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Implementation of Twelve-Sector based Direct Torque Control for Induction motor

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ABSTRACT : *Direct torque control (DTC) is an advanced control technique, in which the torque produced by the motor is directly controlled by controlling the inverter switching states. Each switching state represents a voltage vector. DTC have the following features, it does not requires current controllers, elimination of rotor position sensors, fast torque response, lesser parameter dependence, and it does not requires any axes transformation. Due to the above said attractive features, DTC gains more popularity in industrial motor control. In basic DTC the circular locus is divided into 6 sectors and a total of 8 voltage vectors obtained from two level inverter used, these vectors cannot always generate exact stator voltage and produce more torque ripples. In this proposed work, the basic 6 sector DTC scheme is modified with 12 sector and conventional two level inverter is replaced by three level neutral point clamped inverter to get different voltage vectors to a maximum of 27 and they are classified into large, medium, small and zero voltage vectors. New optimum switching table is proposed for different voltage vector combinations and the response of the proposed DTC scheme is analysed with the basic DTC scheme which shows considerable torque ripple minimisation. The simulation is performed in MATLAB / SIMULINK environment.*

Keywords: *Direct Torque Control (DTC), induction motor drives, neutral point clamped inverter (NPC), ripple reduction.*

I. INTRODUCTION

Induction motors are the main workforce of every industry and the industry needs better product quality, which is achieved through fast torque response characteristics of the drive. The voltage and current drawn by motor are measured, from that the actual flux and torque is estimated. The estimated torque and flux is compared with the reference torque and flux, which is measured using a speed controller. Depending on this instantaneous error value the voltage vector is selected from the switching table to restrict the torque and flux errors within the torque and flux hysteresis bands and corresponding gate signals are produced and applied to the voltage source inverter. In basic DTC the circular locus is divided into 6 sectors and a total of 8 voltage vectors are used, these vectors cannot always generate exact stator voltage and produce more torque ripples, which is undesirable and affects the product quality. In this proposed work, the flux sectors are increased to twelve and two level inverter is replaced by neutral point clamped three level inverter. The simulation results are compared and the proposed method produces lesser torque ripples.

II. NEUTRAL POINT CLAMPED INVERTER

A schematic of the neutral point clamped inverter (NPC) also called as three-level diode clamped inverter is shown in Fig.1. The main advantage of the three level voltage source inverters are, it can be applied in medium and high power applications. The capacitors maintain a constant voltage in neutral point. The main reason adding capacitors will reduce the additional distortion in the output voltage. The entire bus voltages divided into two by the equal series connected capacitors in the bus, the diode are connected with the mid-point of the DC bus to secure that the voltage across any single switch should not exceeds half of the DC bus voltage. Each leg consists of four switching devices and two diodes as clamped. The mid-point of the two capacitors is defined as the neutral point.

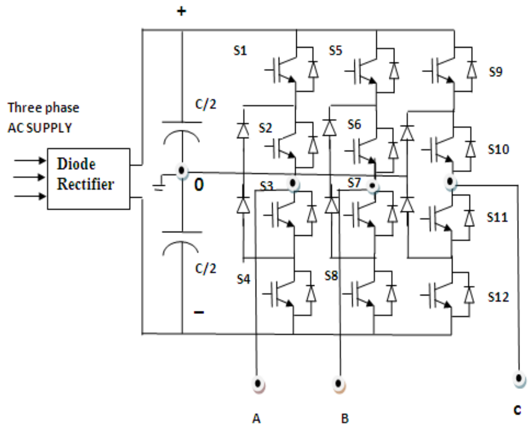

Figure 1: Neutral point clamped inverter

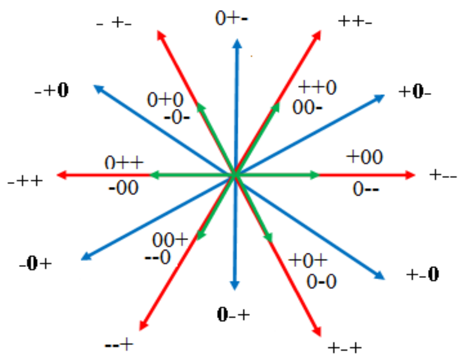

Figure 2: Switching state vectors of 3-level inverter

In practice, there are only three switching combinations of the switching devices in each leg that can be used. '+' indicates first two switches ON in each leg; '-' indicates second and third switches ON in each leg; '0' indicates last two switches ON in each leg. From the following table we can easily understand this concept.

Table 1: Switching states of a 3-level inverter

Status	S1	S2	S3	S4
-	Off(0)	Off(0)	on(1)	on(1)
0	Off(0)	On(1)	On(1)	off(0)
+	On(1)	On(1)	Off(0)	Off(0)

A total of 27 switching states can be get from a three level inverter. The entire 27 switching vectors can be grouped into four groups.

Zero vectors: V0, V25, and V26.
Large vectors: V1, V3, V5, V7, V9, V11.
Medium vectors: V2, V4, V6, V8, V0, V12.
Small vectors: V13, V14, V15, V16, V17, V18, V19, V20, V21, V22, V23, V24.

III. DTC WITH THREE-LEVEL INVERTER AND TWELVE-SECTOR CONCEPT

In Direct Torque Control, the torque and the stator flux are regulated to their reference values by selecting the adequate switching state. The conventional DTC with a two- level inverter makes no difference between large and small flux and torque errors. The switching states chosen for the large error that occurs during the start up or during a step change in torque or flux reference are the same that have been chosen for the fine control during steady-state. A better quantification of the input variables increasing the number of levels of the hysteresis blocks together with splitting the stator flux position into 12 sectors of 360 degrees and the increased number of inverter states available for a three level inverter may lead to a better performance of the control. A DTC control strategy has been designed for the three-level inverter. The stator flux position has been divided into 12 sectors of 360 degrees, starting with the first sector situated between -15°and 15°. The table for the inverter state selection has been decided to achieve an accurate control of both torque and stator flux and reduce the torque ripple inherent in the DTC method. The numbers in the table for the output voltage vector or inverter state are written according to Fig. 2.

III.1 OVERALL OPERATION

The block diagram of a Direct Torque Controlled Induction Motor Drive is shown in Fig. 3.The reference value of the stator flux magnitude is compared with the actual flux magnitude. The error obtained is given to a two-level hysteresis controller. If the error is positive value, it implies that the flux magnitude has to be increased and this is denoted as Hf = 1. If the error is negative, it implies that the flux magnitude has to be decreased and this is denoted as Hf = -1. The flux controller conditions are given as

$$H_f = 1 \text{ for } |\psi_s| \leq |\psi_s^*| - |\Delta\psi_s| \rightarrow (1)$$

$$H_f = 1 \text{ for } |\psi_s| \geq |\psi_s^*| - |\Delta\psi_s| \rightarrow (2)$$

The rotor reference speed is compared with the feedback speed and processed through PI controller and this error is converted into reference torque. The reference torque is compared with the actual torque and the error obtained is fed to a three-level hysteresis controller. The torque hysteresis controller conditions are given as

$$H_t = 1 \text{ for } |T_e| \le |T_e^*| - |\Delta T_e| \quad \rightarrow (3)$$

$$H_t = -1 \text{ for } |T_e| \ge |T_e^*| + |\Delta T_e| \quad \rightarrow (4)$$

$$H_t = 0 \text{ for } |T_e^*| - |\Delta T_e| \le |T_e| \le |T_e^*| + |\Delta T_e| \quad \rightarrow (5)$$

If the error is positive value, it implies that the torque has to be increased and this is denoted by Ht = 1.If the error is negative value, it implies the torque has to be reduced and this is denoted by Ht = - 1.It the error is zero, it implies the torque needs to be constant and this is denoted by Ht = 0.The reference flux is calculated online, with changing reference torque using the maximum torque per ampere concept (MTPA).

$$|\psi_s^*| = \sqrt{\psi_f^2 + \left(\frac{L_s T_e^*}{\frac{3}{2} P \psi_f}\right)^2} \quad \rightarrow (6)$$

III.2 ESTIMATION PROCEDURE

In the Direct Torque Controlled Induction Motor Drive the actual torque and flux are estimated using simple estimation equations. The direct and quadrature flux components are obtained by using the voltage equations of the induction motor and are given by

$$T_e = \frac{3}{2}\frac{p}{2}(i_q \psi_{ds} - i_d \psi_{qs}) \rightarrow (7) \qquad |\psi_s| = \sqrt{\psi_{ds}^2 + \psi_{qs}^2} \rightarrow (8) \qquad \psi_{ds} = \int (V_d - R_s i_d) dt \rightarrow (9)$$

$$\psi_{qs} = \int (V_q - R_s i_q) dt \rightarrow (10) \qquad \theta = \tan^{-1}\left(\frac{\psi_{qs}}{\psi_{ds}}\right) \rightarrow (11)$$

Where, Ψ_s -reference flux, Ψ_{ds} and Ψ_{qs}- direct and quadrature axis flux, V_d and V_q - direct and quadrature axis voltage, I_d,I_q- direct and quadrature axis current, R_s- stator resistance, Θ – sector.

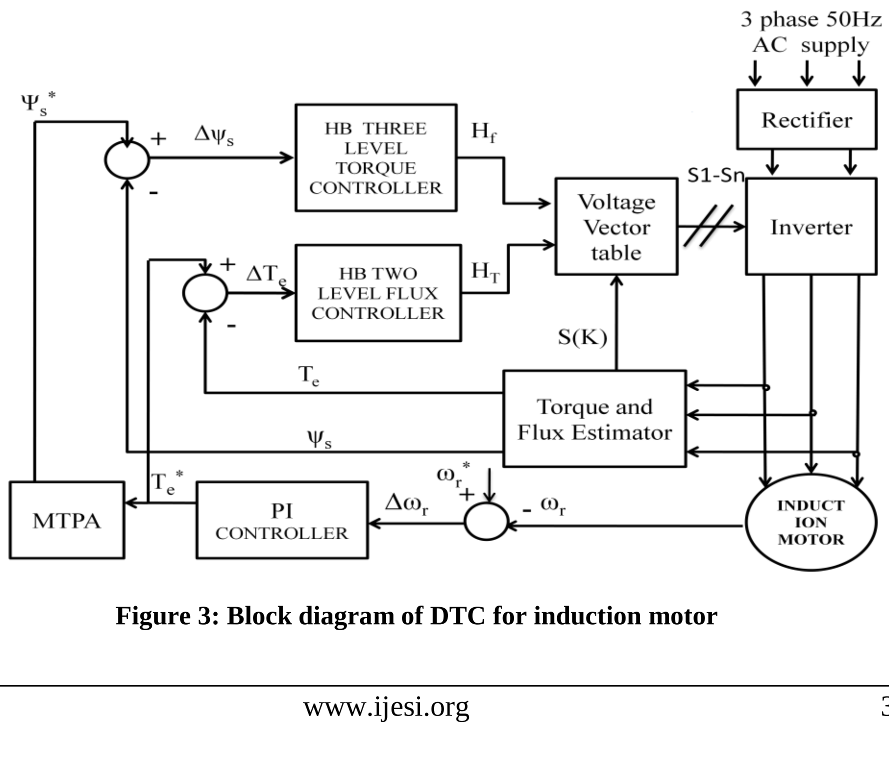

Figure 3: Block diagram of DTC for induction motor

III.3 SWITCHING TABLES

Table 2: Switching table for basic 6-sector DTC

Hf	Ht	1	2	3	4	5	6
1	-1	V2	V3	V4	V5	V6	V1
	0	V0	V7	V0	V7	V0	V7
	+1	V6	V1	V2	V3	V4	V5
-1	-1	V3	V4	V5	V6	V1	V2
	0	V7	V0	V7	V0	V7	V0
	+1	V5	V6	V1	V2	V3	V4

Table 3: Proposed switching table for 12-sector DTC

Hf	Ht	1	2	3	4	5	6	7	8	9	10	11	12
1	-1	V3	V16	V5	V18	V7	V20	V9	V22	V11	V24	V1	V14
	0	V0	V26	V0	V26	V0	V26	V0	V26	V0	V26	V0	V26
	+1	V11	V24	V1	V14	V3	V16	V5	V18	V7	V20	V9	V22
-1	-1	V5	V18	V7	V20	V9	V22	V11	V24	V1	V14	V3	V16
	0	V26	V0	V26	V0	V26	V0	V26	V0	V26	V0	V26	V0
	+1	V9	V22	V11	V24	V1	V14	V3	V16	V5	V18	V7	V20

IV. SIMULATION RESULTS

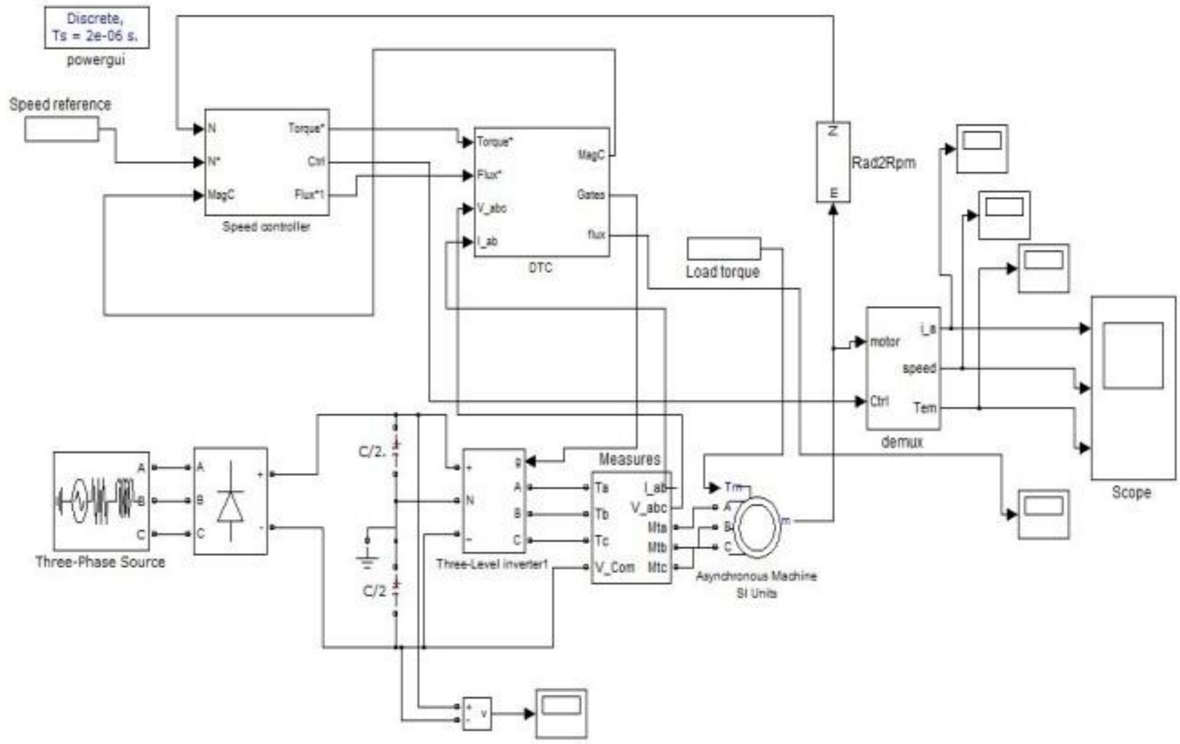

Figure 4: Simulation model of proposed 12-sector DTC

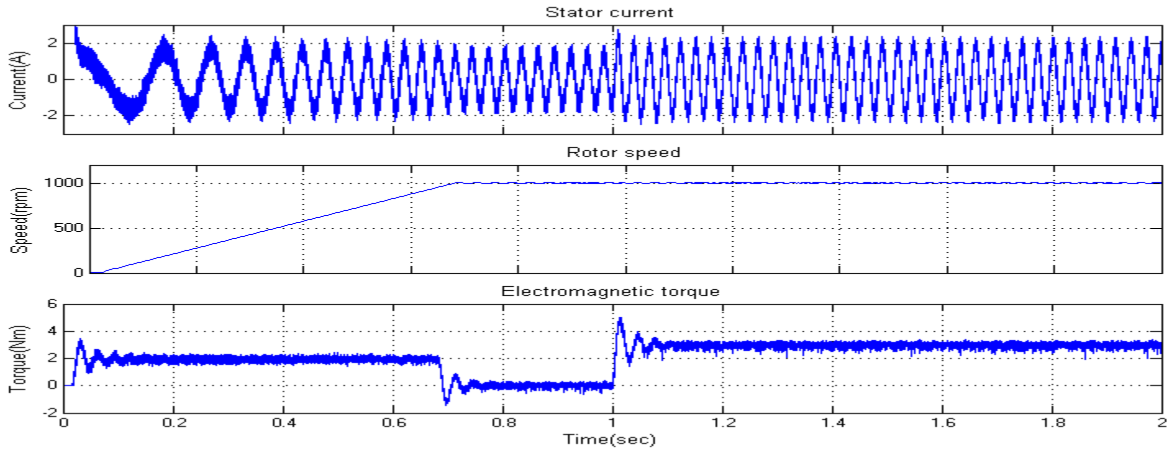

Figure 5: Simulation result of basic 6-sector DTC showing current, speed, and torque

The rotor speed is maintained at 1000 rpm when reference speed is set to 1000 rpm. Fig.6 shows the Electromagnetic Torque waveform of Proposed DTC at 75% rated Speed. Here the electromagnetic Torque remains same to the value 3 Nm when Load Torque is set to 3Nm. The torque ripple is around **0.6 Nm.**

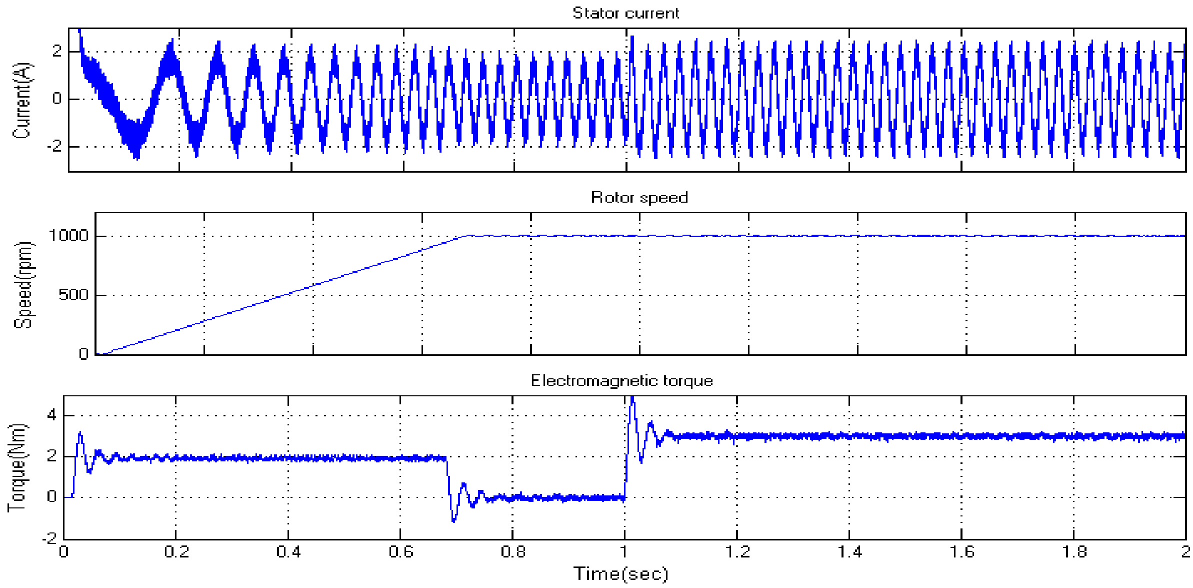

Figure 6: Simulation result of basic 6-sector DTC showing current, speed, and torque

The rotor speed is maintained at 1000 rpm when reference speed is set to 1000 rpm. Fig. 7 shows the electromagnetic torque waveform of Proposed DTC at 75% rated Speed. Here the Electromagnetic Torque remains same to the value 3 Nm when Load Torque is set to 3Nm. The torque ripple is around **0.3 Nm.** In the torque waveform, until the motor reaches the steady state there is initial starting torque and then torque goes to zero. A load torque of 3 Nm is applied at 1 second and motor produces the corresponding torque with lesser ripples than the conventional basic 6-sector DTC.

Table 4: Analysis and comparison of torque ripples

Percentage of Rated Speed	Torque Ripple In Conventional DTC	Torque Ripple In Proposed DTC	Torque ripple reduction in percentage
10(140 rpm)	**0.8 Nm**	**0.5 Nm**	**37.50**
50(700 rpm)	**0.7 Nm**	**0.4 Nm**	**42.85**
70(1000 rpm)	**0.6 Nm**	**0.3 Nm**	**50.0**
100(1415 rpm)	**0.6 Nm**	**0.3Nm**	**50.0**

V. CONCLUSION

In this paper a new method of torque ripple reduction based on the increased number of sectors and vectors is discussed. The induction motor drive is simulated for both 6-sector based DTC method and the 12-sector based DTC method and the results are comparatively analyzed. The torque waveforms are compared in steady state. It is observed that the 12-sector DTC strategy brings about a slight reduction in torque ripple, which enhances the drive characteristics.

APPENDIX

The parameters of the three-phase Induction Motor, used for simulation in SI units are listed below:

NOMINAL POWER	P = 750 W (1HP)
VOLTAGE	V = 415 V
FREQUENCY	f = 50 Hz
STATOR RESISTANCE	R_S = 22.1 Ohm
ROTOR RESISTANCE	R_r = 7.5296 Ohm
STATOR INDUCTANCE	L_{ls} = 0.01670 H
ROTOR INDUCTANCE	L_{lr} = 0.01670 H
MUTUAL INDUCTANCE	L_m = 0.53714 H
POLE PAIRS	p = 2
MOMENT OF INERTIA	J = 0.01225 kgm^2
FRICTION COEFFICIENT	B = 0.000027 Nms
RATED TORQUE	T_e = 5.1 Nm
RATED CURRENT	I = 1.8 A
RATED SPEED	N = 1415 rpm

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