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Performance Comparison of Six phase PMSM Drive system by Using Conventional PI and Fuzzy Logic controller

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Abstract
This Paper gives a comparative analysis between proportiona-integral(PI) controlled and Fuzzy logic controlled six phase PMSM drive system.The PI controller has some disadvantages like Overshooting, more settling time, sluggish response due to sudden change in load torque.So a new intelligent controller based on fuzzy logic is introduced to overcome the disadvantages of PI controller. The performance of both the controller has been investigated through Matlab/Simulink environment, for different operating conditions like No-load, steady load and Dynamic load. Finally, the results of both the controllers are compared and It is observed from the result that fuzzy logic based controller is robust and effective than the conventional PI controller for Six Phase PMSM drive system.

Keywords: PMSM, Multiphase, PI controller, Fuzzy logic controller,

1. Introduction

Now days Power Electronics has been widely used in many applicaton such as drive or as energy generation and conversion system.It is also said that elelctric machines with power electronics converter connected are now in a mature level. Even After, When it is about selecting a machine on the basis of reducing the current per phase without increasing the voltage per phase, reducing the rotor harmonic currents, reducing the amplitude and increasing the frequency of torque pulsations, and lowering the dc-link current harmonics and higher reliability, it is always the Multiphase variable speed drive [1] [2] [3] [4] [5]. Multiphase variable speed drive has received growing interest because of several advantages of multiphase and superiority of PMSM drive system over other drive system. This growing imterest is due to the fact that this machine can provide noticeable improvements in performance related to various aspects when compared to either three phase drive or six phase induction motor drive.

PMSM have the following advantages over the DC Motors [6] [7] [8] [9] :-

Less audible noise, longer life, Spark less (no fire hazard), higher speed, higher power density and smaller size, Better heat transfer.

PMSM have the following advantages over Induction Motors:-

Higher efficiency, Higher power factor, Higher power density for lower than 10 KW applications, resulting in smaller size, better heat transfer.

Two kinds of Six phase PMSM are available symetrical and asymetrical. The first is symmetrical machine in which stator windings are either 0^0 or 60° apart. Zero degree phase shift is similar to three phase system. The most common is asymmetrical machine. In this kind of machine, the stator winding is composed of two sets of 3-phase windings, which are spatially apart by 30° [10] [11] [12].

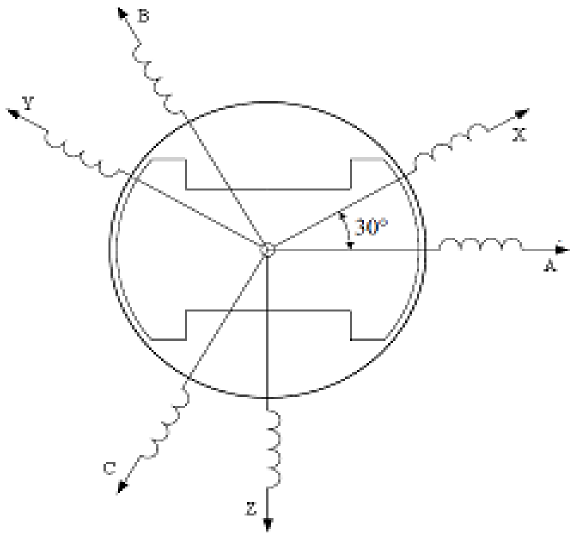


Fig. 1: Stator winding in asymmetrical machine.

Larger number of asymmetrical motor application is due to the fact that design of the symmetrical motor causes more interference in the individual phases. This paper concentrate on complete modeling and simulation of asymmetrical 6-phase PMSM drive system controlled by conventional PI controller and Fuzzy logic controller.

Vector control is one of the standard techniques used for the control of a six phase permanent magnet synchronous motor (PMSM) drive system. The outer speed loop in vector controlled PMSM drive greatly affects the drive performance. Therefore the electrical drives good dynamic performance is mandatory so as to respond the changes in command speed and torques. The Proportional –Integral controller is one of the traditional controller which is widely used in many drive system.It maintains a zero steady state error to a sudden step change in reference. Simultaneously P-I controller has some disadvantages mainly; the undesirable speed overshoot, long settling time, the sluggish response due to sudden change in load torque and the sensitivity to controller gains K_I and Kp.

These problems can be overcome by the fuzzy logic controllers whichdo not require any mathematical model and are based on the linguistic rules obtained from the experience of the system operator [13] [14].

2. Modeling of Six phase PMSM

The six phase permanent magnet synchronous machine has two identical, balanced, star connected assumed stator windings. Commonly, these sets of winding can have a phase shift of 0, 30 and 60 degrees. Zero degree phase shift is similar to three phase system. Sixty degree phase shift forms symmetrical arrangement and can be reduced to three phase system because two phases of different stars are always collinear. Thirty degree phase shift forms unsymmetrical arrangement which cannot be further simplified. The thirty degree phase shift arrangement is most favorable with respect to voltage harmonic distortion and torque pulsation Therefore, thirty degree phase shift between star connections is preferred in this paper [11] [12] assumptions are made to develop mathematical model such as negligible winding capacitance, each of the distributed winding may be represented by a concentrated winding, higher harmonics are absent, linear magnetic circuit and core losses are neglected [5] [15].

The phase voltage and flux linkage equations in the stationary reference frame for *ABC* winding and *XYZ* winding of six-phase PMSM are shown as:

$$V_{ABC} = R_S I_{ABC} + \frac{d\phi_{ABC}}{dt} \quad (1)$$

$$\phi_{ABC} = L_{11} I_{ABC} + L_{12} I_{XYZ} + \phi'_{MABC} \quad (2)$$

$$V_{XYZ} = R_S I_{XYZ} + \frac{d\phi_{XYZ}}{dt} \quad (3)$$

$$\phi_{XYZ} = L_{22} I_{XYZ} + L_{21} I_{ABC} + \phi'_{MXYZ} \quad (4)$$

Where R_s = diag $[R_s, R_s, R_s]^T$ is the stator resistance vector; V_{ABC}= $[V_A \ V_B \ V_C]^T$ is the phase voltage vector of ABC winding; I_{ABC}= $[I_A \ I_B \ I_C]^T$ is the current vector of ABC winding; V_{XYZ}= $[V_X \ V_Y \ V_Z]^T$ is the phase voltage vector of XYZ winding; I_{XYZ}= $[I_X \ I_Y \ I_Z]^T$ is the current vector of XYZ winding; $Ø_{ABC}$=$[Ø_A \, Ø_B \, Ø_C]^T$ is the stator flux linkage vector of ABC winding; $Ø_{XYZ}$=$[Ø_X \, Ø_Y \, Ø_Z]^T$ is the stator flux linkage vector of XYZ winding; $\mathbf{L_{11}}$ is the stator inductance vector of win ABC winding;L_{22} is the stator inductance vector of XYZ winding; $\mathbf{L_{12}}$ and $\mathbf{L_{21}}$ are the mutual inductance vectors; $Ø'_{MABC}$ is the permanent-magnet flux linkage vector of ABC winding; $Ø'_{MXYZ}$ is the permanent-magnet flux linkage vector of XYZ winding. In order to control the six-phase PMSM, the following Transformation matrixes have been used to transfer the above Equations into the synchronous rotating reference frame:

$$Tqd1 = \frac{2}{3}\begin{bmatrix} \cos\theta_e & \cos(\theta_e - 120^0) & \cos(\theta_e + 120^0) \\ \sin\theta_e & \sin(\theta_e - 120^0) & \sin(\theta_e + 120^0) \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{bmatrix} \quad (5)$$

$$Tqd2 = \frac{2}{3}\begin{bmatrix} \cos(\theta_e - 30^0) & \cos(\theta_e - 150^0) & \cos(\theta_e + 90^0) \\ \sin(\theta_e - 30^0) & \sin(\theta_e - 150^0) & \sin(\theta_e + 90^0) \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{bmatrix} \quad (6)$$

Where T_{qd1} is the transformation matrix for *ABC* winding; T_{qd2} is the transformation matrix for *XYZ* winding; θ_e is the rotor flux angle. Moreover, the machine model of a six-phase PMSM can be described in synchronous rotating reference frame as follows:

$$v_{q1} = R_s I_{q1} + L_{q11}\frac{dI_{q1}}{dt} + \omega_e (L_{d11} I_{d1} + \phi_{PM}) \quad (7)$$

$$v_{d1} = R_s I_{d1} + L_{d11}\frac{dI_{d1}}{dt} - \omega_e L_{q11} I_{q1} \quad (8)$$

$$v_{q2} = R_s I_{q2} + L_{q22}\frac{dI_{q2}}{dt} + \omega_e (L_{d22} I_{d2} + \phi_{PM}) \quad (9)$$

$$v_{d2} = R_s I_{d2} + L_{d22}\frac{dI_{d2}}{dt} - \omega_e L_{q22} I_{q2} \quad (10)$$

$$\omega_e = \frac{P}{2}\omega_r \quad (11)$$

Where v_{d1} and v_{q1} are the *d-q* axis voltages of *ABC* winding;v_{d2} and v_{q2} are the *d-q* axis voltages of *XYZ* winding; i_{d1} and i_{q1} are the *d-q* axis currents of *ABC* winding; i_{d2} and i_{q2} are the *d-q* axis currents of *XYZ* winding; L_{d11} and L_{q11} are the *d-q* axis inductances of *ABC* winding; L_{d22} *and* L_{q22} are the *d-q* axis inductances of *XYZ* winding; ω_r is the rotor angular velocity; ω_e is the electrical angular velocity; $Ø_{PM}$ is the permanent magnet flux linkage; P is the no. of pole pairs of six phase PMSM. As assumed that winding sets are identical (L_{q11}=L_{q22}= L_q and L_{d11}=L_{d22}= L_d). Furthermore, the developed electric torque *Te* can be represented by the following equation:

$$T_e = \frac{3}{2}\frac{P}{2}\left[\phi_{PM}\left(I_{q1} + I_{q2}\right) + \left(L_d - L_q\right)\left(I_{d1}I_{q1} + I_{d2}I_{q2}\right)\right] \quad (12)$$

However, the electromagnetic torque cannot be estimated accurately in a general case without knowledge of the currents of both winding sets and the inductance parameters that describe the magnetic coupling between them. In addition, the mechanical dynamic equation of the six-phase PMSM is:

$$T_e = J\frac{d\omega_r}{dt} + B\omega_r + T_L \quad (13)$$

Where *J* is the inertia of six-phase PMSM; *B* is the damping Coefficient; T_L *is* the load torque[4] [12] [15] The machine parameter for the above modeling is given in table:1 [12] [16]

TABLE: 1 Machine Parameter

S.NO.	*NAME*	*RATING*
1.	Nominal voltage V_n	380 volts
2.	Nominal speed n_n	350RPM(36.5rad/s)
3.	No. of Poles	8
4.	Stator Resistance Rs	0.64 ohm
5.	PM flux Linkage $Ø_{PM}$	2.04 wb
6.	L_d, L_q	24mH,31.4mH
7.	Inertia J	.014Nm/(rad/sec^2)
8.	Damping coefficient B	.0124Nm/(rad/sec)

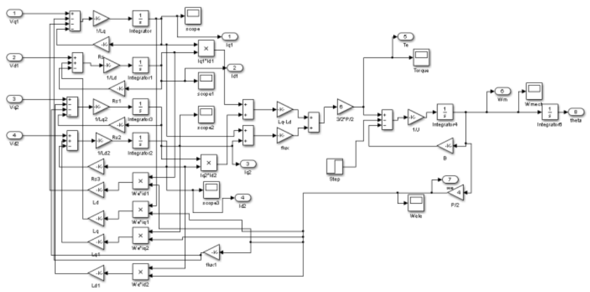


Fig. 2: Matlab/Simulink model for Six Phase PMSM.

3. Controller schemes

The difference between the desired input (ωm_{ref}) and the actual output ($\omega m_{act.}$) is a variable $\Delta\omega r$ which is known as tracking error.this tracking error signal is send to controller which generates iq* known q-axis command current.this output of controller and id*(=0)are transformed to ABC and XYZ current command using inverse park's transform.These command currents are now compared with the actual currents to generate the PWM signal which will than fire the semicinductor devices to produce actual voltages for Six Phase motor to operate properly.

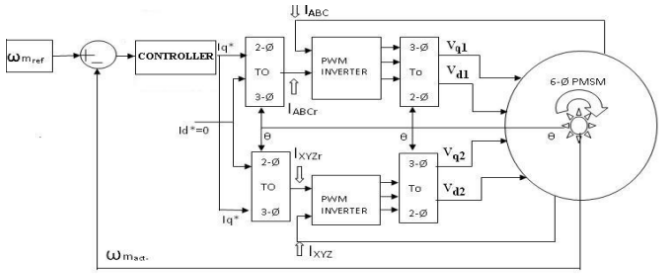


Fig:3 Block Diagram Of Six Phase PMSM drive

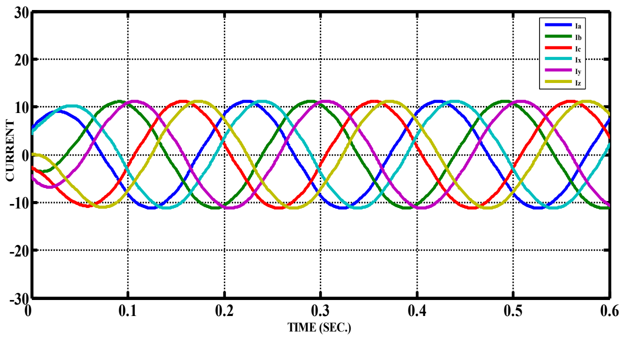


Fig:4 General Six Phase Current

3.1 Proportional-Integral controller (PI)

The PI controller produces an output signal consisting of two terms-one proportional to input signal and the other proportional to the integral of input signal. The concerns of PI controller in the system are to reduce the steady state error and increased the order and type of the system by one which is shown in Fig.5.

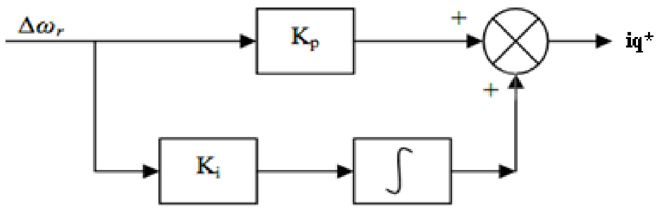


Fig.5: PI controller

Transfer function $PI = K_p + \frac{K_i}{S}$ (14)

$$i_{q*} = K_p \Delta\omega_r + K_i \int \Delta\omega_r dt \quad (15)$$

This iq* is than sent further in the system to control the operation of Six Phase PMSM drive system as shown in block diagram in Fig:2 For tunning of PI controller Closed Loop Ziegler-Nichols Method is used. Since it is trial and error method it is time consuming. After seeing the improvements in response of the model, the most suitable value of Kp and Ki is chosen. [17] [18].

3.2 Fuzzy Logic Controller

Initially the fuzzy input vector should be defined. It consists of two variables; the speed error $e(t) = \omega_{ref} * -\omega_{mact}$ and its derivative $\frac{d[e(t)]}{dt} = \frac{d}{dt}(\omega_{ref} * -\omega_{mact})$. A fuzzy set for input and output variables is designed. Fig; 4(a) and Fig; 4(b), shows the 7 linguistic variables used for each fuzzy input variable, while the output variable fuzzy set is shown in Fig:5. The linguistic variables used for inputs shown are PS(Positive Small), PM (Positive Medium); PB (Positive Big); ZE (Zero); NB (Negative Big); and NM (Negative Medium), NS(Negative Small) The same LV's are used for the output fuzzy set.A look-up table is required to develop the set of rules, in which the relation between the input variables, e(t) and d[e(t)}/ dt] are defined and the output variable of fuzzy logic controller can be obtained 16. To define the control rules, the results from PI controller give an opportunity and guidance for rule justification Therefore after thorough series of analysis; the total 49 rules have been justified as shown in Table 2 This look-up table:2 is used in the simulation program [16] [19] [20] [21].

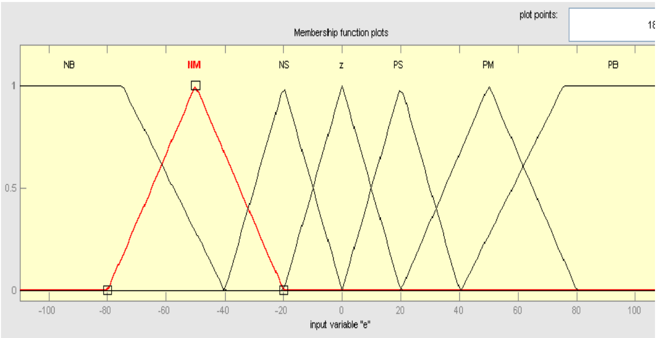
The Input/output depends on the fuzzy rule expressed as follows;

If(E is NB AND CE is NB) THEN Iq* is NB. If (E is Z AND CE in PS) THEN Iq* is PS

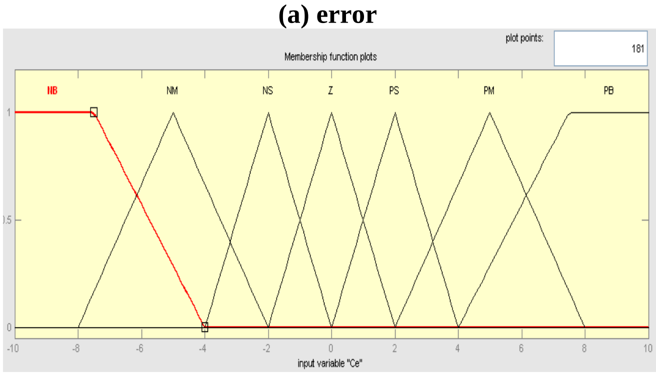
In total 49 fuzzy rules are made to meet the goal.

TABLE:2 Fuzzy Rule look up table

CE / E	NB	NM	NS	Z	PS	PM	PB
NB	NB	NB	NB	NB	NM	NS	Z
NM	NB	NB	NB	NM	NS	Z	PS
NS	NB	NB	NM	NS	Z	PS	PM
Z	NB	NM	NS	Z	PS	PM	PB
PS	NM	NS	Z	PS	PM	PB	PB
PM	NS	Z	PS	PM	PB	PB	PB
PB	Z	PS	PM	PB	PB	PB	PB



(a) error



(b) change in error

Fig:6 (a),(b) Membership function plots, The Input error 'e' and change in error 'Δe'

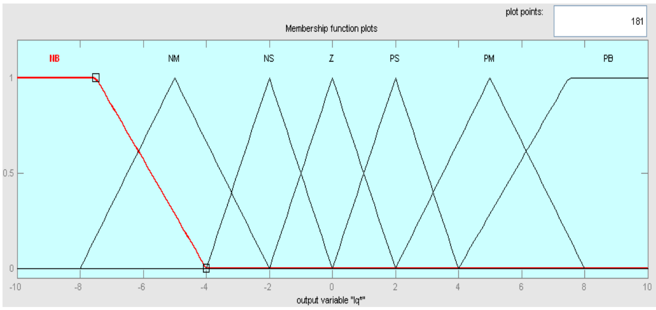


Fig:7 Membership function plot for Output variable iq*

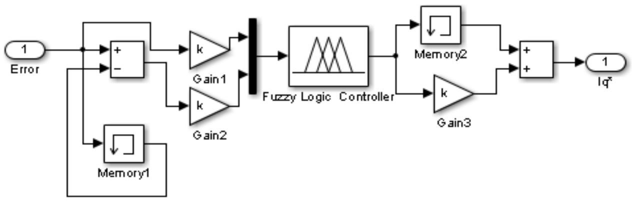


Fig:8 Fuzzy Logic Based Controller

4. Result and Discussion

4.1 Case I: Under No-Load Condition:-

The proposed model is simulated at no-load (T_L = 0) and at rated reference speed (ω_r = 36.5 rad/sec.). Fig.9 and Fig::10 shows the rotor speed, torque response of both the proposed scheme.

The simulation results show that settling time for PI controller is 0.045sec and for Fuzzy controller is 0.02sec.The proposed model is run for 0.15 sec.

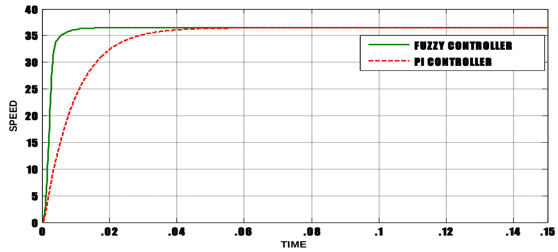


Fig:9 Speed response at No-Load (T_L=0)

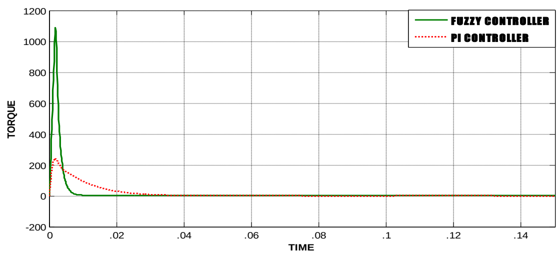


Fig:10 No-Load Torque response (T_L=0)

4.2. Case II: Steady State Operation: (Load Torque Is Fixed)

The model is simulated at load Torque (T_L=50 N-M) and at rated speed (ω_r = 36.5 rad/sec.). Fig:11 and Fig:12 shows, rotor speed and torque response respectively, of both the proposed scheme.

The simulation results show that at 0.02sec. Speed and Torque reaches, it's Set value for Fuzzy controller, and for PI controller the settling time is delayed at 0.08 sec. The proposed model is run for 0.15 sec.

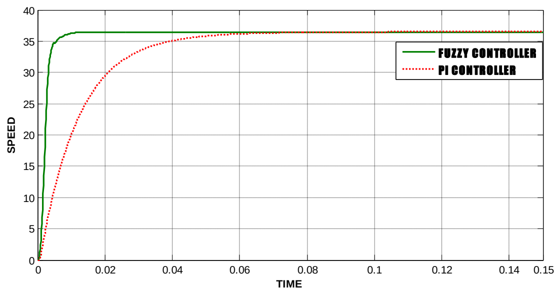


Fig:11 Speed response at load Torque (T_L=50N-M)

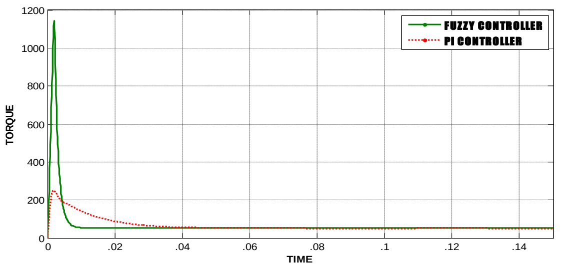


Fig:12 Torque response at load Torque (T_L=50N-M)

4.3 Case III: Dynamic operation:

The model has been simulated for dynamic load operation, load torque is initially set to zero and at 0.1sec.load torque is suddenly changed to 150 N-M. Fig:13 and Fig:14 shows that When load Torque is applied suddenly at 0.1sec.(from T_L=0 to T_L=150N-M). In PI controller the speed falls very heavily (25.5rps).The recovery time of rotor speed to come back to rated speed(36.5rps) after applying load torque (at 0.1sec.) is after 0.08sec. While in Fuzzy controller the speed falls very slightly (35.6 rps) and recovers very fastly (after.004sec).

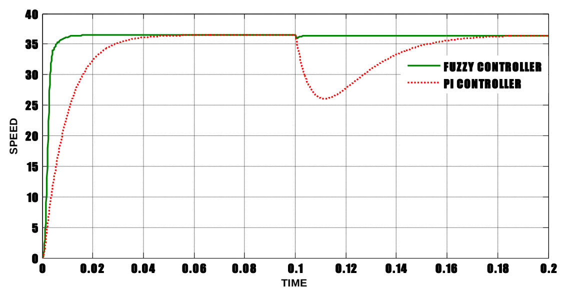


Fig:13 Speed response at dynamic load torque

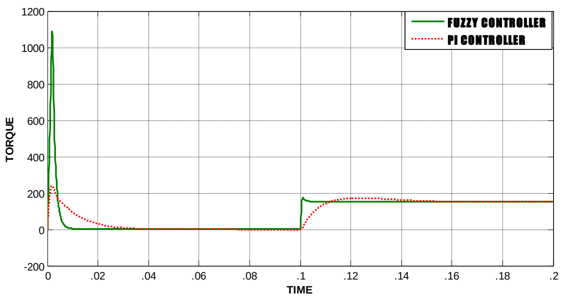


Fig:14 Torque response at dynamic load

5. Conclusion

This paper shows the designing & performance of conventional PI controller & Fuzzy logic controller. In fuzzy control it is not necessary to change the control parameters as the reference speed changes, however with the classical PI controller this does not happens. The simulation results under different load conditions, shows that of speed and torque responses are better in Fuzzy logic based controller as compared to PI controller. Under different load conditions the settling of rated speed and torque is quick in fuzzy logic controller. it is also seen from the torque diagram that fuzzy controller gives high starting torque to that of conventional PI controller. With results obtained from simulation, it is clear that for the same operating condition the PMSM drive control using fuzzy controller technique had better performance than the conventional PI controller.

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