Analysis of Direct Torque Control of Interior Permanent Magnet Synchronous Motor using PID and Fuzzy Logic Controllers

N. Krishna Kumari [1] G. Tulasi Ram Das [2] and Dr.M.P.Soni [3]

[1] Department of Electrical and Electronics Engineering, VNR VJIET, Hyderabad, A. P., India

[2] Vice chancellor, Jawaharlal Nehru Technological University, Kakinada, A. P., India

[3] Department of Electrical and Electronics Engineering, MJCET, Hyderabad, A. P., India

E-Mail: nkksrm@gmail.com

Abstract— This paper deals with the novel modified direct torque control (MDTC) scheme based on space vector modulation for interior permanent magnet synchronous motor drive . The torque and flux ripples are greatly reduced compared with the conventional direct torque control scheme. The proposed MDTC for interior permanent magnet synchronous motor is modelled using Matlab/ simulink. The comparative results show that the FLC is more robust and, hence, found to be a suitable replacement of the PID controller for the high performance industrial drive applications.

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***Keywords**:* Fuzzy Logic Control (FLC), PermanentMagnet Synchronous Motor (PMSM), Space Vector Pulse Width Modulation (SVPWM), MDTC.

I. INTRODUCTION

This paper deals with the detailed modeling of a interior permanent magnet synchronous motor (IPMSM) drive system in Matlab/simulink. Permanent magnet synchronous motors are used where in general high demands are made with regards to speed stability and the synchronous speed operation sof several inter connected motors. They are suitable for applications where load – independent speeds or synchronous operation are required under strict observance of defined speed relations with in a large frequency range. Moreover, use of flux weakening control based on salient pole behavior supports a wider range of speeds at any given output level. As efficiency is important due to the energy scarcity of the world and higher performance is needed for modern motion control applications. The interior permanent magnet synchronous motor is used in such applications due to its various advantages which include high dynamic response, high efficiency providing reduction in machine size, long operating life and high power factor.

The direct torque control (DTC) of Interior Permanent Magnet Synchronous Motor was proposed in 1990’s [1,2]. It was originated from the DTC of Induction motor in 1980’s [3]. The DTC scheme has many advantages compared with Field Oriented Control, such as less machine parameter dependance, simpler implementation and faster dynamic response. No current controller is needed in DTC, and hence the time delay caused by the current loop is eliminated. Except the initial flux linkages, the rotor position information is no more needed in DTC. This is a significant advantage of the DTC over vector controlled PM machine drive. This makes the torque and flux control of a PM machine independent of the rotor position.

Although DTC has many advantages over vector control, it still has some drawbacks. As shown in fig 1, the switching state of the inverter is updated once in every sampling interval. The inverter keeps the same state till the outputs of the hysteresis controllers change states. As a result, the ripples in torque and flux are relatively high when compared with those of the vector control drive system. Also, the swithching frequency of the inverter is not constant it changes with rotor speed , load torque and the bandwidth of the two hysteresis controllers.Smoother torque can be expected [4, 5] with multi level inverters using DTC scheme. However, more power switches are required to achieve a low torque ripple and almost fixed switching frequency, which will increase system cost and complexity.

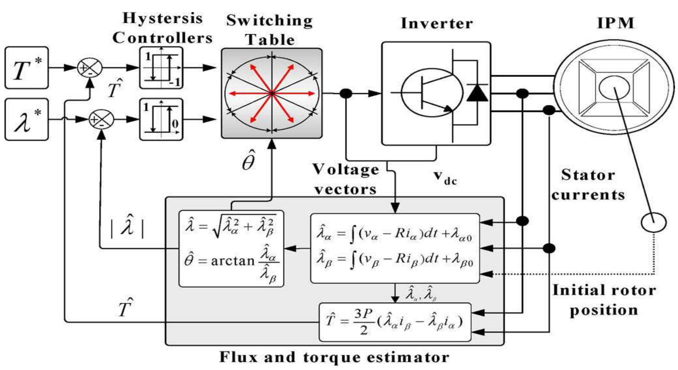

Fig. 1. Block diagram of the DTC.

In this paper, a novel and simple MDTC for IPMSM is proposed to reduce the flux and torque ripple. The IPMSM is modelled with PID controller and Fuzzy controller in Matlab/ Simulink, results show that torque and flux ripples are greatly reduced using MDTC. Further more these ripples are less with fuzzy controller.

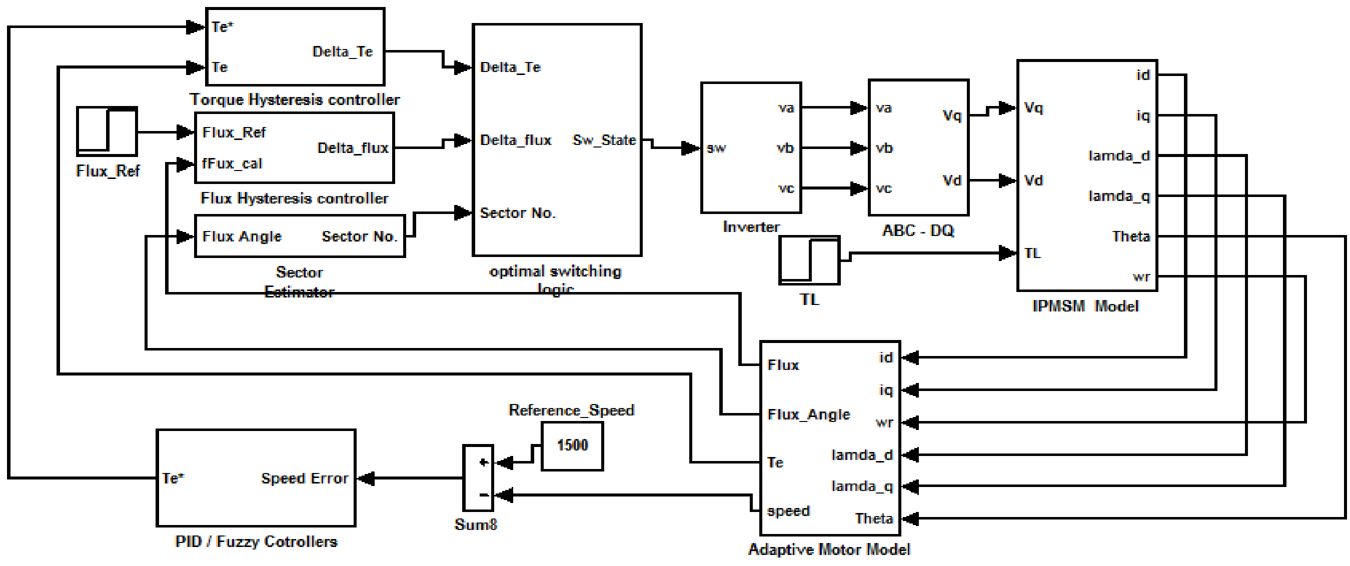

Fig 2 Simulation block Diagram of Modifed DTC IPMSM

II. MACHINE EQUATIONS

In the rotor reference frame, the voltage equation and the torque equation of IPMSM are extressed as follows [1].

$$V_d = R_s i_d + L_d \frac{di_d}{dt} - (\omega_r) L_q i_q \quad \text{-----(1)}$$

$$V_q = R_s i_q + L_q \frac{di_q}{dt} + (\omega_r) L_d i_d + (\omega_r) \lambda_f \quad \text{----(2)}$$

$$\lambda_d = L_d i_d + \lambda_f \quad \text{----(3)}$$

$$\lambda_q = L_q i_q \quad \text{---- (4)}$$

$$T_e = \frac{3}{2}\frac{P}{2}[L_d i_q i_d + \lambda_f i_q - L_q i_q i_d] \quad \text{------ (5)}$$

Where R_s stator armature resistance, Ω

L_d, L_q direct and quadrature inductances, H

ω_r rotor speed in electrical rad/s

T_e electromagnetic torque,Nm

P no. Of poles

λ_f magnetic flux linkage,wb

As indicated in [6], stable torque control can be achieved if

$$\lambda_s \le \frac{L_q}{L_q - L_d} \lambda_f \quad \text{-------(6)}$$

Where

λ_s stator flux linkage,wb

III. DIRECT TORQUE CONTROL

The Fig.1 shows the complete block diagram of DTC. There are two hysteresis control loops, one for the control of torque and the other for the control of flux. The flux controller controls the machine operating flux to maintain the magnitude of the operating flux at the rated value till the rated speed and at a value decided by the field weakening block for speeds above the rated speeds. Torque control loop maintains the torque to the torque demand. The outputs of these controllers are depending on the instantaneous position of flux vector

A. MODIFIED DTC

In order to overcome the disadvantage of the Conventional DTC the Modified DTC is used. In modified DTC instead of taking the first sector of -30° to +30° it is taken of 0° to 60°, then gets the new operation of the Modified DTC as shown in fig 3, the behaviour of the flux is given in the table 1.

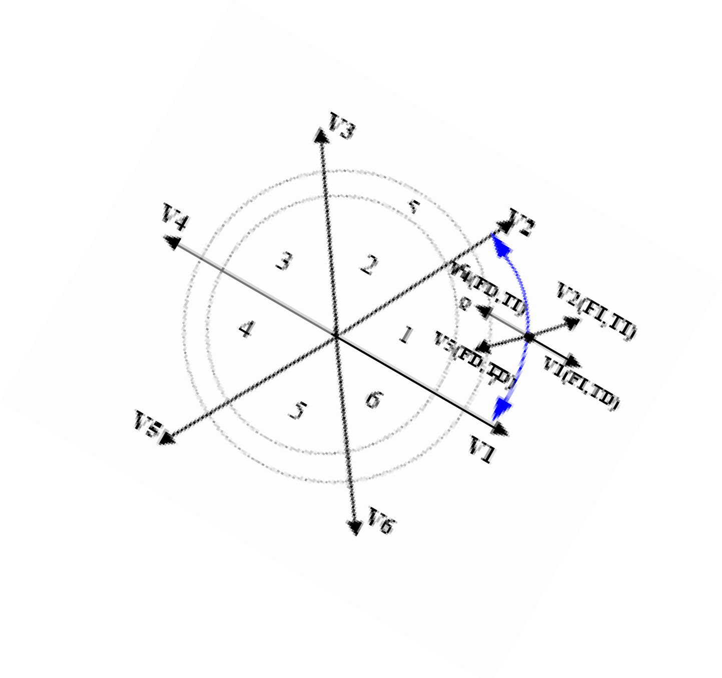

Fig 3 Modified DTC and its new sectors

Behaviour of each state just in the first zone for the Conventional DTC (C_DTC) and the Modified DTC (M_DTC).TI/ID: Torque increase/decease. FI/FD: Flux increase/Decrease is shown in table 2.

Table 1. Torque producing vectors in each region (CW-clockwise; CCW- counter clockwise)

Region θ (N)	**Vector that increases the flux Magnitude**	**Vector that reduces the flux Magnitude**
θ (1) (-π/6) to (π/6)	v_2 (accelerate the flux in CCW) v_6 (accelerate the flux in CW)	v_3 (accelerate the flux in CCW) v_5 (accelerate the flux in CW)
θ (2) (π/6) to (π/2)	v_3 (accelerate the flux in CCW) v_1 (accelerate the flux in CW)	v_4 (accelerate the flux in CCW) v_6 (accelerate the flux in CW)
θ (3) (π/2) to (5π/6)	v_4 (accelerate the flux in CCW) v_2 (accelerate the flux in CW)	v_5 (accelerate the flux in CCW) v_1 (accelerate the flux in CW)
θ (4) (5π/6) to (7π/6)	v_5 (accelerate the flux in CCW) v_3 (accelerate the flux in CW)	v_6 (accelerate the flux in CCW) v_2 (accelerate the flux in CW)
θ (5) (7π/6) to (3π/2)	v_6(accelerate the flux in CCW) v_4 (accelerate the flux in CW)	v_1 (accelerate the flux in CCW) v_3 (accelerate the flux in CW)
θ (6) (3π/2) to (-π/6)	v_1 (accelerate the flux in CCW) v_5 (accelerate the flux in CW)	v_2 (accelerate the flux in CCW) v_4 (accelerate the flux in CW)

Table 2: Flux and Torque status of C_DTC and M_DTC

Voltage vector	**Modified DTC**	**Conventioanal DTC**
V_1	$-30^0 \rightarrow -30^0$ Torque ambiguity	$0^0 \rightarrow 60^0$ TD,FI
V_2	$90^0 \rightarrow 30^0$ TI,FI	$60^0 \rightarrow 0^0$ TI,FI
V_3	$150^0 \rightarrow 90^0$ TI,FI	$120^0 \rightarrow 60^0$ Flux ambiguity
V_4	$-150^0 \rightarrow 150^0$ Torque ambiguity	$180^0 \rightarrow 120^0$ TI,FD
V_5	$-90^0 \rightarrow 150^0$ TD,FD	$-120^0 \rightarrow 180^0$ TD,FD
V_6	$-30^0 \rightarrow -90^0$ TD,FI	$-60^0 \rightarrow -120^0$ Flux ambiguity

From the figure 3, the general conclusions are given as shown in table 2.It can be seen that the states V_1 and V_4, are not used in the Conventional DTC (C_DTC). The reason of this; is that they can increase or decrease the torque at the same sector depending on if the position is in its first 30 degrees or in its second ones. In the modified DTC (M_DTC), the vectors V_3 and V_6 are not used, now the reason is the ambiguity in flux instead of torque, as it was in the C_DTC. This considered as an advantage in favour of the M_DTC as the main point is to control the torque. Therefore, it is better to loose the usage of two voltage vectors for flux ambiguities. The look up table in the case of M_DTC for all its six sectors is given in table 3.

An accurate dynamic model of the motor is necessary which can explain the dynamic behavior of the machine under both transient and steady state conditions. Adaptive motor model is responsible for generating four internal feedback signals, stator flux, electromagnetic torque, rotor speed, stator flux linkages phasor angle (in radians). The function of the optimal switching logic is to select the appropriate stator voltage vector that will satisfy both the torque status output and the flux status output.Table 3 shows the modified DTC look up table for all its six sectors.

Table 3: Switching table for modified DTC

Sector No. (θ(N))		θ(1)	θ(2)	θ(3)	θ(4)	θ(5)	θ(6)
S_λ	S_T						
1	1	V_2	V_3	V_4	V_5	V_6	V_1
1	0	V_8	V_7	V_8	V_7	V_8	V_7
1	-1	V_6	V_1	V_2	V_3	V_4	V_5
0	1	V_3	V_4	V_5	V_6	V_1	V_2
0	0	V_7	V_8	V_7	V_8	V_7	V_8
0	-1	V_5	V_6	V_1	V_2	V_3	V_4

This paper implements two control schemes of an interior permanent magnet synchronous motor drive using MDTC technique namely PID and fuzzy logic controller . The following are the inferences from the implementation of the two control scheme.

1). Reduced Torque Ripple with Modified DTC
2). The performance indices of the control schemes are also evident from the fast tracking capability and robustness to load changes.
3). The results are compared with PID amd fuzzy logic controller. It is found that torque and flux ripples are less fuzzy logic controller

i) OPTIMAL SWITCHING LOGIC

By using switching functions S_a, S_b and S_c of which value is either 1 or 0, the primary voltage vector v is represented as (IsaoTakahashi1986)

$$v(S_a, S_b, S_c) = \sqrt{\frac{2}{3}} V_{dc} \left[S_a + S_b \exp\left(j\frac{2\pi}{3} \right) + S_c \exp\left(j\frac{4\pi}{3} \right) \right] \quad (7)$$

The machine voltages corresponding to the switching states can be calculated by using the following relations

$$\left. \begin{aligned} v_{ab} &= v_a - v_b \\ v_{bc} &= v_b - v_c \\ v_{ca} &= v_c - v_a \end{aligned} \right\} \quad (8)$$

and machine phase voltages for a balanced system are

$$\left. \begin{aligned} v_{as} &= \frac{v_{ab} - v_{ca}}{3} \\ v_{bs} &= \frac{v_{bc} - v_{ab}}{3} \\ v_{cs} &= \frac{v_{ca} - v_{bc}}{3} \end{aligned} \right\} \quad (9)$$

and q and d axes voltages are given by

$$\left. \begin{aligned} v_{qs} &= v_{as} \\ v_{ds} &= \frac{1}{\sqrt{3}}(v_{cs} - v_{bs}) = \frac{1}{\sqrt{3}} v_{cb} \end{aligned} \right\} \quad (10)$$

The total number of switching states possible with S_a, S_b and S_c are eight.

ii) FLUX HYSTERESIS CONTROLLER

The hysteresis block is realized using a relay block. The output S_λ takes the value 0 or 1 according to the equations given below.

If $|\psi_{s-ref}| - |\psi_{s-est}| \rangle \frac{\Delta\psi_s}{2}$, then the output of the flux controller $S_\lambda = 1$ i.e. it will command to increase the flux magnitude. If $|\psi_{s-ref}| - |\psi_{s-est}| \langle -\frac{\Delta\psi_s}{2}$, then the output of the flux controller $S_\lambda = 0$ i.e. it will command to decrease the flux magnitude. The simulink block diagram for flux hysteresis controller is shown in Fig. (4).

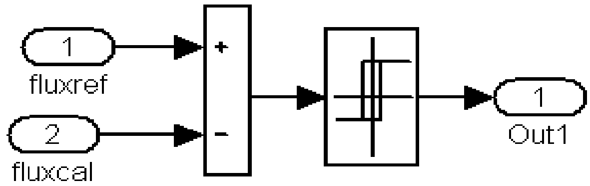

Fig.4 Simulink Block Diagram for Flux Hysteresis Controller

iii) TORQUE HYSTERESIS CONTROLLER

The torque controller has two switch blocks, which represents the hysteresis band for both positive and negative values of torque reference. The output takes values 1 or -1 or 0.
If $(T_{ref} - T_e) > \Delta T_e$ then $S_T = 1$ i.e. increase the torque by switching the states which will accelerate (decelerate) the ψ_s in counter clockwise (clockwise) direction. If $-\Delta T_e < (T_{ref} - T_e) < \Delta T_e$ then $S_T = 0$ i.e. reduces the torque by switching the zero states. If $(T`_{ref} - T_e) < -\Delta T_e$ then $S_T = -1$ i.e. decrease (increase) .

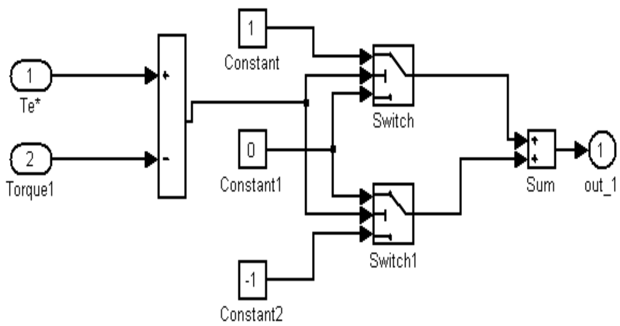

Fig. 5 Simulink Block Diagram For Torque Hysteresis Controller

the torque by switching the states which will decelerate (accelerate) the ψ_s in counter clockwise (clockwise) direction. The simulink block diagram of torque hysteresis controller is shown in Fig.5

An important factor in these operations is the hysteresis band of the two comparators. A too small value may have the effect of losing the control. The stator flux linkage may exceed the values required by the tolerance band. A narrow window will give better current and flux waveforms but will also increase the inverter switching frequency

iv) INVERTER

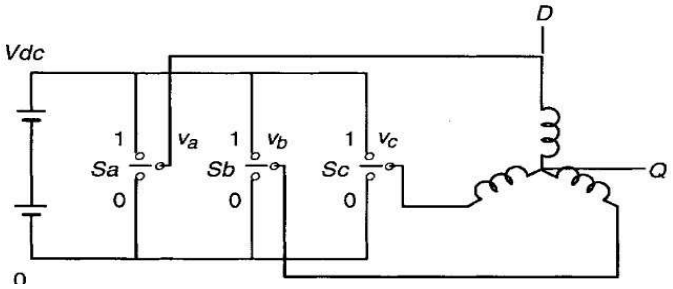

Figure 6 Three phase inverter

If the input voltage is 0.5 Vdc then the upper switch or if the input voltage is -0.5 Vdc then the lower switch is connected to the load. Otherwise the input voltage is zero as shown in fig 6.

IV. DESIGNN OF FUZZY LOGIC CONTROLLER

The mathematical tool for the FLC is the Fuzzy set theory introduced by Zadeh [10]. As compared to the MTPA(Maximum Torque per Ampere) and their adaptive versions the FLC has some advantages such as: 1) it does not need any exact system mathematical model; 2) it can handled nonlinearity of arbitrary complexity; 3) it is based on the linguistic rules with an IF-THEN general structure, which is the basis of human logic. The general block diagram of FLC is shown in fig 7.

Fuzzy logic control consists of fuzzification process, linguistic rule base, and defuzzification process. The input variables for fuzzy logic controller are speed error and change of speed error .The speed is fed to the fuzzy speed estimator. The speed error and change in speed error are defined as

$$e(k) = \omega(k)^* - \omega(k) \qquad (11)$$

$$\Delta e(k) = e(k) - e(k-1) \qquad (12)$$

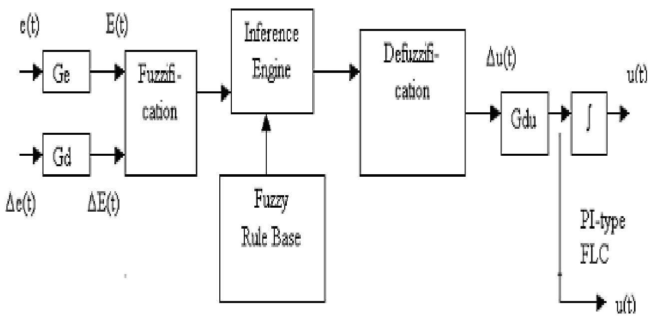

Fig. 7. Block Diagram of Fuzzy Logic Controller

The two input variables are e(k),Δe(k) and output variable T_e are divided into different fuzzy segments shown in fig, 8, 9 and 10 respectively.

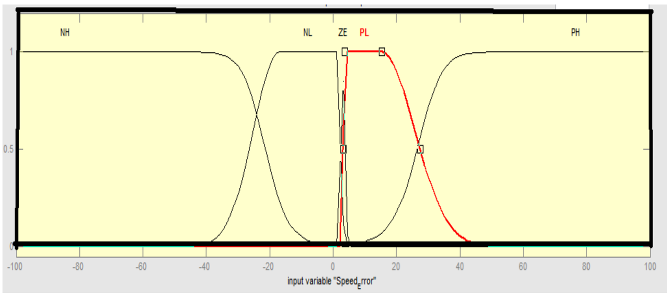

Fig 8.Membership function for speed error

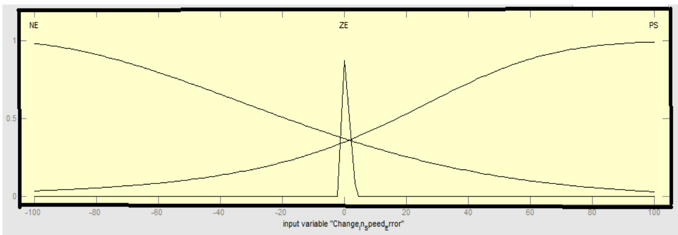

Fig 9 .Membership function for change in speed error

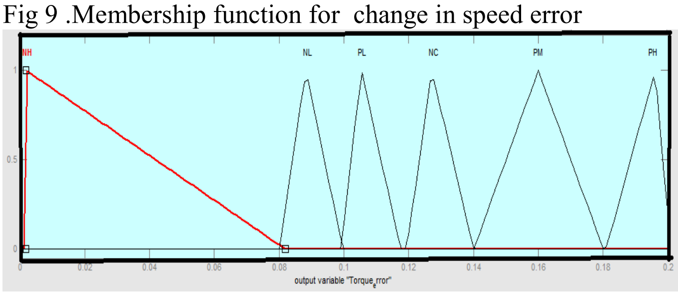

Fig 10 .Membership function for Electromagnetic Torque

Table 4 Rule Base Table

$\Delta\omega$ e / ω e	NH	NL	ZE	PL	PH
NE	NH	NL	NC	PM	PH
ZE	NH	NL	NC	PM	PH
PS	NH	NL	PL	PM	PH

The rules used for the proposed FLC algorithms are as follows:

(i) if $\Delta\omega$ e is PH (Positive High), T_e is PH (Positive High).

(ii) if $\Delta\omega$ e is PL (Positive Low), T_e is PM (Positive Medium).

(iii) if $\Delta\omega$ e is ZE (Zero) and ω e is PS (Positive Small) T_e is PL (Positive Low).

(iv) if $\Delta\omega$ e is ZE (Zero) and ω e is not PS (Positive Small) T_e is NC (No change).

Simulation results:

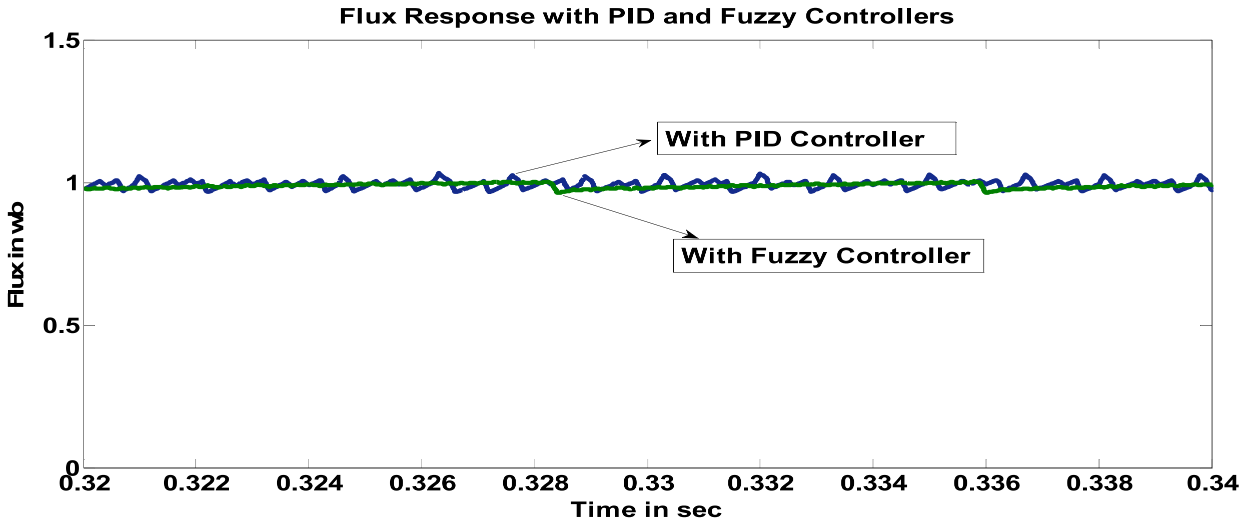

Fig 11. Flux ripples with PID and Fuzzy Controllers

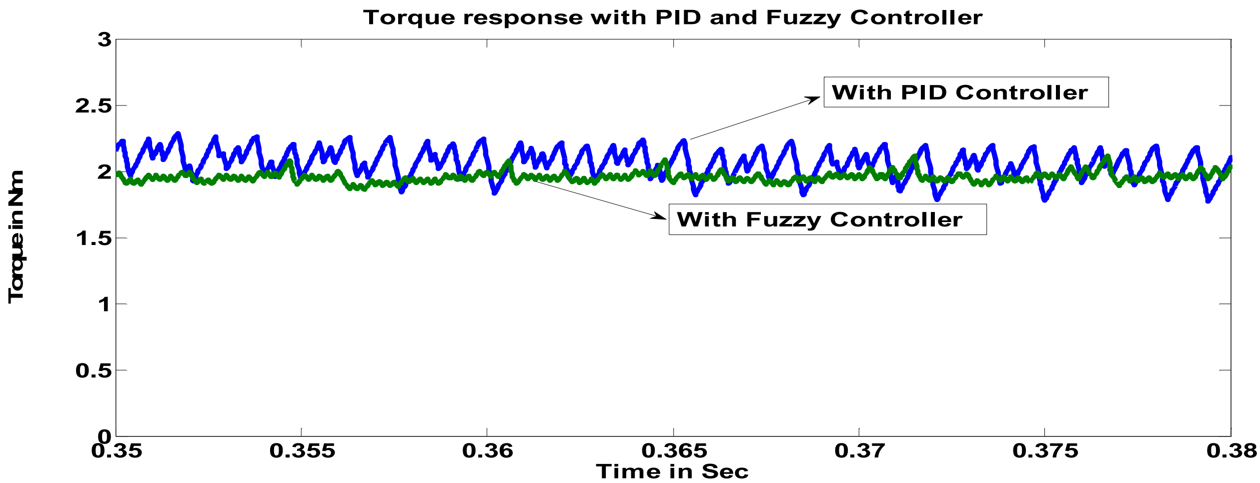

Fig 12. Torque ripples with PID and Fuzzy Controllers

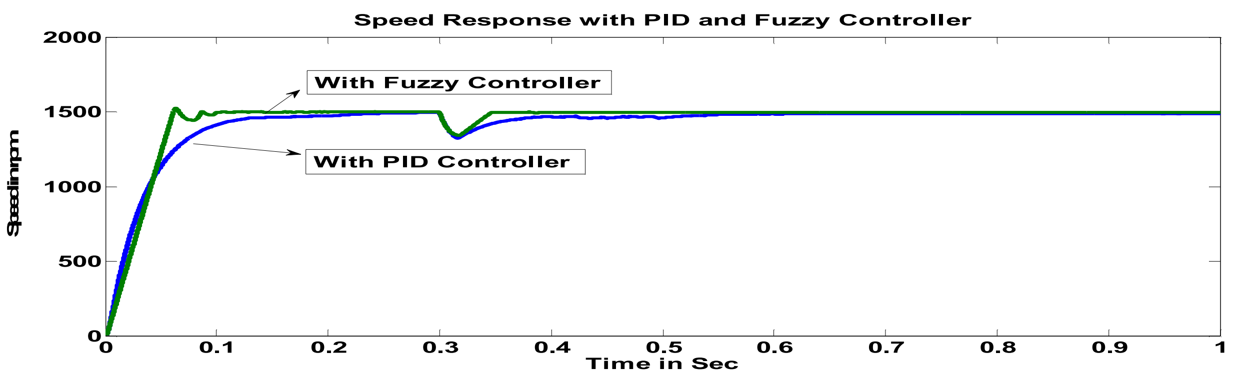

Fig 13. Flux ripples with PID and Fuzzy Controllers

(v) if Δ ω e is NL (Negative Low), T_e is NL (Negative Low).

(vi) if Δ ω e is NH (Negative high), T_e is NH (Negative high).

Based on the above rules the fuzzy rule base matrix is show in table 4. For the present works, Mamdani type fuzzy inference is used. The values of the constants, membership functions, fuzzy sets for the input output variables and the rules used in this paper are selected by trial and error to obtain the optimum drive performance.

Percentage of Torque Ripple can be calculated by using formula

$$\text{Torque Ripple \%} = (T_{max} - T_{min}) / T_{avg}$$

Ex: for Load Torque of 1.95 N-m

Summary of observation and analysis of torque ripple for the proposed control schemes

Table 4 for Torque Ripple Percentage

Load Torque(N-m)	Torque Ripple for Fuzzy Control	Torque Ripple for PI Control
1.95N-m	10%	19.5%

V. RESULTS AND DISCUSSION

The simulated responses of the drive are shown in fig 11.to13. For IPMSM with PID and Fuzzy controllers.

From these figures, one can observe that the starting performance as well as the response with a load disturbance. The drive system is started at no load condition with the speed reference set at 1500 rpm. It is seen from fig 11 that the proposed drive with FLC can follow the command speed within 0.08 sec with out any over shoot, under shoot and steady state error where as PID controller takes a long time to reach the steady state. At t= 0.3 sec , a load torque of 1.95 N-m is applied to the motor shaft in a step wise manner . In both the controllers the speed momentarily follows with load disturbances and immediately within no time reaches to the reference value. However with Fuzzy controller the drive reaches to the reference value faster than with PID controller.

From fig 12, the magnitude of the torque ripple with Fuzzy controller is less compared to the PID controller which is shown in Table 5. Similarly the magnitude of flux ripples are less with Fuzzy controller which is clearly shown in fig 13.

The proposed FLC based modified direct torque control of an IPMSM drive over PID controller has been investigated through simulation. The torque and flux ripples are reduced with FLC compared to PID controller. And the simulation results confirms that the proposed Fuzzy logic controller with simple design approach and smaller rule base can provide better performance comparing with the PID controller

APPENDIX

Parameters of the IPMSM Used

Number of pole pairs	p	2
Stator resistance	R_s	19.4 Ω
Magnetic flux linkage	λ_f	0.477 Wb
d-axis inductance	L_d	0.3875 H
q-axis inductance	L_q	0.4755 H
Phase voltage	V	145 V
Phase current	I	3 A
Base speed	ω_b	1500 rpm
Rated torque	T_b	1.95 Nm
Moment of Inertia	J	3.8e-3Kg-m2
Viscous Coefficient	B	1e-5
DC link Voltage	Vdc	848 V
Reference Flux	λ	1.7 Wb

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