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SWITCHING TABLE BASED 2-LEVEL INVERTER AND 3-LEVEL DIODE CLAMPED INVERTER

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ABSTRACT

This paper proposes a switching table based 2-level inverter and 3-level diode clamped multilevel inverter (DCMLI) for the purpose of direct torque control of induction motor. The proposed scheme determines the sector of reference vector and the voltage vector is selected from switching table to generate gating signals for the inverter. The 2-level inverter and 3-level DCMLI are used to explain this scheme. This can be extended to n-level inverter and to all major topologies. The performance measures in terms of total harmonic distortion (THD) and fundamental voltage of line voltage and phase voltage are computed and compared with and without filter. The results show that the performance is greatly improved by increasing the number of levels. The significant feature of the proposed scheme is that it can be utilized for direct torque control of induction motor with affecting its simplicity.

Keywords: *2-Level Inverter, 3-Level Inverter, Multilevel Inverter, DCMLI, Direct Torque Control*

1. INTRODUCTION

In recent years the industrial demand increases to high power equipments up to mega watts level. But the power handling capacity of power semiconductor devices are less only up to kilo volts level. The controlled ac drives in that range are connected with medium voltage networks. To increase the power handling capacity, multilevel topologies are proposed since 1980s. A 2-level inverter generates an output voltage with two values and 3-level inverter generates an output voltage of three values and so on. Increasing the number of levels increases the number of steps in the output. The advantages of multilevel topologies are, the voltage across each power semiconductor devices are less, the output voltage harmonic distortion are reduced [1, 2]. However the drawbacks are, the required number of power semiconductor devices are increased and control becomes more complex [1, 2]. They can also used for medium or even low power application with better performance [3].

The main topologies of multilevel inverters are diode clamped or neutral point clamped multilevel inverter (DCMLI), capacitor clamped or flying capacitor multilevel inverter (FCMLI) and cascaded H-bridge multilevel inverter (CHBMLI). Comparing the devices and components used, the diode clamped inverter requires more number of diodes and the flying capacitor inverter requires more number of capacitors while the cascaded H-bridge inverter requires less number [4]. The CHBMLIs are used for high voltage high power applications like flexible AC transmission systems (FACTS) including static VAR generation (SVC), power line conditioning, series compensation, phase shifting, voltage balancing and photo voltaic utility systems interfacing [5]. The FCMLIs are used for distribution shunt compensation systems called distribution static compensators (DSTATCOM) [6] and transmission shunt and series compensation systems like static compensators (STATCOM) and static synchronous series compensators (SSSC) [7]. The DCMLI is the common multilevel inverter found in several applications like induction motor drives, dynamic voltage restorers (DVR) [8], unified power flow controllers [9] and static synchronous compensator [10].

Several modulation techniques are developed for multilevel inverters. The commonly used modulation techniques are multilevel sinusoidal pulse width modulation (SPWM) [11, 12], multilevel selective harmonic elimination pulse width modulation (SHEPWM) [1, 13] and space vector pulse width modulation (SVPWM) [14, 15].

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In SPWM, a sinusoidal waveform is compared with triangular waveforms to generate switching sequence. It requires more number of triangular carrier waveforms in different levels [16]. In SHEPWM, the transcendental equations characterizing harmonics are solved to compute switching angles, which are difficult to solve [1, 17]. In SVPWM the complexity is due to the difficulty of determining the location of the reference vector, the calculation of on-times, the determination and selection of switching states and the existence of many redundant switching vectors as the number of levels increases [18, 19].

The direct torque control technique has been developed for low voltage 2-level inverters as an alternate to the field oriented method to effectively control torque and flux in ac drives [20]. Direct torque control method utilized the vector relationships, but replaces the coordinate transformation concept of vector control method. It also gives the fast torque response [21]. It is used in many applications instead of vector control due to its simplicity. Compared to the vector control the direct torque control has no current control loop, no separate pulse width modulation and co-ordinate transformation is not required [22].

A simple control method for multilevel inverter which can be utilized for direct torque control of induction motor without affecting it simplicity. In direct torque control method the sector of the reference vector is identified. Based on the required flux and torque the next vector is selected. Without any complex calculations it can be done using a switching table. Since, the direct torque control method does not require any separate pulse width modulations the next vector is simply selected from the switching table. The diode clamped multilevel inverter is the common multilevel inverters used for direct torque control of induction motor.

This paper presents a switching table 2-level inverter and 3-level diode clamped multilevel inverters for direct torque control method. The direct torque control principle is explained in Section 2. The sector identification, switching table and the output phase voltages and line--to-line voltages of 2-level inverter and 3-level diode clamped inverters are explained in section 3 and 4. Section 5 presents the simulation results.

2. DIRECT TORQUE CONTROL

Direct torque control method is based on control of torque and flux to desired magnitude by selection of the appropriate voltage vector according to the predefined switching table [23]. In direct torque control method first the sector is identified, then the torque error and flux error is computed from the actual and the desired values. To increase or decrease the torque and flux the suitable voltage vector is selected from the switching table. 2-level inverter with six sectors or 3-level diode clamped multilevel inverter with twelve sectors can be utilized for this purpose without affecting its simplicity.

In vector form the developed torque is expressed as,

$$\bar{T}_e = \frac{3}{2}\frac{P}{2}\,\bar{\Psi}_s \times \bar{I}_s \qquad (1)$$

Where, Ψ_s is stator flux and I_s is stator current.

The magnitude of developed torque can be and expressed in terms of stator and rotor fluxes as,

$$\bar{T}_e = \frac{3}{2}\frac{P}{2}\frac{L_m}{L_r L_s'}\,|\bar{\Psi}_r||\bar{\Psi}_s|\sin\gamma \qquad (2)$$

Where, $L_s' = L_s L_r - L_m^2$, and Ψ_r is rotor flux and γ is the angle between the fluxes.

Generally the rotor time constant is larger than stator time constant. The rotor flux changes slowly compared to stator flux [24]. The developed torque can be varied, if the rotor flux remains constant and stator flux and the angle γ is varied [24].

The rate of change of stator flux is given as

$$\frac{d\Psi_s}{dt} = \bar{V}_s - R_s\bar{I}_s \qquad (3)$$

If the ohmic drop is neglected,

$$\frac{d\Psi_s}{dt} = \bar{V}_s \qquad (4)$$

or

$$\Delta\bar{\Psi}_s = \bar{V}_s\,\Delta t \qquad (5)$$

The stator flux can be varied by varying stator voltage vector for time increment.

3. 2-LEVEL INVERTER

The three phase 2-level inverters are normally used for high power applications. A three phase output can be obtained from a configuration of six devices as shown in figure 1 [25]. Each device conducts for 180°. Three devices remain on at any instant. The on state and off state of a switch is represented by 1 and 0 respectively. The pairs S_{a1} S_{a1}', S_{b1} S_{b1}' and S_{c1} S_{c1}' are complementary. Therefore, $S_{a1}'=1-S_{a1}$, $S_{b1}'=1-S_{b1}$ and $S_{c1}'=1-S_{c1}$. There are eight combinations using these switching states which produce eight voltage vectors. The voltage vectors are from V_0 to V_7. The voltage

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vectors V_1 to V_6 are nonzero vectors and vectors V_0 and V_7 are the zero vector.

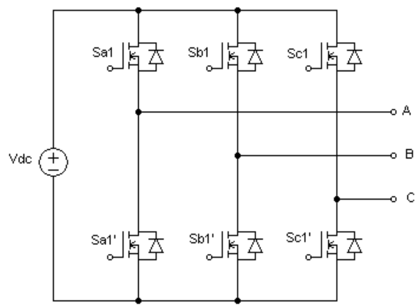

Figure 1: 2-Level Inverter

The sector is identified from three phase reference voltage and the corresponding voltage vector is selected from the switching table to generate the gating pulses for the inverter. The vector sequence is $V_1 \rightarrow V_2 \rightarrow V_3 \rightarrow V_4 \rightarrow V_5 \rightarrow V_6 \rightarrow V_1$ each for 60^o and there are no zero vectors.

3.1. Sector Identification

The balanced three phase voltages can be represented in two phase. The coordinate transformation from a-b-c in d-q can be obtained using the following equations (6) and (7).

$$v_q = \frac{2}{3}\left[v_a - \frac{1}{2}(v_b + v_c)\right] \quad (6)$$

$$v_d = \frac{1}{\sqrt{3}}(v_b - v_c) \quad (7)$$

Using the three phase to two phase transformation in equations 1 and 2 and the line voltage ($\sqrt{3}$ phase voltage) as reference, the d-q components of the rms voltage (phase voltage/$\sqrt{2}$) the voltages can be expressed as in equations (8) and (9) as follows.

$$v_{lq} = \sqrt{\frac{3}{2}}\,\frac{2}{3}\left[v_a - \frac{1}{2}(v_b + v_c)\right] \quad (8)$$

$$v_{ld} = \sqrt{\frac{3}{2}}\,\frac{1}{\sqrt{3}}(v_b - v_c) \quad (9)$$

The angle of the reference voltage can be found using equation (10).

$$\theta = \tan^{-1}\left(\frac{v_{ld}}{v_{lq}}\right) \quad (10)$$

One cycle is divided into six sectors with 60^o each. Sector 1 is from 0^o to $+60^o$, sector 2 is from $+60^o$ to $+120^o$, sector 3 is from $+120^o$ to $+180^o$, sector 4 is from -180^o to -120^o, sector 5 is from -120^o to -60^o and the sector 6 is from -60^o to 0^o.

3.2. Switching Table

The switching table is formed using the sector, the corresponding voltage vector and the switch state. For example, the angle of the reference voltage is between 0^o and 60^o, it is in sector 1 and it selects the voltage vector V_1. The corresponding switching state is 100. The switch S_{a1} is in on state. The switches S_{b1} and S_{c1} are in off state. The switches S_{a1}', S_{b1}' and S_{c1}' are complementary. The summary of various states are given in table 1.

Table 1: 2-Level Inverter Switching Table

Sector	Voltage Vector	Switch State		
		S_{a1}	S_{b1}	S_{c1}
1	V_1	1	0	0
2	V_2	0	1	0
3	V_3	0	0	1
4	V_4	1	0	1
5	V_5	1	1	0
6	V_6	0	1	1
Note: S_{a1}'=1–S_{a1}, S_{b1}'=1–S_{b1} and S_{c1}'=1–S_{c1}				

3.3. Output Voltages

Generally the load is in star connection. The inverter is operated in six sectors. In sector 1, switches S_{a1}, S_{b1}', and S_{c1}' are in on state.

The phase voltages are given by,

$$v_{an} = +\frac{V_s}{3},\ v_{bn} = -\frac{2V_s}{3}\ and\ v_{cn} = +\frac{V_s}{3}$$

The line-to-line voltages are given by,

$$v_{ab} = +V_s, v_{bc} = 0\ and\ v_{ca} = -V_s$$

The phase and line voltages for all sectors are given in table 2.

Table 2: Output Phase voltages and Line-to-Line Voltages of 2-Level Inverter

Sector	Phase Voltage			Line Voltages		
	v_{an}	v_{bn}	v_{cn}	v_{ab}	v_{bc}	v_{ca}
1	$+\frac{V_s}{3}$	$-\frac{2V_s}{3}$	$+\frac{V_s}{3}$	$+V_s$	0	$-V_s$
2	$+\frac{2V_s}{3}$	$-\frac{V_s}{3}$	$-\frac{V_s}{3}$	0	$+V_s$	$-V_s$
3	$+\frac{V_s}{3}$	$+\frac{V_s}{3}$	$-\frac{2V_s}{3}$	$-V_s$	$+V_s$	0
4	$-\frac{V_s}{3}$	$+\frac{2V_s}{3}$	$-\frac{V_s}{3}$	$-V_s$	0	$+V_s$
5	$-\frac{2V_s}{3}$	$+\frac{V_s}{3}$	$+\frac{V_s}{3}$	0	$-V_s$	$+V_s$
6	$-\frac{V_s}{3}$	$-\frac{V_s}{3}$	$+\frac{2V_s}{3}$	$+V_s$	$-V_s$	0

The line-to-line voltage has two levels. The simulation and analysis of 2-level inverter is given the section 5.

4. 3-LEVEL DIODE CLAMPED INVERTER

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The three phase 3-level diode clamped multilevel inverter is the common multilevel inverter used for various applications [18]. A three phase 3-level diode clamped multilevel inverter is adopted in this paper. It is obtained from a configuration of twelve switching devices and six clamping diodes as shown in figure 2. The pairs S_{a1} S_{a1}', S_{a2} S_{a2}', S_{b1} S_{b1}', S_{b2} S_{b2}', S_{c1} S_{c1}' and S_{c2} S_{c2}' are complementary. Therefore, S_{a1}'=1–S_{a1}, S_{a2}'=1–S_{a2}, S_{b1}'=1–S_{b1}, S_{b2}'=1–S_{b2}, S_{c1}'=1–S_{c1} and S_{c2}'=1–S_{c2}. There are twelve active combinations were taken using these switching states which produce twelve active voltage vectors. The nonzero voltage vectors are from V_1 to V_{12}.

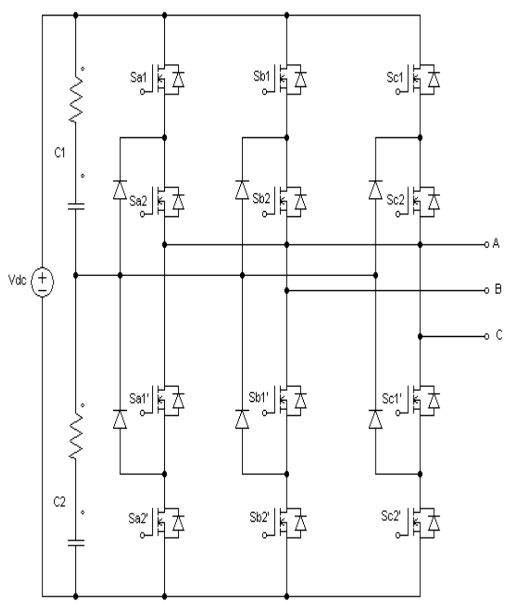

Figure 2: 3-Level Diode Clamped Inverter

The sector is identified from three phase reference voltage and the corresponding voltage vector is selected from the switching table to generate the gating pulses for the inverter. The vector sequence is $V_1 \rightarrow V_2 \rightarrow V_3 \rightarrow V_4 \rightarrow V_5 \rightarrow V_6 \rightarrow V_7 \rightarrow V_8 \rightarrow V_9 \rightarrow V_{10} \rightarrow V_{11} \rightarrow V_{12} \rightarrow V_1$ each for 30°.

4.1. Sector Identification

The angle of reference is found using equation (10). In 3-level inverter one cycle is split into twelve sectors with each 30°. Sector 1 is from 0° to +30°, sector 2 is from +30° to +60°, sector 3 is from +60° to +90°, sector 4 is from +90° to +120°, sector 5 is from +120° to +150° and the sector 6 is from +150° to +180°, Sector 7 is from -180° to -150°, sector 8 is from -150° to -120°, sector 9 is from -120° to -90°, sector 10 is from -90° to -60°, sector 11 is from -60° to -30° and the sector 6 is from -30° to 0°.

4.2. Switching Table

The switching table is formed using the sector, the corresponding voltage vector and the switch state. For example, the angle of the reference voltage is between 0° and 30°, it is in sector 1 and it selects the voltage vector V_1. The corresponding switching state is 110000. Switches S_{a1} and S_{a2} are in on state. Switches S_{b1}, S_{b2}, $S_{c1}$and S_{c2} are in off state. Switches S_{a1}', S_{a2}', S_{b1}', S_{b2}', S_{c1}'and S_{c2}' are complementary. The summary of various states are given in table 3.

Table 3: 3-Level Diode Clamped Inverter Switching Table

Sector	Voltage Vector	Switch State					
		S_{a1}	S_{a2}	S_{b1}	S_{b2}	S_{c1}	S_{c2}
1	V_1	1	1	0	0	0	0
2	V_2	1	1	0	1	0	0
3	V_3	1	1	1	1	0	0
4	V_4	0	1	1	1	0	0
5	V_5	0	0	1	1	0	0
6	V_6	0	0	1	1	0	1
7	V_7	0	0	1	1	1	1
8	V_8	0	0	0	1	1	1
9	V_9	0	0	0	0	1	1
10	V_{10}	0	1	0	0	1	1
11	V_{11}	1	1	0	0	1	1
12	V_{12}	1	1	0	0	0	1
Note: S_{a1}'=1–S_{a1}, S_{a2}'=1–S_{a2}, S_{b1}'=1–S_{b1}, S_{b2}'=1–S_{b2}, S_{c1}'=1–S_{c1} and S_{c2}'=1–S_{c2}							

4.3. Output Voltages

The load is in star connected. The inverter is operated in twelve sectors. In sector 1, switches S_{a1}, S_{a2}, S_{b1}', S_{b2}', S_{c1}' and S_{c2}' are in on state.

The phase voltages are given by,

$$v_{an} = +\frac{2V_s}{3}, v_{bn} = -\frac{V_s}{3} \text{ and } v_{cn} = -\frac{V_s}{3}$$

The line-to-line voltages are given by,

$$v_{ab} = +V_s, v_{bc} = 0 \text{ and } v_{ca} = -V_s$$

The phase and line voltages for all sectors are given in table 4.

Table 4: Output Phase voltages and Line-to-Line Voltages of 3-Level Diode Clamped Inverter

Sector	Phase Voltage			Line Voltages		
	v_{an}	v_{bn}	v_{cn}	v_{ab}	v_{bc}	v_{ca}
1	$+\frac{2V_s}{3}$	$-\frac{V_s}{3}$	$-\frac{V_s}{3}$	$+V_s$	0	$-V_s$

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2	$+\frac{V_s}{2}$	0	$-\frac{V_s}{2}$	$+\frac{V_s}{2}$	$+\frac{V_s}{2}$	$-V_s$
3	$+\frac{V_s}{3}$	$+\frac{V_s}{3}$	$-\frac{2V_s}{3}$	0	$+V_s$	$-V_s$
4	0	$+\frac{V_s}{2}$	$-\frac{V_s}{2}$	$-\frac{V_s}{2}$	$+V_s$	$-\frac{V_s}{2}$
5	$-\frac{V_s}{3}$	$+\frac{2V_s}{3}$	$-\frac{V_s}{3}$	$-V_s$	$+V_s$	0
6	$-\frac{V_s}{2}$	$+\frac{V_s}{2}$	0	$-V_s$	$+\frac{V_s}{2}$	$+\frac{V_s}{2}$
7	$-\frac{2V_s}{3}$	$+\frac{V_s}{3}$	$+\frac{V_s}{3}$	$-V_s$	0	$+V_s$
8	$-\frac{V_s}{2}$	0	$+\frac{V_s}{2}$	$-\frac{V_s}{2}$	$-\frac{V_s}{2}$	$+V_s$
9	$-\frac{V_s}{3}$	$-\frac{V_s}{3}$	$+\frac{2V_s}{3}$	0	$-V_s$	$+V_s$
10	0	$-\frac{V_s}{2}$	$+\frac{V_s}{2}$	$+\frac{V_s}{2}$	$-V_s$	$+\frac{V_s}{2}$
11	$+\frac{V_s}{3}$	$-\frac{2V_s}{3}$	$+\frac{V_s}{3}$	$+V_s$	$-V_s$	0
12	$+\frac{V_s}{2}$	$-\frac{V_s}{2}$	0	$+V_s$	$-\frac{V_s}{2}$	$-\frac{V_s}{2}$

The line-to-line voltage has three levels. The simulation and analysis of 3-level inverter is given the next section.

5. SIMULATION RESULTS

The simulations of 2-level and 3-level inverters were carried out with dc supply of 400 V. The phase voltage and line voltage waveforms without and with filter are plotted. Using FFT analysis the fundamental values and total harmonic distortion are found and tabulated.

The sectors are identified as discussed in section 3 and 4 for 2-level inverter and 3-level diode clamped inverter. It is shown in figure 3. The phase voltage waveforms without and with filter are shown in figure 4 and 5. The FFT analyses of phase voltage waveform without and with filter are given in figure 6 and 7. The line-to-line voltage waveforms without and with filter are shown in figure 8 and 9. The FFT analyses of line-to-line voltage waveform without and with filter are shown in figure 10 and 11.

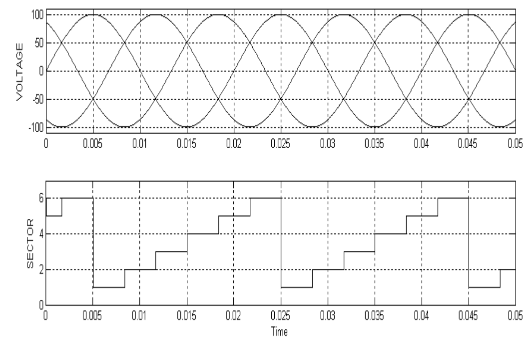

Figure 3: 2-Level Inverter Sector Identification

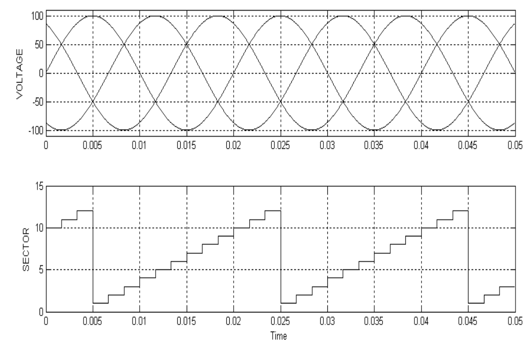

Figure 4: 3-Level Inverter Sector Identification

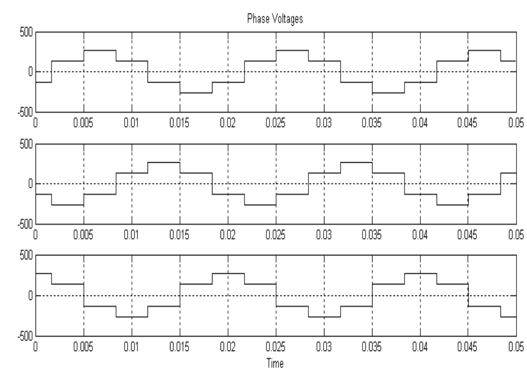

Figure 5:2-Level Inverter Phase Voltages Without Filter

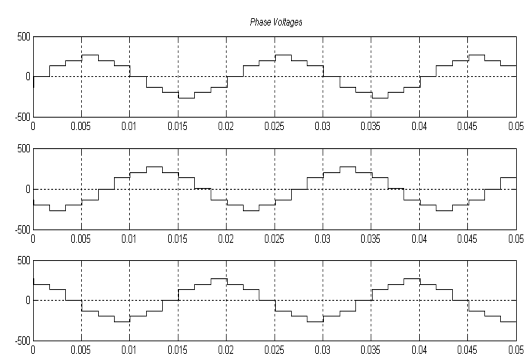

Figure 6: 3-Level Inverter Phase Voltages Without Filter

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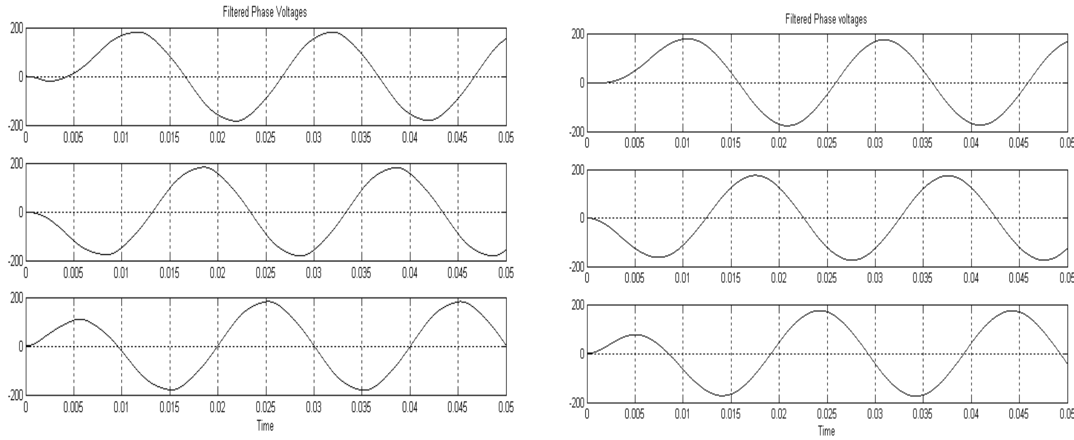
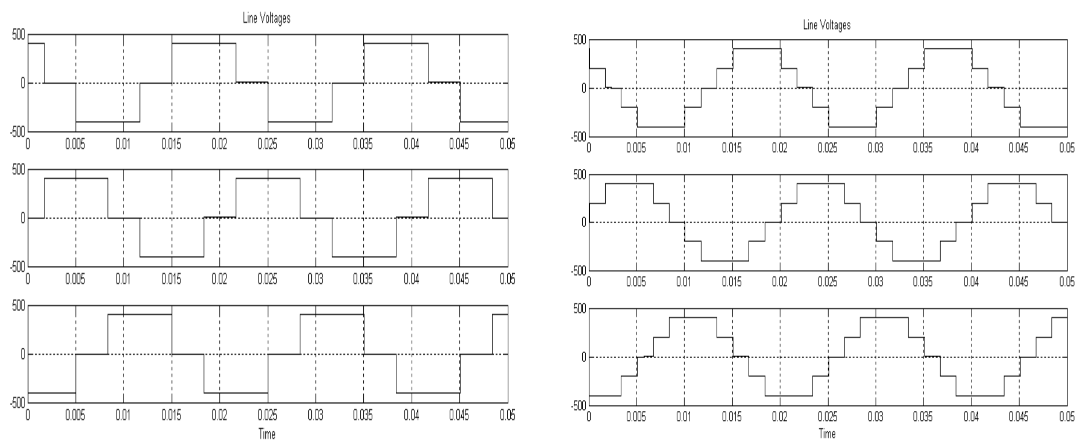


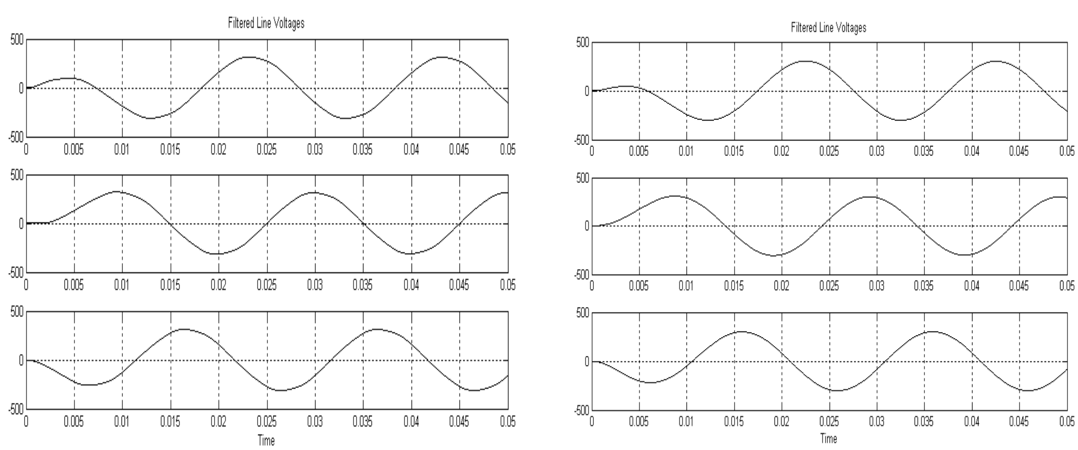
(a) *(b)*

Figure 7: Filtered Phase Voltages (a)2-Level Inverter (b) 3-Level Inverter



(a) *(b)*

Figure 7: Line to Line Voltages Without Filter (a)2-Level Inverter (b) 3-Level Inverter



(a) *(b)*

Figure 8: Line to Line Voltages With Filter (a)2-Level Inverter (b) 3-Level Inverter

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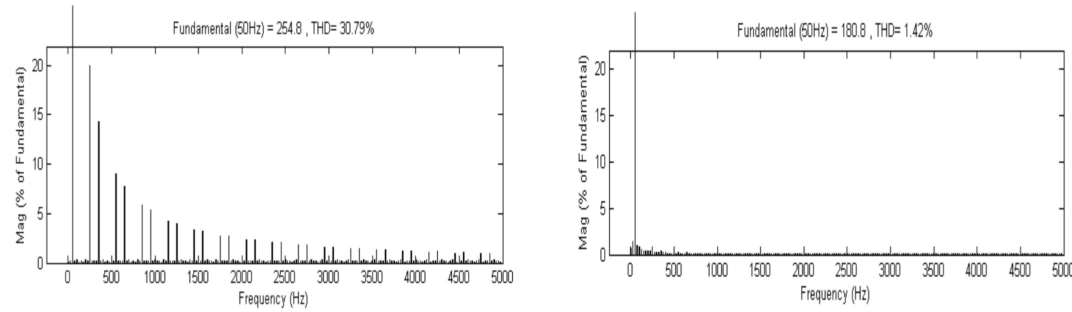
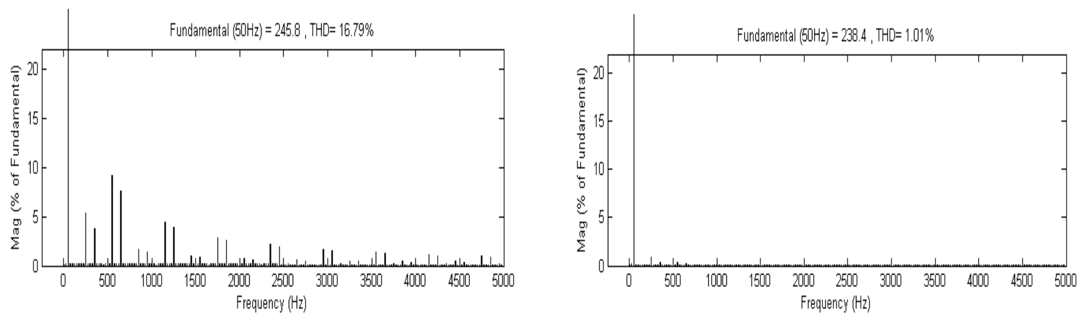


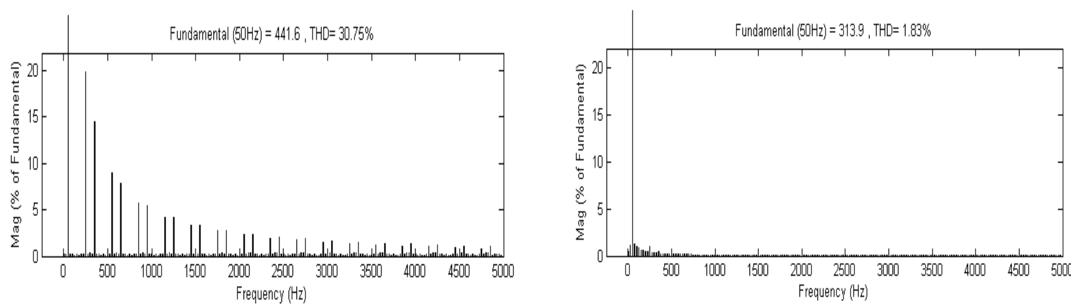
(a) *(b)*

Figure 9: FFT Analysis of 2-Level Inverter Phase Voltage (a)Without Filter (b) With Filter



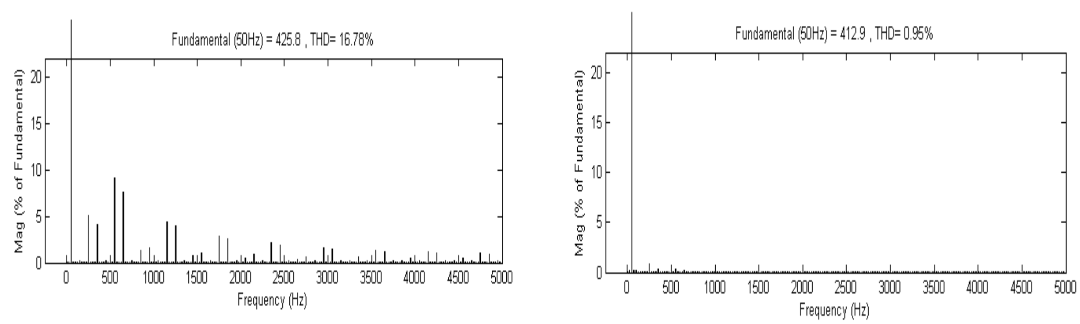
(a) *(b)*

Figure 10: FFT Analysis of 3-Level Inverter Phase Voltage (a)Without Filter (b) With Filter



(a) *(b)*

Figure 11: FFT Analysis of 2-Level Inverter Line to Line Voltage (a)Without Filter (b) With Filter



(a) *(b)*

Figure 12: FFT Analysis of 3-Level Inverter Line to Line Voltage (a)Without Filter (b) With Filter

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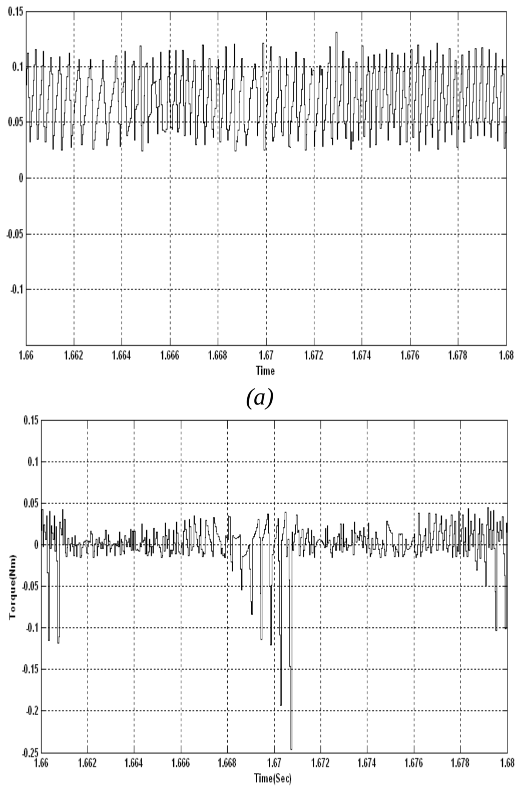

(a)

(b)

Figure 13: Steady State Torque (a) 2-Level Inverter (b) 3-Level Diode Clamped Inverter

Figure 9(a) and (b) shows the harmonic spectrum of the phase voltage of 2-level inverter. The fundamental phase voltage without filter is 254.8V and with filter is 180.8V. The total harmonic distortion is 30.79% and 1.42%. Figure 10 (a) and (b) shows the harmonic spectrum of the phase voltage of 3-level diode clamped inverter. The fundamental phase voltage without filter is 245.8V and with filter is 238.4V. The total harmonic distortion is 16.79% and 1.01%.

Figure 11(a) and (b) shows the harmonic spectrum of the line-to-line voltage of 2-level inverter. The fundamental line-to-line voltage without filter is 441.6V and with filter is 313.9V. The total harmonic distortion is 30.75% and 1.83%. Figure 12 (a) and (b) shows the harmonic spectrum of the line-to-line voltage of 3-level diode clamped inverter. The fundamental line-to-line voltage without filter is 425.8V and with filter is 412.9V. The total harmonic distortion is 16.78% and 0.96%.

The FFT analysis of 2-level inverter and 3-level diode clamped inverter are summarized in table 5.

Table 5: Performance of Inverters

Inverter	Phase Voltage		Line-to-Line Voltage	
	Without filter	With filter	Without filter	With filter
	Fundamental Voltage			
2-level	254.8V	180.8V	441.6V	313.9V
3-level	245.8V	238.4V	425.8V	412.9V
	Total Harmonic Distortion			
2-level	30.79%	1.42%	30.75%	1.83%
3-level	16.79%	1.01%	16.78 %	0.96%

The simulation results show that harmonics are very much reduced and the fundamental voltages are also increased in 3-level diode clamped inverter. Figure 13 shows the steady state no load toque of direct torque control of induction motor with 2-level inverter and 3-level diode clamped inverter. It shows that the torque ripple is reduced using 3-level diode clamped inverter

The switching table based 3-level diode clamped inverter has better performance than the 2-level inverter and it is suitable for direct torque control of induction motor.

6. CONCLUSION

This paper provides the comparative analysis of switching table based 2-level inverter and 3-level diode clamped inverter. A particular emphasis on fundamental voltages and total harmonic distortion has been studied. The simulation results suggest that increasing the levels of inverter can achieve the higher fundamental output voltage and low total harmonic distortion. Compared to 2-level inverter, the presented 3-level diode clamped inverter is also easily implemented for direct torque control of induction motor. The simulation result shows the reduction in steady state torque ripples of the induction motor. It is a simple control method for the 3-level diode clamped inverter for direct control of induction motor without affecting its simplicity.

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