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Performance Enhancement of 3 Φ IM Drive using Fuzzy Logic Based DTC Technique

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ABSTRACT - This paper presents a direct flux and torque control (DTC) of three phase induction motor drive (IMD) using PI and fuzzy logic controllers (FLC) for speed regulator (SR) and low torque ripples. This control method is based on DTC operating principles. The DTC is one of the most excellent direct control strategies of stator flux and torque ripples of IMD. The key issue of the DTC is the strategy of selecting proper stator voltage vectors to force stator flux and developed torque within a prescribed band. Due to the nature of hysteresis control adopted in DTC, there is no difference in control action between a large torque error and a small one. This results in high torque ripple. It is better to divide the torque error into different intervals and give different control voltages for each of them. To deal with this issue a fuzzy logic controller has been introduced. The main drawback with the conventional DTC of IMD is high stator flux and torque ripples and the speed of IMD is reduced under transient and dynamic state of operating condition. This drawback is reduced by the proposed system, the speed is regulated by PI controller and torque is controlled by fuzzy logic controller. The amplitude of the reference stator flux is kept constant at rated value. The simulation results of proposed DTC shows the low stator flux linkage, torque ripples and good speed regulator than conventional DTC technique using MATLAB/SIMULINK.

Keywords- Direct Torque Control (DTC), Fuzzy Logic Control (FLC), Induction Motor Drive (IMD), Space Vector Modulation (SVM).

I.INTRODUCTION

Nowadays around 70% of electric power is consumed by electric drives. This electric drives are mainly classified into AC and DC drives. During last four decades AC drives are become more and more popular, especially induction motor drives (IMD), because of robustness, high efficiency, high performance, and rugged structure, ease of maintenance so widely used in industrial application, such as paper mills, robotics, steel mills, servos, transportation system, elevators, machines tools etc. Commonly used techniques for speed control of induction motor drive are V/F ratio control, Direct Torque Control (DTC) and Vector Control. In the scalar or the V/F ratio control technique, there is no control over the torque or flux of the machine. Torque and Flux control is possible with vector control in induction motor drive. However, vector control is highly computationally complex and hence the DTC technique with less computational complexity along with control of torque and flux is preferred in many applications. Comparing with FOC, DTC has a simple control scheme and also very less computational requirements, such as current controller, and co-ordinate transformations are not required. The main feature of DTC is simple structure and good dynamic behaviour and high performance and efficiency [1,2,3]. The new control strategies proposed to replace motor linearization and decoupling via coordinate transformation, by torque and flux hysteresis controllers [4]. This method is referred as conventional DTC [5].

In the conventional DTC has some drawbacks such as, variable switching frequency, high torque and flux ripples, problem during starting and low speed operating conditions, and flux and current distortion caused by stator flux vector changing with the sector position [5], and the speed of IMD is changing under transient and dynamic state operating condition. In order to overcome with this problem, the proposed DTC with PI and FLC are used. The PI controller is used for speed control in the SR loop and the FLC is used for stator flux and torque ripple reduction in the torque control loop [6]. The conventional and proposed DTC of IMD simulation results are presented and compared.

II. DIRECT TORQUE CONTROL

The conventional DTC of IMD is supplied by a three phase, two level voltage source inverter (VSI). The main aim is to directly control of stator flux linkage or rotor flux linkage and electromagnetic torque by selection of proper voltage switching states of inverter. The schematic diagram of conventional DTC of IMD is shown in Fig.1. This schematic diagram consists of a torque and flux hysteresis band comparators (T, Ψ), voltage vector sector selection, stator flux and torque estimators (Ψ_s, T_e), induction motor, speed controller, and voltage source inverter (VSI) [7].

A. Voltage Source Inverter (VSI)

The three phase and two level VSI is shown in Fig.2, it has eight possible voltage space vectors, in those six active voltage vectors (U1-U6) and two zero voltage vectors (U7,U8), according to the combination of the switching modes are S_a, S_b, and S_c. When the upper part of switches is ON, then the switching value is ‘1’ and when the lower switch is ON, then the switching value is ‘0’. The stator voltage vector is written as in equation (1).

$$\bar{U}s,k = \frac{2}{3} U_{DC} [S_{a} + aS_{b} + a^2 S_c] \qquad (1)$$

Where UDC is the dc link voltage of inverter, $a = e^{j2\Pi/3}$.

The inverter output voltages U_a^s , U_b^s and U_c^s are converted to U_{ds}^s and U_{qs}^s by following equations (2), and (3):

$$U_{ds}^s = \frac{2}{3} S_a - \frac{1}{3} S_b - \frac{1}{3} S_c \qquad (2)$$

$$U_{qs}^s = - (1/\sqrt{3})\, S_b + (1/\sqrt{3})\, S_c \qquad (3)$$

The behaviour of induction motor drive using DTC can be described in terms of space vector model is written in the stator stationary reference frame[11],[12]:

$$U_{ds}^s = R_s\, i_{ds}^s + \frac{d}{dt} \psi_{ds}^s \qquad (4)$$

$$U_{qs}^s = R_s\, i_{qs}^s + \frac{d}{dt} \psi_{qs}^s \qquad (5)$$

$$0 = R_r\, i_{qr}^s + \frac{d}{dt} \psi_{qr}^s - \acute{\omega}_r \psi_{dr}^s \qquad (6)$$

$$0 = R_r\, i_{dr}^s + \frac{d}{dt} \psi_{dr}^s - \acute{\omega}_r \psi_{qr}^s \qquad (7)$$

$$\psi_s = L_s\, i_s + L_m\, i_r \qquad (8)$$

$$\psi_r = L_r\, i_r + L_m\, i_s \qquad (9)$$

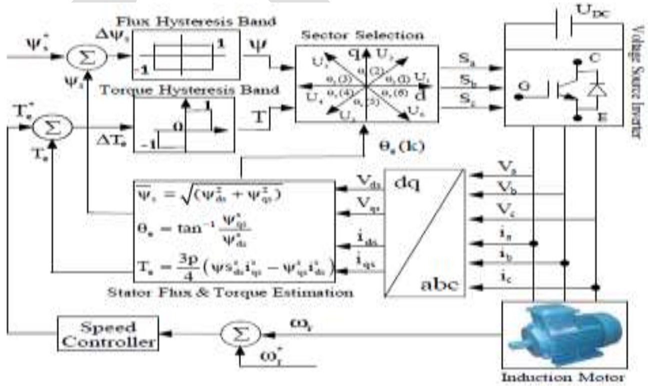


Figure 1. Schematic diagram of direct torque control of induction motor.

B. Direct Flux Control

The implementation of the DTC scheme requires the torque, flux linkage computation and generation of vector switching states through a feedback control of the flux and torque directly without inner current loops. The stator flux in the stationary reference frame (d_s-q_s) can be estimated as [10]:

$$\bar{\psi}_{ds}^s = \int (U_{ds}^s - i_{ds}^s R_s)\, dt \qquad (10)$$

$$\bar{\psi}_{qs}^s = \int (U_{qs}^s - i_{qs}^s R_s)\, dt \qquad (11)$$

The estimated stator flux, ψ_s , is given by:

$$\overline{\psi}_s = (\overline{\psi}^{s}_{ds}{}^{2} + \overline{\psi}^{s}_{qs}{}^{2}) \wedge (1/2) \qquad (12)$$

$$\overline{U}_s = \frac{d}{dt} (\overline{\psi}_s) \text{ or } \Delta\overline{\psi}_s = \overline{U}_s.\Delta t \qquad (13)$$

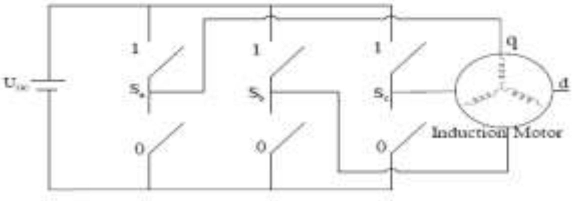


Figure 2.Schematic diagram of voltage source inverter.

The change in input to the flux hysteresis controller can be written as:

$$\Delta\psi_s = \psi_s^* - \psi_s \qquad (14)$$

The flux hysteresis loop controller has two level of digital output ψ, according to the following relation shown in Table 1.

TABLE 1. SWITCHING LOGIC FOR FLUX ERROR

State	Flux Hysteresis (ψ)
$(\psi_s^* - \psi_s) > \Delta\psi_s$	1
$(\psi_s^* - \psi_s) < -\Delta\psi_s$	-1

C. Direct Torque Control

The torque hysteresis loop control has three levels of digital output, which have the following relations is shown in Table 2.

TABLE 2. SWITCHING LOGIC FOR TORQUE ERROR

State	Torque Hysteresis(T)
$(T_e^* - T_e) > \Delta T_e$	1
$-\Delta T_e < (T_e^* - T_e) < \Delta T_e$	0
$(T_e^* - T_e) < -\Delta T_e$	-1

When the torque hysteresis band is T=1 increasing torque, when T=0 means torque at zero and T=-1 decreasing the torque. The instantaneous electromagnetic torque and angle in terms of stator flux linkage is given in equation (15), (16).

$$T_e = \frac{3}{2}\frac{P}{2} (\psi_{ds}{}^{s} i_{qs}{}^{s} - \psi_{qs}{}^{s} i_{ds}{}^{s}) \qquad (15)$$

$$\theta_e(k) = \tan^{-1}(\overline{\psi}_{ds}{}^{s} / \overline{\psi}_{qs}{}^{s}) \qquad (16)$$

The change in electromagnetic torque error can be written as:

$$\Delta T_e = T_e^* - T_e \qquad (17)$$

The eight possible voltage vector switching configuration is shown in Fig.3.The voltage vector is selected using torque or flux need to be increased or decreased comes from the three level and two level hysteresis comparators for torque and stator flux respectively. The selection of increasing and decreasing the stator flux and torque is shown in Table 3.The Fig.3., illustrates the 2-hysteresis optimized voltage vector in six sectors and which are selected from six active and two zero voltage vector switching configurations, using the voltage vector selection table is shown in Table 4.

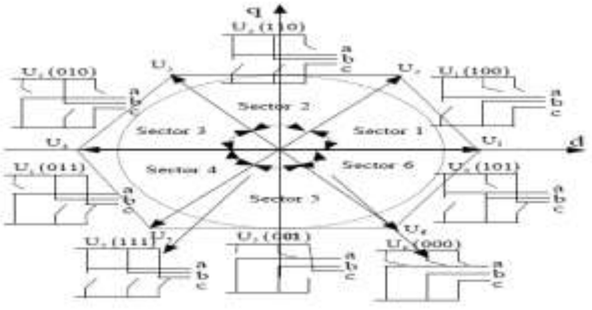


Figure 3. Eight possible switches configuration of the voltage source inverter.

TABLE 3. GENERAL SELECTION FOR DTC

K^{th} Sector	**Increase**	**Decrease**
Stator Flux (ψ)	U_k , U_{k+1} , U_{k-1}	U_{k+2} , U_{k+3} , U_{k-2}
Torque (T)	U_k , U_{k+1} , U_{k+2}	U_{k+3} , U_{k-2} , U_{k-1}

TABLE 4. VOLTAGE VECTOR SELECTION

Hysteresis Controller		**Sector Selection $\theta_e(k)$**					
ψ	**T**	**$\theta_e(1)$**	**$\theta_e(2)$**	**$\theta_e(3)$**	**$\theta_e(4)$**	**$\theta_e(5)$**	**$\theta_e(6)$**
1	1	U2	U3	U4	U5	U6	U1
	0	U7	U8	U7	U8	U7	U8
	-1	U6	U1	U2	U3	U4	U5
-1	1	U3	U4	U5	U6	U1	U2
	0	U8	U7	U8	U7	U8	U7
	-1	U5	U6	U1	U2	U3	U4

III. PROPOSED FUZZY LOGIC CONTROLLER

The fuzzy logic control is one of the controllers in the artificial intelligence techniques. Fig.4 shows the schematic model of Fuzzy based DTC for IMD. In this project, Mamdani type FLC is used and the DTC of IMD using PI controller based SR(speed regulator) are requires the precise mathematical model of the system and appropriate gain values of PI controller to achieve high performance drive. Therefore, unexpected change in load conditions would produce overshoot, oscillation of the IMD speed, long settling time, high torque ripple, and high stator flux ripples. To overcome this problem, a fuzzy control rule look-up table is designed from the performance of torque response of the DTC of IMD. According to the torque error and change in torque error, the proportional gain values are adjusted on-line [8].

The fuzzy controller is characterized as follows:
1) Seven fuzzy sets for each input and output variables,
2) Fuzzification using continuous universe of discourse,
3) Implication using Mamdani's ‘min’ operator,
4) De-fuzzification using the ‘centroid’ method.

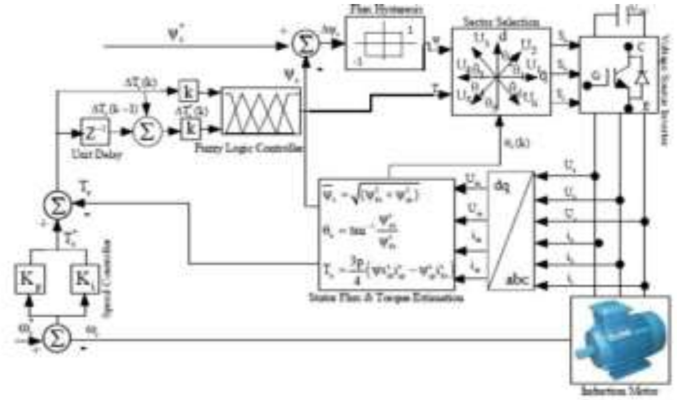


Figure 4. Proposed Structure of FLC Based Direct Torque Control.

Fuzzification**:** the control process of converting a numerical variable (real number) convert to a linguistic variable (fuzzy number) is called fuzzification.

De-fuzzification**:** the rules of the FLC generate required output variable in a linguistic variable (Fuzzy Number), according to the real world requirements, linguistic variables have to be transformed to crisp output (Real number).

Database**:** the database stores the definition of the membership Function required by fuzzifier and defuzzifier [10].

A. Fuzzy Variables

In the crisp variables of the torque error and change in torque error are converted into fuzzy variables $\Delta T_e(k)$ and $\Delta T_e*(k)$ that can be identified by the level of membership functions in the fuzzy set. The fuzzy sets are defined with the triangular membership functions.

B. Fuzzy Control Rules

In the fuzzy membership function there are two input variables and each input variable have seven linguistic values, so 7x7=49 fuzzy control rules are in the fuzzy reasoning is shown in Table.5 and flowchart of FLC is shown in Fig.6.

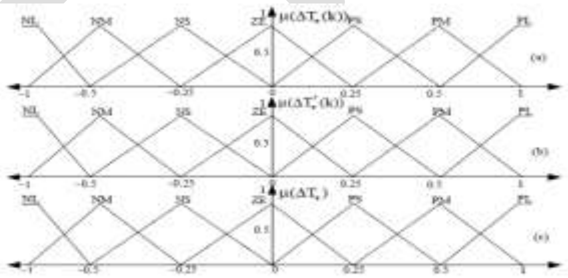


Figure 5. Fuzzy membership functions of input variables (a) torque error, (b) change in torque error, and (c) output variable.

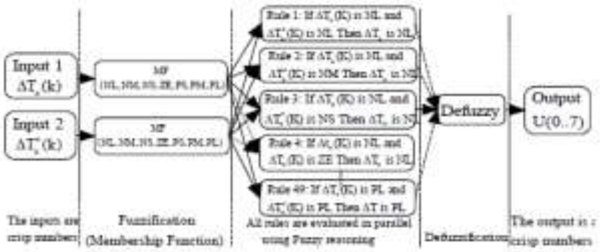


Figure 6. Flowchart of Fuzzy logic controller

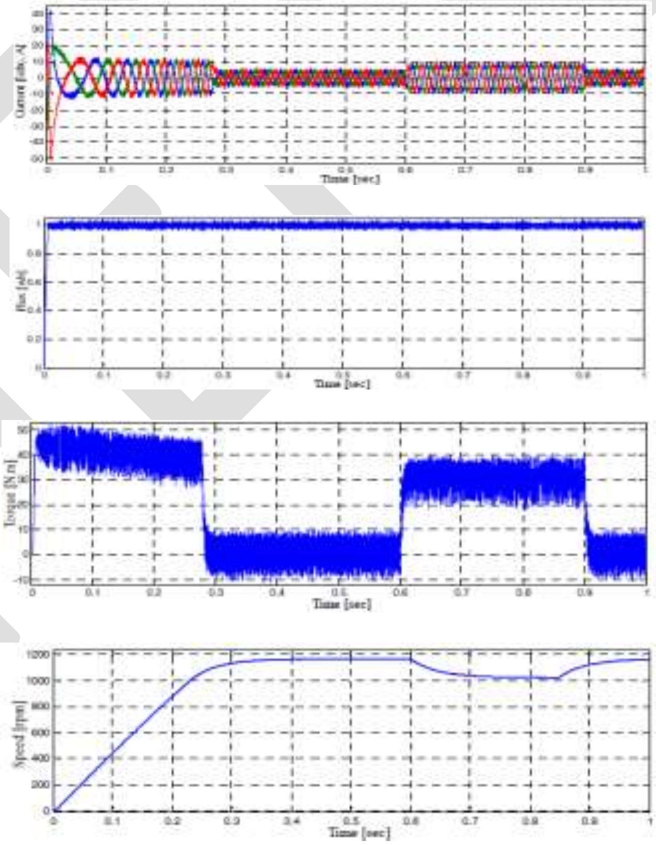
TABLE 5. FUZZY LOGIC CONTROL RULES

ΔT_e	NL	NM	NS	ZE	PS	PM	PL
NL	NL	NL	NL	NL	NM	NS	ZE
NM	NL	NL	NL	NM	NS	ZE	PS
NS	NL	NL	NM	NS	ZE	PS	PM
ZE	NL	NM	NS	ZE	PS	PM	PL
PS	NM	NS	ZE	PS	PM	PL	PL
PM	NS	ZE	PS	PM	PL	PL	PL
PL	ZE	PS	PM	PL	PL	PL	PL

A FLC converts a linguistic control strategy into an automatic control strategy and fuzzy rules are constructed by expert knowledge or experience database. Firstly, the input torque ΔT_e (k) and the change in torque error ΔT_e*(k) have been placed of the torque to be the input variables of the FLC. Then the output variable of the FLC is presented by the control of change in torque ΔT_e. To convert these numerical variables into linguistic variables, the following seven fuzzy levels or sets are chosen as: NL (negative large), NM (negative medium), NS (negative small), ZE (zero), PS (positive small), PM (positive medium), and PL (positive large) as shown in Fig.5.

IV. SIMULATION AND RESULTS

The conventional and proposed DTC MATLAB models were developed for 3hp IMD. The simulation results of conventional and proposed DTC for forward motoring operation are shown in Fig.7, and Fig.8, it represents the stator current, stator flux, developed torque at no load and full load, speed, and stator dq-axis.



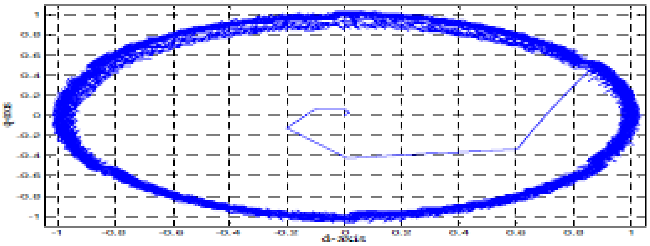


Figure 7. Simulation results of conventional DTC: Stator Currents, Stator flux, Electromagnetic load torque of 30 N.m is applied at 0.6 sec and removed at 0.85 sec, rotor Speed from 0 to 1200rpm, and stator flux dq-axis of IMD.

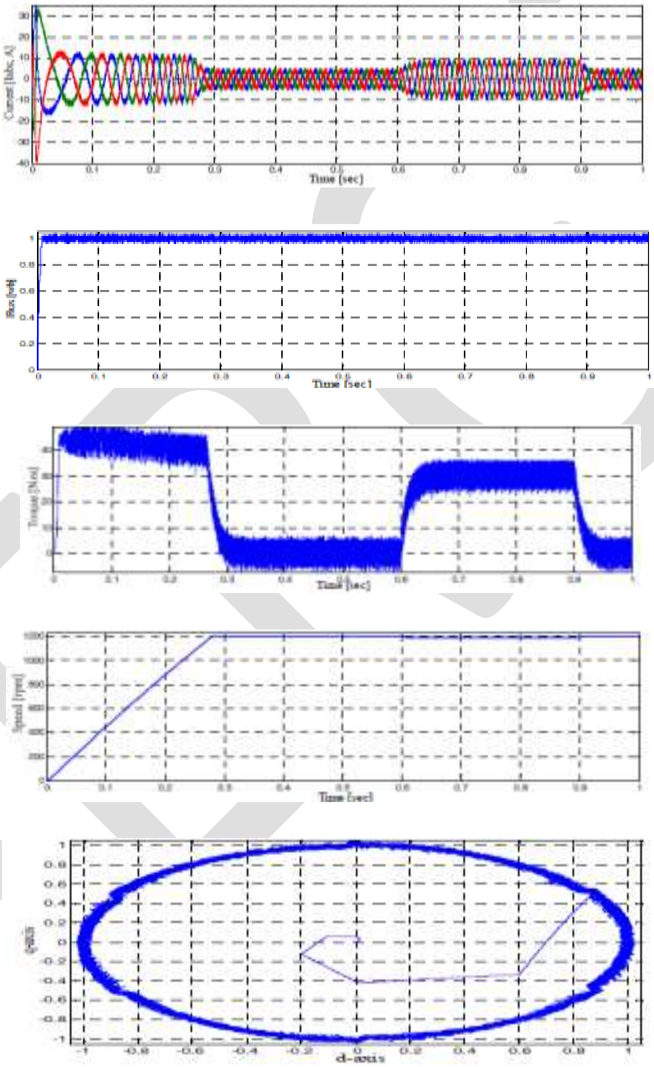


Figure 8. Simulation results of proposed DTC: Stator Currents, Stator flux, Electromagnetic load torque of 30 N.m is applied at 0.6 sec and removed at 0.85 sec, rotor Speed from 0 to 1200rpm, and Stator flux dq-axis of IMD.

V. ACKNOWLEDGMENT

We take this opportunity to express our deepest gratitude and appreciation to all those who have helped us directly or indirectly towards the successful completion of this paper.

VI. CONCLUSION

In this paper, an effective control technique is presented for direct flux and torque control of three-phase IMD. In this proposed control technique the PI controller is regulates the speed of IMD and the fuzzy logic controller is reduced the stator flux and torque ripples. It is proposed a decoupled space vector control between the stator flux and electromagnetic torque hysteresis controller for generating the pulses for VSI. The two independent torque and flux hysteresis band controllers are used in order to control the limits of the torque and flux. The simulation results of both conventional and proposed techniques are carried out for DTC of three-phase IMD, among both of them proposed control technique is superior for good speed regulator, low stator flux linkage, and torque ripples under transient and dynamic state operating conditions using MATLAB/SIMULINK. The main advantage is the improvement of torque and flux ripple characteristics at low speed region; this provides an opportunity for motor operation under minimum switching loss and noise.

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