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Direct Torque Control of Induction Motor With Fuzzy Logic for Minimization of Torque Ripples

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Abstract -The induction motor, which is the most widely used motor type in the industry, has been favored because of its good self-starting capability, simple and rugged structure, low cost and reliability etc. Over last few decades, Direct Torque Control (DTC) is known to provide high dynamic performance and also fast and robust response for induction motors (IM). Conventional DTC produces notable torque and flux ripples. Several techniques have been developed to improve the torque performance. In this paper, Fuzzy Logic Direct Torque Control (FLDTC) has been suggested to improve the system performance which gives better torque and flux response and also reduces the undesirable torque ripple

Keywords – Direct torque control (DTC), Fuzzy logic direct torque control (FLDTC), Induction motor, D-Q Model

1 INTRODUCTION

IN the mid – 1980s, an advanced scalar control technique, known as direct torque and flux control or direct self-control, was introduced for voltage fed PWM inverter drives. This technique was claimed to have nearly comparable performance with the vector controlled drives. The scheme, as the name indicates, is the direct control of torque and stator flux of a drive by inverter voltage space vector selection through a look up table. Conventional direct torque controller mainly consists of two level hysteresis comparator for calculating stator flux error and three level hysteresis comparator for calculating electromagnetic torque error. After determining the stator flux error and electromagnetic torque error the proper state of voltage vector is selected.

2 DYNAMIC D-Q MODEL OF AN INDUCTION MOTOR

In an adjustable speed drive, the machine normally constitutes an element within a feedback loop, and therefore its transient behavior has to be taken into consideration. Besides, high performance drive control, such as vector or field oriented control is based on the dynamic d-q model of the machine.[1]

The voltages vdss and vqss can be resolved into as-bs-cs components and can be represented in the matrix form as

$$\begin{bmatrix} v_{as} \\ v_{bs} \\ v_{cs} \end{bmatrix} = \begin{bmatrix} cos\theta & sin\theta & 1 \\ cos(\theta - 120^0) & sin(\theta - 120^0) & 1 \\ cos(\theta + 120^0) & sin(\theta + 120^0) & 1 \end{bmatrix} \begin{bmatrix} v_{qs}^s \\ v_{ds}^s \\ v_{0s}^s \end{bmatrix}$$

The corresponding relation is

$$\begin{bmatrix} v_{qs}^s \\ v_{ds}^s \\ v_{0s}^s \end{bmatrix} = \frac{2}{3} \begin{bmatrix} cos\theta & cos(\theta - 120^0) & cos(\theta + 120^0) \\ sin\theta & sin(\theta - 120^0) & sin(\theta + 120^0) \\ 0.5 & 0.5 & 0.5 \end{bmatrix} \begin{bmatrix} v_{as} \\ v_{bs} \\ v_{cs} \end{bmatrix}$$

The electrical transient model in terms of voltages and currents can be given in matrix form as

$$\begin{bmatrix} v_{qs} \\ v_{ds} \\ v_{qr} \\ v_{qr} \end{bmatrix} = \begin{bmatrix} R_s + SL_s & \omega_e L_s & SL_m & \omega_e L_m \\ -\omega_e L_s & R_s + SL_s & -\omega_e L_m & SL_m \\ SL_m & (\omega_e - \omega_r)L_m & R_r + SL_r & (\omega_e - \omega_r)L_r \\ -(\omega_e - \omega_r)L_m & SL_m & -(\omega_e - \omega_r)L_r & R_r + SL_r \end{bmatrix} \begin{bmatrix} i_{qs} \\ i_{ds} \\ i_{qr} \\ i_{dr} \end{bmatrix}$$

Where S is the Laplace operator. For a singly fed motor such as cage motor, vqr = vdr = 0.
The speed ωr cannot be treated as constant. It can be related to the torque and it is given by

$$T_e = \frac{3}{2}\left(\frac{P}{2}\right) L_m\left(i_{qs}i_{dr} - i_{ds}i_{qr}\right)$$

3 ELECTRICAL SUB MODEL OF THE INDUCTION MOTOR

The three-phase to two-axis voltage transformation is achieved by

$$\begin{bmatrix} v_{qs}^s \\ v_{ds}^s \\ v_{0s}^s \end{bmatrix} = \begin{bmatrix} 2/3 & -1/3 & -1/3 \\ 0 & -1/\sqrt{3} & 1/\sqrt{3} \\ 1/3 & 1/3 & 1/3 \end{bmatrix} \begin{bmatrix} v_{as} \\ v_{bs} \\ v_{cs} \end{bmatrix}$$

A. Simulation System of Induction Motor

The complete simulation system of the Induction Motor includes a power supply sub-model and the Induction Motor model. Fig.1 shows the complete simulation model of Induction Motor consisting of all sub models used in MATLAB / SIMULINK.

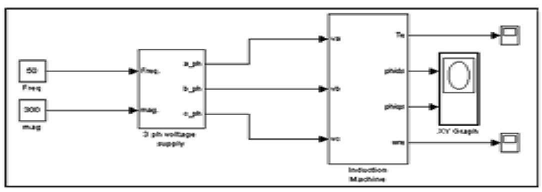


Fig.1 Simulation model of Induction Motor in SIMULINK

4 DIRECT TORQUE AND FLUX CONTROL (DTC)

Direct torque control technique was claimed to have nearly comparable performance with the vector controlled drives. The name direct torque control is derived from the fact that on the basis of the errors between the reference and the estimated values of torque and flux it is possible to directly control the inverter states in order to reduce the torque and flux errors within the prefixed band limits

A. Control strategy of DTC

The block diagram for direct torque control is shown in Fig. 2. The command stator flux ψs* and torque Te* magnitudes are compared with the respective estimated values, and the errors are processed through hysteresis band controller. The flux loop controller has two levels of digital output according to the following relation.[1]

$$H_\psi = 1 \text{ for } E_\psi > +HB_\psi$$

$$H_\psi = -1 \text{ for } E_\psi < -HB_\psi$$

Where 2 HBψ = total hysteresis band width of the flux controller.

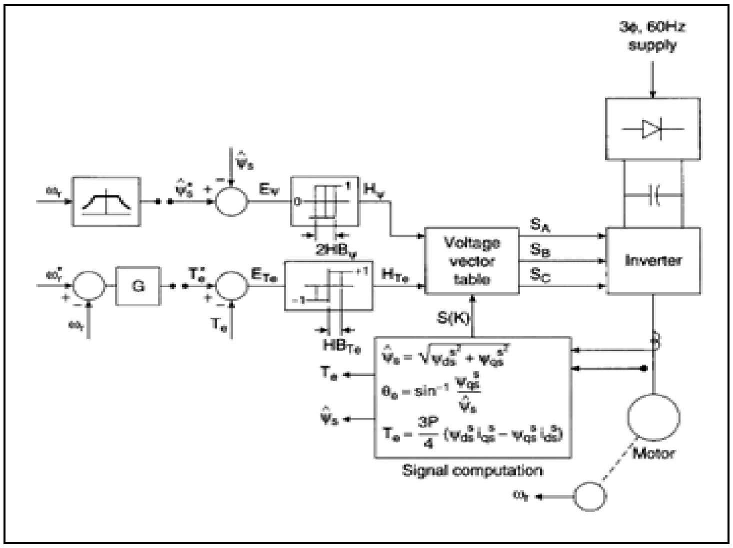


Fig. 2 Block Diagram of DTC

The circular trajectory of the command flux vector ψs* with the hysteresis band rotates an anti-clockwise direction. The actual stator flux ψs is constrained within the hysteresis band and it tracks the command flux in a zigzag path. The torque control loop has three levels of digital output, which have the following relations

HTe = 1 for ETe> + HBTe

HTe = -1 for ETe< - HBTe

HTe = 0 for -HBTe<ETe< + HBTe

The feedback flux and torque are calculated from the machine terminal voltages and currents. The signal computation block also calculates the sector number S(k) in which the flux vector ψs lies. There are six sectors each Π/3 angle wide. The voltage vector block in Fig. 2 receives the input signals Hψ, HTe, and S(k) and generates the appropriate control voltage vector for the inverter by a look up table, which is shown in table 1

Table 1Switching Table Of Inverter Voltage Vectors

Hψ	The	S(1)	S(2)	S(3)	S(4)	S(5)	S(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	V1	V2

B. Switching Selection

Due to the decoupled control of torque and stator flux in DTC, a high performance torque control can be established. If the stator flux lies in sector k with the motor rotating in counter clockwise, active voltage vector VS,k+1 is used to increase both the stator flux and torque. Voltage vector VS,k+2 is selected to increase the torque but decrease the stator flux. The two zero voltage vectors (VS,7 and VS,8) are used to reduce the torque and at the same time, freezes the stator flux. Reverse voltage vector VS,k-2 is used to decrease the torque and flux in forward braking mode. Whereas VS,k-1 will reduce the torque and increase the flux. Table 2 shows flux and torque variations due to applied voltage vector in sector II (Arrow indicates magnitude and direction).

Table 2Flux and Torque Variations Due to Applied Voltage vector

Voltage Vector	V1	V2	V3	V4	V5	V6	V0 or V7
ψs	↑	↑	↓	↓	↓	↑	0
Te	↓	↑	↑	↑	↓	↓	↓

Fig. 3 shows SIMULINK diagram for DTC of IM Drives.

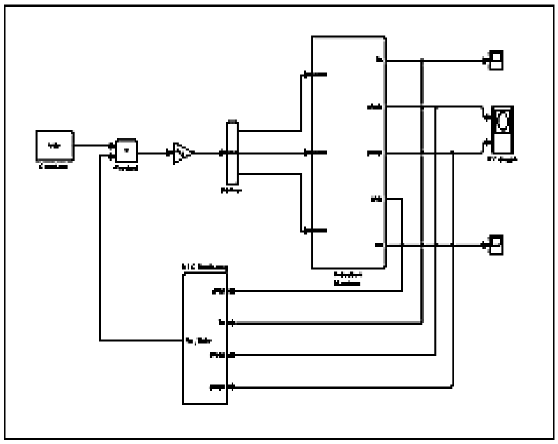


Fig. 3 SIMULINK diagram for DTC of Induction Motor Drive.

5 FUZZY LOGIC CONTROLLER

The Fuzzy Logic Controller is designed to have three fuzzy state variables and one control variable for achieving Direct Torque Control of the Induction Motor. These three input variable are the stator flux error, electromagnetic torque error, and the position of stator flux space vector and the output variable is the voltage space vector.

Each control rule can be described using the state variables flux error, torque error, and flux sector and the control variable ‘n’ which characterize the inverter switching state. The inference method used in this simulation is Mamdani's procedure based on min-max decision.

For flux linkage error two terms are used for the fuzzy sets i.e. negative value and positive value which are denoted ne and ps respectively. The fuzzy sets are then defined by the triangular membership functions.

For electromagnetic torque error three linguistic terms are used for the fuzzy sets i.e. negative value, zero value and positive value which are denoted by ne, zo and ps respectively. The fuzzy sets for negative value and positive value are defined by the trapezoidal membership functions and for zero value it is defined by the triangular membership function.

The flux sector indicates the position of flux within the path of rotation. The total angle i.e. 3600 is divided into six sectors and these sectors are defined by membership functions 1 to 6. The six numbers i.e. 1 to 6 are used for the fuzzy sets which are denoted by mf1 to mf6 respectively. The fuzzy sets for these sectors are defined by the triangular membership function.

The output of Fuzzy Logic Controller gives the proper selection of switching state. These possibilities are numbered from 1 to 8 at the output of multiport switch. The eight numbers i.e. 1 to 8 are used for the fuzzy sets which are denoted by mf1 to mf8 respectively. The fuzzy sets for these output possibilities are defined by the triangular membership function.

Rule Base For FLC

The proper activities of fuzzy system are based on derivational (inferential) rules, similarly to expert systems. The benefit of such representation of knowledge is the transparency for users. These rules are of type IF and THEN and are illustrated with the help of Look-up table. The total number of rules after their reduction is 36.

Fig. 4 shows SIMULINK diagram for fuzzy logic controller for Direct Torque Control of Induction Motor Drives.

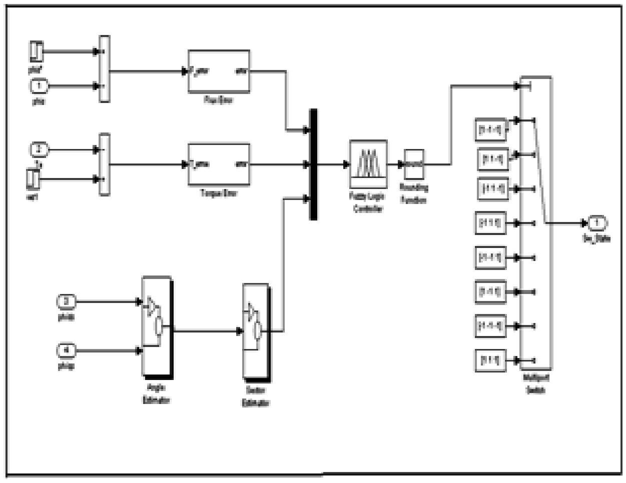
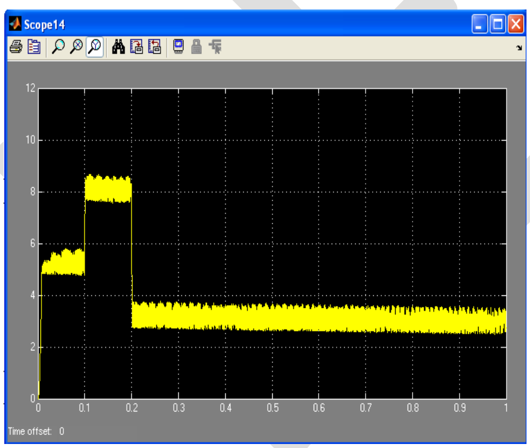


Fig. 4 SIMULINK diagram for fuzzy logic controller for DTC of IM

6 SIMULATION WITH CONVENTIONAL DTC

Simulation of the developed model is done with a Flux reference value and variable Torque reference value with conventional DTC. Fig. 5 to Fig. 7 shows the Torque response, Stator Flux locus and Stator Current obtained using conventional DTC. Fig. 5 shows the Torque response which is less than the reference with some ripples. Fig. 6 shows the locus of Stator Flux. From which it is observed that the value of Stator Flux decreases between the sectors. Fig.7 shows the Stator Current taken by motor which is a sinusoidal in nature. The IM takes high current initially and then it becomes a sinusoidal. For high torque it takes more current as compared to low Torque reference. The current remains constant during constant Torque reference.



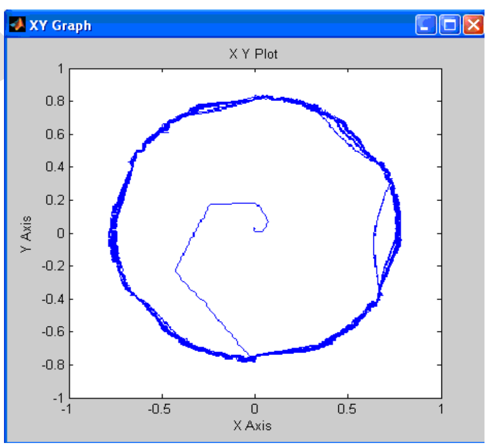


Fig. 5 Torque response obtained using conventional DTCFig. 6 Stator flux locus using conventional DTC

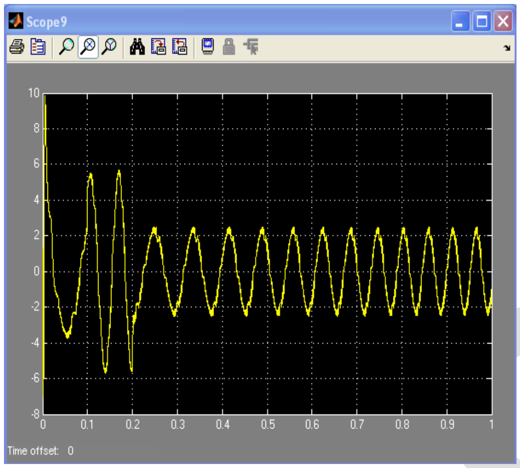
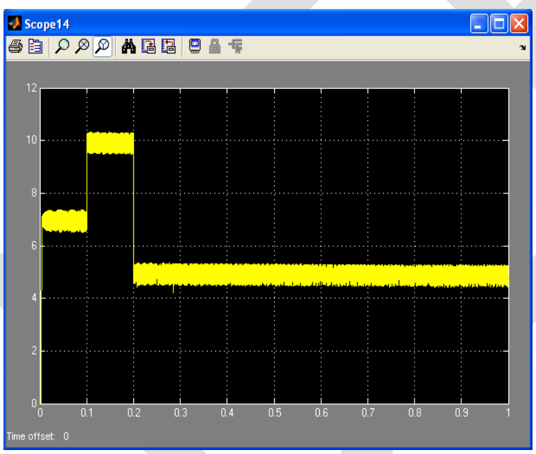


Fig.7 Stator Current using conventional DTC

SIMULATION WITH FLDTC

Simulation of the developed model is done using fuzzy logic direct torque control with the same reference of Flux and Torque used for conventional DTC. Fig. 8 to Fig. 10 shows the Torque response, Stator Flux locus and Stator Current obtained using FLDTC. Fig. 8 shows the Torque response which gives the Torque equal to the reference value with some ripples. Fig. 9 shows the locus of Stator Flux. From which it is observed that the value of Stator Flux remains constant during its circular trajectory. Fig. 10 shows the Stator Current taken by motor which is a sinusoidal in nature which changes according to the Torque.



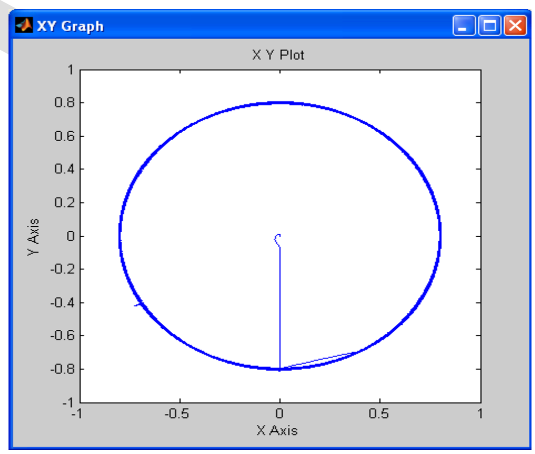


Fig. 8 Torque response obtained using FLDTCFig. 9 Stator flux locus using FLDTC

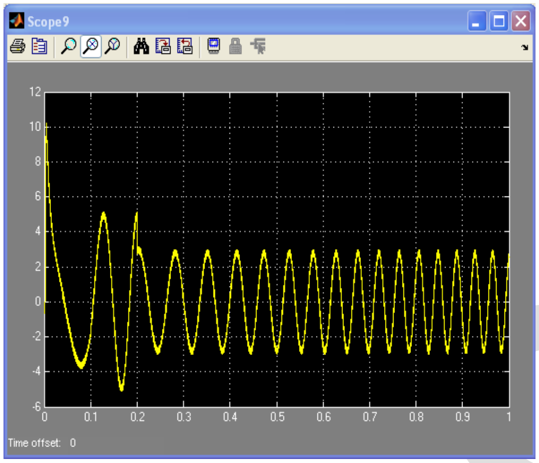


Fig. 10 Stator Current using FLDTC

7 CONCLUSION

This paper has presented improvements on direct torque control of induction machine drives. The main contribution of this paper is to propose Fuzzy Logic based controller that significantly reduce torque and stator flux ripples. At the same time a constant switching frequency is achieved. The controllers have also managed to reduce the phase current distortion. Simulations results had verified the feasibility of the proposed controllers. Results proved that the proposed controllers are capable of significantly reducing torque ripples and flux ripples as compared to the conventional hysteresis based controller.

The main improvements shown are:

a. Reduction of torque and current ripples.
b. No flux droppings caused by sector changes circular trajectory.
c. Fast torque response.
d. Increase in output torque with almost same stator current.
e. Increase in efficiency of the Drive.

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