ISSN No. 0976-8602 VOL.-II, ISSUE-IV, OCTOBER-2013

Asian Resonance

Direct Torque Control of Induction Motor using Fuzzy Logic Controller for Low Torque Ripple

Abstract

This paper focuses on the simulation of direct torque control (DTC) of induction motor drive (IMD) using Fuzzy Logic Controller (FLC) in MATLAB/Simulink. The aim is to devise a more effective method for speed control of IMD. The DTC scheme is simple in structure and provides good dynamic response. But the major drawback with the conventional DTC scheme is the presence of high torque along with stator flux ripples. The deviation of electromagnetic torque from its set value causes vibrations and noise which reduces the efficiency of motor. Thus, a FLC is designed and applied to minimize the torque ripple. In this paper the DTC principle and its formulation is discussed and a Simulink model of fuzzy logic controlled DTC drive is developed using AC4 DTC induction motor drive blockset available in SIMULINK 5.0. Finally the simulation results of conventional DTC drive and FLDTC drive are compared. The torque ripples in case of FLDTC is low.

Keywords: Direct Torque Control (DTC), Fuzzy Logic Controller (FLC), Induction Motor Drives (IMD), torque ripples, flux ripples, Voltage Source Inverter (VSI).

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Introduction

In this era of industrialization for a developing economy like India the growth and development of its industries play a vital role. The 21st century has witnessed the growth of many industries starting from steel plants to power plants, manufacturing and processing industries, cement, textile and paper mills, machine tools, servos and robotics, electric vehicles and subway transportation and many more. With this the demand for drive systems has also increased. Industrial drive applications are generally classified into constant-speed and variable-speed drive. Although currently, the majority of variable-speed drive applications use DC machines, they are progressively being replaced by ac drives. In most cases, new applications use AC drives. Among all types of AC machines, the induction machine, particularly the cage type, is most commonly used in industry. With the advances in the field of semiconductor technology and solid-state devices it is now possible to develop a variable speed IMD. The inverter-fed IM control methods are basically divided into scalar and vector control methods. The scalar based controllers provide good steady-state but poor dynamic response. From the traces of the dynamic responses, the cause of such poor dynamic response is found to be that the air gap flux linkages deviate from their set values. The deviation is not only in magnitude but also in phase and these control strategies utilized only the stator phase current magnitude and frequency and not their phases which resulted in the deviation of the phase and magnitudes of the air gap flux linkages from their set values. The oscillations in air gap flux results in the oscillations in electromagnetic torque and if left unchecked, reflect as speed oscillations [5].

To obtain a fast torque response and speed control the vector controllers were devised. Vector control made the AC drives equivalent to DC drives in the independent control of torque and flux and superior to them in their dynamic response. One of the vector control method is the Field Oriented Control (FOC) proposed in early 1970' [3]. FOC scheme gives high performance for industrial applications but has some drawbacks. In mid 80's a simplified variation of FOC known as Direct Torque Control was proposed by I. Takahashi [1] and Depenbrock [2]. Unlike the FOC scheme this scheme does not need any co-ordinate transformation and is less sensitive to motor parameter variations. The DTC has become a very popular method because of simple structure and resulting fast dynamic response of motor. But the conventional DTC scheme has got some drawbacks such as problem during starting, sluggish speed response during startup and abrupt change in torque command and presence of inherent torque along with stator flux ripples.

Researchers have implemented many techniques to overcome these drawbacks and improve the performance of DTC drives. One of the methods is to use FLC [8-11]. The FLC can reduce the electromagnetic torque ripples in classical DTC. In this paper the Simulink model of a 200 hp DTC IMD is developed and FLC is designed to minimize the torque and flux ripples present in the conventional drive model [10].

Direct Torque Control Principle

DTC is a control algorithm which describes the way to control torque and speed directly from the electromagnetic state of the motor, similar to a DC motor. It allows independent control of torque and flux by selection of proper switching states of inverter. The switching states of the inverter are selected according to a switching table formulated using three variables which are stator flux and electromagnetic torque errors and the spatial position of flux vector. The schematic diagram of the basic DTC of IMD is given in Fig.1. It consists of a VSI, stator flux and torque estimators, a pair of hysteresis band comparators , voltage vector selection table, speed controller and a induction motor.

Voltage Source Inverter (VSI)

The three phase VSI will produce six active voltage vectors (V_1, V_{II}, ….V_{VI}) and two zero voltage vectors (V_{VII}, V_{VIII}), according to the combination of the switching modes are S_a, S_b, and S_c. Considering the three phase inverter shown in Fig.2 a set of switches are defined for the three lines a, b, c. The inverter has three legs and each leg has two switches. When the upper switch of a leg is ON the switching value is '1'and when the lower switch is ON the switching value is '0'.

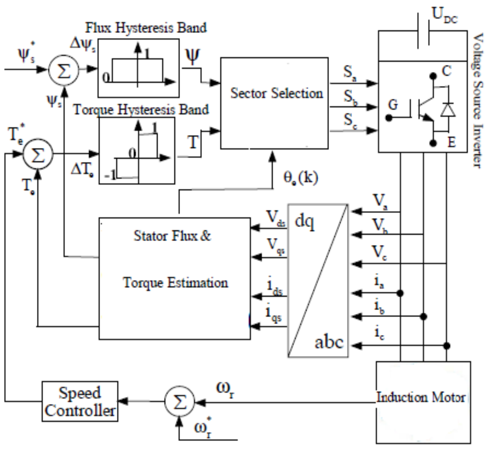

Fig.1. Schematic diagram of conventional DTC drive

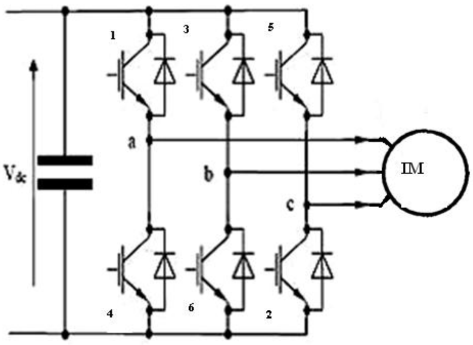

Fig.2. Three phase Voltage Source Inverter

Flux and Torque Estimation

Stator flux based calculator method is used for calculating the electromagnetic torque, using only the stator flux linkages and stator currents. Only the stator resistance is employed in the computation of stator flux linkages, thereby removing the dependence of mutual and rotor inductances of the machine on its calculation.

As from Fig.2. first the three phase inverter output voltages V_{as}, V_{bs}, V_{cs} and currents i_{as}, i_{bs}, i_{cs} are obtained and then transformed into two phase stationary 'd' and 'q' axes voltages and currents [4-5] as given by (1)-(4).

$$V_{qs} = V_{as} \tag{1}$$

$$V_{ds} = \frac{1}{\sqrt{3}}\left(V_{cs} - V_{bs}\right) \tag{2}$$

$$i_{qs} = i_{as} \tag{3}$$

$$i_{ds} = \frac{1}{\sqrt{3}}\left(i_{cs} - i_{bs}\right) \tag{4}$$

The stator d- and q-axis flux linkages are given by (5) and (6), where stator resistance drop has been compensated.

$$\psi_{qs} = \int \left(V_{qs} - R_s i_{qs}\right) dt \tag{5}$$

$$\psi_{ds} = \int \left(V_{ds} - R_s i_{ds}\right) dt \tag{6}$$

The resultant flux magnitude and position is given by (7) and (8) respectively. The developed electromagnetic torque 'Te' is given by (9).

$$\psi_s = \sqrt{\left(\psi_{ds}^2 + \psi_{qs}^2\right)} \angle \theta_e \tag{7}$$

$$\theta_e = \tan^{-1}\left(\frac{\psi_{qs}}{\psi_{ds}}\right) \tag{8}$$

$$T_e = \frac{3}{2}\cdot\frac{p}{2}\left(\psi_{ds} i_{qs} - \psi_{qs} i_{ds}\right) \tag{9}$$

ISSN No. 0976-8602 VOL.-II, ISSUE-IV, OCTOBER-2013

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Direct Flux Control

As per Fig.1 the resultant stator linked flux ψ_s is compared with the reference flux magnitude and the difference between the reference value and the estimated value gives the flux error which is given as input to the two level flux hysteresis comparator as shown in Fig.3. In DTC the stator flux magnitude is limited within the hysteresis band. When the stator flux touches its upper or lower hysteresis band, a suitable voltage vector is selected to reduce or increase it respectively, hence it follows a circular path. The output of the flux hysteresis comparator is the flux error status dψ. When dψ is '1' it calls for increase in flux and '0' for decrease in flux. The switching logic for flux error is given in Table I. In order to select the appropriate voltage vector the stator flux orientation or position must be known. The stator flux plane is divided into six sectors as shown in Fig. 4. Each sector will have a different set of voltage vectors to increase or decrease the flux.

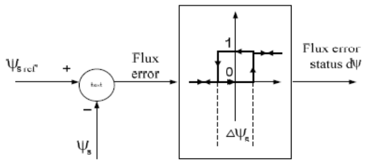

Fig. 3. Two Level Flux Hysteresis Comparator

Table I. Switching Logic For Flux Error

state	Flux Error Status dψ
$(\psi_{ref} - \psi) > \Delta\psi$	1
$(\psi_{ref} - \psi) < -\Delta\psi$	0

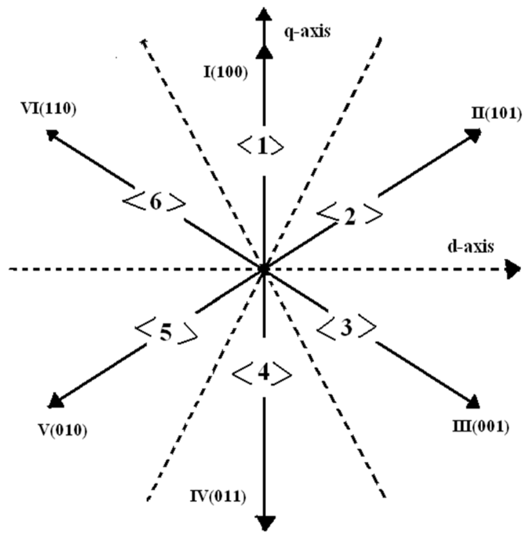

Fig. 4. Space voltage vectors and spatial sectors

Direct Torque Control

The estimated torque from the stator flux linkages and stator currents in (9) is compared with the command torque generated by the speed controller. Depending on the torque error the torque has to be increased or decreased by selecting suitable voltage vectors. The torque error has to be limited within its hysteresis band. The output of the three level torque hysteresis comparator is the torque error status dTe as shown in Fig.5. When it is '1' it calls for control action to increase torque, '-1' to decrease and '0' to maintain as it is. The switching logic for torque error is given in table II.

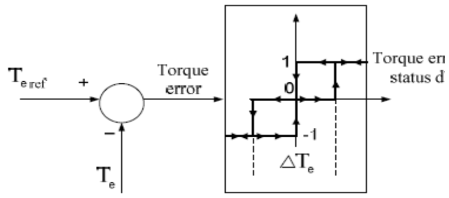

Fig. 5. Three-level torque hysteresis comparator

Table II. Switching Logic For Torque Error

State	Torque error status dT_e
$(T_{ref} - T_e) > \Delta T_e$	1
$-\Delta T_e < (T_{ref} - T_e) < \Delta T_e$	0
$(T_{ref} - T_e) < -\Delta T_e$	-1

Formulation of the switching table

A switching table is formulated combining the flux error status dψ, torque error status dT_e, and flux vector position S_θ , which decides switching states of the inverter [5], given in table III. and the flux phasor sextant logic is given in table IV.

Table III. DTC Switching Table

dψ	dT_e			S_θ			
		<1>	<2>	<3>	<4>	<5>	<6>
1	1	VI (110)	I (100)	II (101)	III (001)	IV (011)	V (010)
1	0	VIII (111)	VII (000)	VIII (111)	VII (000)	VIII (111)	VII (000)
1	-1	II (101)	III (001)	IV (011)	V (010)	VI (110)	I (100)
0	1	V (010)	VI (110)	I (100)	II (101)	III (001)	IV (011)
0	0	VII (000)	VIII (111)	VII (000)	VIII (111)	VII (000)	VIII (111)
0	-1	III (001)	IV (011)	V (010)	VI (110)	I (100)	II (101)

Table IV. Flux-Phasor Sextant Logic

Θ_e	Sextant
$0 \le \theta_e \le \Pi/3$	<2>
$-\Pi/3 \le \theta_e \le 0$	<3>
$-2\Pi/3 \le \theta_e \le -\Pi/3$	<4>
$-\Pi \le \theta_e \le -2\Pi/3$	<5>
$2\Pi/3 \le \theta_{fs} \le \Pi$	<6>
$\Pi/3 \le \theta_e \le 2\Pi/3$	<1>

In table III, the roman numerals specify the inverter output voltage vector. There are six active voltage vectors (I–VI) and the two null vectors (VII and VIII) each corresponding to a particular switching pattern which is given in numerals below it. For example, active voltage vector I will require, as per Fig.2, turning on of upper switch in leg 'a' and lower switches in legs 'b' and 'c'. Fig. 4 shows the six active space vectors and all the six spatial sectors described before. Each voltage vector is situated in the center of the corresponding sector. As we move in anticlockwise direction in the d-q plane, the sectors <6>, <5>, <4>, <3>, <2> and <1> come in sequence. Sector <1> extends from 60^0 to 120^0 (from d-axis, in the anticlockwise direction) of Fig.4 and so on.

Fuzzy-PI Based Torque Controller

The fuzzy controller was first implemented by Mamdani and Assilian [6]. A FLC designed on the basis of fuzzy logic [7] is an approximate reasoning based controller, which does not require exactly analytical models and much similar to human thinking and natural language.

The proposed Fuzzy PI-based controller block diagram is shown in Fig.7.The Fuzzy PI- based torque controller is added before the torque hysteresis block of the classical DTC Simulink model.

The fuzzy PI controller has two inputs. The first one is the torque error signal, $T_E = T_{e,ref} - T_e$ and the second one is the rate of change of torque error, $dT_E = T_E(t) - T_E(t\text{-}\Delta t)$. Both gains are being normalized using the input normalization gains G_1 and G_2 before being delivered into fuzzy controller.

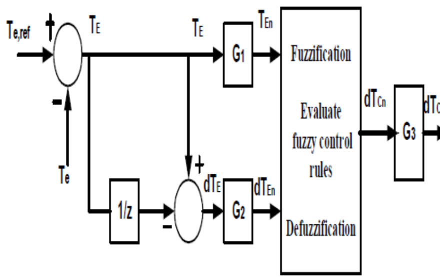

Fig. 7. Fuzzy PI controller block diagram

The output of the controller is a normalized change of control signal dT_{cn}. The actual change of the control signal value dT_c is obtained by using output unnormalisation gain G_3. In the proposed controller the universe of discourse of both the input variables and the output variable is defined from -3 to 3 and fuzzified into seven fuzzy subsets given in table V. A set of 49 rules that are designated to achieve the desired response [10] are tabulated in table VI. The membership functions for the input and output variables are given in Fig.8 and Fig.9 respectively.

Table V. Fuzzification Of Input And Output

Linguistic Term	**Symbol**	**Fuzzy Subset**
Positive Big	PB	+3
Positive Medium	PM	+2
Positive Small	PS	+1
Zero	Z	0
Negative Small	NS	-1
Negative Medium	NM	-2
Negative Big	NB	-3

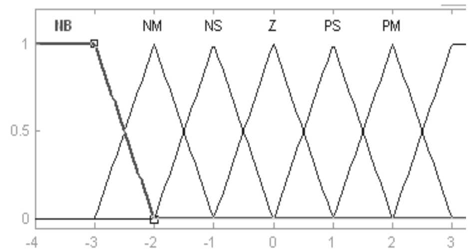

Fig. 8. Membership function for input variables (T_{En} and dT_{En})

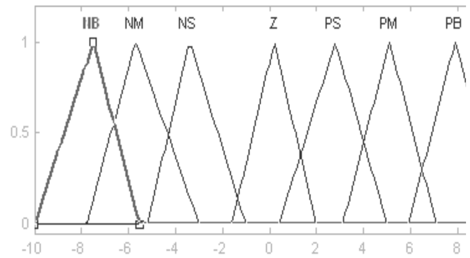

Fig. 9. Membership function for output variable (dT_{cn})

Table VI. Fuzzy Control Rules

dTEn \ TEn	-3	-2	-1	0	+1	+2	+3
-3	0	0	-3	-3	0	0	0
-2	-3	-2	-3	-1	-2	0	0
-1	-2	-2	-3	-3	0	+1	0
0	-2	-1	-3	0	0	+1	0
+1	-1	-1	0	0	0	+2	0
+2	-1	0	-3	+1	0	+2	0
+3	0	+1	-3	-3	0	+3	0

Simulation Results

Simulation study is performed on a 200 hp DTC induction motor drive. The parameters of the induction motor used in simulation study of classical DTC and FLDTC are tabulated in table VII of appendix.

Fig. 10 and Fig. 11 shows the electromagnetic torque output waveform and the resultant stator flux waveform of classical DTC drive respectively. Fig. 12 and Fig. 13 shows the torque output waveform and resultant stator flux waveform of Fuzzy- PI based torque controlled IMD respectively. Fig. 14 and Fig. 15 show the waveform of torque and flux respectively where a comparison is made between the simulation results of classical DTC and FLDTC.

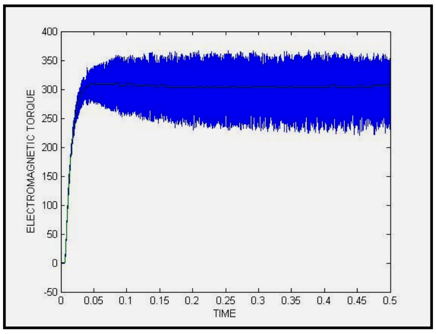

Fig. 10. Torque output waveform of classical DTC drive

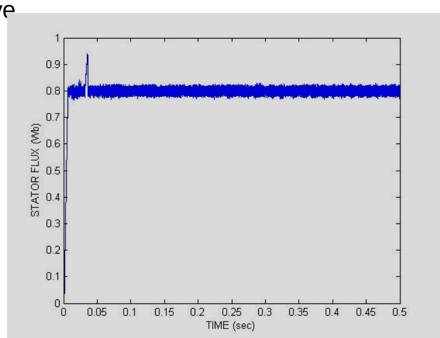

Fig. 11. Stator flux waveform of classical DTC drive

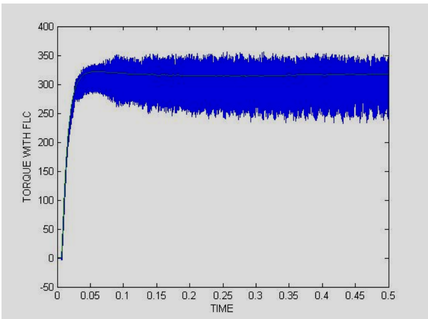

Fig.12. Torque output waveform of FLDTC

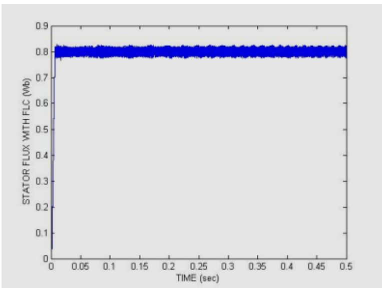

Fig. 13. Stator flux waveform of FLDTC

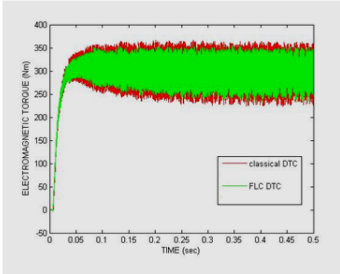

Fig. 14. Comparison of electromagnetic torque waveforms

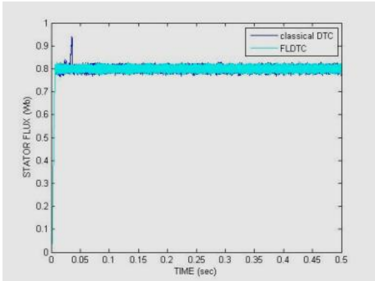

Fig. 15. Comparison of Stator flux waveforms

Conclusion

The DTC scheme is supposed to be one of the best speed control strategy for induction motor. But the major drawback of the classical hysteresis based torque controller is the presence of high torque along with flux ripples. This paper has proposed a fuzzy PI-based torque controller for classical DTC drive to overcome this drawback and improve the performance of drive. The development of the controller is thoroughly discussed. From the simulation results it is apparent that with the proposed controller, the torque and the stator flux ripples, especially at low speed region are reduced.

Appendix

Table VII. Parameters of Induction Motor Used

Motor Parameters	Nominal Values
Stator resistance (R_s)	14.85 mΩ
Rotor resistance (R_r)	9.295 mΩ
Mutual inductance (L_m)	10.46 mH
Stator self inductance (L_s)	0.3027 mH
Rotor self inductance (L_r)	0.3027mH
Inertia constant (J)	3.1 Kg.m^2
Friction constant B_m	0.08 Nm/rad/s
Poles (P)	4
Rated Power	200 hp
Frequency	60 Hz
Phase Voltage	460 V

Acknowledgment

The authors gratefully acknowledge the contributions of Department of Electrical Engineering, VSSUT, Burla for their work on the original version of this document.

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