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Article

Analysis and investigation of PID, Fuzzy PD, Fuzzy PI Speed Controlled DC motor

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Abstract: This paper deals about mathematical model and analysis of PID/Fuzzy PD/Fuzzy PI controlled DC motor drives. Dynamic responses of speed, torque, current and the time domain specification of speed response are simulated and analyzed using simulink toolbox of MATLAB environment for the above controllers. From the simulation results, it shows that Fuzzy PI controller is outperformed than other controllers.

Keywords: DC Motor; Electric Drive Simulation; Fuzzy PI controller; Fuzzy PD controller; Matlab/Simulink; Proportional Integral Derivative controller.

1. Introduction

Now days, DC motors are applied into electric traction and electric vehicle applications. The torque –speed characteristics of the DC motor are more suitable and compatible with along kind of mechanical loads. The speed of the DC motor is controlled easily but speed control is more complex in AC motor and control of speed from low speed to above rated speed can be easily achieved by DC motor. Recent industrial automation applications include precise control of velocity and rotor position in DC motor. Various types of advanced controllers have recently been developed to increase the speed efficiency of the DC motor drives. Various simulink prototypes are produced using Fourier transform; state space model and variable structure model for the study of DC motor controls have been developed and investigated in [1].

From last four decades, industries are equipped with advanced process control techniques. Different variety of controllers such as conventional PID controller, neural network controller, variable structure controller, sliding mode controller and adaptive controller has been extensively investigated. Among them, the conventional PID controller is best suited controller in today industries; this has been extensively utilized by the manufacturing industries due to its robust behavior in all operating conditions and simple construction and easy to implement using low cost microcontrollers [2]. Although PID controller performance not satisfactory during abrupt change in operating conditions of the industrial load.

Various artificial intelligent controls has been developed and widely utilized to enhance or to replace the PID controller techniques because most artificial intelligent techniques do not need an exact transfer function model of the system. Fuzzy logic control is basic artificial intelligent technique and it was developed by Zadeh [3]. It has been applied as a controller in electrical drives applications [4]. The fuzzy logic controller is known as nonlinear controller because this controller uses the nonlinear defuzzification method [5]. In addition, the consequences from the assessments of classical controller and fuzzy logic controllers in the structure of the fuzzy compensator and FLC [6] illustrated that nonlinearity DC motor is effectively eliminated by the fuzzy logic control and improve speed output of the dc motor drives.

Comparative evaluation of Fuzzy Proportional integral controller, fuzzy proportional derivative controller are examined in experimentally in [7, 8] and comparative investigation between Fuzzy based PI controller, Fuzzy based PID controller and conventional PID controller is described for non-linear, linear and time-delay transfer function models [9]. The comparative analysis of defuzzification methods in fuzzy logic control with various fuzzy logic control structure is explained for time-invariant transfer function model and it was justified that the centroid defuzzification technique has better performance in non-linear transfer function system [10]. From the literature review, the Fuzzy logic control is the most advantageous system for electric DC motors.

In this paper mathematical model of PID/Fuzzy PD/Fuzzy PI controlled DC motor has been presented. The performance indexes i.e., steady state error, settling time, rise time, recovery time and percentage peak overshoot are evaluated for the PID, Fuzzy PD and Fuzzy PI controlled DC motor. This paper is organized as given below. DC motor electrical drive strategy is proposed in the proceeding section. In section 3, control development for PID, Fuzzy based PI and Fuzzy based PD controller is specified. The simulation results investigation is explained in section 4. Controller advantages and paper conclusion are outlined in section 5.

2. DC Motor Drive strategy

The schematic electric circuit of a DC drive is illustrated in Figure 1. Its fundamental equations governing the function of the armature-controlled DC motor are as follows in Eq. (1) [11-12],

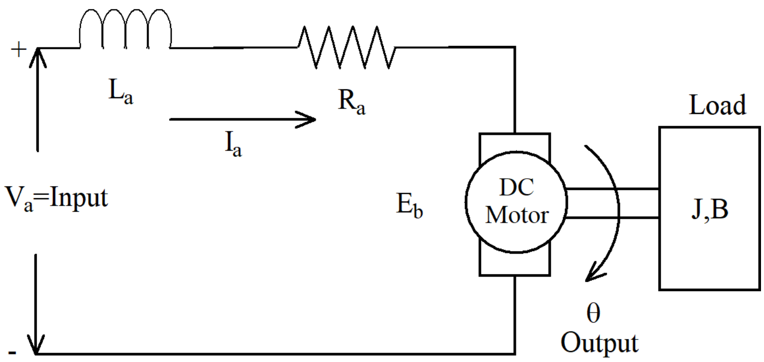

Figure 1. Schematic diagram of a DC motor.

$$i_a R_a + L_a \frac{di_a}{dt} + e_b = V_a \tag{1}$$

Where armature current is denoted by i_a, armature resistance denoted by R_a, armature inductance denoted by La, back emf of the motor denoted by e_b and motor terminal voltage denoted by V_a.

Torque of the dc motor is depending on armature current of the motor and field flux of the motor. Normally, in permanent magnet DC motor has constant flux and the torque produced by the motor is depends only on armature current (i_a) alone and it is expressed in Eq. (2),

$$T = K_t * i_a \tag{2}$$

Where K_t is torque constant.

The mechanical dynamics of the dc motor are related with differential equation and it relates the electromagnetic torque, moment of inertia and friction coefficient of the motor and expressed by the following Eq.(3),

$$J\frac{d^2\theta}{dt^2}+B\frac{d\theta}{dt}=T \tag{3}$$

Where J denotes the moment of inertia, θ denotes the angular rotor position and B denotes the frictional coefficient of the motor.

The back emf of DC motor is proportional to shaft speed and it is expressed in Eq. (4),

$$e_b=K_b*\frac{d\theta}{dt} \tag{4}$$

Where Kb is back emf constant. With zero initial condition, Laplace transform of the above-mentioned system differential equations is given in Eq. (5),

$$\frac{\theta(s)}{V_a(s)}=\frac{K_t}{\left(R_a+sL_a\right)\left(Js^2+Bs\right)+\left(K_bK_ts\right)} \tag{5}$$

The control system representation of the armature controlled electrical dc drive is depicted in Figure 2.

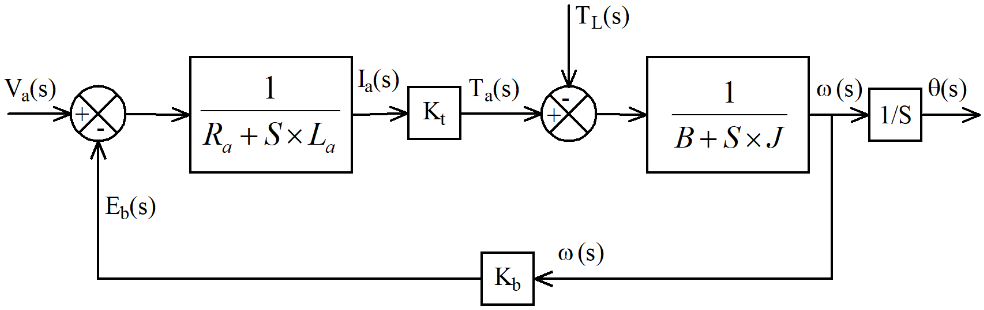

Figure 2. Block diagram of armature controlled DC motor.

3. Control Development

In this section, mathematical model of PID, Fuzzy based PD and Fuzzy based PI controller is explained.

3.1. PID Controller

The transfer function representation of the PID controlled DC motor drive is depicted in Figure 3. The mathematical model in time domain is expressed in Eq. (6),

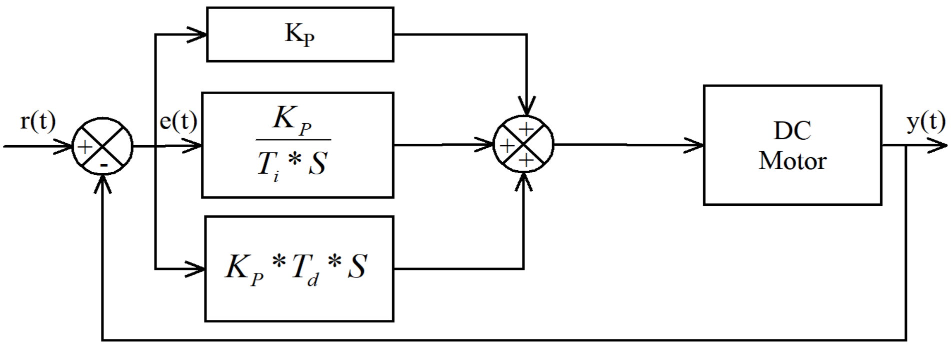

Figure3. Transfer function representation of PID controlled DC motor drive.

$$u(t) = K_P\left[e(t) + \frac{1}{T_i}\int_0^t e(t) + T_d \frac{de(t)}{dt} \right] \quad (6)$$

Where, the error signal is denoted by e(t), the controlled voltage of the motor is denoted by u(t), the proportional parameter is represented by K_P, the integral parameter is signified by $K_i=K_P/T_i$ and the derivative parameter is denoted by $K_d=K_PT_d$. The proportional controller enhances the system by improving control precisions. In addition, it produces stability problem due to higher gain value. The Integrated Controller removes the steady state error in the speed response. The derivative controller improves the motor's transient state response.

3.2. Fuzzy Based PD Controller

The control system representation of the fuzzy based PD controlled dc motor drive is depicted in Figure 4. Fuzzification, input normalization factor, fuzzy inference system, rule base, defuzzification and output denormalization factor are the element of the Fuzzy based PD controller. The rate of change of speed error and value of speed error are input for fuzzy based PD controller and controlled voltage is output from the controller [13].

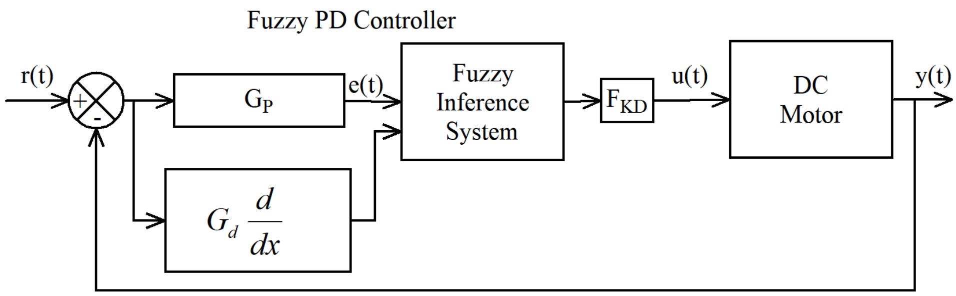

Figure 4. Control system representation of Fuzzy based PD controlled dc motor drive.

The mathematical model for Fuzzy based PD controller in time domain is expressed in Eq. (7),

$$u(t) = \frac{1}{M}\left[G_P e(t) + G_d \frac{de(t)}{dt} \right] \quad (7)$$

Where M denotes the universe range, G_P and G_d denote the input normalization factor. Input variables are fuzzified and output variable is defuzzified and control output from the controller is represent by following Eq. (8),

$$u(t) = F_{KD} * MD\left\{ F\left\{ \frac{1}{M}\left[G_P e(t) + G_d \frac{de(t)}{dt} \right] \right\} \right\} \quad (8)$$

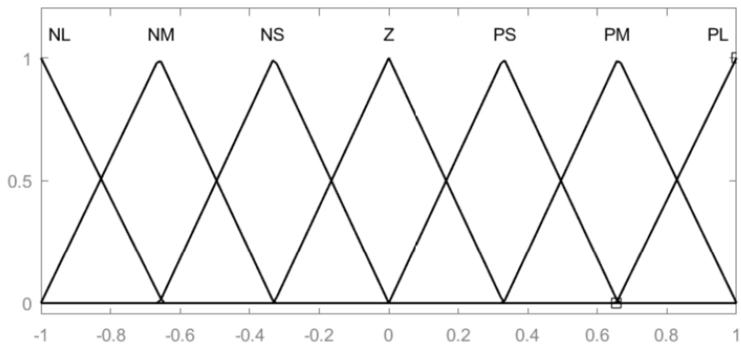

Figure 5. Membership functions for e(t), ce(t) and u(t).

Where F_{KD} denotes the denormalization, MD denotes the defuzzification of the output and F denotes the Fuzzification of input. Membership function for input and output is depicted in Figure 5. The rule surface for Fuzzy based PD controller is depicted in Figure 6.

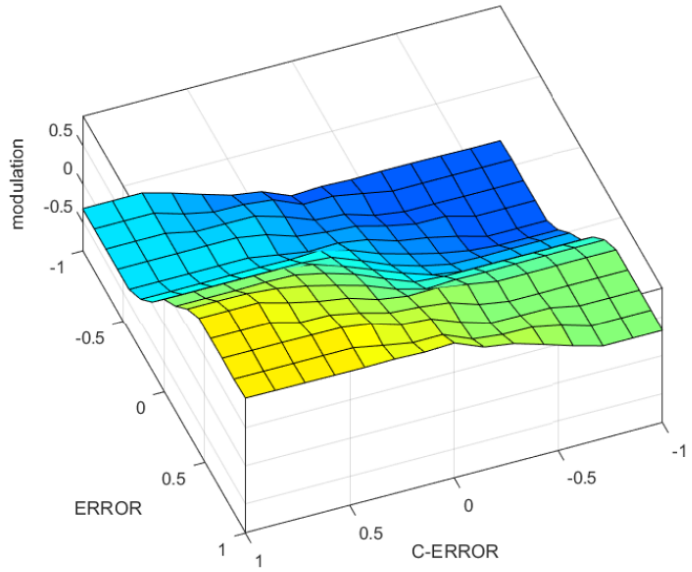

Figure 6. Fuzzy based PD controller rule surface

3.3. Fuzzy Based PI Controller

The identical design procedure applied to the fuzzy based proportional integral controller as in design steps of fuzzy based PD controller. Fuzzy based PI controlled dc motor drive is depicted in Figure 7.

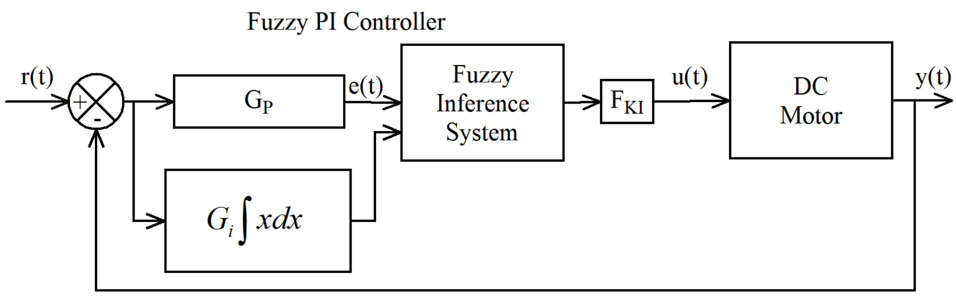

Figure 7. Control system representation of Fuzzy based PI controlled dc motor drive.

The time domain mathematical model of Fuzzy based PI controller is expressed by the resulting Eq. (9),

$$u(t) = \frac{1}{M}\left[G_P e(t) + G_i \int e(t)dt \right] \tag{9}$$

Where M denotes the universe range, G_P and G_i denote the input normalization factor. Input variables are fuzzified and output variable is defuzzified and control output from the controller is represent by following Eq. (10),

$$u(t) = F_{KI} * MD\left\{ F\left\{ \frac{1}{M}\left[G_P e(t) + G_i \int e(t)dt \right] \right\} \right\} \tag{10}$$

Where F_{KI} denotes the denormalization, MD denotes the defuzzification of the output and F denotes the Fuzzification of input. Membership function for input and output is depicted in Figure 5. The rule surface of the Fuzzy based PI controller is depicted in Figure 8.

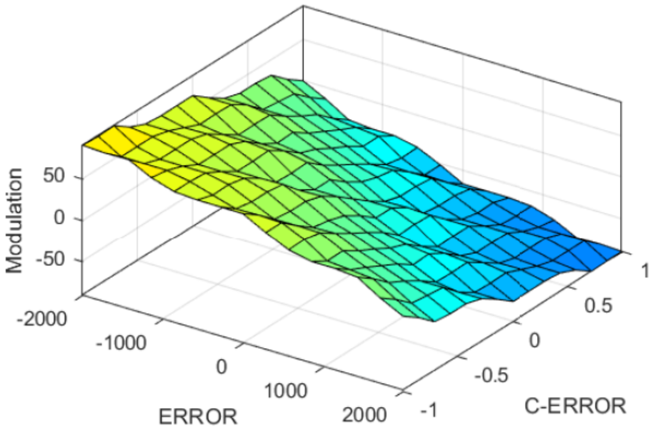

Figure 8. Fuzzy based PI controller rule surface

4. Simulation Results and Investigations

Digital simulation models were generated using MATLAB / SIMULINK to test the performance of the established controller and also system performances are analysed under different operating conditions of the dc motor drive. The dc motor, PID controller, Fuzzy PD controller and Fuzzy PI controller specification used for simulation is shown in Table 1.

Table 1. The specification of DC Motor, PID Controller, Fuzzy PD and Fuzzy PI Controller

Specifications	Value	PID Controller	Fuzzy PD Controller	Fuzzy PI Controller
Resistance of the armature (Ra)	2 Ω	-	-	-
Inductance of the armature(La)	0.1(H)	K_p=0.1	G_P=0.5	G_P=0.5
Back emf constant	0.3 (V/(rad/sec))	-	-	-
Torque Constant	1 (Nm/A)	K_i=0.2	G_d=1.3	G_i=0.6
Moment of Inertia	0.11(Kg-m2/rad)	-	-	-
friction factor	0.011(N-M/(rad/sec))	K_d=0.1	F_{KD}=0.64	F_{KI}=0.78
Rated Load Torque	20 Nm	-	-	-
Rated Power	2000 Watts	-	-	-

Table 2. The Performance indexes at no load condition

Parameters	PID	Fuzzy PD	Fuzzy PI
Rise time(sec)	1.07	0.1	0.9
Settling time(sec)	4.75	0.4	1
Peak over shoot (%)	6.74	20	2
Steady state error (rad/sec)	0.2	0.35	0.1

Figure 9 shows the simulation result of dc motor Speed, torque and current response of DC motor Drive for the rotor speed at 100 rad/sec. Performance indexes like rise time, peak over shoot, settling time and steady state error for speed response at no load condition is evaluated and tabulated in Table 2.

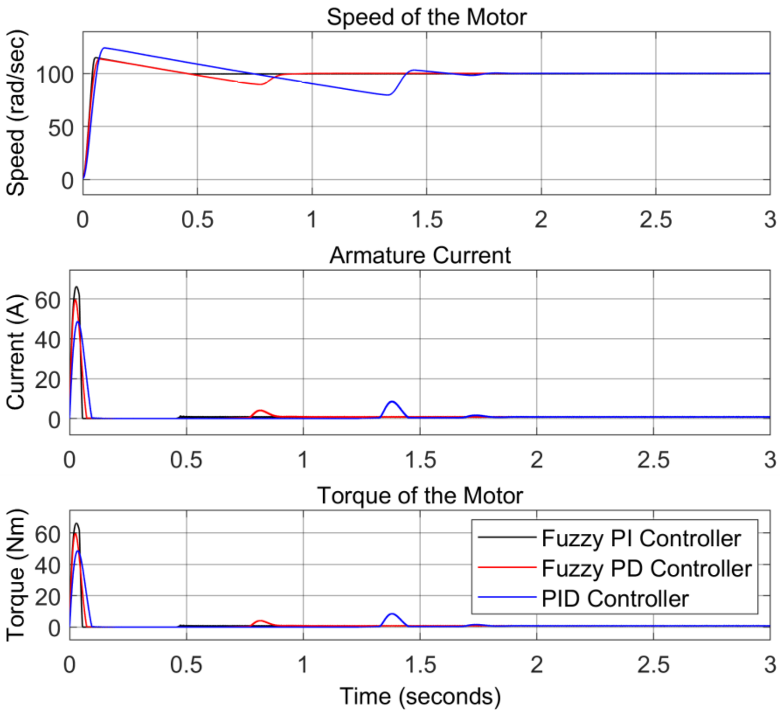

Figure 9. DC motor Speed, torque and current response at 100 rad/sec

Figure 10 shows the simulation result of dc motor Speed, torque and current response of drive when load shifted from no load to rated load after 5 sec. Performance indexes like steady state error, peak over shoot and recovery time for system response is evaluated and mentioned in Table 3.

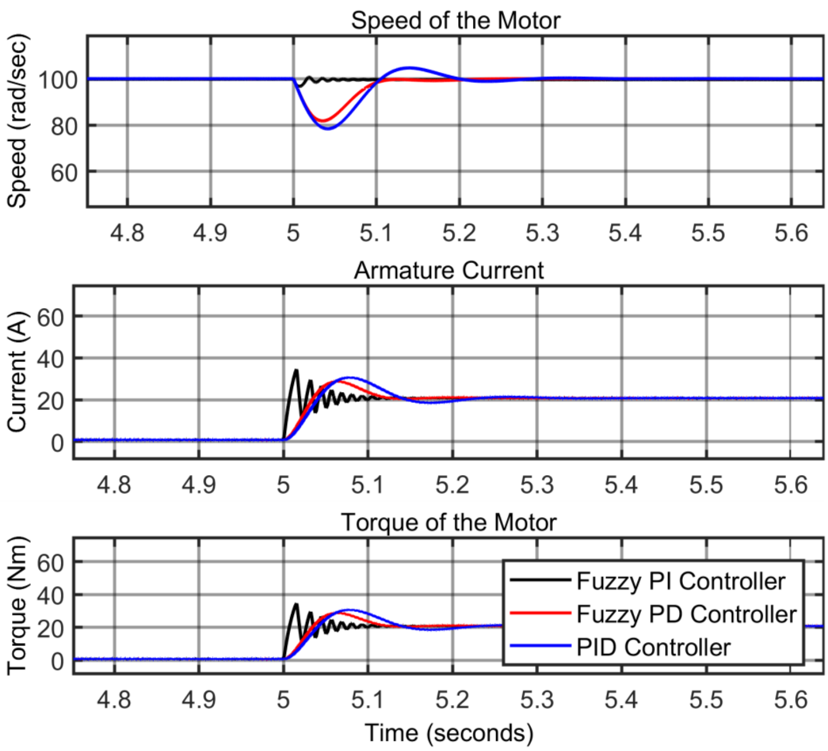

Figure 10. DC motor Speed, torque and current response for load change from no load to rated load condition.

Table 3. The Performance indexes at load shifted from no load to rated load condition

Parameters	PID	Fuzzy PD	Fuzzy PI
Peak over shoot (%)	25	3	1
Steady state error (rad/sec)	0.3	0.35	0.1
Recovery time (sec)	9	5.1	5.2

Figure 11 shows the simulation result of dc motor Speed, torque and current response of Drive when load is shifted from rating load to no load after 5 seconds. Performance indexes such as steady state error, peak over shoot and recovery time for system response is evaluated and these values are given in Table 4.

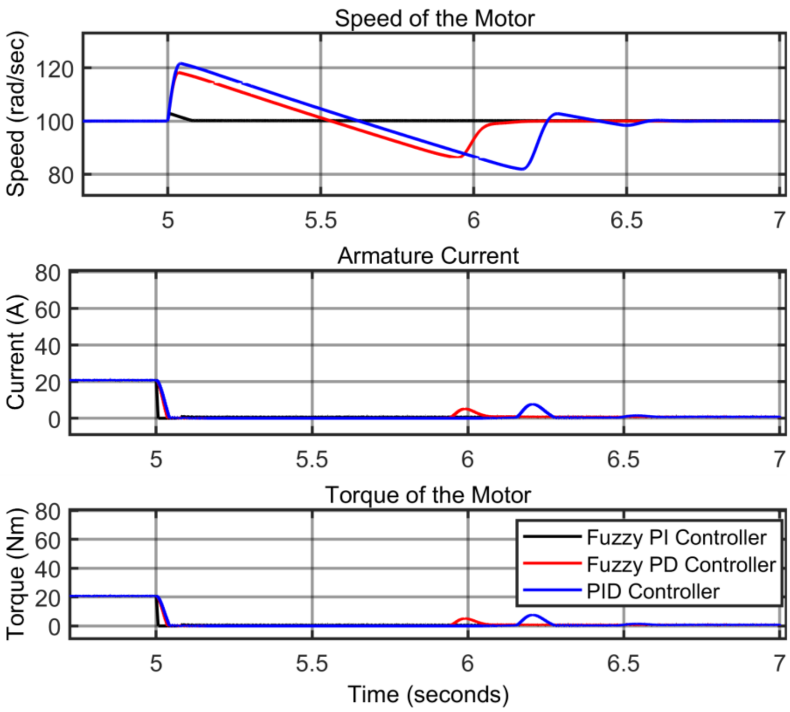

Figure 11. DC motor Speed, torque and current response when load shifted from rated load to no load condition.

Table 4. The Performance indexes at load shifted from rated load to no load condition

Parameters	PID	Fuzzy PD	Fuzzy PI
Peak over shoot (%)	23	3	2
Steady state error (rad/sec)	0.25	0.3	0.2
Recovery time (sec)	8	5.2	5.3

Figure 12 shows the simulation result of Speed, torque and current response of DC motor Drive when angular speed shifted from 100 rad/sec to 75 rad/sec after 5 sec. Performance indexes like steady state error, peak over shoot and recovery time for response is evaluated and mentioned in Table 5.

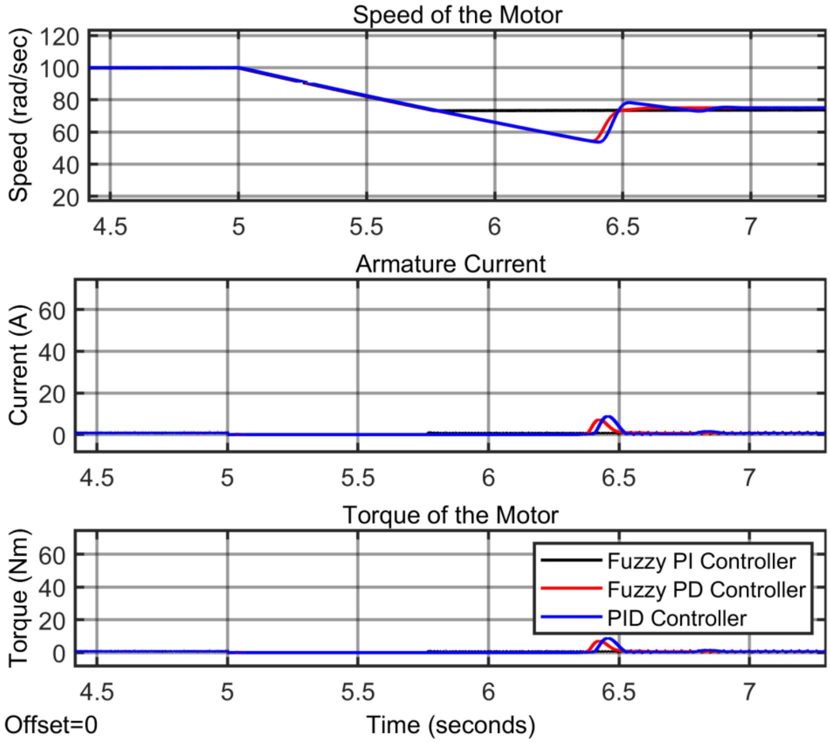

Figure 12. DC motor Speed, torque and current response when angular speed shifted from 100 rad/sec to 75 rad/sec.

Table 5. The Performance indexes at angular speed shifted from 100 rad/sec to 75 rad/sec

Parameters	PID	Fuzzy PD	Fuzzy PI
Peak over shoot (%)	3	3	1
Steady state error (rad/sec)	0.2	0.3	0.1
Recovery time (sec)	7	5.1	5.2

Figure 13 shows the simulation result of Speed, torque and current response of DC motor Drive when angular speed shifted from 75 rad/sec to 100 rad/sec after 5 sec. Performance indexes like peak over shoot steady state error and recovery time for speed response is evaluated and mentioned in Table 6.

Table 6. The Performance indexes at angular speed shift from 75 rad/sec to 100 rad/sec

Parameters	PID	Fuzzy PD	Fuzzy PI
Peak over shoot (%)	6.74	4	1
Steady state error (rad/sec)	0.2	0.35	0.1
Recovery time (sec)	8	5.1	5.3

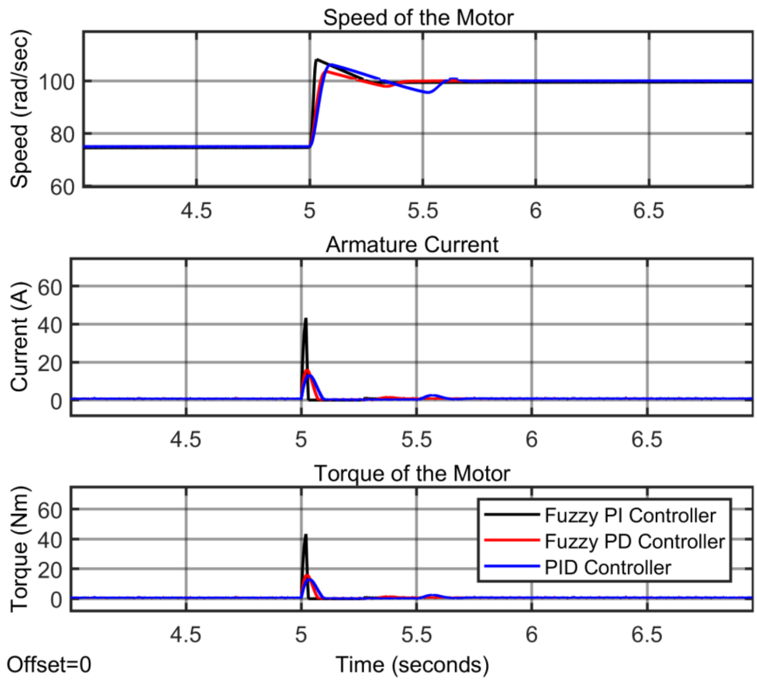

Figure 13. DC motor Speed, torque and seed current response when angular speed shifted from 75 rad/sec to 100 rad/sec.

From the Table 2 to Table 6, it shows that peak over shoot, steady error, settling time and recovery time for speed response under Fuzzy PI controller gives good results than other two controllers.

5. Conclusions

In this study, a detailed analysis of DC motor drive system has been carried out by using PID, Fuzzy PD and Fuzzy PI Controller. The simulation model implemented modularly under MATLAB / SIMULINK framework allows for successful consideration of several dynamic characteristics such as speed, torque, and speed error. In addition, the control algorithms, Fuzzy Logic Controllers, and PID controllers were compared using the model developed. The results show that Fuzzy PI controller improves the performance indexes and also maintain stability of the system than PID and Fuzzy PD controller.

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