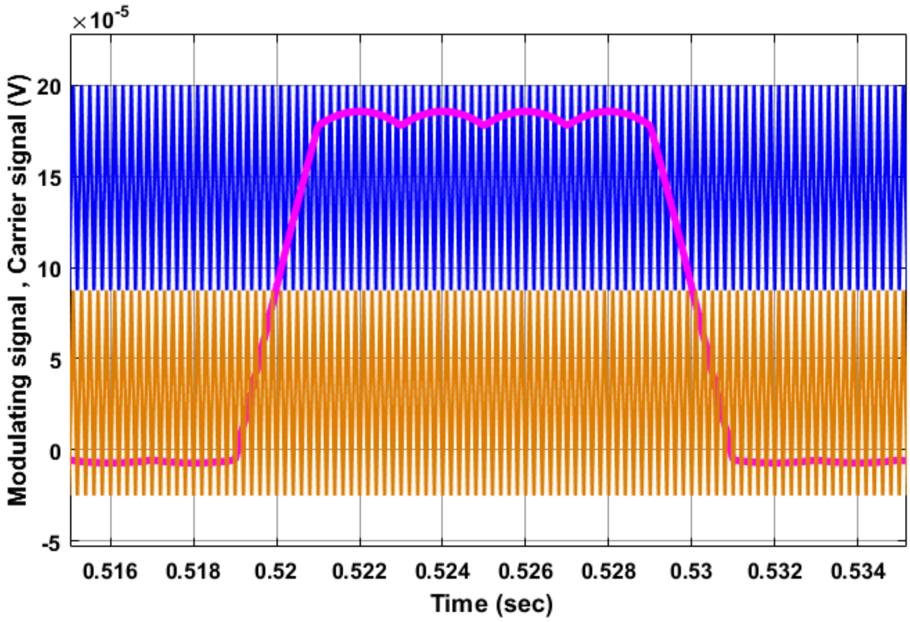


Fig. 7 Phase Disposition SVPWM – Modulating and carrier signal

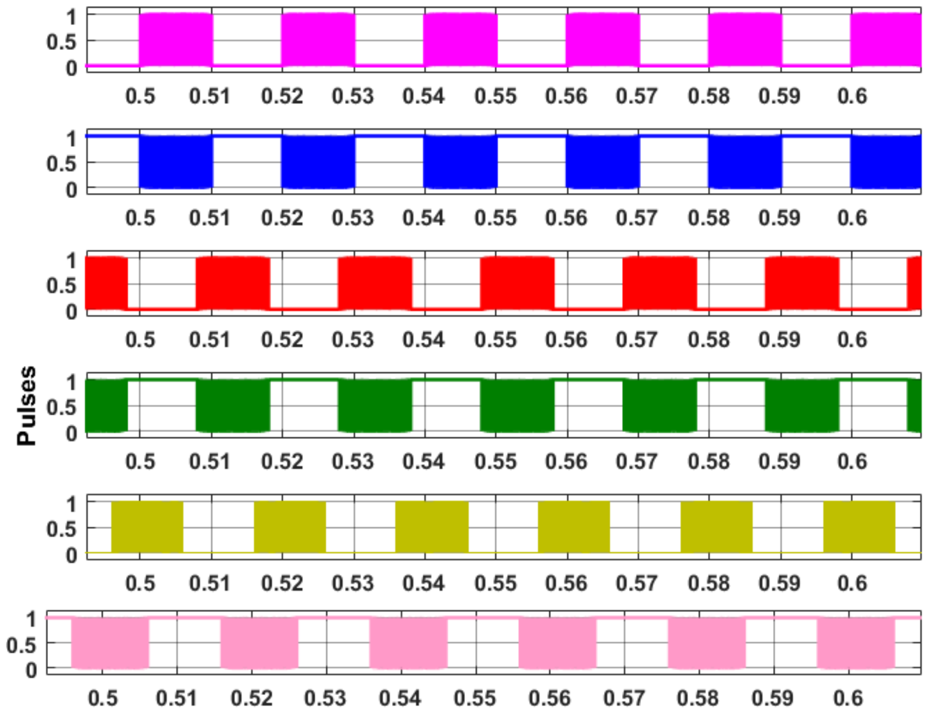
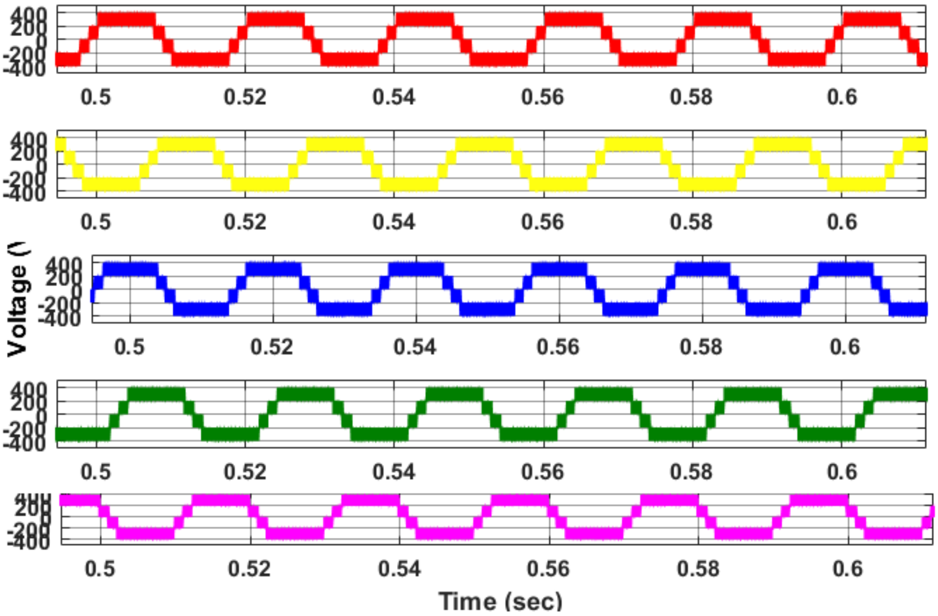


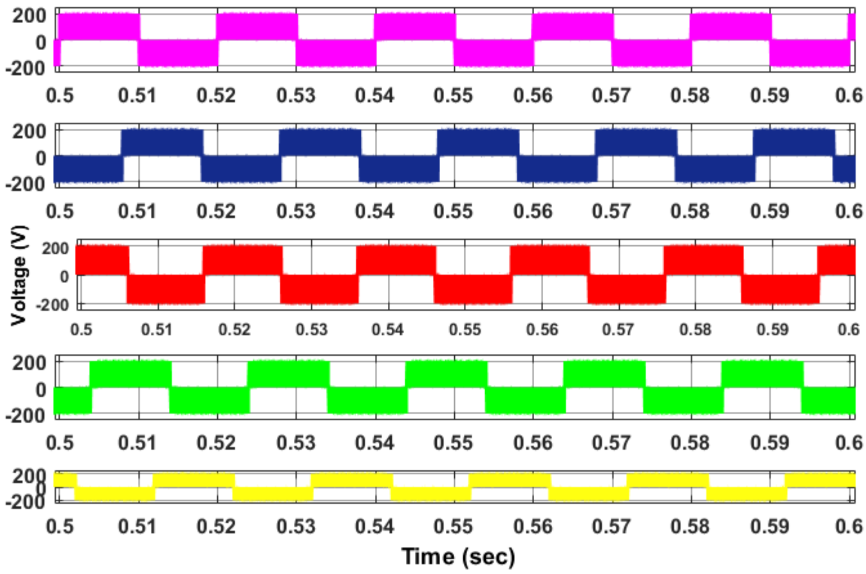
Fig.8 Pulse signal for three level VSI

V. RESULTS AND DISCUSSION

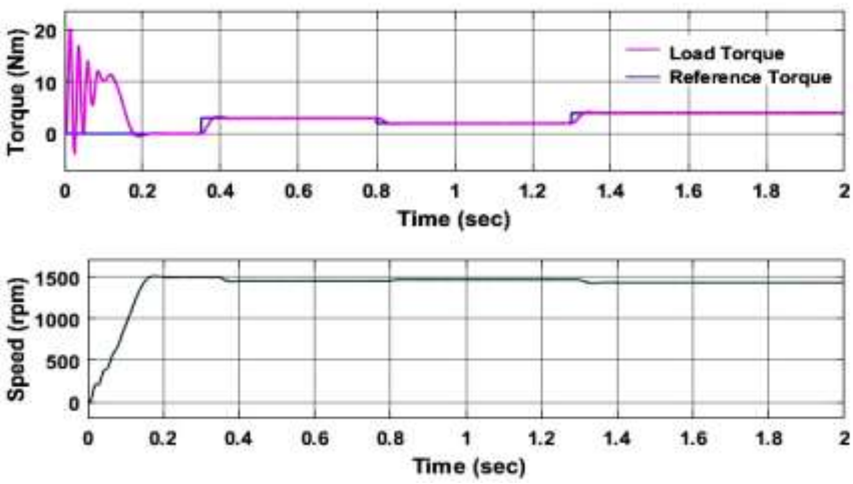
A MATLAB software simulation is used to determine the effect of SV based switching techniques and to compare the results of various switching techniques such as medium vector, large vector and the grouping of a medium and large vector in d1-q1 subspace. The simulation parameters used for the system are: Vdc=400V, the fundamental output frequency of VSI is 50Hz, switching frequency fs = 5 kHz and the dead time of switches present in the same leg has not been considered. Table 1 lists the simulation parameters of the system, and the performance characteristics are shown in Fig. 9. The phase and line voltage of 5-ϕ VSI is shown in Fig. 9 (a) & (b). The 5-phase induction motor electromagnetic torque is tracking the reference torque command of 3 Nm, 2 Nm and 4.4 Nm at the instants 0.4 sec, 0.8 and 1.3 sec respectively as shown in Fig. 9 (c). The stator and rotor current variations regarding the load changes have been recorded and shown in Fig. 9 (d).


Voltage (V)
Time (sec)

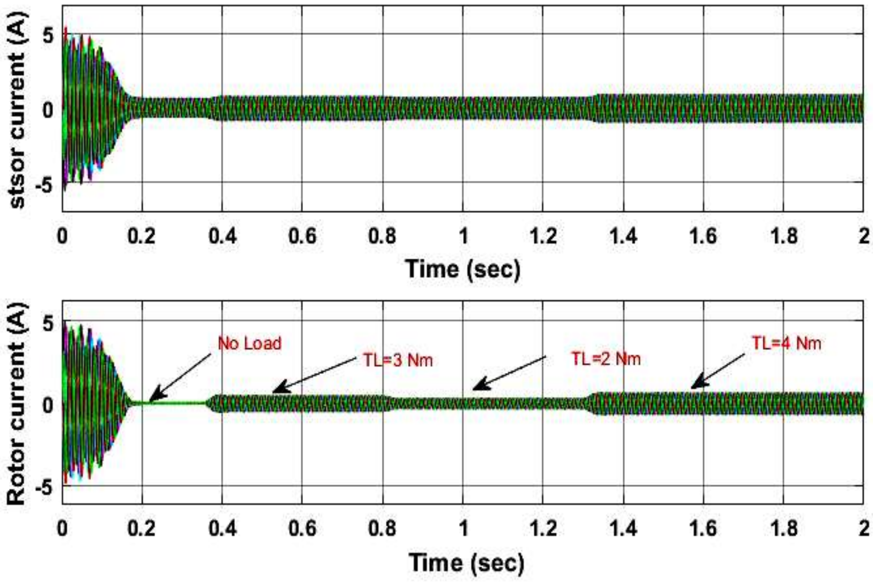
(a)


Voltage (V)
Time (sec)

(b)


Torque (Nm)
Load Torque
Reference Torque
Time (sec)
Speed (rpm)
Time (sec)

(c)



(d)

Fig.9 output Response of three level VSI fed IM drive (a) Line Voltage (b) phase Voltage (c) Speed and torque response (d) current response

Table 1
Parameters of 5-ϕ VSI fed IM Drive

Parameters	Values
DC Bus voltage	400 V
Switching frequency	5 KHz
Power (P)	1 hp
Motor RMS Input Voltage (V)	220
No. of Phases	5
Number of Poles (p)	4
Resistance (stator)	10.1 Ω
Inductance (stator)	0.833 Henry
Resistance (rotor)	9.854 Ω
Inductance (rotor)	0.782 Henry
Mutual Inductance	0.782 Henry
Inertia	0.0088

The phase disposition SVPWM switching scheme is used to design for 5-ϕ three level SVPWM VSI fed IM drive. The fundamental voltage peak is high for the three level SVPWM switching scheme when compared to two level SVPWM technique. The %THD in the phase voltage of 5-ϕ SVPWM VSI fed IM drive is observed is as shown in the Fig.10.

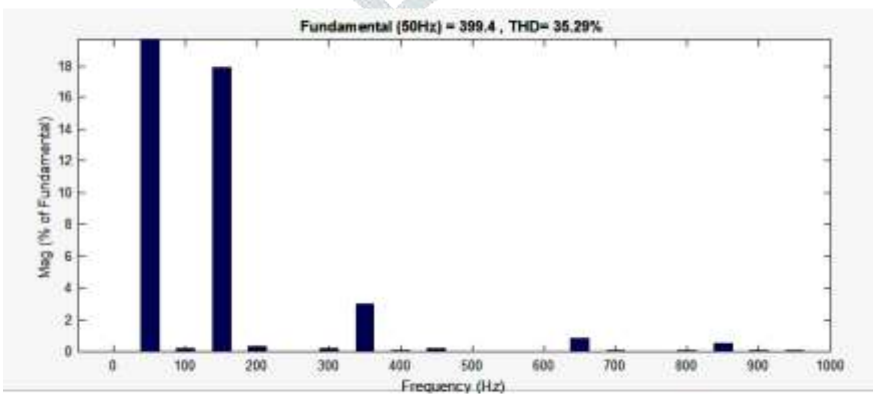


Fig. 10 FFT analysis of line voltage of three level VSI fed IM drive

VI. CONCLUSION

A 5- ϕ three level VSI with SVPWM technique is presented to improve the power quality of input voltage applied to 5-ϕ IM drive. Use of three level SVPWM technique improves the utilization of DC bus voltage when compared to SPWM techniques. This control technique also improves the fundamental output voltage by 25% greater than the sinusoidal pulse width modulation techniques and two level SVPWM switching techniques. This investigation is performed in the MATLAB Simulink for 5-ϕ VSI fed IM drive. The characteristic curves are obtained for the different load conditions and the performance of the system is found to be good by the use of proposed three level VSI for five phase IM drive.

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