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Comparison of Direct Torque Control of Induction Motor Using Two-Level and Three-Level Inverter

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Abstract: This paper compares the performance of direct torque control of induction motor using two-level and three-level inverters. The main objective of this paper is to improve the performance of direct torque control of induction motor using three-level inverter without affecting its simplicity. The basic switching table based direct torque control of induction motor using two-level inverter is first investigated. The three-level inverter for direct torque control of induction motor has been developed. The performance of direct torque control of induction motor using two-level and three-level inverters are examined. The simulation results show that the toque and flux ripples are considerably reduced by implementing three-level inverter. The proposed scheme is very simple and easy to implement.

Key words: Induction Motor · Direct Torque Control · Three Level Inverter · Multilevel inverter

INTRODUCTION

Induction motors have been widely used in industrial applications due to the reliability, robustness, low cost and greatly reduced maintenance compared with other motors [1]. Electrical motors take more than 50 percent of the total electrical power in the industries; in this more than 65 percent of the power is used by induction motor drives [2]. Even the principle of induction motor has been known for more than 100 years, still a considerable progress is being achieved due to the advances in materials, power electronics and high speed digital controllers [3]. The industrial standard for high performance applications require, four quadrant operation, minimum torque ripple, rapid speed recovery under load disturbances and fast dynamic torque and speed responses [4]. The high performance control methods of induction motor are, the vector control method proposed in 1970s and the DTC method proposed in 1980s. Compared with vector control, the direct torque control does not require current control loops, coordinate transformation and separate pulse width modulation [5].

The DTC method is classified into ST-DTC, DSC and DTC-SVM [5]. The ST-DTC method is suitable for very fast torque and flux controlled drives because of the simplicity of the control algorithm [6]. The ST-DTC is adopted in this paper. In DTC the non sinusoidal output voltages of voltage source inverter reduces the drive performance [7]. To improve the drive performance, various pulse width modulation schemes are implemented, but it reduces the simplicity of control algorithm [8]. Alternatively, the improved drive performance is achieved by using multilevel inverters. The multilevel inverters offer nearly sinusoidal output voltages using lower voltage rating devices and reduction in harmonics and also they can be used for medium or even low power application with better performance [9]. The main topologies of multilevel inverters are DCMLI, FCMLI and CHBMLI [10]. Comparing these topologies, the DCMLI has higher efficiency and simple control method and it is adopted for DTC.

This paper presents the implementation of three-level DCMLI for DTC of induction motor. The modified switching tables without using medium vectors have been developed and investigated.

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Direct Torque Control Principle: The DTC is based on controlling the torque and flux errors directly by controlling the inverter switching states. The magnitude of developed torque can be and expressed in terms of stator and rotor fluxes as,

$$\bar{T}_e = \frac{3}{2}\frac{P}{2}\frac{L_m}{L_{lr}L'_{ls}}|\bar{\Psi}_r||\bar{\Psi}_s|\sin\gamma \qquad (1)$$

Where, $L'_{ls} = L_{ls}L_{lr} - L_m^2$ and γ is the angle between the fluxes.

Generally rotor time constant is very large and rotor flux changes slowly compared to stator flux. The rotor flux is kept constant. By varying the stator flux and angle γ the developed torque can be varied.

It can be expressed as,

$$\Delta\bar{T}_e = \frac{3}{2}\frac{P}{2}\frac{L_m}{L_{lr}L'_{ls}}|\bar{\Psi}_r||\bar{\Psi}_s + \Delta\bar{\Psi}_s|\sin\Delta\gamma \qquad (2)$$

The dynamic model in stationary reference frame is given by,

$$v_{ds}{}^s = R_s i_{ds}{}^s + \frac{d}{dt}\Psi_{ds}{}^s \qquad (3)$$

$$v_{qs}{}^s = R_s i_{qs}{}^s + \frac{d}{dt}\Psi_{qs}{}^s \qquad (4)$$

$$R_r i_{dr}{}^s + \frac{d}{dt}\Psi_{dr}{}^s + \omega_r \Psi_{qr}{}^s = 0 \qquad (5)$$

$$R_r i_{qr}{}^s + \frac{d}{dt}\Psi_{qr}{}^s - \omega_r \Psi_{dr}{}^s = 0 \qquad (6)$$

From equation (3) and (4), the rate of change of stator flux is given as,

$$\frac{d\bar{\Psi}_s}{dt} = \bar{V}_s - R_s\bar{I}_s \qquad (7)$$

Neglecting the ohmic drop,

$$\frac{d\bar{\Psi}_s}{dt} = \bar{V}_s \qquad (8)$$

or

$$\Delta\bar{\Psi}_s = \bar{V}_s\,\Delta t \qquad (9)$$

From the above relation, the stator flux can be varied by varying the stator voltage vector as shown in figure 1.

DTC using Two-Level Inverter: The overall block diagram of DTC of induction motor using two-level inverter is shown in figure 2. It consists of a voltage source inverter (VSI), hysteresis flux comparator, hysteresis torque comparator, flux angle estimator, sector identification, inverter switching table, speed controller and voltage source inverter (VSI).

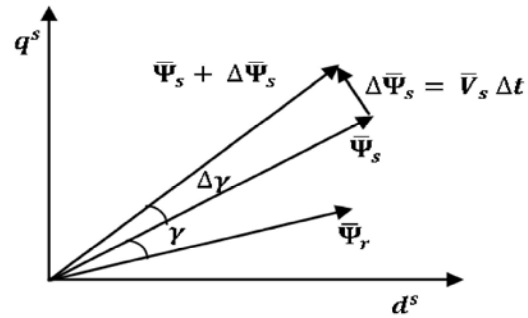

Fig. 1: Stator and rotor flux vectors

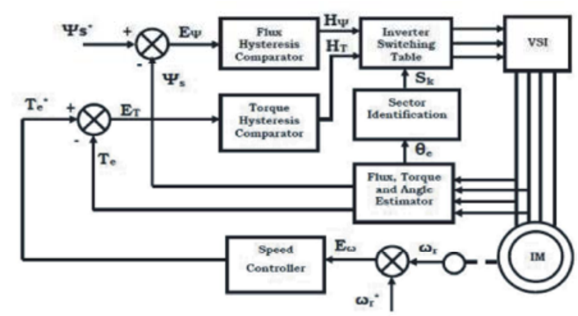

Fig. 2: ST-DTC block diagram

The appropriate vector is selected from inverter switching table, using the information from hysteresis flux comparator H_Ψ, hysteresis torque comparator H_T and the sector information S_K. The corresponding switches of the inverter are turned “ON” and produce the required voltage vector. Thus the stator flux and developed torque of the induction motor are regulated within their hysteresis band. The flux, torque and angle estimator is used to estimate their actual values. These actual values are compared with required values and the error signals are given to hysteresis comparators.

The stator flux locus is divided into six sectors The six sectors are defined as, sector 1 is from -30° to +30°, sector 2 is from +30° to +90°, sector 3 is from +90° to +150°, sector 4 is from +150° to -150°, sector 5 is from -150° to -90° and the sector 6 is from -90° to -30°.

The output voltages are determined by the switching states of the inverter. The “ON” state and “OFF” state of a switch is represented by “1” and “0” respectively. In two-level inverter, there are eight combinations using these switching states which produce eight voltage vectors as shown in figure 3. The voltage vectors V_1 to V_6 are active vectors and vectors V_0 and V_7 are the zero vector.

Based on the output of flux and torque hysteresis controllers and the sector information the appropriate voltage vector has been selected from the switching table. The switching table is given in Table 1.

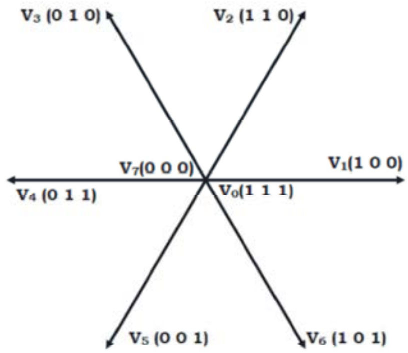

Fig. 3: Two-level inverter voltage vectors

Table 1: Two-level inverter switching table

	Flux ($H_ø$)					
	+1			-1		
	Torque (H_{Te})					
Sector	+1	0	-1	+1	0	-1
1	V_2	V_0	V_6	V_3	V_7	V_5
2	V_3	V_7	V_1	V_4	V_0	V_6
3	V_4	V_0	V_2	V_5	V_7	V_1
4	V_5	V_7	V_3	V_6	V_0	V_2
5	V_6	V_0	V_4	V_1	V_7	V_3
6	V_1	V_7	V_5	V_2	V_0	V_4

Three Level Diode Clamped Inverter: A three phase output can be obtained from a configuration of twelve power switches of three-level DCMLI as shown in figure 4. "1" represents "ON" state and "0" represents "OFF" state of the switch.

The pair of switches are complementary. $S_{a1} S_{a1}'$, $S_{b1} S_{b1}'$, $S_{c1} S_{c1}'$, $S_{a2} S_{a2}'$, $S_{b2} S_{b2}'$ and $S_{c2} S_{c2}'$

Using these switching states, 6 large vectors, 6 medium vectors, 12 small vectors and 3 zero vectors can be generated.

Zero vectors: V_0, V_7, V_{26}
Small vectors: V_1, V_2, V_3, V_4, V_5, V_6, V_8, V_9, V_{10}, V_{11}, V_{12}, V_{13}
Large vectors: V_{14}, V_{15}, V_{16}, V_{17}, V_{18}, V_{19}
Medium vectors: V_{20}, V_{21}, V_{22}, V_{23}, V_{24}, V_{25}

Among the small vectors V_1 to V_6 has the redundant vectors V_8 to V_{13}. The voltage vectors are shown if Figure 5.

The vectors and its switching states of three level inverter are given in Table 2.

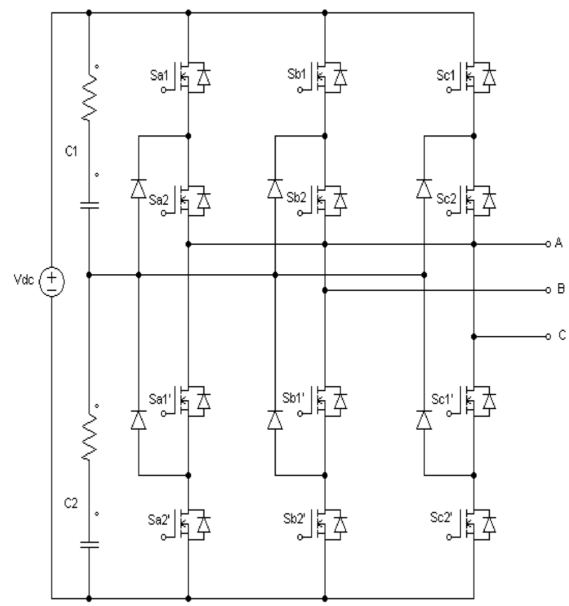

Fig. 4: Diode clamped three-level Inverter

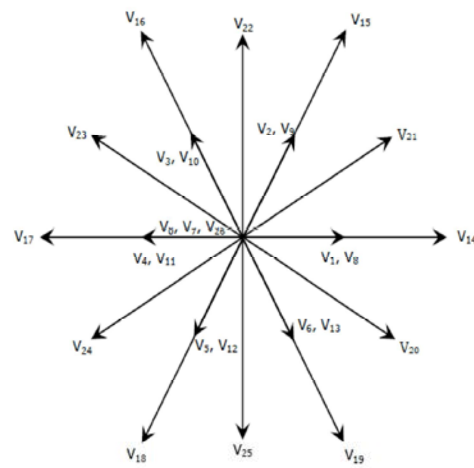

Fig. 5: Three-level inverter voltage vectors

DTC using Three-Level Inverter: In direct torque control using three-level inverter consists of three-level DCMLI, modified switching table, flux, toque and angle estimator, two-level flux hysteresis comparator, five-level torque comparator and speed controller in the outer loop. The two-level inverter, inverter switching table and three-level torque hysteresis comparator of basic ST-DTC are replaced by three-level DCMLI, modified inverter switching table and five-level hysteresis torque comparator respectively.

Three-level inverter has more number of voltage vectors, different switching tables can be formed. In order to avoid rapid change of stator flux, the vectors producing it should be avoided. Two types of switching table without using medium vectors are proposed in this paper.

Table 2: Three-level inverter voltage vectors and switching states

		Switch State					
S.No.	Voltage Vector	S_{a1}	S_{a2}	S_{b1}	S_{b2}	S_{c1}	S_{c2}
			Zero Vectors				
1	V_0 (000)	0	0	0	0	0	0
2	V_7 (111)	0	1	0	1	0	1
3	V_{26} (222)	1	1	1	1	1	1
			Small Vectors				
4	V_1 (100)	0	1	0	0	0	0
5	V_2 (110)	0	1	0	1	0	0
6	V_3 (010)	0	0	0	1	0	0
7	V_4 (011)	0	0	0	1	0	1
8	V_5 (001)	0	0	0	0	0	1
9	V_6 (101)	0	1	0	0	0	1
10	V_8 (211)	1	1	0	1	0	1
11	V_9 (221)	1	1	1	1	0	1
12	V_{10} (121)	0	1	1	1	0	1
13	V_{11} (122)	0	1	1	1	1	1
14	V_{12} (112)	0	1	0	1	1	1
15	V_{13} (212)	1	1	0	1	1	1
			Large Vectors				
16	V_{14} (200)	1	1	0	0	0	0
17	V_{15} (220)	1	1	1	1	0	0
18	V_{16} (020)	0	0	1	1	0	0
19	V_{17} (022)	0	0	1	1	1	1
20	V_{18}(002)	0	0	0	0	1	1
21	V_{19}(202)	1	1	0	0	1	1
			Medium Vectors				
22	V_{20} (210)	1	1	0	1	0	0
23	V_{21} (120)	0	1	1	1	0	0
24	V_{22} (021)	0	0	1	1	0	1
25	V_{23} (012)	0	0	0	1	1	1
26	V_{24} (102)	0	1	0	0	1	1
27	V_{25} (201)	1	1	0	0	0	1

$S_{a1}' = 1 - S_{a1}$, $S_{b1}' = 1 - S_{b1}$, $S_{c1}' = 1 - S_{c1}$

$S_{a2}' = 1 - S_{a2}$, $S_{b2}' = 1 - S_{b2}$ $S_{c2}' = 1 - S_{c2}$

Table 3: Switching table

	Flux Error ($H_ø$)									
	+1					-1				
	Torque Error (H_{Te})									
Sec	+2	+1	0	-1	-2	+2	+1	0	-1	-2
1	V_{15}	V_2	V_0	V_6	V_{19}	V_{16}	V_3	V_0	V_5	V_{18}
2	V_{16}	V_3	V_0	V_1	V_{14}	V_{17}	V_4	V_0	V_6	V_{19}
3	V_{17}	V_4	V_0	V_2	V_{15}	V_{18}	V_5	V_0	V_1	V_{14}
4	V_{18}	V_5	V_0	V_3	V_{16}	V_{19}	V_6	V_0	V_2	V_{15}
5	V_{19}	V_6	V_0	V_4	V_{17}	V_{14}	V_1	V_0	V_3	V_{16}
6	V_{14}	V_1	V_0	V_5	V_{18}	V_{15}	V_2	V_0	V_4	V_{17}

The switching tables are developed based on the output of the two-level flux hysteresis comparator (“+1”, “-1”), output of the five level torque hysteresis comparator (“+2”, “+1”, “0”, “-1”, “+1”) and the sector information (1 to 6).

The output of two-level hysteresis flux comparator, “+1” and “-1” denotes that it requires flux increase and flux decrease respectively. The output of five-level hysteresis torque comparator, “+2”, “+1”, “0”, “-1” and “-2” denotes that it requires high increase, small increase, no change, small decrease and high decrease in torque respectively.

Switching Table: In this scheme the zero voltage vector V_0, the small vectors V_1 to V_6 and large vectors V_{14} to V_{19} are considered. According to the flux and torque demand and in which sector the stator flux vector lies the switching table is formed as given in Table 3.

The direct torque control using three-level inverter is implemented and the simulated results are presented in the next section.

RESULTS

The proposed schemes were implemented and simulated using MATLAB/SIMULINK. 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 m2, friction factor B = 0.0027 Nm.sec.

To analyse the performance of induction motor, the simulations were carried out for the following conditions.

Case.1: Constant speed and constant torque

Case.2: Step change in speed and constant torque

Case.3: Constant speed and step change in torque

Initially the desired speed of the induction motor is set at 700 rpm at no load (Case.1). At 1 sec the step change in speed from 700 rpm to 1415 rpm is applied (Case.2). At 2 sec the step change in load from 0 Nm to 4 Nm is applied (Case.3).

The speed, torque, stator flux and the stator current responses of direct torque control of induction motor using two-level inverter are shown in figure 6. The enlarged view of steady state torque and stator flux responses for 1415 rpm and 4 Nm are shown in figure 7.

The speed, torque, stator flux and the stator current responses of direct torque control of induction motor using two-level inverter are shown in Figure 8.

The enlarged view of steady state torque and stator flux responses for 1415 rpm and 4 Nm are shown in Figure 9.

The direct torque control of induction motor using two-level inverter in case.1, the torque response in steady state has the torque ripples of 0.0512 Nm. The stator flux response in steady state has the flux ripples of 0.001098 Wb. In case 2, the torque and flux ripples are increased.

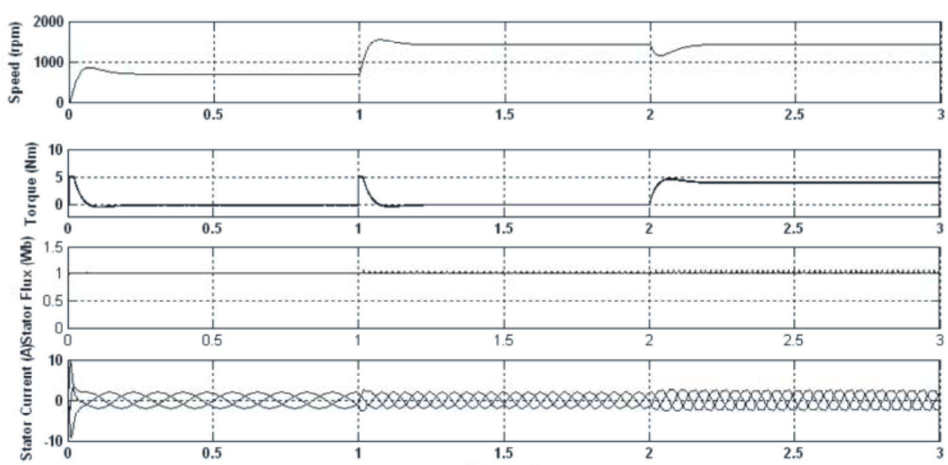

Fig. 6: Speed, Torque, Stator flux and Stator current responses (Two-level Inverter)

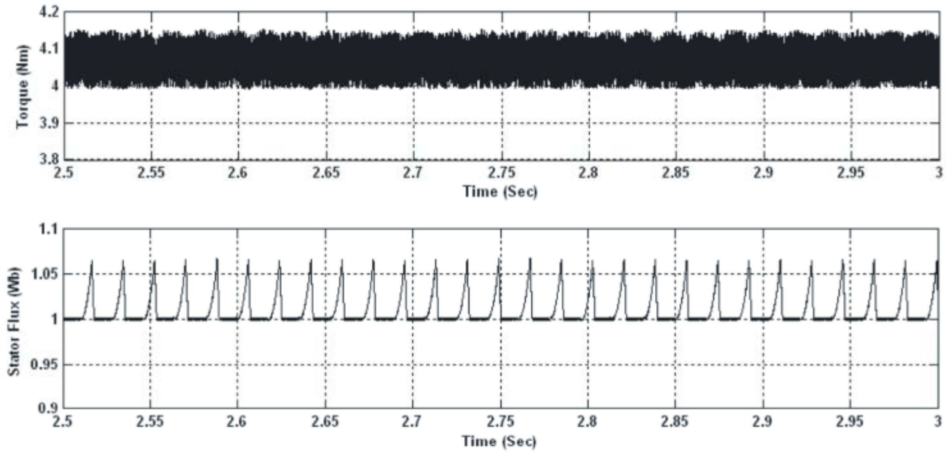

Fig. 7: Steady state Torque and Stator flux responses for 1415 rpm at 4 Nm (Two-level Inverter)

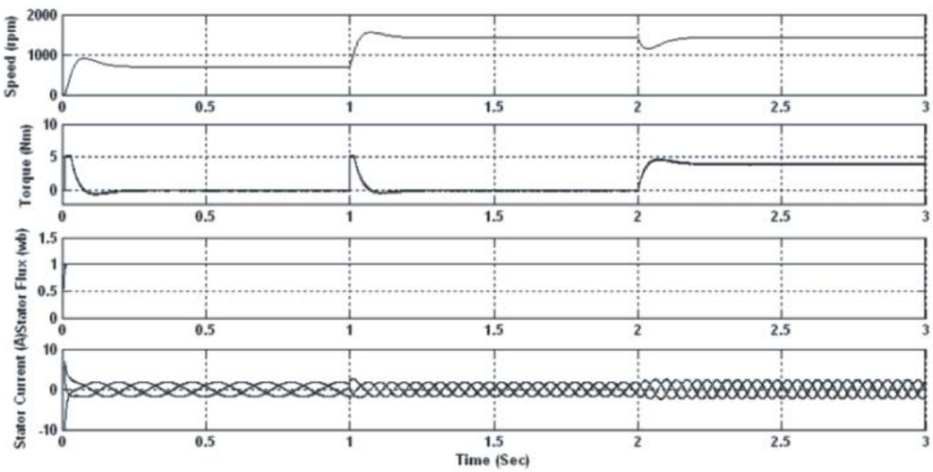

Fig. 8: Speed, Torque, Stator flux and Stator current responses (Three-level inverter)

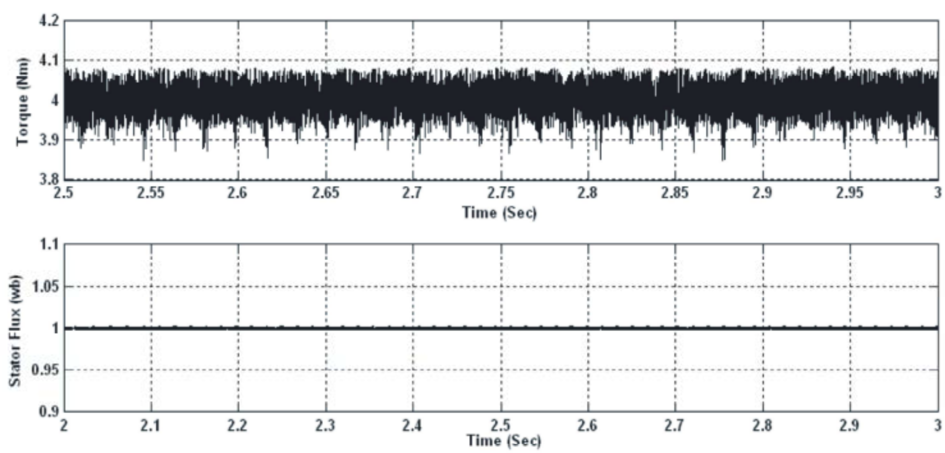

Fig. 9: Steady state Torque and Stator flux responses for 1415 rpm at 4 Nm (Three-level inverter)

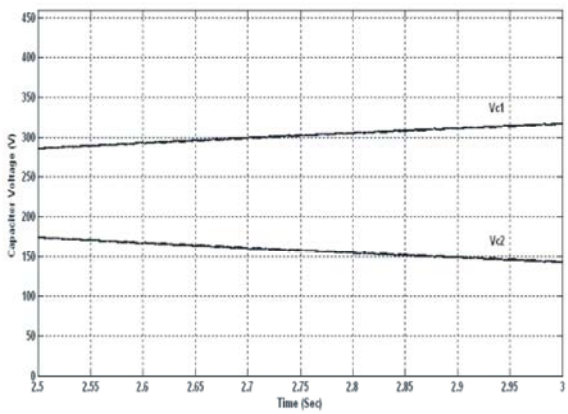

Fig. 10: Capacitor voltages

It has the torque ripples of 0.0758 Nm and flux ripples of 0.001134 Wb. And in case 3, the torque and flux ripples are increased. It has the torque ripples of 0.0772 Nm and flux ripples of 0.001227 Wb.

The simulation of direct torque control of induction motor using three-level inverter, in case 1, torque response in steady state has the torque ripples of 0.0570 Nm. The stator flux response in steady state has the flux ripples of 0.000821 Wb. In case 2, the torque and flux ripples are increased. It has the torque ripples of 0.0584 Nm and flux ripples of 0.000886 Wb. And in case 3, the torque and flux ripples are increased. It has the torque ripples of 0.0618 Nm and flux ripples of 0.000919 Wb. It shows that the torque ripples are higher in high speed and high torque. But compared with DTC using two-level inverter the torque and flux ripples are considerably reduced in DTC using three-level inverter.

The capacitor voltages of three-level diode clamped inverter are shown in figure.10.

The above figures show that the capacitor voltages are not balanced in DTC using three-level inverter. It is due to the redundancy switching states of small vectors.

Future Work: The capacitor voltages of three-level inverter are not balanced due to the redundancy of small vectors. The future work of this paper is proposed to minimise the capacitor voltage balancing problem by alternatively using the redundant small vectors based on direction of capacitor currents.

CONCLUSION

The proposed direct torque control of induction motor using three-level inverter is simulated using MATLAB/SIMULINK. The simulated results show that the torque and flux ripples are considerably reduced using three-level inverter compared with using two-level inverter. But the capacitor voltages of three-level inverter are not balanced. It is due to the redundancy switching states of small vectors. It can be overcome by alternative using the redundant small vectors based on the direction of capacitor currents as it is proposed in the future work of this paper.

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