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Performance of Induction Motor driven by Three Level Neutral Clamped Inverter using Space Vector Modulation as Voltage Control Technique

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Abstract **- This paper deals with the performance of Induction Motor which is driven by a three-level neutral clamped inverter using space vector modulation technique as voltage control strategy. SVM has increasing applications in power converters and motor control. Compared to other modulation techniques, space vector modulation technique has the advantages like higher modulation index, utilizing DC bus voltage more effectively, generating less THD and thus less harmonics and low ripple content. In this paper, DC voltage is given as input to the three-level neutral clamped Inverter. This inverter has been designed and implemented in MATLAB/SIMULINK software. IGBTs are used as active switches. The triggering pulses to these IGBTs are given by using space vector modulation technique. By selecting proper switching states and by calculating the time-period in particular switching state AC voltage with less THD, low dV/dt is obtained as output. AC output of this inverter is given as input to the Induction Motor. After simulating, the output parameters of induction motor like torque, speed, load current is studied.**

Keywords: Induction Motor (IM), Neutral Clamped Inverter (NCI), Space Vector Modulation Technique (SVM), Total Hormonic Distortion (THD).

I. INTRODUCTION

Multilevel inverters are gaining importance in high power and high voltage applications like manufacturing industry, transportation, renewable energy and in reactive power compensation due to their superior performance compared to two-level inverters. If we use two-level inverters in high voltage and high-power applications, the rate of rise of voltage (dV/dt) is significantly high, the switching losses will be more and also there will be constraints of device rating [1]. Hence, Multilevel Inverters are becoming popular which produce high power, high voltages without requiring transformers or higher rating individual devices. Multilevel Inverters produce higher level voltages with low dV/dt, low hormonic content and low ripple content [3]. The only disadvantage of this technique is that by increasing the levels, the number of switches will increase, and the switching combination will become complex and control will become complicated and expensive [9]. Its various applications are in Renewable DC source utilization, Uninterruptible Power Supplies (UPS), Power Transmission through high voltage DC (HVDC), Variable frequency drives and electrical vehicle drives [1]. The multilevel inverters are classified into three types:

1. Neutral clamped multilevel inverter
2. Flying-capacitors multilevel inverter
3. Cascade H-Bridge multilevel inverter.

II. NEUTRAL CLAMPED MULTILEVEL INVERTER

Neutral clamped multilevel inverter is also known as Diode clamped multilevel inverter. Circuit diagram of a three-level neutral clamped inverter is shown in the Fig.1. In "m" level inverter with one leg consists of (m-1) dc bus capacitors, (m-1) (m-2) clamping diodes and 2(m-1) main switching devices. Thus, a 3-level neutral clamped inverter with one leg consists of 2 dc bus capacitors, 2 clamping diodes and 4 main switching devices. There fore, for a 3-phase, 3-level neutral clamped inverters there are 2 dc bus capacitors, 6 midpoint clamping diodes, 12 main switching devices [1], [4], [5]. Table.I shows the switching states of three-level inverter. Each phase has three output states, P, O, and N, corresponding to positive voltage (+), zero voltage (0), and negative voltage (-). Take phase 'a' as an example, if switch Sa1 and Sa2 are turned on, then phase a is on P state; if switch Sa2 and Sa3 are turned on, then phase a is on O state. Similarly, when switch Sa3 and Sa4 are turned on, then phase a is on N state.

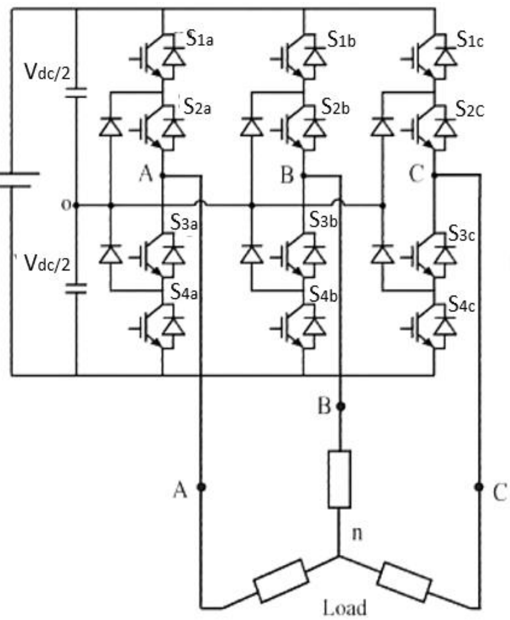

Fig.1. Circuit diagram of a three-level neutral clamped inverter

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Switches S1x and S3x are complementary and switches S2x and S4x are complimentary. If one of the complementary switch pairs is turned ON, the other of the same pair must be OFF. Two switches are always turned ON at the same time [3], [4], [5].

Table I: Switching states and terminal voltages of a three-level inverter

symbols	Switching States				Output Voltage
	S1x	S2x	S3x	S4x	
P	ON	ON	OFF	OFF	Vdc/2
O	OFF	ON	ON	OFF	0
N	OFF	OFF	ON	ON	-Vdc/2

III. SPACE VECTOR PULSE WIDTH MODULATION TECHNIQUE

Space Vector Pulse Width Modulation Technique is a voltage control technique used in inverters which is used to regulate voltage of inverters, cope up with variations of DC input voltage and maintain constant voltage and frequency. Voltage is controlled in each sampling period by Space Vector Transformation concept [1] by

(i) Properly selecting the switching states for the inverter and
(ii) Calculation of appropriate time-period for each state [4], [7], [8].

Since three kinds of switching states exist in each phase, three-level inverter has (3^3=) 27 switching states, out of which 3 are null states, and remaining are active states [3], [7]. But we consider only 19 states to avoid redundancy and memory wastage in MATLAB [10].

From Fig.1. The resultant output load phase voltage of inverter is

$$V_R(t) = \frac{2}{3}(V_{AN}(t)+V_{BN}(t)e^{j\frac{2\pi}{3}}+V_{CN}(t)e^{j\frac{4\pi}{3}} \quad (1)$$

Here,

$$V_{AN}(t) = \frac{2}{3}V_{AO}-\frac{1}{3}V_{BO}-\frac{1}{3}V_{CO} \quad (2)$$

$$V_{BN}(t) = \frac{2}{3}V_{BO}-\frac{1}{3}V_{AO}-\frac{1}{3}V_{CO} \quad (3)$$

$$V_{CN}(t) = \frac{2}{3}V_{CO}-\frac{1}{3}V_{BO}-\frac{1}{3}V_{AO} \quad (4)$$

By substituting the values of V_{AO}, V_{BO}, V_{CO} we can find the voltage vector magnitudes and phase angles of all switching states [1], [10] as shown in Table II.

Table II. All Switching states with their corresponding voltage vectors: magnitude and angle

Switching States			Corresponding Voltage Vectors		
Va	Vb	Vc	Vector	Magnitude	Angle
P	P	P	V_0	0	0
O	O	O			
N	N	N			
P	O	O	V_1	$\frac{2}{3}V_{dc}$	0
O	N	N			
P	N	N	V_2	$\frac{4}{3}V_{dc}$	0
P	O	N	V_3	$\frac{2}{\sqrt{3}}V_{dc}$	$\frac{\pi}{6}$
P	P	O	V_4	$\frac{2}{3}V_{dc}$	$\frac{\pi}{3}$
O	O	N			
P	P	N	V_5	$\frac{4}{3}V_{dc}$	$\frac{\pi}{3}$
O	P	N	V_6	$\frac{2}{\sqrt{3}}V_{dc}$	$\frac{\pi}{2}$
O	P	O	V_7	$\frac{2}{3}V_{dc}$	$\frac{2\pi}{3}$
N	O	N			
N	P	N	V_8	$\frac{4}{3}V_{dc}$	$\frac{2\pi}{3}$
N	P	O	V_9	$\frac{2}{\sqrt{3}}V_{dc}$	$\frac{5\pi}{6}$
O	P	P	V_{10}	$\frac{2}{3}V_{dc}$	π
N	O	O			
N	P	P	V_{11}	$\frac{4}{3}V_{dc}$	π
N	O	P	V_{12}	$\frac{2}{\sqrt{3}}V_{dc}$	$-\frac{5\pi}{6}$
O	O	P	V_{13}	$\frac{2}{3}V_{dc}$	$-\frac{2\pi}{3}$
N	N	O			
N	N	P	V_{14}	$\frac{4}{3}V_{dc}$	$-\frac{2\pi}{3}$
O	N	P	V_{15}	$\frac{2}{\sqrt{3}}V_{dc}$	$-\frac{\pi}{2}$
P	O	P	V_{16}	$\frac{2}{3}V_{dc}$	$-\frac{\pi}{3}$
O	N	O			
P	N	P	V_{17}	$\frac{4}{3}V_{dc}$	$-\frac{\pi}{3}$
P	N	O	V_{18}	$\frac{2}{\sqrt{3}}V_{dc}$	$-\frac{\pi}{6}$

When all these switching states are represented in space by using space vectors then we get a hexagon with 6 sectors [3], [6] and with 4 subsectors in each sector as shown in Fig.2.

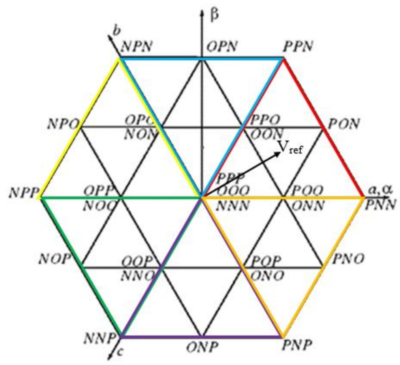

Fig.2. Space Vector representation of 3-level Inverter

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A. Space Vector Modulation Algorithm:

Steps to execute SVM logic in MATLAB/SIMULINK are as follow:

Step I: Give three-phase sinusoidal input voltage V_a, V_b, V_c.

$$V_a = V_m \sin wt \quad (5)$$

$$V_b = V_m \sin(wt-120^o) \quad (6)$$

$$V_c = V_m \sin(wt-240^o) \quad (7)$$

Step II: The coordinate transformation from the a–b–c-axis to the α–β axis.

The transformation from the a–b-c axis to the α-β axis, which is rotating with an angular velocity of ω, can be obtained by clerk and perk transformations as shown below

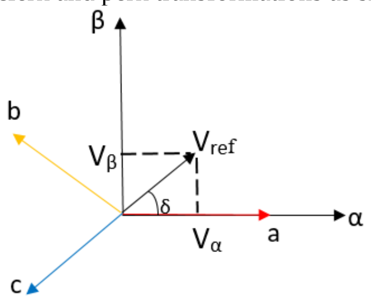

Fig.3. Transformation from a–b-c axis to the α-β axis

$$\begin{bmatrix} V\alpha \\ V\beta \end{bmatrix} = \frac{2}{3}\begin{bmatrix} 1 & cos(\frac{2\pi}{3}) & cos(\frac{2\pi}{3}) \\ 0 & sin(\frac{2\pi}{3}) & sin(\frac{2\pi}{3}) \end{bmatrix}\begin{bmatrix} Va \\ Vb \\ Vc \end{bmatrix}$$

$$\begin{bmatrix} V\alpha \\ V\beta \end{bmatrix} = \frac{2}{3}\begin{bmatrix} 1 & \frac{-1}{2} & \frac{-1}{2} \\ 0 & \frac{\sqrt{3}}{2} & \frac{-\sqrt{3}}{2} \end{bmatrix}\begin{bmatrix} Va \\ Vb \\ Vc \end{bmatrix}$$

Which can also be written as

$$V\alpha = \frac{2}{3}\left(Va - \frac{1}{2}Vb - \frac{\sqrt{3}}{2}Vc\right) \quad (8)$$

$$V_\beta = \frac{2}{3}\left(\frac{\sqrt{3}}{2}Vb - \frac{\sqrt{3}}{2}Vc\right) \quad (9)$$

Here α-axis is direct axis (real axis) and β-axis is quadrature axis (imaginary axis).

Step III: Calculate the value of deta (δ) and Reference voltage (V_{ref})

Which is given by,

$$\text{deta} = \delta = \tan^{-1}\left(\frac{V\beta}{V\alpha}\right) \quad (10)$$

$$\text{Reference voltage} = V_{ref} = \sqrt{V\alpha^2 + V\beta^2} \quad (11)$$

This Reference voltage is selected as control instruction, which rotates in the space with an angular frequency 'ω'. When we consider the reference vector in one of the 6 sectors, two active space vectors nearest to Vref is selected along with one of the three null vectors by means of their corresponding operating times [7], [8], [10].

Step IV: Selection of sector in which V_{ref} is considered

Let 'n' be the sector. As there are 6 sectors, n can be from 1 to 6. 'n' is the function of deta (δ) [9]. The sector in which the command vector V_{ref} is located, is determined as follow:

- If δ is between 0° and 60°, then V_{ref} is located in Sector 1, n=1.
- If δ is between 60° and 120°, then V_{ref} is located in Sector 2, n=2.
- If δ is between 120° and 180°, then V_{ref} is located in Sector 3, n=3.
- If δ is between 180° and 240°, then V_{ref} is located in Sector 4, n=4.
- If δ is between 240° and 300°, then V_{ref} is located in Sector 5, n=5.
- If δ is between 300° and 360°, then V_{ref} is located in Sector 6, n=6.

Step V: Selection of Sector angle

Let 'ϕ' be the sector angle. sector angle is the function of deta and n. The value of sector angle is given as follow:

- If n=1 i.e., in sector 1: ϕ=δ
- If n=2 i.e., in sector 2: ϕ = δ-60°
- If n=3 i.e., in sector 3: ϕ = δ-120°
- If n=4 i.e., in sector 4: ϕ = δ+180°
- If n=5 i.e., in sector 5: ϕ = δ+120°
- If n=6 i.e., in sector 6: ϕ = δ+ 60°

Step VI: Selection of Subsector

Let 'y' be the subsector. 'y' is the function of V_{dc}, V_{ref} and sector angle (ϕ). In each sector there are 4 subsectors, 'y' can be from 1 to 4. Subsector is selected by using Modulation Index (MI). Modulation Index differs from modulation to modulation and from inverter to inverter. For space vector modulation technique, the modulation index is given by

$$M = \frac{Vref}{\frac{2}{3}Vdc} \quad (12)$$

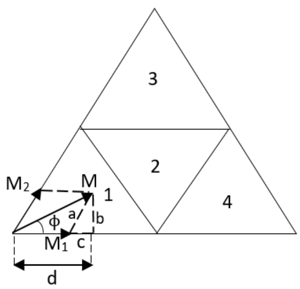

Fig.4. Calculation of M1 and M2

From above figure, by using trigonometric ratios we get

$$M_1 = M\frac{2}{\sqrt{3}}\sin\left(\frac{\pi}{3} - \phi\right) \quad (13)$$

$$M_2 = M\frac{2}{\sqrt{3}}\sin\phi \quad (14)$$

Table III. Conditions for Subsector selection

y =1	M_1<0.5, M_2<0.5 and (M_1+M_2) <0.5
y = 2	M_1<0.5, M_2<0.5 and (M_1+M_2) >0.5
y = 3	M_2>0.5
y = 4	M_1>0.5

Step VII: Calculation of Switching Timings

$$V_{ref}\,T_s = V_1T_A + V_7T_B + V_2T_C \qquad (15)$$

Consider a resultant vector in sector 1. Choose any three vectors nearest to the resultant vector.

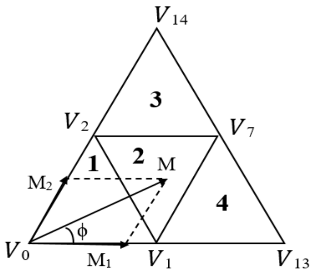

Fig.5. calculation of switching timings

$$V_1 = \frac{Vdc}{3}e^{j\,0} \qquad V_2 = \frac{Vdc}{3}e^{j\,\frac{\pi}{3}} \qquad V_7 = \frac{Vdc}{\sqrt{3}}e^{j\,\frac{\pi}{3}}$$

Substituting V_1, V_2 and V_7 in (15) we get $\frac{Vref}{\frac{2VDC}{3}}\,e^{j\phi}T_s$

$$= \frac{1}{2}T_A + \frac{\sqrt{3}}{2}e^{j\,\frac{\pi}{6}}T_C + \frac{1}{2}e^{j\,\frac{\pi}{3}}T_C \qquad (16)$$

$$M\,e^{j\phi}\,T_s = \frac{1}{2}T_A + \frac{\sqrt{3}}{2}e^{j\,\frac{\pi}{6}}T_B + \frac{1}{2}e^{j\,\frac{\pi}{3}}T_C \qquad (17)$$

$M\,T_s\,[\cos\phi + j\sin\phi\,] = \frac{1}{2}T_A + \frac{\sqrt{3}}{2}[\cos\frac{\pi}{6} + j\sin\frac{\pi}{6}]\,T_B + \frac{1}{2}[\cos\frac{\pi}{3} + j\sin\frac{\pi}{3}]\,T_C \qquad (18)$

Equating real and imaginary terms we get,

$$M_n\,T_s\cos\phi = \frac{1}{2}T_A + \frac{\sqrt{3}}{2}e^{j\,\frac{\pi}{6}}T_B + \frac{1}{2}\cos\frac{\pi}{3}T_C \qquad (19)$$

$$M_n\,T_s\sin\phi = \frac{\sqrt{3}}{2}\sin\frac{\pi}{6}T_B + \frac{1}{2}\sin\frac{\pi}{3}T_C \qquad (20)$$

$$T_s = T_A + T_B + T_C \qquad (21)$$

By solving equations (19), (20) and (21) we get

$$T_A = T_s - 2\,k\sin\phi \qquad (22)$$

$$T_B = 2\,k\sin(\tfrac{\pi}{3} + \phi) - T_s \qquad (23)$$

$$T_C = T_s - 2\,k\sin(\tfrac{\pi}{3} - \phi) \qquad (24)$$

Similarly, we can calculate the switching timings for all subsectors. The calculated values are tabulated below

Table IV. Calculated values of Switching Timings

Subsector	T_A	T_B	T_C
1	$2k\sin(\frac{\pi}{3}-\phi)$	$T_s - 2k\sin(\frac{\pi}{3}+\phi)$	$2k\sin\phi$
2	$T_s - 2k\sin\phi$	$2k\sin(\frac{\pi}{3}+\phi) - T_s$	$T_s - 2k\sin(\frac{\pi}{3}-\phi)$
3	$2k\sin\phi - T_s$	$2k\sin(\frac{\pi}{3}-\phi)$	$2T_s - 2k\sin(\frac{\pi}{3}+\phi)$
4	$2T_s - 2k\sin(\frac{\pi}{3}+\phi)$	$2k\sin\phi$	$2k\sin(\frac{\pi}{3}-\phi) - T_s$

Step VIII: Subsector Switching

Now time period for each switching device is calculated by using the switching timings calculated in each subsector in the above step and tabulated below.

Table V. Subsector Switching Timings

Region / time	1	2	3	4
S_{1a}	$\frac{Tc}{4}+\frac{Ta}{4}$	$\frac{Tc}{4}+\frac{Ta}{4}+\frac{Tb}{2}$	$\frac{Ts}{2}-\frac{Tc}{4}$	$\frac{Ts}{2}-\frac{Ta}{4}$
S_{2a}	$\frac{Ts}{2}$	$\frac{Ts}{2}$	$\frac{Ts}{2}$	$\frac{Ts}{2}$
S_{1b}	$\frac{Tc}{4}$	$\frac{Tc}{4}$	$\frac{Tc}{4}+\frac{Ta}{4}$	**0**
S_{2b}	$\frac{Ts}{2}-\frac{Ta}{4}$	$\frac{Ts}{2}-\frac{Ta}{4}$	$\frac{Ts}{2}$	$\frac{Ta}{4}+\frac{Tb}{2}$
S_{1c}	**0**	**0**	**0**	**0**
S_{2c}	$\frac{Ts}{2}-\frac{Ta}{4}-\frac{Tc}{4}$	$\frac{Tc}{4}+\frac{Td}{4}$	$\frac{Ts}{2}$	$\frac{Ta}{4}$

- To reduce the harmonics, S_{1c} is kept zero

Step IX: All Sector Switching

Reference voltage in sector 'A' is given by

$$V_{ref}^{(A)} = \frac{2}{3}(V_a + V_b e^{\frac{2j\pi}{3}} + V_c e^{\frac{-2j\pi}{3}}) \qquad (24)$$

When $V_{ref}^{(A)}$ is rotated in anticlockwise direction at an angle of 60 degree.

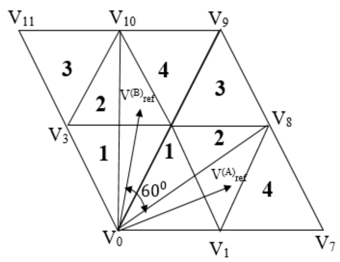

Fig.6. All sector switching

$$V_{ref}^{(B)} = V_{ref}^{(A)} * e^{\frac{j\pi}{3}} \qquad (25)$$

$$V_{ref}^{(B)} = \frac{2}{3}\;(-v_b + -v_C)\,e^{\frac{2j\pi}{3}} + (-v_a)\,e^{\frac{-2j\pi}{3}} \qquad (26)$$

Similarly, reference voltages are calculated in all sectors. Now, the relationship between phase voltages and the reference voltages in the subsectors is:

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Table VI. Relation between phase voltages and the reference voltages in the subsectors

Sector	Phase Voltage A	Phase Voltage B	Phase Voltage C
A	Va	Vb	Vc
B	$-V_b$	$-V_c$	$-V_a$
C	Vc	Va	Vb
D	$-V_a$	$-V_b$	$-V_c$
E	Vb	Vc	Va
F	$-V_c$	$-V_a$	$-V_b$

IV. SIMULATION

The MATLAB\SIMULINK diagram of 3-phase, 3-level neutral clamped inverter connected to an induction motor is shown in Fig.6. The input given to the inverter is DC voltage and the output voltage of inverter is given to the 3-phase induction motor. The Output voltage of inverter is observed in the scope using voltage measurement blocks. Output parameters of induction motor i.e., torque, speed, and load current are observed in the scope.

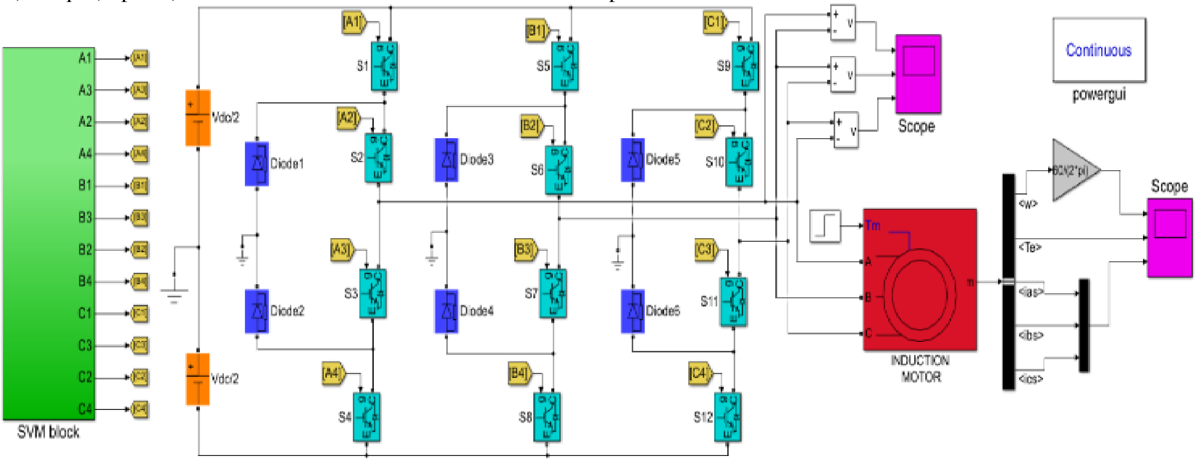

Fig.6. Simulation model of 3-phase, 3-level neutral clamped inverter fed Induction Motor

In MATLAB software 3-phase induction motor is available as Asynchronous machine (Implements a three-phase asynchronous machine modelled in a selectable d_q reference frame). Stator and rotor windings are connected in wye to an internal neutral point. In SVM block 3-phase sinusoidal voltage is given as input. The output pulses obtained from all sector switching block are compared with the triangular pulses, and the resultant pulses generated by SVM block are given to the IGBTs in the inverter by using GOTO and FROM blocks. These IGBT switches are used to control the output voltage.

Parameters:

- DC input voltage of inverter = 400V
- Output frequency = 50Hz
- Induction motor Rotor type = Squirrel cage
- Number of poles in the Induction motor = 4
- Inertia of Induction motor = 0.0131 J(kg.m^2)
- Rated Power of Induction motor = 4KW (5.4 HP)
- Rated Speed of Induction motor = 1430 rpm
- Stator Resistance of Induction motor = 1.405 Ω
- Rotor Resistance of Induction motor = 1.395 Ω
- Stator Inductance of Induction motor = 5.839 mH
- Rotor Inductance of Induction motor = 5.839 mH
- Mutual Inductance of Induction motor = 0.1722 mH

V. SIMULATION RESULTS

The output voltage of three phases of 3-level neutral clamped inverter by using space vector modulation as voltage control strategy is shown in Fig.7.

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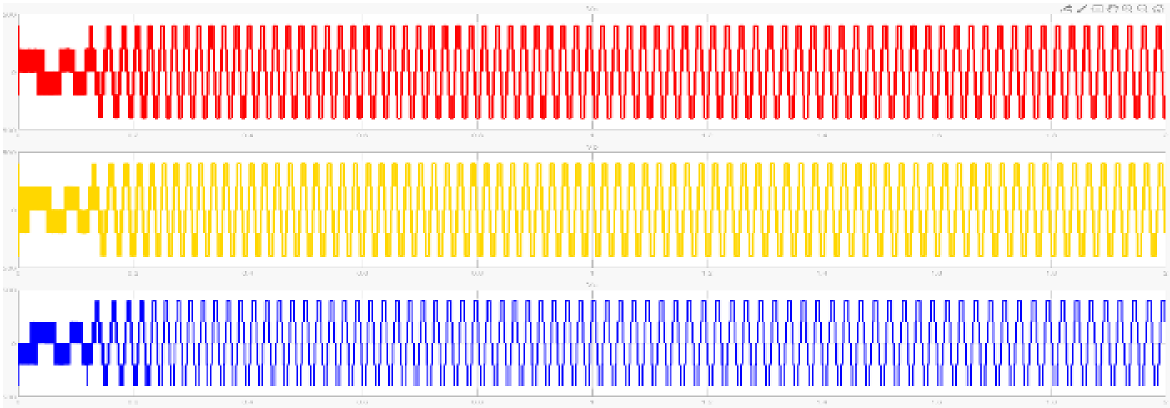

Fig.7: Output voltage of 3-phase, 3-level neutral clamped inverter.

The FFT (Fast Fourier Transform) analysis is used to calculate the total harmonic distortion present in the output voltage and output current of inverter. The FFT analysis of output current of 3-phase, neutral clamped 3-level inverter for Space Vector Modulation is shown in the Fig.8.

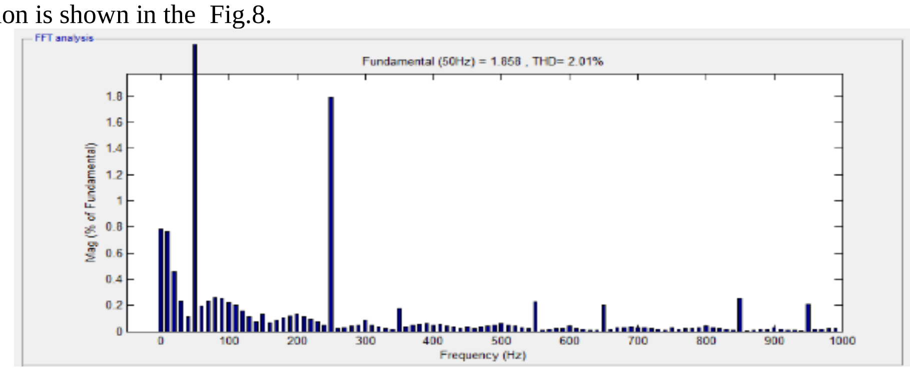

Fig.8: FFT analysis of output current of inverter for Space Vector Pulse Width Modulation.

The waveforms of electromagnetic torque (T_e), speed (w) and three-phase current (I_{abc}) of induction motor are shown below in Fig.9. In MATLAB/SIMLINK a step input (magnitude of 10 from 0 sec to 1 sec and magnitude of 20 after one second) is given to the torque terminal of Induction motor. Initially the magnitude of torque is 10 N-m and at 1 second the torque magnitude is increased from10 N-m to 20 N-m as shown in Fig.9. As a result, the magnitude of speed decreases and current increases at 1 second [10].

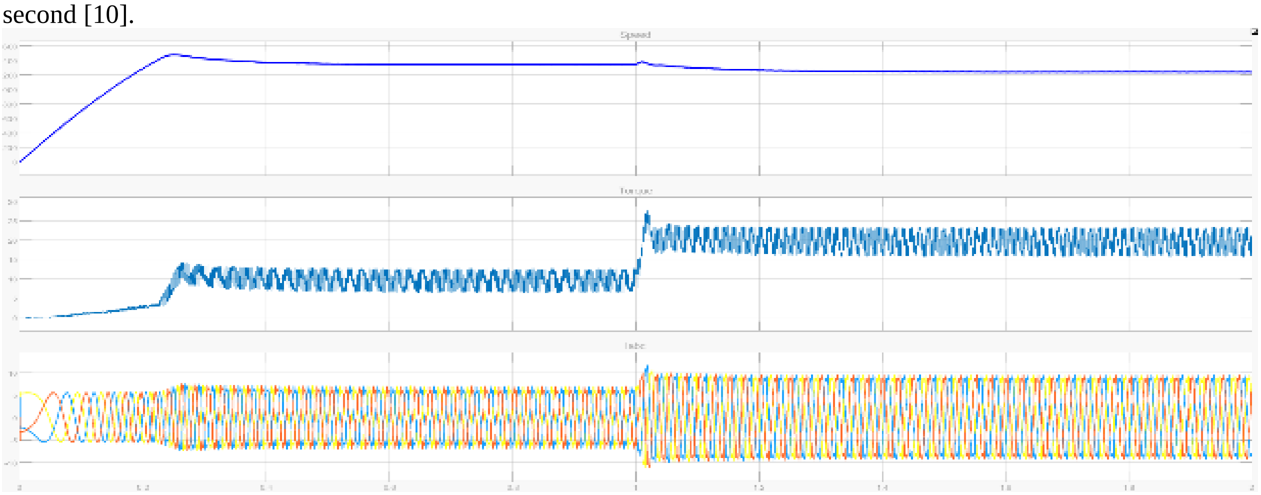

Fig.9: Waveforms of Speed, Torque and 3-phase output current of Induction Motor

VI. CONCLUSION

In this paper, the performance of induction motor which is driven by a three-phase, three-level neutral clamped Inverter using space vector modulation technique as voltage control strategy has been studied. A MATLAB/Simulink model for implementation of SVM is presented. The step-by-step algorithm of SVM is reported. The Speed, Torque and Output current of the Induction Motor, the output voltage of the inverter have been plotted. From the above results we observe that the THD value of output current of 3-phase, 3-level neutral clamped inverter with space vector pulse width modulation technique is less than 5% i.e., **2.01%.**

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