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DIRECT TORQUE CONTROL OF INDUCTION MOTOR USING MULTILEVEL INVERTER

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Abstract-. ***This paper proposes the three level diode clamped multilevel inverter fed direct torque control of induction motor. The proposed multilevel inverter has the advantages of fewer harmonic in the output and low torque ripples. The switching table direct torque control scheme is adopted due to the simplicity of the control algorithm. The PI speed controller is used in the outer loop. To demonstrate the performance of proposed multilevel inverter fed direct torque control, the simulations are carried out for constant speed under constant load, constant speed under step change in load and step change speed under constant load conditions and the results are presented. The comparison of the dynamic and steady state performance in terms of torque ripple and settling time of the two level inverter and three level inverters are presented.***

Keywords - Multilevel inverter, Diode clamped inverter, Three level Inverter, Direct torque control, ST-DTC, Induction Motor

I. INTRODUCTION

The induction motors has found wide industrial applications due to the simple construction, reliability, ruggedness, low cost and it can be used in aggressive environments. The scalar control methods give an economical drive with good steady state behaviour, but the transient behavior may not be well controlled [1]. High performance drives applications usually require quick transient response. The advancement in power semiconductor devices, digital data processing and control has led to great improvements in torque response control of AC motors. Such controllers have good steady state and transient performance [1- 2]. The vector control method gives the quick transient response. It requires coordinate transformation, current control loops and pulse width modulation. The direct torque control technique has been developed as an alternate to the vector control method to effectively control torque and flux in ac drives [3]. Direct torque control method utilized the vector relationships, but replaces the coordinate transformation concept of vector control method and gives the fast torque response [4]. 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 [5].

The direct torque control methods have been divided into three groups: hysteresis based switching table direct torque control (ST-DTC), hysteresis based direct self control (DSC) and constant switching frequency direct torque control operating in association with space vector modulation (DTC-SVM) [6-7]. The constant switching frequency DTC-SVM methods improve considerably the drive performance in terms of reduced torque and flux pulsations, reliable startup and low speed operation, low harmonics and radiated noise [7-12]. It is an excellent method for general purpose induction motor in a wide power range. DSC is preferred for high power low switching frequency drives and it is very effective in square wave operation, where fast flux weakening and torque control are achieved [13]. Instead the short sampling time required by ST-DTC methods make them suitable for very fast torque and flux controlled drives because of the simplicity of the control algorithm [14]. It is very simple to design and implement the proportional plus integral conventional speed controller in the outer loop of direct torque control of induction motor drive [15].

To increase the power handling capacity, multilevel topologies are proposed since 1980s. The advantages of multilevel topologies are, the voltage across each power semiconductor devices are less, the output voltage harmonic distortion are reduced [16-17]. They can also used for medium or even low power application with better performance [18]. 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). 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 [19]. The FCMLIs are used for distribution shunt compensation systems called distribution static compensators (DSTATCOM) [20] and transmission shunt and series compensation systems like static compensators (STATCOM) and static synchronous series compensators (SSSC) [21]. The DCMLI is the common multilevel inverter found in several applications like induction motor drives, dynamic voltage restorers (DVR) [22], unified power flow controllers [23] and static synchronous compensator [24].

Several modulation techniques are developed for multilevel inverters. The commonly used modulation techniques are multilevel sinusoidal pulse width modulation (SPWM) [25-26], multilevel selective harmonic elimination pulse width modulation (SHEPWM) [27] and space vector pulse width modulation (SVPWM) [28-29]. 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 [30]. In SHEPWM, the transcendental equations characterizing harmonics are solved to compute switching angles, which are difficult to solve [31]. 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 [32-33].

A simple control method for multilevel inverter 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 selected from the switching table. The diode clamped multilevel inverter is the common multilevel inverters used for control of induction motor.

The main purpose of this paper is to improve the performance of direct torque control of three phase induction motor using three level diode clamped multi level inverter. Section 2 and section 3 presents the dynamic model of the induction motor and direct torque control principles. The two level inverter fed direct torque control of induction motor has been explained in section 4. In section 5 the three level inverter fed direct torque control of induction motor has been explained. The simulation results under three different test conditions are presented in section 6. In this section the torque ripple and settling time with two level inverter and three level inverter are compared and discussed.

II. INDUCTION MOTOR EQUATIONS

A three phase symmetric induction motor is considered with sinusoidally distributed winding and short circuited rotor [3].

The stator voltage equations are,

$$V_{qs} = R_s i_{qs} + \frac{d}{dt}\Psi_{qs} \qquad (1)$$

$$V_{ds} = R_s i_{ds} + \frac{d}{dt}\Psi_{ds} \qquad (2)$$

The rotor voltage equations are,

$$0 = R_r i_{qr} + \frac{d}{dt}\Psi_{qr} - \omega_r \Psi_{dr} \qquad (3)$$

$$0 = R_r i_{dr} + \frac{d}{dt}\Psi_{dr} + \omega_r \Psi_{qr} \qquad (4)$$

Where, V_{qs} and V_{ds} are q and d axis stator voltages, i_{qs} and i_{ds} are q and d axis stator currents, i_{qr} and i_{dr} are q and d axis rotor currents, Ψ_{qs} and $\Psi_{ds}$are q and d axis stator flux linkages, Ψ_{qr} and $\Psi_{dr}$are q and d axis rotor flux linkages, R_s and $R_r$are stator and rotor resistances and ω_r is the rotor speed.

The stator flux linkages equations are,

$$\Psi_{qs} = L_{ls} i_{qs} + L_m (i_{qs} + i_{qr}) \qquad (5)$$

$$\Psi_{ds} = L_{ls} i_{ds} + L_m (i_{ds} + i_{dr}) \qquad (6)$$

The rotor flux linkages equations are,

$$\Psi_{qr} = L_{lr} i_{qr} + L_m (i_{qs} + i_{qr}) \qquad (7)$$

$$\Psi_{dr} = L_{lr} i_{dr} + L_m (i_{ds} + i_{dr}) \qquad (8)$$

Where, L_{ls}, L_{lr} are stator and rotor leakage inductance and L_m is the magnetizing inductance.

The torque developed in vector form,

$$\bar{T}_e = \frac{3}{2}\frac{P}{2}\bar{\Psi}_s \times \bar{I}_s \qquad (9)$$

Where, P is the number of poles.

III.DIRECT TORQUE CONTROL PRINCIPLE

The direct torque control method is based on control of torque and flux to desire magnitude by selection of the appropriate voltage vector according to the pre defined vector table [18].

The magnitude of torque developed torque is,

$$\bar{T}_e = \frac{3}{2}\frac{P}{2}\frac{L_m}{L_r L_s'}|\bar{\Psi}_r||\bar{\Psi}_s| \sin\gamma \qquad (10)$$

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

The rotor flux changes very slowly compared with stator flux then it can be kept constant. The developed torque can be varied, by varying the stator flux and the angle γ.

From equations (1) and (2), the rate of change of flux is,

$$\frac{d}{dt}\bar{\bar{\Psi}}_s = \bar{V}_s - R_s \bar{I}_s \qquad (11)$$

If the ohmic drop is neglected,

$$\frac{d}{dt}\bar{\bar{\Psi}}_s = \bar{V}_s \qquad (12)$$

(or)

$$\Delta\bar{\Psi}_s = \bar{V}_s \Delta t \qquad (13)$$

The stator flux can be varied by varying stator voltage vector for time increment (Fig. 1).

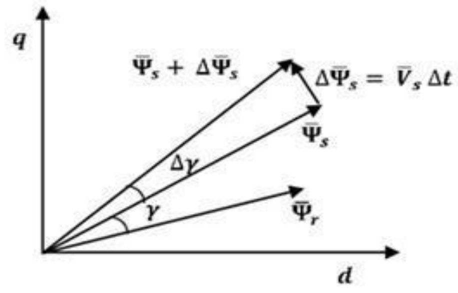


Fig. 1: Stator and rotor flux vectors

The desired torque T_e^* and actual toque T_e are compared to generate torque error. From the motor speed error the actual torque is estimated. The desired flux Ψ_s^* and actual flux Ψ_s are compared to generate flux error. From the stator voltage and current the magnitude of actual flux is estimated.

IV. DIRECT TORQUE CONTROL USING TWO LEVEL INVERTER

The hysteresis band flux controller processes the flux error E_Ψ and generates two levels of output H_Ψ, as flux increase (+1) or decrease (-1). The band width of the controller is 2HB.

$$H_\Psi = +1 \quad for \quad E_\Psi > +HB_\Psi \qquad (14)$$

$$H_\Psi = -1 \quad for \quad E_\Psi < -HB_\Psi \qquad (15)$$

The actual stator flux is Ψ_s controlled within the hysteresis band.

By comparing the desired torque T_e^* and actual torque T_e, the torque error E_{Te} is generated. The hysteresis band torque controller processes the torque error E_{Te} and generates three levels of output H_{Te}, as increase (+1), decrease (-1) or equal (0).

$$H_{T_e} = +1 \quad for \quad E_{T_e} > +HB_{T_e} \qquad (16)$$

$$H_{T_e} = -1 \quad for \quad E_{T_e} < -HB_{T_e} \qquad (17)$$

$$H_{T_e} = 0 \quad for \quad -HB_{T_e} < E_{T_e} > +HB_{T_e} \qquad (18)$$

The flux angle γ is calculated as,.

$$\gamma = \tan^{-1}\left(\frac{\Psi_{qs}}{\Psi_{ds}}\right) \qquad (19)$$

The six sectors are shown in fig.2, taking the first sector as – 30º to + 30º based on flux angle. The magnitude of stator flux and developed torque can be varied by selecting the appropriate voltage vector based on equation (10). Assume the stator flux vector is in first sector as shown in Fig.2. Vector V_2 is used to increase the flux and torque. Vector V_3 is used to decrease the flux and increase the torque.

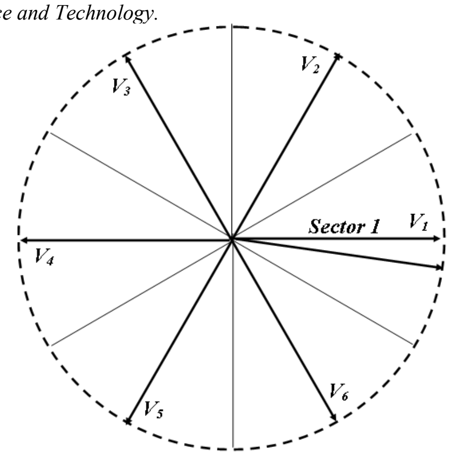


Fig. 2: Sectors and flux vector for two level inverter

The voltage vectors to be selected for variation of stator flux and torque in each sector is identified as above and it is given in Table I.

TABLE I VECTOR SELECTION TABLE

Sector	Flux (H_Ψ)					
	+1			-1		
	Torque (H_{Te})					
	+1	0	-1	+1	0	-1
1	V_2	V_0	V_6	V_3	V_0	V_5
2	V_3	V_0	V_1	V_4	V_0	V_6
3	V_4	V_0	V_2	V_5	V_0	V_1
4	V_5	V_0	V_3	V_6	V_0	V_2
5	V_6	V_0	V_4	V_1	V_0	V_3
6	V_1	V_0	V_5	V_2	V_0	V_4

The PI speed controller is used to compute the desired value of torque T_e^* from desired speed ω_r^* and actual speed ω_r.

V. DIRECT TORQUE CONTROL USING THREE LEVEL INVERTER

The same flux controller used in this to processes the flux error. The five level torque controller is used to generate the output H_{Te}, as high increase (+2), small increase (+1), high decrease (-2), small decrease (-1) or equal (0).

$$H_{T_e} = +2 \quad for \quad E_{T_e} > +2HB_{T_e} \qquad (20)$$

$$H_{T_e} = +1 \quad for \ +2HB_{T_e} > E_{T_e} > +HB_{T_e} \qquad (21)$$

$$H_{T_e} = 0 \quad for \ +HB_{T_e} > E_{T_e} > -HB_{T_e} \qquad (22)$$

$$H_{T_e} = -1 \quad for \ -HB_{T_e} > E_{T_e} > -2HB_{T_e} \qquad (23)$$

$$H_{T_e} = -2 \quad for \ -2HB_{T_e} > E_{T_e} \qquad (24)$$

The twelve sectors are shown in fig.3, taking the first sector as – 15º to + 15º based on flux angle. The magnitude of stator flux and developed torque can be varied by selecting the appropriate voltage vector based on equation (10). The vectors are grouped into large vectors, medium vectors, small vectors and zero vectors. In these large vectors, medium vectors and the zero vectors are used. The small vectors are not utilised. Assume the stator flux vector is in first sector as shown in fig.4 vector V_8 is used for small increase and V_9 is used for large increase. Vector V_{18} is used for small decrease and V_{17} is used for large decrease.

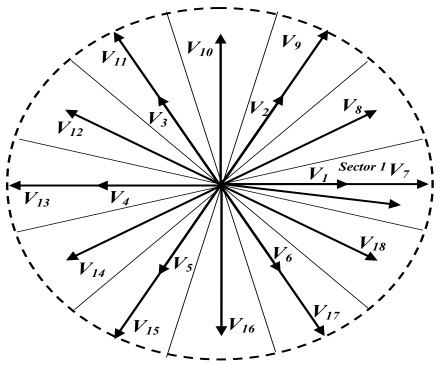


Fig. 3: Sectors and flux vector for three level inverter

The voltage vectors to be selected for variation of stator flux and torque in each sector is identified as above and it is given in Table II.

TABLE III VECTOR SELECTION TABLE

Sector	Flux (H_Ψ)									
	+1					-1				
	Torque (H_{Te})									
	+2	+1	0	-1	-2	+2	+1	0	-1	-2
1	V_9	V_8	V_0	V_{18}	V_{17}	V_{11}	V_{12}	V_0	V_{14}	V_{15}
2	V_{10}	V_9	V_0	V_7	V_{18}	V_{12}	V_{13}	V_0	V_{15}	V_{16}
3	V_{11}	V_{10}	V_0	V_8	V_7	V_{13}	V_{14}	V_0	V_{16}	V_{17}
4	V_{12}	V_{11}	V_0	V_9	V_8	V_{14}	V_{15}	V_0	V_{17}	V_{18}
5	V_{13}	V_{12}	V_0	V_{10}	V_9	V_{15}	V_{16}	V_0	V_{18}	V_7
6	V_{14}	V_{13}	V_0	V_{11}	V_{10}	V_{16}	V_{17}	V_0	V_7	V_8
7	V_{15}	V_{14}	V_0	V_{12}	V_{11}	V_{17}	V_{18}	V_0	V_8	V_9
8	V_{16}	V_{15}	V_0	V_{13}	V_{12}	V_{18}	V_7	V_0	V_9	V_{10}
9	V_{17}	V_{16}	V_0	V_{14}	V_{13}	V_7	V_8	V_0	V_{10}	V_{11}
10	V_{18}	V_{17}	V_0	V_{15}	V_{14}	V_8	V_9	V_0	V_{11}	V_{12}
11	V_7	V_{18}	V_0	V_{16}	V_{15}	V_9	V_{10}	V_0	V_{12}	V_{13}
12	V_8	V_7	V_0	V_{17}	V_{16}	V_{10}	V_{11}	V_0	V_{13}	V_{14}

The PI speed controller is used to compute the desired value of torque T_e^* from desired speed ω_r^* and actual speed ω_r.

VI. SIMULATION RESULTS

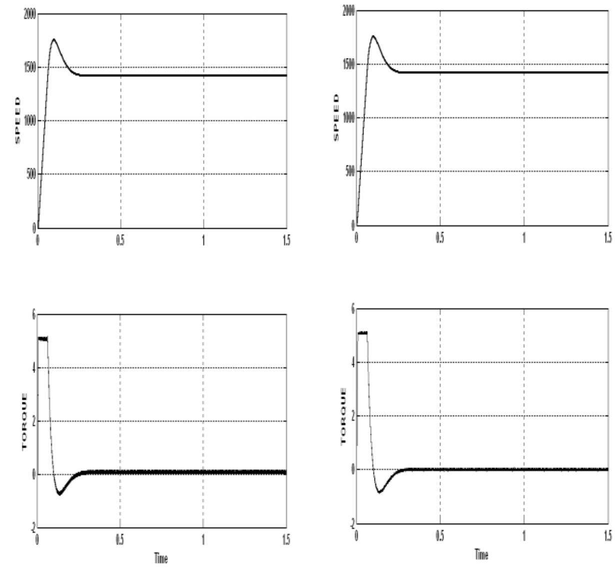
To demonstrate the performance of the three level inverter direct torque control of induction motor, the simulation results using the three level inverter are compared with the simulation results using two level inverter under three different test conditions. These cases are constant rotor speed at no load, step change in rotor speed at no load and constant rotor speed at step change in load. Sliding mode and PI speed controllers have been implemented in MATLAB / SIMULINK to compare their performance.

For simulation a 1HP, 415V, 50 Hz star connected three phase induction motor has been taken and its rated parameters are R_s = 6.03 Ohms, R_r = 6.085 Ohms, L_{ls} = 29.9 mH, L_{lr} = 29.9 mH and L_m = 489.3 mH. Motor inertia J = 0.011787 kg m^2, friction factor B = 0.0027 Nm.sec.

A. *Constant Speed at no load*

In this section the rotor speed and torque of the induction motor using two level inverter and three level inverter are compared under the constant speed of 1415 rpm at no load.

Fig.4 shows the speed and torque response of direct torque control of induction motor with two level inverter and three level inverter. The speed response of both inverters has the over shoot and it settles at the desired speed of 1415rpm at 0.288sec. The torque response shows that three level inverter has more ripples. The torque ripples using two level inverter is 0.07152 Nm and using three level inverter is 0.02986 Nm



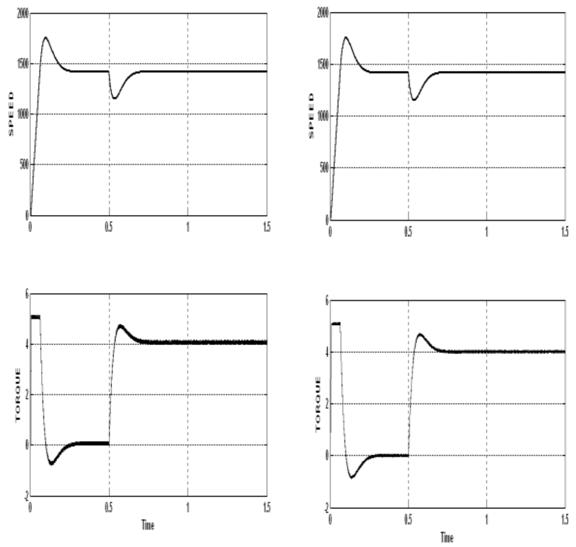
(a) (b)

Fig. 4: Speed and torque response under constant speed at no load
(a). Two level inverter (b). Three level inverter

B. *Constant Speed at Step Change in load*

In this section the rotor speed and torque of the induction motor using two level inverter and three level inverter are compared under the constant speed of 1415 rpm at step change in load from 0 Nm to 4 Nm at 0.5 sec.

Fig.5 shows the response of direct torque control of induction motor with two level inverter and three level inverter at step change in load. The step change in load of 0 Nm to 4 Nm is applied at 0.5 sec. The speed response of two level inverter has the over shoot and it settles at the desired speed of 1415rpm at 0.288sec. At 0.5sec the load of 4Nm is applied. The speed decreases and come back to the desired speed at 0.725sec. The speed response of three level inverter also has overshoot in the speed response and the motor reaches the desired speed at 0.286sec.



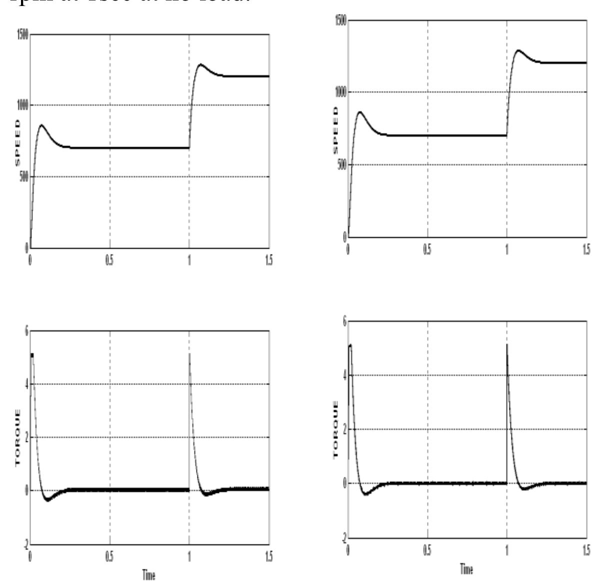
(a) (b)

Fig. 5: Speed and torque response under constant speed at step change in load (a). Two level inverter (b). Three level inverter

When the step change is applied the speed decreases and comeback to desired speed at 0.713sec. The torque response of two level inverter shows that it has more torque ripples than three level inverter. The torque ripples using two level inverter is 0.1072Nm and three level inverter is 0.0043 Nm.

C. Change in Speed at no load

In this section the rotor speed and torque of the induction motor using two level inverter and three level inverter are compared under the step change in speed from 700rpm to 1415 rpm at 1sec at no load.



(a) (b)

Fig. 6: Speed and torque response under step change in speed at no load (a). Two level inverter (b). Three level inverter

Fig. 6 shows the response of direct torque control of induction motor with two level inverter three level inverter at step change in speed. The step change in speed of 700rpm to 1415rpm is applied at 1 sec. The speed response of two level inverter has the over shoot and it settles at the desired speed of 700rpm at 0.261sec and after the step change it attains the desired speed at 1.263sec with overshoot. The speed of three level inverter reaches 700rpm at 0.253sec after the step change in speed at 1sec it settled in the desired speed of 1415rpm at 1.251sec.

The torque response of two level inverter and three level inverter have over shoot in the torque during the change in desired speed from 700rpm to 1415rpm at 1sec. The torque ripples using two level inverter at 1415rpm is 0.05335Nm and three level inverter is 0.02288.

VII. CONCLUSION

This paper presents a very simple implementation of three level diode clamped inverter for switching table based direct torque control of induction motor. The results of numerical simulations show that the speed response using two level and three level inverters are similar. But the torque ripple using three level inverter is very less compared to two level inverter. The main advantage of the proposed method is the simplicity of switching table direct torque control method using three level inverter and it is easy to design and implement. It has the good dynamic and steady state performance.

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