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Improved Fuzzy Logic based DTC of Induction machine for wide range of speed control using AI based controllers

This paper presents improvements in Direct Torque control of induction motor using Fuzzy logic switching controller (FDTC). The conventional DTC (CDTC) and FDTC drive performance is compared using Conventional PI, Fuzzy controller and Neural Network controllers. The major disadvantages of CDTC are high torque and flux ripples in steady state operation of the drive, inferior performance at low speed operation and variable switching frequency. The presence of hysteresis bands is the major reason for high torque and flux ripples in CDTC. In FDTC the hysteresis band and switching table are replaced by Fuzzy logic switching controller. Using fuzzy logic torque, stator flux space are divided into smaller subsections which results in precise and optimal selection of switching state to meet load torque. In high performance drives accurate tuning of PI speed controller is required. The conventional PI controller cannot adapt to the variation in model parameters. Artificial intelligence based fuzzy controller and neural network controller are compared with PI controller for both CDTC and FDTC of Induction machine. The proposed schemes are developed in Matlab/Simulink environment. Simulation results shows reduction in torque and flux ripples in FDTC and dynamic performance of the drive at low speeds and sudden change in load torque can be improved using Fuzzy logic controller compared to PI and neural network controller.

Keywords: CDTC, FDTC, FLSC, IM, Fuzzy logic controller, neural controller, AI.

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1. Introduction

A quick response and high performance Direct Torque control (DTC) of IM is proposed by Takahashi [1-2]. The interest of researches in improvement of DTC increased after ABB introduced commercial product in 1996. DTC emerged as an alternative to FOC where High performance and fast dynamic response of the drive is required [3].The advantages of DTC are fast dynamic response, simple control scheme, absence of coordinate transformations, absence of position feedback and current regulators[4,31]. Conventional DTC (CDTC) suffer from disadvantages like High torque and flux ripples under steady state due to presence hysteresis bands, poor performance at starting and low speeds and stator current distortions. In past decades researches came out with different type of solutions to improve the performance of the CDTC. In order to reduce torque ripples Space vector Modulation is proposed by researchers but it increases switching complexity [5-7]. Few researchers employed multilevel inverters to improve drive performance, but cost and switching losses of inverters are increased [8-10]. Introduction of duty cycle in switching is proposed in[11-13]. Due to advantages of artificial intelligence (AI) techniques like neural networks, Fuzzy logic, Genetic algorithms are used to improve the performance of drive. Fuzzy logic switching controller is simpler to design as it is independent of mathematical model and based on expert rule base. The torque and flux ripples under steady state can be

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reduced by fuzzy logic switching controller [14-19]. The transient and dynamic response of the drive depends upon the speed controller. In general PI controller is employed in DTC drives due to its simple structure. Fixed gain and offline tuned PI controllers fail to provide control action in parameter variations, nonlinear operating conditions and cannot adapt to eternal disturbances. Conventional PI controller can be replaced by Fuzzy sliding mode controllers [20-21], hybrid PI/Fuzzy controller [22-24,40], neural network controllers [25, 26] neuro fuzzy controllers [27-29]. This paper presents improvement in CDTC using fuzzy logic switching controller (FDTC) which replaces the hysteresis bands and switching table. The proposed FDTC shows satisfactory performance for wide range of speed including zero speed. The performance of CDTC and FDTC drives are compared using conventional PI, Fuzzy and Neural network controller. Both CDTC and FDTC with simulation models with PI, Fuzzy and Neural networks speed controllers are developed in Matlab/Simulink. Simulation results shows the clearly depicts reduction of torque and flux ripples in FDTC and improves dynamic behaviour of the drives with Fuzzy speed controller.

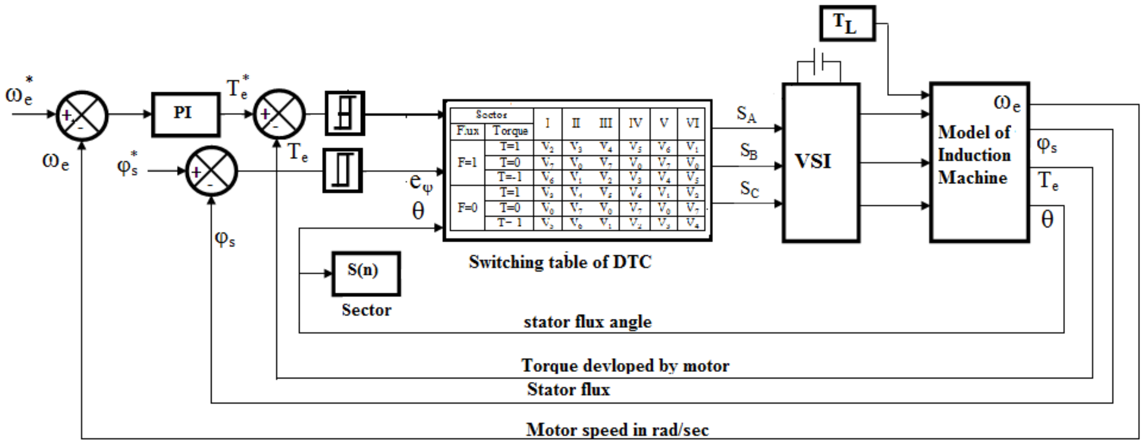

Fig1. Block diagram of conventional Direct Torque control (CDTC) of Induction Machine

2. Conventional DTC of Induction machine

Fig.1. shows the block diagram of conventional DTC of IM. Mathematical model of induction machine referred to stationary (α, β) axis is given by state space mode. The three phase to two phase transformation is given by:

$$V_\alpha^s = \frac{2}{3}V_a - \frac{1}{3}V_b - \frac{1}{3}V_c \tag{1}$$

$$V_\beta^s = 0 + \frac{1}{\sqrt{3}}V_b - \frac{1}{\sqrt{3}}V_c \tag{2}$$

The state space model of the induction machine is given by following equations:

$$\frac{dX}{dt} = AX + BU\,; Y = CX \tag{3}$$

$$X = \begin{bmatrix} i_s^\alpha \\ i_s^\beta \\ \psi_s^\alpha \\ \psi_s^\beta \end{bmatrix}; U = \begin{bmatrix} V_s^\alpha \\ V_s^\beta \end{bmatrix}\; ; \; Y = \begin{bmatrix} i_s^\alpha \\ i_s^\beta \end{bmatrix} \tag{4}$$

$$\begin{bmatrix} \dot{i}_s^\alpha \\ \dot{i}_s^\beta \\ \dot{\varphi}_s^\alpha \\ \dot{\varphi}_s^\beta \end{bmatrix} = \begin{bmatrix} -\frac{R_a}{L_{ss}} & -\omega & \frac{R_r}{L_{ss}L_r} & -\frac{\omega}{L_{ss}} \\ \omega & -\frac{R_a}{L_{ss}} & -\frac{\omega}{L_{ss}} & \frac{R_r}{L_{ss}L_r} \\ -R_s & 0 & 0 & 0 \\ 0 & -R_s & 0 & 0 \end{bmatrix} \begin{bmatrix} i_s^\alpha \\ i_s^\beta \\ \psi_s^\alpha \\ \psi_s^\beta \end{bmatrix} + \begin{bmatrix} \frac{1}{L_{ss}} & 0 \\ 0 & \frac{1}{L_{ss}} \\ 1 & 0 \\ 0 & 1 \end{bmatrix} \begin{bmatrix} V_s^\alpha \\ V_s^\beta \end{bmatrix} \tag{5}$$

$$L_{ss} = s.L_s\,;\ s = 1 - \frac{L_m^2}{L_s L_r};\ T_r = \frac{L_r}{R_r};\ R_a = R_s + R_s\,\frac{L_m^2}{L_r^2} \tag{6}$$

The mechanical speed of motor is given by

$$\frac{d\omega}{dt} = \frac{1}{J}(T_e - T_L) \tag{7}$$

The basic concept of CDTC is selection of optimal voltage vector, which makes the flux to rotate and produce desired torque [18, 30]. During its rotation flux is restricted with in hysteresis band limits. As shown in Fig.1, block diagram of CDTC the speed error of the motor is given to speed controller produces reference torque (T_e^*). The reference flux is determined from Induction machine parameters (ψ_s^*). The actual torque and flux and stator flux angle of induction motor are estimated using following equations [19]:

$$\varphi_{s(\alpha,\beta)} = \int_0^t (V_{s(\alpha,\beta)} - R_s i_{s(\alpha,\beta)}) \tag{8}$$

$$\varphi_s = \sqrt{\varphi_{s\alpha}^2 + \varphi_{s\beta}^2}\ ;\quad \theta_s = \tan^{-1}\left(\frac{\varphi_{s\beta}}{\varphi_{s\alpha}}\right) \tag{9}$$

$$T_e = \frac{3}{2}p\left(\varphi_{s\alpha} i_{s\beta} - \varphi_{s\beta} i_{s\alpha}\right) \tag{10}$$

The motor speed is compared with reference speed, speed error is processed through PI controller develops reference Torque (T_e^*). The T_e^* is compared with estimated motor Torque T_e develops torque error given to three level hysteresis comparator. The reference stator flux (φ^*) is compared with estimated stator flux (φ), flux error is given to two level hysteresis comparator. The circular stator flux is divided in six sectors of 60^0 each. The sector is selected based on stator flux angle (θ_s). There are 8 possible switching state vectors of VSI (6 active states V_1 to V_6 and 2 zero states V_0, V_7). When the stator flux is in sector k, if both torque and flux errors are increased V_{k+1}, if Torque error is increasing but flux error is decreasing V_{k+2} is selected. For decrease in torque error zero switching states are selected as shown in Table 1[31].

Table 1: CDTC switching table

Sector		I	II	III	IV	V	VI
Flux	Torque						
F=1	T=1	V_2	V_3	V_4	V_5	V_6	V_1
	T=0	V_7	V_0	V_7	V_0	V_7	V_0
	T=-1	V_6	V_1	V_2	V_3	V_4	V_5
F=0	T=1	V_3	V_4	V_5	V_6	V_1	V_2
	T=0	V_0	V_7	V_0	V_7	V_0	V_7
	T=-1	V_5	V_6	V_1	V_2	V_3	V_4

3. DTC with Fuzzy logic controller

In CDTC as torque and flux hysteresis band amplitudes are fixed results in ripples during switching from one state to another. The flux and torque ripples are reduced using fuzzy logic switching controller (FLSC) based DTC (FDTC). The design of Fuzzy logic switching controller is discussed in this section. Fuzzy logic is an expert based system and fuzzy variables can have membership values in between 0 to 1. Fuzzy logic switching controller replaces the hysteresis controllers and switching table. Torque error, flux error and stator flux are divided into fuzzy sets represented by linguistic terms which helps is selection optimal voltage vector. The block diagram of FDTC is shown in Fig.2. FLSC has three inputs Flux error(φ_s^*- φ_s), Torque error (T_e*- T_e), sector in flux space (θ_s) and one output switching state (n)[33].

Mamdani type FLSC is developed using fuzzy logic toolbox in Matlab. The analog inputs are fuzzzfied and represented by fuzzy membership functions before applying to FLSC. The input errors are converted into fuzzy variables before applying to rule base.

The stator flux error (e_T) is divided into three linguistic variables: negative (N), zero (Z) and positive (P) values The N and P variables are represented by trapezoidal membership function and Z by triangular membership function as shown in Fig. 3(a).The Torque error (e_φ) is divided into five linguistic variables: Positive Large (PL), Positive Small (PS), Negative Small (NS) and Negative Large (NL). The NL and PL are represented by trapezoidal membership functions and NS, Z, PS are represented by triangular membership functions as shown in Fig. 3(b).The Stator flux trajectory is divided in 12 sectors ($\theta_1$to θ_{12}) [31-32]. All fuzzy sets are represented by isosceles triangular membership functions of 60^0 wide and an overlap of 30^0 with neighborhood fuzzy sets. So that each fuzzy set works for an angle of 30^0.The membership function distribution over 0^0 to 360^0 is shown in Fig. 3(c)[33].

The output of fuzzy controller ‘n’ is divided into seven fuzzy output variables (one zero switching state and six active switching states) as shown in Fig.4. Each state is represented by sharp triangular membership function.

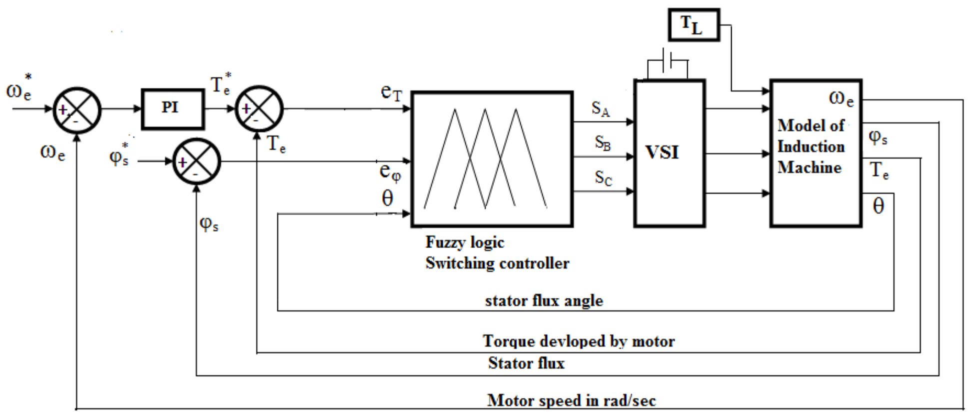

Fig.2. Block diagram of Fuzzy Direct Torque control (FDTC) of Induction Machine

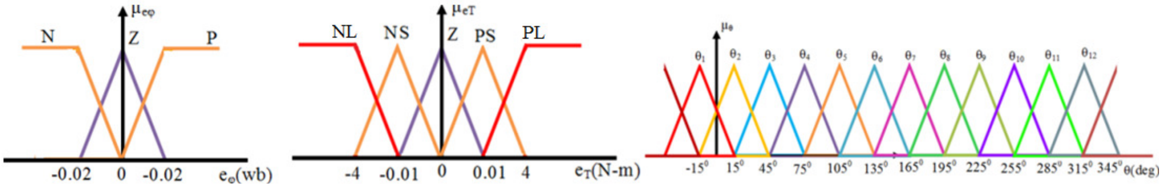

Fig. 3(a),3(b)&3(c). Membership functions of inputs flux error, torque error and sector

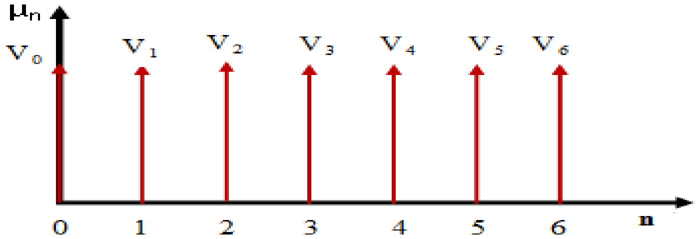

Fig.4.Membership functions of Output of Fuzzy logic switching controller

The mapping of Inputs and output depends upon rule base. The Fuzzy rules are developed based on expert knowledge and intuition in order to meet objective of controller. Since there are three MF's for e_φ, five MF's for e_T and twelve MF' s for θ signals so 3×5×12 = 180 fuzzy rules are developed to select one of seven MF' s for the output as shown in Table 2. The fuzzy rules are developed based on min-max fuzzy inference method. The fuzzy rules are developed using Min-Max method. For example:

Rule: If e_T is PL and e_φ is P and θ is θ_1 then output is V_1.

Table 2: Fuzzy switching logic rule base

θ		θ_1	θ_2	θ_3	θ_4	θ_5	θ_6	θ_7	θ_8	θ_9	θ_{10}	θ_{11}	θ_{12}
e_T	e_φ												
PL	P	V_1	V_2	V_2	V_3	V_3	V_4	V_4	V_5	V_5	V_6	V_6	V_1
	Z	V_2	V_2	V_3	V_3	V_4	V_4	V_5	V_5	V_6	V_6	V_1	V_1
	N	V_2	V_3	V_3	V_4	V_4	V_5	V_5	V_6	V_6	V_1	V_1	V_2
PS	P	V_1	V_2	V_2	V_3	V_3	V_4	V_4	V_5	V_5	V_6	V_6	V_1
	Z	V_2	V_3	V_3	V_4	V_4	V_5	V_5	V_6	V_6	V_1	V_1	V_2
	N	V_3	V_3	V_4	V_4	V_5	V_5	V_6	V_6	V_1	V_1	V_2	V_2
ZE	P	V_0	V_0	V_0	V_0	V_0	V_0	V_0	V_0	V_0	V_0	V_0	V_0
	Z	V_0	V_0	V_0	V_0	V_0	V_0	V_0	V_0	V_0	V_0	V_0	V_0
	N	V_0	V_0	V_0	V_0	V_0	V_0	V_0	V_0	V_0	V_0	V_0	V_0
NS	P	V_6	V_6	V_1	V_1	V_2	V_2	V_3	V_3	V_4	V_4	V_5	V_5
	Z	V_0	V_0	V_0	V_0	V_0	V_0	V_0	V_0	V_0	V_0	V_0	V_0
	N	V_4	V_5	V_5	V_6	V_6	V_1	V_1	V_2	V_2	V_3	V_3	V_4
NL	P	V_6	V_6	V_1	V_1	V_2	V_2	V_3	V_3	V_4	V_4	V_5	V_5
	Z	V_5	V_6	V_6	V_1	V_1	V_2	V_2	V_3	V_3	V_4	V_4	V_5
	N	V_5	V_5	V_6	V_6	V_1	V_1	V_2	V_2	V_3	V_3	V_4	V_4

The minimum of membership functions of e_T , e_φ and θ is selected using Fuzzy AND operation. So output of i^{th} rule depends upon torque error, flux error and stator flux position.

The output of FLSC is in fuzzified form. The fuzzified output is converted into crisp value using maximum criteria. Out of available defuzzification methods the Centroid method is employed. The output of FLSC determines the switching sector V_n (n= 0 to 6)

need to be applied to VSI. So the output is converted in S_A, S_B, S_C switching signal using Boolean expression given by:
S_A (n) is 1 if n= 1 or 2 or 6.
S_B (n) is 1 if n= 2 or 3 or 4.
S_C (n) is 1 if n= 4 or 5 or 6.

4. Speed controllers.

4.1. PI Speed controller

Fixed gain PI controllers are widely used in speed control of industrial drives [21, 35]. A PI controller responds to an error signal in a closed control loop and attempts to adjust the controlled quantity like speed, torque and flux to achieve the desired system response. The benefit of the PI controller is that it can be adjusted empirically by adjusting one or more gain values and observing the change in system response. However in fixed gain PI controllers exhibit poor performance for nonlinear systems, continuous variation of machine parameters and low speed operation of induction motors. It is very difficult for an offline tuned PI controller to perform satisfactory control action for continuous variation of system parameters and nonlinearities present in the systems due to inverter, controllers. The PI controllers is designed with K_P = 2 and K_I = 300 with a limiter at output to limit the reference torque to +/- 8 N-m as shown in Fig.5. The K_P and K_I values of the PI controller for a linear system are determined using Ziegler–Nichols tuning method. But for a dynamic machine like Induction machine drive is linearised and PI controller parameters are determined. The values are determined using trial and error method so that P term tends to reduce the overall error as time elapses and the Integral (I) term of the controller is used to eliminate small steady state errors. In order to limit the current drawn by the induction machine to 11A during closed loop operation the maximum allowable torque is determined as 8 N-m. The reference torque is limited so that the controller limits the current drawn by the induction machine when subjected sudden perturbation in reference speed.

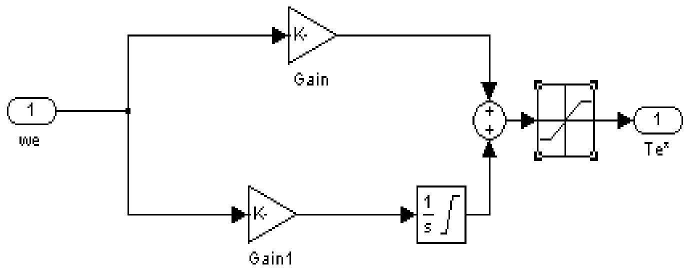

Fig. 5. Conventional PI controller

Tuning of PI controllers using Genetic Algorithms [21], Particle swarm optimization [35], sliding mode control and Model resonant Adaptive Control are exclusively used by researchers in past decade. AI based controllers like neural network controllers, Fuzzy controllers and Neuro-Fuzzy controllers are developed to improve the performance.

4.2. Fuzzy speed Controller

Fuzzy logic speed controller design is designed based on the human expert knowledge rule base. It does not require any mathematical model of the plant. Fuzzy control can be applied in the speed loop of Direct Torque control of induction motor [39]. The fuzzy controller will then have two input signals, i.e., the loop error (E) and the error rate of change (CE in discrete form). The control output is the increment of Torque (U) which is integrated to generate the current command T_e^*. The error and change in error are normalized before applying to the Mamdani type Fuzzy controller developed in Matlab. The normalized gains are calculated using the formulae shown below.

$$K_P = GCE \times GCU \tag{11}$$

$$\frac{1}{T_i} = \frac{GE}{GCE} \tag{12}$$

E and CE are the input fuzzy variables are divided in to seven fuzzy sets given by linguistic terms NB, NM, NS, ZE, PS, PM and PB. The output is divided into nine fuzzy sets given by linguistic terms NVB, NB, NM, NS, Z, PS, PM, PB, PVB. The fuzzification of inputs is done by representing them using triangular and trapezoidal membership functions. All the MF's are symmetrical for positive and negative values of the variable as shown in Fig.6.Mapping of inputs and outputs is done using Fuzzy rule base. Table 3 shows the corresponding rule base for the Fuzzy speed controller. There may be 7 x 7 = 49 possible rules in the matrix, where a typical rule reads as:

Rule^i = If E is NB and CE is then output is NVB.

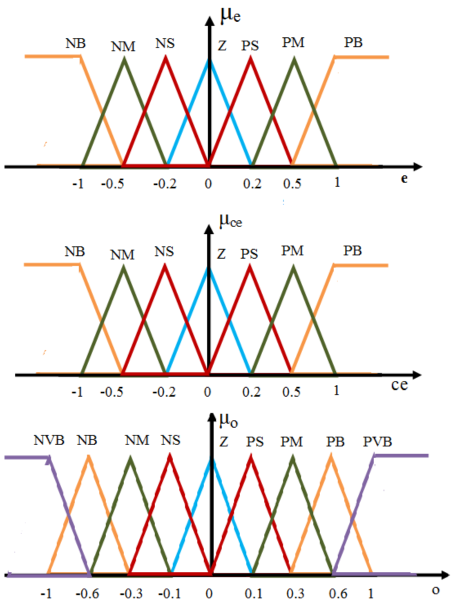

Fig.6. Input and output membership functions of Fuzzy controller

Table 3: Rule base of Fuzzy speed controller

E / CE	NB	NM	NS	ZE	PS	PM	PB
NB	NVB	NVB	NVB	NB	NM	NS	Z
NM	NVB	NVB	NB	NM	NS	Z	PS
NS	NVB	NB	NM	NS	Z	PS	PM
ZE	NB	NM	NS	Z	PS	PM	PB
PS	NM	NS	Z	PS	PM	PB	PVB
PM	NS	Z	PS	PM	PB	PVB	PVB

4.3. Neural network speed Controller

Neural network (NN) is an interconnected group of artificial neurons that uses a mathematical model or computational model for information processing based on a connectionist approach to computation. In most cases an ANN is an adaptive system that changes its structure based on external or internal information that flows through the network. Feed forward neural networks are capable of handling nonlinear functions and adapt themselves for variation of parameters due to external disturbances. In this paper the ANN (Artificial Neural networks) based speed controller is using feed forward network topology[37-38]. In this paper a two layered feed forward neural network is designed with 5 neurons in hidden layer and 1 neuron in output layer. The developed neural network is trained using back propagation training algorithm with input output database. The Neural network block in MATLAB can be generated using neural network toolbox or programming. In this paper the neural network controller is developed using program in MATLAB.

```
load m;
k1=max (i');
k2=max (o1');
P=i'/k1;
T=o1'/k2;
n=157128;
net = newff(minmax(P),[5 1],{'tansig' 'purelin'});
 net.trainParam.epochs = 200;
net = train(net,P,T);
Y = sim(net,P);
plot(P,T,P,Y,'o')
gensim(net,-1)
```

In the above program “load m” loads the values of the input and output samples collected across the gains of the PI controller. “k1= max(i’)” and “k2= max(o1’)” are used to normalize the inputs and outputs as the number of samples collected are more in number which may lead to inaccurate training of the neural network. “P” and “T” are the inputs and the targets respectively. “n” is the number of samples collected. “net = newff(minmax(P),[5 1],{'tansig' 'purelin'});” The function newff creates a feedforward network. “net.trainParam.epochs = 200;” trains the network for 200 echos. “net = train(net,P,T) ”trains the network with the inputs and outputs of the PI controller. “Y = sim(net,P) **”** The function sim simulates a network. sim takes the network input p, and the network object net, and returns the network outputs Y. “plot(P,T,P,Y,'o')” plots the graph between the inputs ,targets, and the outputs. “gensim(net,-1)” creates the simulink model of the neural network. The developed Simulink neural network block is used in place of PI controller.

5. Simulation model and Results

The proposed Simulink model of CDTC with different controllers is shown in Fig.7. The induction machine is developed using state variable equation as mentioned in section 2.The Direct torque control of IM is implemented by Simulink blocks developed based on mathematical equations. The motor parameters and switching table developed using Matlab programming m file.

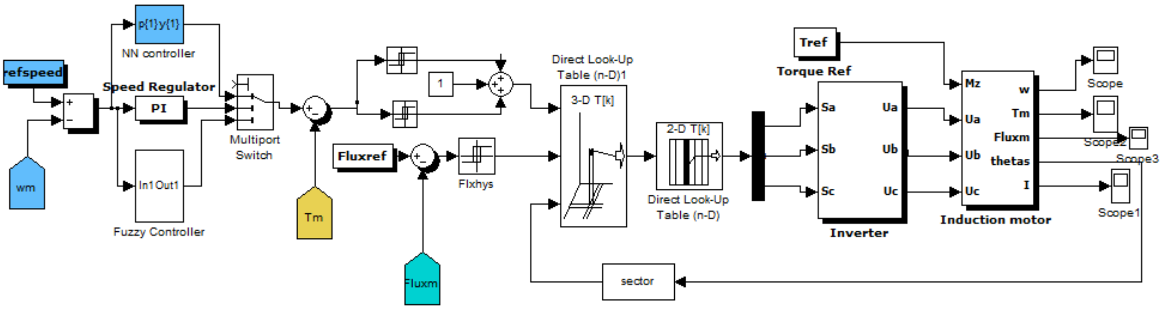

Fig.7. Simulink model of CDTC with different controllers

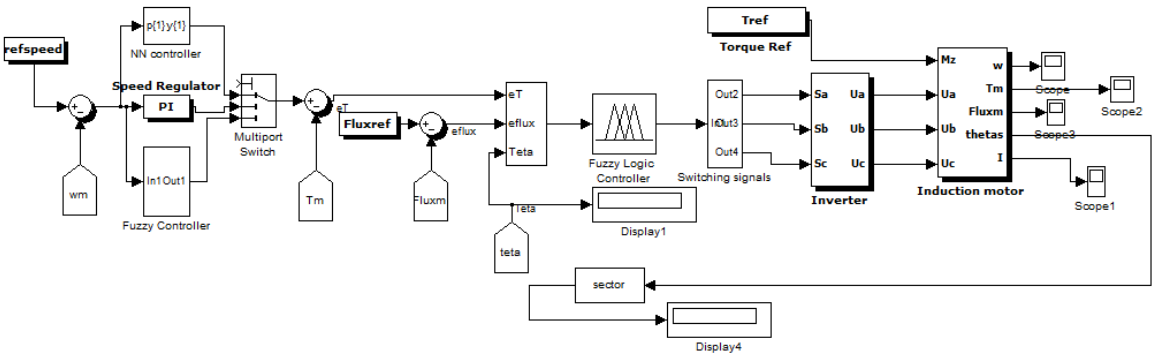

Fig.8. Simulink model of FDTC with different controllers

Fig.8. shows Simulink model of FDTC with different controllers. As shown in the figure the two hysteresis bands and switching table sector identification block are replaced by Fuzzy controller block. FLSC is developed using Fuzzy logic toolbox, once the inputs, output membership functions and rules are assigned the file is save with .fis extension. PI controller is replaced with neural network and fuzzy speed controller block which are developed using neural networks and fuzzy logic toolboxes.

The dynamic and steady state behaviour of CDTC and FDTC drive using proposed controllers are investigated using simulations. The simulations are carried out on the 1.1 kW induction machine, whose parameters are tabulated in Table 4. The simulations are carried out at a sampling frequency of 10 kHz. In order to study effectiveness of proposed method initially the motor is started at low speed of 20 rad/sec and reference speed is suddenly varied to 100 rad/sec at 0.2 sec. A load torque of 4 N-m is applied at t = 0 sec and changes to 0 N-m at t =0.3 sec. The reference flux of IM is 1 Wb. In order to compare effectiveness of PI Speed controller with Fuzzy and Neural controller all simulations are carried out with three controllers subjected to same variations load torque and reference speed.

Table 4. Induction Machine parameters

Symbol	Parameters	values
P_n	Power	1.1 kW
V_n	Nominal Voltage	400/230 V
I_n	Nominal current	2.6 /4.5 A
n	Motor Speed	1420 rpm
f	Supply frequency	50 Hz
p	Pole pairs	2
R_s	Stator resistance	7.6 Ω
R_r	Rotor resistance	3.6 Ω

L_s	Stator inductance	0.6015 H
L_r	Rotor inductance	0.6015 H
L_m	Mutual inductance	0.5796 H
J	Moment of inertia	0.0049 $Kg{\cdot}m^2$

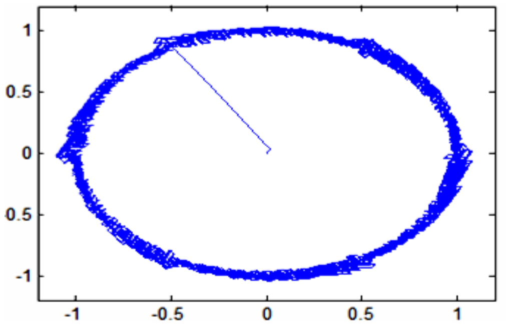

Fig.9 (a) Flux trajectory path of CDTC

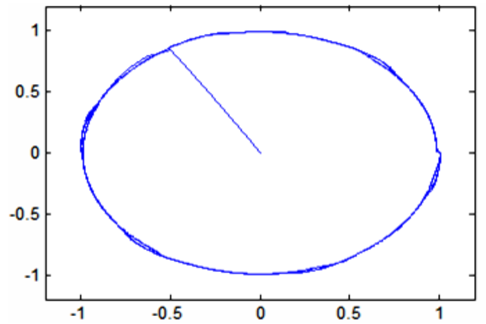

Fig.9 (b) Flux trajectory path of FDTC

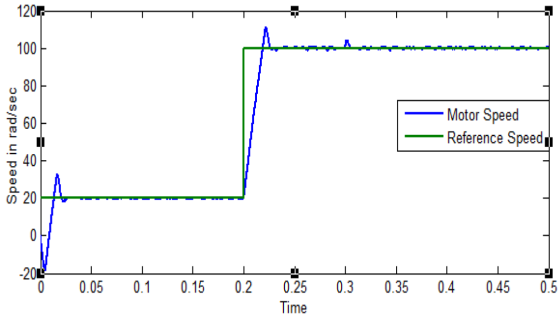

Fig.10 (a) Speed response of CDTC

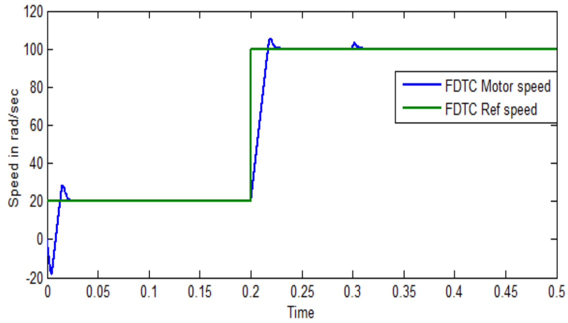

Fig.10 (b) Speed response of FDTC with PI

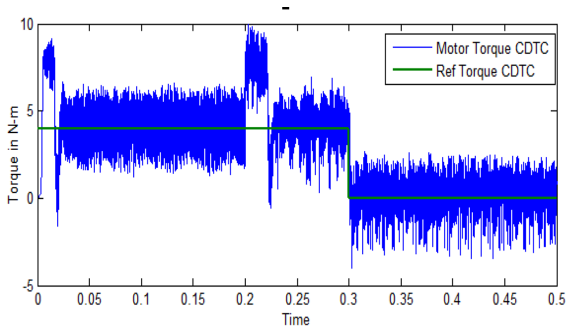

Fig.11 (a) Torque response of CDTC

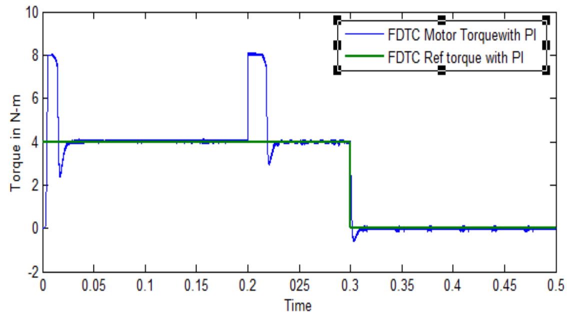

Fig.11 (b) Torque response of FDTC with PI

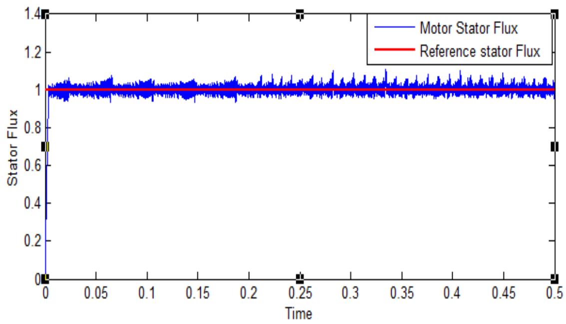

Fig.12 (a) Flux response of CDTC

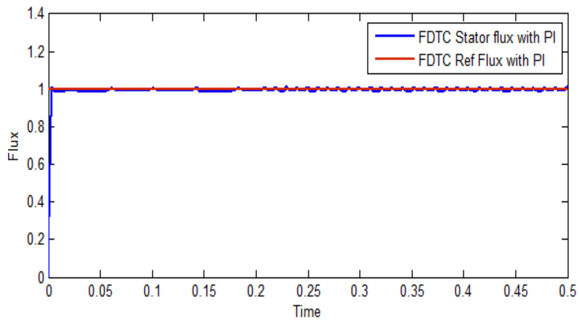

Fig.12 (b) Flux response of FDTC with PI

Fig.9 (a) & 9(b) shows that FDTC has smooth flux trajectory path compared to CDTC while moving from one switching state to another. Fig 10 (a) & (b) shows that using FDTC the Induction machine attains the reference speed with less ripples in steady state compared to CDTC. Fig 11 (a) & (b) shows that using FDTC the torque ripples under steady stator are significantly by 80% compared to CDTC. Fig 12 (a) & (b) shows the stator flux ripples of IM under steady state reduced significantly by 40% in FDTC compared to CDTC.

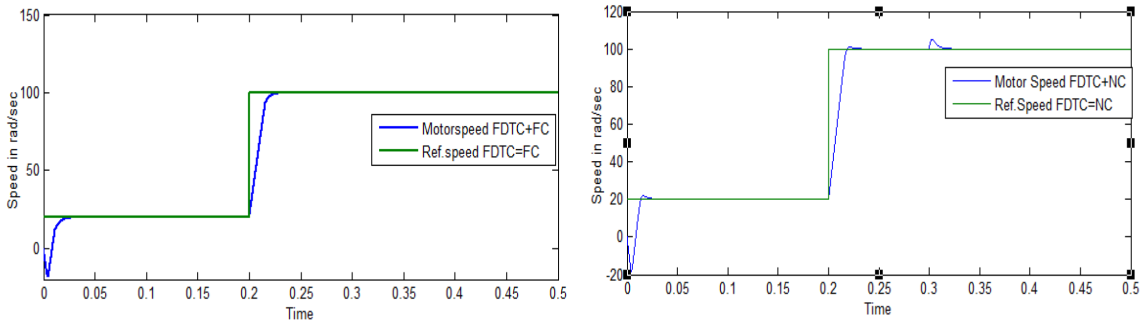

Fig.13 (a) & (b) Speed response of FDTC with Fuzzy Controller & Neural Speed controller

Table 5. Reduction in Torque and Flux ripples using FDTC compared to CDTC

	CDTC		FDTC	
	Max-min	% ripples	Max-min	% ripples
Torque ripples	± 2 N-m	± 50 %	± 0.2 N-m	± 5 %
Stator flux ripples	± 0.05 wb	± 5 %	± 0.02 wb	± 2 %

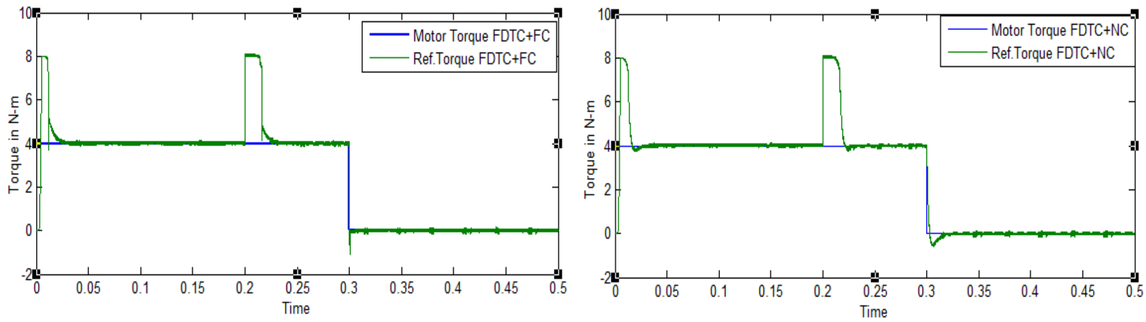

Fig.14 (a) & (b)Torque response of FDTC with Fuzzy Controller & Neural Speed controller

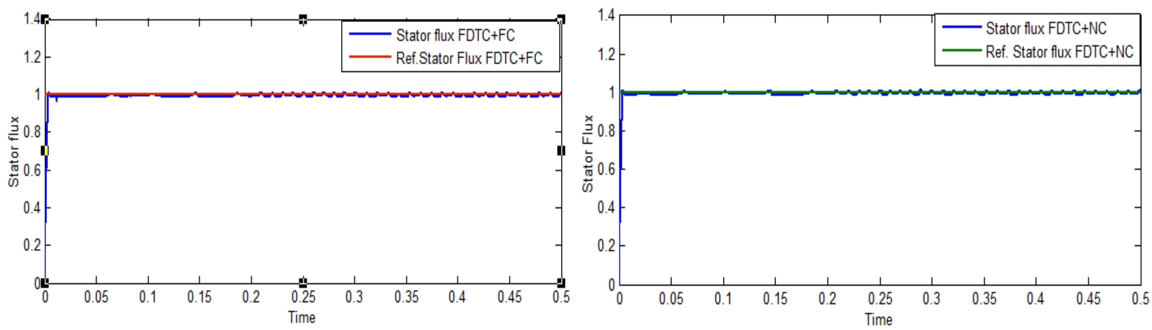

Fig.15 (a) & (b) Flux response of FDTC with Fuzzy Controller & Neural Speed controller

Simulation results depicts major disadvantages of CDTC i.e., torque and flux ripples are reduced by FDTC and drive shows the satisfactory performance even at low speed. The percentage reduction in torque and flux ripples in FDTC compared to CDTC is shown in Table 5.

The dynamic or transient performance of FDTC is improved using Fuzzy logic and neural network controller compared to conventional PI controller. Fig 13(a) & 13(b) shows the speed response of FDTC with Fuzzy controller is compared to Fig 10 (b) speed response with PI. Fig 13(a) clearly shows that peak overshoot is reduced almost to zero using Fuzzy controller. Fig.13 (b) shown reduction of peak overshoot and rise time using neural network controller compared to PI speed controller response. FDTC with Fuzzy controller shows better speed response under transient period compared to other two controllers.

Fig 14(a) & 14(b) shows the speed response of FDTC with Fuzzy controller is compared to Fig 11 (b) Torque response with PI. Fig 14(a) clearly shows that electromagnetic torque reaches the reference torque in less time without any undershoots.. Fig.13 (b) improvement in torque response compared to PI especially whenever the load torque is subjected to sudden variations.

Fig 15(a) & 15(b) shows the stator flux response of FDTC with Fuzzy controller is compared to Fig 12 (b) stator flux response with PI. FDTC with all three controllers shows satisfactory stator flux response.

FDTC with Fuzzy controller shows better Speed and Torque response under transient period compared to other two controllers. The improvement in transient characteristics is shown in Table 6.

Table 6. Speed response of FDTC with proposed three controllers

	PI controller	Fuzzy controller	Neural controller
Rise time	0.015 sec	0.01 sec	0.01 sec
Peak overshoot	39 %	0 %	9.09 %
Settling time	0.025 sec	0.015 sec	0.013 sec

5. Conclusion

In this paper major drawbacks of the conventional DTC (CDTC) of induction machine are overcome using Fuzzy logic DTC (FDTC). The FDTC transient response using PI speed controller is compared with Fuzzy and Neural controllers. All the Simulink models are developed using Matlab/Simulink software. Form simulation results in FDTC the torque ripples are reduced by 90% and flux ripples are reduced by 40% compared to CDTC. Due to absence of hysteresis comparators and more subsections of torque and flux ripples in Fuzzy switching rule base FDTC shows improved steady state response. FDTC with Fuzzy controller shows improved transient response compared to PI and Neural controller. In FDTC with Fuzzy controller the Peak overshoot is completely eliminated, rise and settling time is improved.

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